WASTE TO ENERGY POTENTIAL ASSESSMENT: CASE STUDY OF NDOLA

By

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DECLARATION

I, **Wildie Mutelo,** declare that this dissertation submitted in completion of the Master in Renewable Energy Engineering is entirely my own work, and further declare that all sources have been accredited in the text and references.

Signed: ……………………………………………………

Date: ………………………………………………………

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DEDICATION

I dedicate this work to my family. Without their sacrifice, understanding, support, and most of all love, the completion of this work would not have been possible.

ABSTRACT

Waste to Energy is a Suitable option for municipal Solid Waste Management and a source of renewable energy. Generation of massive waste due to population growth and urbanization and an energy down turn in Zambia particularly Ndola is a daunting task for the city. The purpose of this study was to assess the potential for waste to energy generation in Ndola. To achieve this, the study assessed disposal methods used and waste composition in the city of Ndola in Zambia.

The demographic characteristic of the study was drawn from Ndola with respondents from Ndola city council, independent Waste pickers, Informal waste pickers and selected housing units across the city compromising of High cost , medium cost and Low cost.

To answer to the objectives the study, the researcher employed a survey approach with simple random sampling method where qualitative as well as quantitative survey questionnaires were used to gather data, and entered into Statistical Package for Social Sciences (SPSS), then tabulated and analysed using Excel and presented in percentages, frequencies, cross tabulation and correlation

The Waste to Energy (WtE) opportunities in Ndola were carried out in the context of simulating two scenarios: Biomethanation and Incineration. The Intergovernmental Panel for Climate Change (IPCC) default model was presented to estimate emission of methane from municipal solid waste at kaloko landfill site Ndola, Zambia. Findings revealed that the estimated Net Annual methane emission potential from solid waste landfills was 22.09 (Gg/yr.) in the year 2015, giving a net power Generation Potential of 7.57MW.The maximum methane production rate by the IPCC default model was calculated to be 32.2(Gg/yr.) and was observed during the year 2035, giving a Net Power Generation Potential of 11.07MW. The power generation potential for Ndola was estimated at 21MW in the year 2015 resulting in Energy Generation Potential of 0.52GWh from incineration.

The Maximum Power generation potential was estimated in the year 2035 giving a Net Power Generation Potential from Incineration of 7.87MW.The Energy Generation potential was found to be 0.75GWh in the year 2035 at an efficiency of 25 percent. Biomethanation can be used as the most suitable technology in Ndola due to availability of degradable organic waste stream (134.13Gg/yr.), high efficiency (25% to 30%); lowest annual capital ($0.1–0.14/ton) and operational cost. Maintenance of methane emissions has a direct impact on national energy security and mitigating potential climate change. It can be assumed that the increased volume of generated methane, from increased solid waste in this landfill, is sufficient enough to be considered for new standard landfill site construction with methane capturing facilities.

***Keywords**: (*Bio-Methanation, Gasification, Landfill, Gasification IPCC default model, Municipal Solid Waste, and Waste to Energy)

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LIST OF ABBREVIATION

MSW	Municipal Solid Waste
WtE	Waste to Energy
SW	Solid Waste
UN	United Nations
ZEMA	Zambia Environment Management Agency
NEP	National Energy Policy
ZESCO	Zambia Electricity Supply Corporation
PMRC	Policy monitoring and Research Centre
US EPA	United nations Environmental Protection Agency
ECA	Economic commission for Africa
ECZ	Examination Council of Zambia
MW	Mega Watts
Gg	Giga Grams
LFG	Landfill Gas
RDF	Refuse Derived Fuel
NCC	Ndola City Council
UNEP	United Nations Environment Program
UN-Habitat	United Nations Human Settlements Program
ISWM	integrated sustainable waste management
WIEGO	Women in Informal Employment Globalizing and Organizing

KW	Kilo Watt
LFG	landfill gas
GRID	Global Resource Information Database
GHG	Greenhouse gas(es)
GDP	Gross domestic product
UNZA	University of Zambia
ISWA	International Solid Waste Association
IPCC	Intergovernmental Panel on Climate Change
NCV	Net Calorific Value
LHV	Lower Heating Value

Chapter 1 : **INTRODUCTION**

1.1 Background

Municipal Solid Waste (MSW) generation has been escalated at a global scale (Farooq et al., 2021; Asase, 2009; Bello et al., 2016). Growing waste generation and unreliable energy requests are related with numerous environmental problems, such as greenhouse gas emission, air pollution, and water pollution.

According to the World Bank (2018), the global annual MSW generation was 2.01 billion tonnes in the year 2018, up from 1.3 billion tonnes in the year 2012. It is expected that the global annual MSW generation rate will increase up to 2.59 billion tonnes by 2030 and 3.40 billion tonnes by the year 2050 (Kaza et al., 2018; Mayer et al., 2019). The urban population of the world has grown rapidly since the year 1950, from 746 million to 3.9 billion in the year 2014 (United Nations, 2014). According to UN (2014), it is expected to increase up to 9.7 billion by the year 2050, with nearly 90 per cent of the increase to take place in the urban areas of Africa and Asia.

It is estimated that 125 million tonnes of MSW are generated annually in African urban areas. Yet, current waste management practices on the African continent are characterised by significant backlogs in waste collection coverage; and disposal to open dumps or unsanitary landfills (UNEP, 2018).

This large increase in MSW generation is attributed to different factors including economic growth, population expansion, industrial development, urbanisation, and rural to urban migration, etc. (Kaza et al., 2018; Agbelie et al., 2015). Waste generated in big quantities, and lack of appropriate waste management system, are two of the most important issues at the present world (Labib et al., 2019). About 70 per cent of MSW still ends up on landfills or uncontrolled dumpsites, which often contaminate surface water, ground water or soil and emit greenhouse gases (Mavropoulos et al., 2012).

Today, the waste of about three billion people is still disposed of in an uncontrolled manner (UN, 2015). The Research by United Nations shows that urban collection services covering no more than 39 per cent of the population in low-income countries (UN, 2015). It has been emphasised by many studies that multiple public health, safety and environmental issues derived from inappropriate or ill waste management have soared Greenhouse Gases (GHG) emissions and decrease the quality of life, promote water and soil contamination (Scarlat et al., 2015; Bogner et al., 2003). Until now, the largest fraction of municipal solid waste generated is still landfilled. In developing countries landfilling and dumping represents the only feasible option for final waste disposal (Munawar and Fellner, 2017). However, landfilling and dumping of waste in many countries is still associated

with severe negative impacts on the environment e.g., groundwater pollution, greenhouse gas emissions, and the human health e.g., land-fill fires, and landslides (Munawar and Fellner, 2017).
Many studies have underscored that different income level groups generate different waste compositions and quantities (Agamuthu et al., 2007; Kaza et al., 2018). The annual MSW generation growth rate for both low income countries and high-income countries was estimated to be 2–3 and 3.2– 4.5 per cent, respectively (Yadav and Samadder, 2017).
Moreover, additional issues from effective waste management are heterogeneity and complexity of MSW composition, due to highly consumer based lifestyles, which cause great difficulty in sustainable disposal of this massive amount of waste that also causes many economic losses and poses drastic impacts on the environment and human health (Farooq et al., 2021). With regards to the waste composition, high-income countries generate more dry waste including paper, plastic, cardboard, glass, metal, etc. that is comparatively easy to recycle, whereas more than 50 per cent of the total MSW generation in low-income countries is organic waste which is much more difficult to manage (Kaza et al., 2018).
In most developed and developing countries with an increasing population, prosperity and urbanisation, it remains a major challenge for municipalities to collect, recycle, treat and dispose off increasing quantities of solid waste and wastewater (Mayer et al., 2019; Bogner et al., 2003).
Waste management is a Challenge in most African countries. Within the current global policy frameworks, waste services prominently feature in the targets and indicators of both SDG 11 and SDG 12, notably with commitments to prevent, reduce, recycle and reuse – as well as to properly collect and discharge – urban solid waste and halve global food waste by 2030; and to properly handle and treat chemical and other hazardous waste through the whole life cycle in accordance with international standards. They also figure under the transformative commitments made by UN Habitat member states in the 2016 New Urban Agenda (NUA), which pledges to realize universal access to sustainable waste management systems, minimizing landfills and converting waste into energy. (Daria Cibrario, 2018)
According to ECA, (2009), about half of the waste generated in Africa is left uncollected, and it is left in urban dumping landscape. According to World Bank, (2012), over the last two decades, Zambia has made significant socio-economic progress. This rapid and sustained growth, coupled with increasing population and urbanisation, has soared waste generation and energy demand (ZEMA, 2011).
As a result Lusaka City in Zambia generates about 1,000 tonnes of solid waste daily. About 300 tonnes of the waste is disposed of at the designated dumpsites and treated in a sustainable environmental manner (UN-Habitat, 2010). Zambia has witnessed an increase in dumping of waste,

unsustainable treatment methods, un-managed burning and uncontrolled burying of waste with adverse health and environmental implications in the past decade. This resulted in the outbreak of waterborne diseases in Zambia in previous years. (Sabo et al., 2020).

1.2 Overview of Energy Demand

Alongside the proliferated dilemma of MSW generation and its sustainable management, global energy demand has also increased (Farooq et al., 2021). It has been widely admitted that the power generation sector and transportation sector are considered the top most energy-intensive sectors around the world. Most of the energy needs in these sectors are fulfilled by expensive fossil fuels (Asamoah et al., 2020; Kamausuor et al., 2014; Ofori, 2016). According to Ofori (2016), the generation of energy from waste also enhances sustainable waste management by avoiding the emission of methane, which is typical with landfilling.

Economic development and related increase in global energy demand, has created pressure on the supply of energy resources and waste management (Beyene et al., 2018). Despite this significant rise of energy demand, about 22 per cent of global population lacks modern energy access. Also, an average of 34 per cent of the people in developing countries lack waste collection services and the waste generation rate is expected to double by 2025 (IEA, 2010).

Electricity demand in Zambia has been growing at an average of four per cent per year. The current annual energy deficit is estimated at 3500 GWh (World Bank, 2017), which leads to load management because the total energy demand exceeded internal generation capacity; shortages in energy supply are not showing slowdown years ahead (PMRC, 2013). Zambia has 2,800 MW of installed electricity generation capacity, of which 85% is hydro based. National access to electricity averages at 31% with 67% of the urban and 4% of the rural population having access to power. The Government of Zambia (GoZ) set a goal for universal electricity access for all Zambians by 2030. Energy has been identified as an important driving force behind economic development in Zambia, and the government has declared its commitment to developing and maintaining energy infrastructure and services. Although there are pockets of private sector activity in generation, transmission, and distribution, the vast majority of power in Zambia is operated by ZESCO (link is external), the vertically integrated state-owned utility. However, the sector is opening up to new IPPs for on-grid and off-grid transactions. The government of Zambia expects to bring online additional MW of solar, hydro, and thermal power through 2030 (USAID, 2021).

The Country has two fossil fuel (Coal) power plants located in Southern province and in the Copperbelt province of Zambia. Though the power plants adds to the country's energy mix, the combustion of fossil fuels poses a direct negative impact on the environment that causes harm to our ecosystem (Nieuwlaar, 2013). Moreover, these conventional energy resources are rapidly depleting and threatening energy security at a global scale (Gumisiriza et al., 2017; Soleymani and Rosentrater, 2017). Exploring strategic solution for the effective and efficient management of waste and meeting skyrocketed energy demands, has become a high priority worldwide. On the other hand, the utilisation of renewable energy resources for heat, power, and different types of biofuels production has become the focus of many studies (Agbelie al., 2015; Cucchiella et al., 2014).

Waste to Energy (WtE) technologies have been recognized to convert MSW into useful energy and minimise the problems related to Waste Management and Energy Shortage (Farooq et al., 2021). The term WtE refers to the treatment of waste for energy recovery in the form of heat and electricity or other alternative fuels in gaseous, liquid, and solid forms. A vast range of WtE technologies is available to produce such a diverse stream of end-products from the complexly composed feedstock, that is, MSW (GIZ, 2017).

Waste to energy conversion is an ecologically and economically attractive practice which is rapidly growing associated with energy demand, waste disposal, and environmental monitoring (Beyene et al., 2018). On a global scale, 70 per cent of MSW is landfilled, 19 per cent is recycled, and only 11 per cent is utilized in WtE schemes this is due to logistical and economic issues such as primary fossil energy scarcity and landfill volume restrictions (Nowling, 2016).

Waste to Energy technology (WtE) is an emerging technology for most developing nations. An effective waste management system needs vital disposal methods which requires manpower, cost, and proper space; As the result waste management is a challenge for the government and city authorities in both developed and developing countries. Ragossnig *et al*. (2008), stressed that the generation of energy from waste through the practice of reducing methane emissions at landfill sites impacts positively on global climate change. This is because, the energy generated from waste such as biogas and biochar replaces fossil fuels making WtE more suitable for Sustainable energy generation and hence suitable in combating climate Change.

1.3 **Municipal Solid Waste: General aspects**

Municipal Solid Waste (MSW) management has been an increasing concern worldwide (Scarlat et al., 2015). Waste management aims at decreasing the volume of waste generated using mechanisms such as reutilization and recovery of its energy content, also through biochemical or thermochemical technological routes (Asamoah et al., 2020). Municipal Solid Waste (MSW), also referred to as trash or garbage, consists of several items that are discarded after use, such as grass clippings, furniture, clothing, food scraps, product packaging, bottles, newspapers, appliances, paint, and batteries, construction, industrial, and hazardous waste are not considered MSW (World Bank, 2017).

The average composition of solid waste worldwide (46 per cent) is organic, 36 per cent is potentially recyclable, and the remaining 18 per cent is composed of other types of materials (including ashes, diapers, ceramics and stone). Here, the "dry fraction" together with the "wet fraction" (mainly organics) constitute the main components of municipal solid waste the relationship between fractions of waste with a high calorific value (such as paper, cardboard and textiles (Hoornweg and Bhada-Tata, 2012).

1.4 **Methane Generation from Landfill**

Landfills generate methane; therefore, there is an opportunity to reduce methane emission by using methane for energy generation. The process of landfill gas recovery is synonymous to that of anaerobic digestion except that in the anaerobic digestion there is the control of the organic decomposition while in landfill gas recovery there is less control of organic decomposition. The decomposition of the organic waste by the microorganism releases two gases; carbon dioxide and methane (Agbelie et al., 2015). The methane captured is burned to give off water and carbon dioxide which produces a great amount of heat when combusted. There is no one sure best technology for generating energy from waste, as such many municipal authorities combine the basic ways to achieve it (Agbelie et al., 2015).

The environmental services association (2013), provides detailed pathways of waste management options and technologies in African countries. The technology pathways for converting MSW into energy include gasification, combustion, pyrolysis, Landfilling etc. Ofori (2016), defines incineration/combustion as the thermal process used in generating energy from waste, through complete oxidation, by converting solid waste into gaseous, liquid and solid products under high pressure through burning. The energy generated as heat through incineration process can be used for heating and electricity generation. The process of incineration or combustion generates about 90 per cent of biomass energy (International Energy Agency IEA, 2007). Worldwide, about 130 million tonnes of MSW are combusted annually in over 600 WTE facilities that produce electricity and steam for district heating and recovered metals for recycling. Since 1995, the global WTE industry increased by more than sixteen million tons of MSW (Themelis, 2022).

Many studies have been done to propose a selection criterion for WtE technologies (GIZ, 2017; Asamoah *et al*., 2020). Farooq *et al*. (2021), conducted a study in which they reviewed different

WtE technologies according to the conversion pathways, end-products, and their applications, and assessed statistical values of these technologies based on six different factors, viz., environmental performance, suitable waste fractions, capital and operational cost, efficiency, and complexity of the technology, the skillset of the labour, and favourable geographical location for the plant. The results of this review showed that biochemical and physicochemical WtE technologies are more favourable to convert organic waste, while thermochemical WtE technologies are suitable to process combustible fractions of organic and inorganic MSW. Based on the statistical review of considered factors from the literature, a general framework in the form of a systematic scheme was proposed for the selection of the most suitable WtE technologies for a sustainable MSW management system.

The scope of their study was limited to set out the best WtE choices for particular waste stream. Moreover, the decision was made on the basis of technological options conversion pathways, end-products, and their applications. The statistical values of these technologies based on six different factors, were assessed. The influence of socio-economic and technological factors of WtE industries were given globally, while specific regions around the world might present different considerations in terms of data production accuracy, lack of skillset for a particular technology, and also different socio-economic outcomes.

Dace *et al*. (2014), conducted a study in which mathematical model was developed and applied to estimate an optimal installed capacity of a power plant that uses landfill gas as a fuel. Economic, technological and climate parameters were considered in the model. For benchmarking purposes, the feed-in tariffs of power production from renewable energy sources, as well as price of CO_2 emission allowances are used.

A landfill in Latvia is taken as a case for modelling. The results show that it is possible to find the optimal capacity for various grades of landfill gas quality. However, findings of the lativia study were narrowed only to Latvia. A study performed by Labib *et al*. (2019), assessed the determination of more suitable and effective method among WtE technologies in the perspective of the Bangladesh economy, energy efficiency, and environmental aspects. This study used the multi-criteria decision making analysis approach for the selection of the most optimal options that can sustain with Bangladesh future energy demand, results revealed that Gasification-based WtE technology as the more suitable method because of its operation flexibility, lower cost, higher efficiency, less GHG emissions, and simplicity in design. However, their study was limited to the most suitable WtE options only for Bangladesh, at the same time influence of technological situation in Bangladesh on their WtE industries was not assessed.

Surroop and Mohee (2011), conducted a study in which they developed a model for predicting the amount of landfill gas generated from a landfill which could be used for power generation. Intergovernmental Panel on Climate Change (IPCC) method was used to estimate the methane generation potential. Based on the flow rate of the landfill gas, it was found that the amount of power generated would vary over time. It will initially increase until it reached a peak. In the case of the Mare Chicose landfill (Mauritius) the peak will be reached in the year 2012 and after this it will decrease. It was found that the amount of power produced in the year 2010 would be 50.50 GWh. This study was limited to Mauritius.

1.5 **WtE Technologies used in effective waste management**

Global municipal solid waste (MSW) generation will increase to 2.2 billion tons per year by 2025 as per the World Bank projection. Improper waste management often leads to environmental degradation (i.e. water, air and soil pollution), transmission of diseases, and the release of greenhouse gases emissions, which contributes to climate change. To combat these problems, several countries are following the waste to energy (WtE) approach, which significantly reduces the volume of waste and generates renewable energy.

Thus, the present study focuses on the municipal solid waste generation, composition, and waste to energy conversion technologies.

Thermal conversion processes including incineration, pyrolysis, and gasification for heat, bio-oil, and syngas generation are already well established and are being employed in several countries (Ram, C., Kumar, A., and Rani, P. (2021))

The prominence of waste-to-energy differs widely from country to country in around the world. In Europe Waste-to-energy is most widespread in Sweden, Switzerland, the Netherlands and Germany. In these countries local governments play a significant role in the organization of the waste sector. In countries like the UK, where waste is primarily managed by private companies, the greater proportion of the waste is still landfilled and waste-to-energy is less widespread and at relatively high cost. Incineration of waste in Denmark is extremely efficient, and it is therefore highly unlikely that a reorganization would lead to improvements and lower gate fees.

In order to recover the resources of the waste, the first priority is to reuse or recycle it. The residual waste is either incinerated at waste-to-energy facilities or, as the last resort, landfilled. A ground-breaking total of 93% is recycled or incinerated at waste-to-energy plants

The production of biogas in Denmark is rapidly increasing. The total production is expected to more than triple from 2012 to 2020, reaching a total annual production of 15 PJ. To date the majority of the produced biogas is used in electricity production. In the future it is expected that a greater share of the produced biogas will be upgraded and delivered to the natural gas grid.

At the end of 2005, Denmark had 29 waste-to-energy facilities that treated a total of 3.5 million tons of waste, which corresponds to roughly 26 percent of the total waste generated in Denmark. Environmentally friendly electricity and district heating are produced from this waste, corresponding to the energy consumption of approximately 400,000 households. The existing legislation on environmental protection, heat and electricity supply ensures favourable framework conditions for waste incineration in Denmark. This has made Denmark the country in Europe that incinerates the greatest amount of waste per capita—under very strict environmental regulations.

Denmark is a leading user of district heating in Europe. District heat is used by approximately 2/3 of the Danish population 60% of households (see also Stockholm). This is mainly in combination with CHP. And waste-to-energy, in the form of incinerating municipal solid waste, provides 20% of the heat for Denmark's over 400 district heating networks (see also San Francisco). Waste to Energy also provided Denmark with 4% of electricity in 2007.Waste is increasingly viewed as a renewable source of energy, not without debate (see below). In Denmark, some 3.5 million tonnes of waste are incinerated annually. The largest sources of renewable energy in Denmark according to 2001 statistics were biomass (wood/straw), followed by waste, and then wind energy. Renewable energy's share in the Danish energy system is growing rapidly: 30% of electricity production and 40% of district heating production in 2007 were from renewables, compared to 10% and 20% respectively in 1997. (Sabina Andrén, 2010)

It might look like a contradiction but in Denmark the system is set up in a way that the worst thing you can do is reduce the size of your waste bin. Why? Well, every city in Denmark has its own incinerator and they are mostly publicly owned. This means that the citizens are actually the owners of the burners and hence if less waste is sent for burning -because it is being avoided, reused or recycled- the incinerator will function under full capacity, lowering the efficiency to generate heat and power. Yet the incinerator has to meet the capital and operating costs with less income which will result in an increase in the waste management fees. I.e. the more waste you generate, the better for your pocket.

With the current system of incentives in Denmark getting to Zero Waste would be a financial catastrophe. It is therefore unsurprising that the country that burns the most also generates more waste than any other. Denmark is the perfect example of the linkage between waste burning and waste generation (Simon, 2014)

In the U.S., land for waste disposal is cheap and plentiful. WTE plants compete with landfills for the trash disposal dollar. According to the Energy Recovery Council, the industry’s Washington-based lobbying group, the U.S. has 84 WTE plants (four are idled but able to come into service), with about 2,800 MW of baseload electricity generating capacity. The two dominant WTE companies are publicly traded Covanta, based in Morristown, N.J., with more than 40 plants, and privately owned Wheelabrator Technologies, located in Hampton, N.H., with 16 U.S. plants.

The first new WTE project in the U.S. in 20 years went into commercial operation in July 2015, in West Palm Beach, Fla., owned by the Palm Beach County Solid Waste Authority. The 95-MW facility joined an existing 20-year-old waste combustion and energy unit. A consortium of Babcock & Wilcox and KBR designed and built the new plant. Covanta commissioned the most recent plant in North America in January this year in the Canadian province of Ontario, the Durham York project which burns 436 metric tons of MSW per day to produce 15.7 MW of baseload power.

In the United States, the majority of MSW is landfilled and less than 35 percent of total MSW is recycled. New energy technology provides an opportunity to lessen the increasing burden of MSW. MSW can be converted into valuable energy sources using Waste-to-

Energy (WTE) technologies such as incineration, pyrolysis, gasification, and plasma arc gasification. Various energy sources produced from the WTE technologies can be used in Lieu of fossil energy resources. It is expected that various aspects of sustainability related to energy and waste treatment can be improved (Urso Campos).In the U.S., there are currently 77 waste-to-energy facilities in 22 states, processing 95,023 tons of waste each day, capable of generating 20,800 gigawatt hours of electricity a year. Europe has over 400 such plants, and another 300 are found in other parts of the world.

Most of these plants are mass burn facilities. Waste is stored in large bunkers, then transported to a moving grate in a furnace where it is burned at over 850˚C for at least two seconds to ensure complete combustion. The heat from the furnace heats water in a boiler, creating steam that turns a turbine to drive a generator that makes electricity. The electricity then enters the grid. In Europe, some plants combine electricity generation with a district heating system, using the excess steam to create heat used to heat homes.(news.climate.columba,2016)

China is the world’s largest waste generator, producing as much as 175 million tons of waste every year. With a current population surpassing 1.37 billion and exponential trends in waste output expected to continue, it is estimated that China’s cities will need to develop an additional hundreds of landfills and waste-to-energy plants to tackle the growing waste management crisis.

China’s three primary methods for municipal waste management are landfills, incineration, and composting

Nevertheless, the poor standards and conditions they operate in have made waste management facilities generally inefficient and unsustainable. For example, discharge of leachate into the soil and water bodies is a common feature of landfills in China. Although incineration is considered to be better than landfills and have grown in popularity over the years, high levels of toxic emissions have made MSW incineration plants a cause of concern for public health and environment protection (Miriam Fernandez 2021)

Salman Zafar, a renowned waste management, waste-to-energy and bioenergy expert was interviewed to discuss waste opportunities in China. As Mr. Zafar commented on the current problems with these three primary methods of waste management used by most developing countries, he said, "Landfills in developing countries, like China and India, are synonymous with huge waste dumps which are characterized by rotting waste, spontaneous fires, toxic emissions and presence of rag-pickers, birds, animals and insects etc." Similarly, he commented that as cities are expanding rapidly worldwide, it is becoming increasingly difficult to find land for siting new landfills.

On incineration, Zafar asserted that this type of waste management method has also become a controversial issue due to emission concerns and high technology costs, especially in developing countries. Many developers try to cut down costs by going for less efficient air pollution control systems". Mr. Zafar's words are evident in the concerns reflected in much of the data that waste management practices in China are often poorly monitored and fraudulent, for which data on emission controls and environmental protection is often elusive

Similarly, given that management of MSW involves the collection, transportation, treatment and disposal of waste, Zafar explains why composting has also such a small number relative to landfills for countries like China. He says, "Composting is a difficult proposition for developing countries due to absence of source-segregation. Organic fraction of MSW is usually mixed with all sorts of waste including plastics, metals, healthcare wastes and industrial waste which results in poor quality of compost and a real risk of introduction of heavy metals into agricultural soils."

Given that China's recycling sector has not yet developed to match market opportunities, even current treatment of MSW calls for the need of professionalization and institutionalization of the secondary materials industry.

While MSW availability is not an issue associated with the potential of the resource given its dispersion throughout the country and its exponential increase throughout, around 50 percent of the studies analysed stated concerns for the high moisture content and low caloric value of waste in China, making it unattractive for WTE processes.

Talking about how this issue can be dealt with, Mr. Zafar commented that a plausible option to increase the calorific value of MSW is to mix it with agricultural residues or wood wastes. Thus,

the biomass resources identified in most of the studies as having the greatest potential are not only valuable individually but can also be processed together for further benefits.
In August last year, Ethiopia opened Africa's first waste-to-energy plant on the outskirts of the capital Addis Ababa. The "Reppie waste-to-energy facility" is built on the Koshe landfill site, which was previously a sprawling open air dump, covering an area approximately the size of 36 football pitches.
The $118 million plant was built through a public-private partnership between Ethiopian Electric Power and a foreign consortium made up of China National Electric Engineering Company (CNEEC), Cambridge Industries Limited from Singapore, and Rambolt, a Danish engineering firm. The plant ceased operations shortly after its inauguration because of a contractual dispute but some news sources reported in April that Ethiopia Electric Power is planning to restart operations
The plant is designed to incinerate 1400 tons of waste a day, and when it eventually operates, it will do so within the CO2 emission limits of the European Union

1.6 **Waste to Energy and the Environmental**

Many studies have underscored the need for WtE options as an effective and efficient source to curtain energy burgeon. Using waste to create energy, is a viable option for most African cities. Waste can be incinerated to produce heat or electricity or methane can be collected from landfills and be used to, again, generate heat or electricity (Scarlat et al., 2015; Agbelie et al., 2015).
The High generation of MSW due to rapid population growth, industrialisation and urbanization in major cities of Zambia specifically for the city of Ndola is becoming an Environmental concern. In response to these setbacks the National Energy Policy (2008) has advanced arguments supporting appropriate methodologies and technologies in waste management that can generate electricity. Poor reliability and quality of electricity supply, combined with the lack of access to electricity services, have an adverse impact on the national economy. This has been exacerbated by severe power shortages that began to be experienced in the year 2015 due to lower than expected rainfall, and which persisted (World Bank, 2017).
The huge annual quantity of MSW and its high-energy contents, show the significant potential for WtE facilities in the country. Many of landfills in Zambia are mature landfills which continue to receive huge amount of waste and odour emissions and all health hazards associated with these will keep increasing (Muller et al., 2017; Edema et al., 2012, Sabo et al.,2020).
However, the selection of appropriate WtE technologies, suitable for waste management systems for Zambia, is still a big challenge for relevant policymakers. Accordingly the present study dealt with the characterisation of MSW and the estimation of energy potential from Kaloko dumpsite, in

Ndola. This study consisted of three parts: MSW characterisation was carried out in Ndola in the first part. This section provided reliable data on the main components of Ndola's MSW. The second part is investigated Landfill Gas recovery potential from solid waste in the Kaloko dumpsite. The third part identified the most suitable technology for designing sustainable MSW management in Ndola.

1.7 **Statement of the Problem**

Zambia is faced with critical waste management problem and a significant increase in the quantity of waste generated in major cities (ECZ, 2004) attributed to industrialisation and rapid population growth (concentrated largely in unplanned, urban and peri-urban settlements. For example Lusaka generates 1000 tonnes of waste per day (Sabo et al., 2020). With this estimated generation rate, the Lusaka City Council estimates that only 40 per cent of waste in Lusaka is actually reaching the dumpsite, 60 per cent is illegally dumped or burnt in people's backyards (Muller et al., 2017).
Unsustainable waste treatment has significant health problems, socio-economic downturns as well as environment risks(ECZ, 2004).On the other hand Increasing demand of electricity has resulted in load shedding of up to eight hours a day in most of the country, in order to manage an estimated annual deficit of 3,500 GWh (World Bank, 2017). The dominance of hydropower generation in the country's generation mix makes it vulnerable to hydrology and climate variations, as proven by the ongoing energy shortage (PMRC, 2013). The National Energy Policy (2008), acknowledges the need to increase the share of renewable energy (apart from large hydro) in the electricity generation system in order to fulfil the "Zambia Vision to 2030" which targets electrification of: 90 per cent for urban and peri-urban areas and 51 per cent for rural areas by the year 2030.WtE is one of the options being considered .However Many studies in Municipal Solid Waste Management in Zambia have concentrated on aspects and challenges of solid waste management, especially in waste collection, characterisation and recycling (Mushimba, 2018; Muller et al., 2014; Edema et al., 2012, MOE, 2015).
Little or no significant attention has been paid to understanding WTE technologies that can improve municipal solid waste management, particularly in Ndola, which has experienced huge increases in urban growth and waste generation (Muller et al., 2014; Edema et al., 2012).Despite the adoption and implementation of modern waste management technologies in many developed countries for sustainable waste management, for instance Japan, China, U.S.A. and Germany (Farooq et al., 2021) and developing nations like Ethiopia, Egypt and south Africa. Zambia is yet to explore and implement any such technologies to manage waste and harness the potential for energy generation.

In view of the above observations, this study recognised the need to determine the potential of energy generation from MSW collected in Ndola.

1.8 Limitation of MSW

Review of different studies on municipal solid waste management system, showed a variation in terms of technological pathways used. Adoption, implementation of technological option results of evaluation in respect to criteria for appropriate technology. Considering or discarding WtE technology, as an alternative to sustainable waste management system, a main factor that should be analysed is the nature (composition) and volume of the waste stream. A key parameter is the energy content of the waste (WIEGO, 2019).

These factors vary from one country to another. Specific framework, data reliability, poor quality of incoming waste, consumption patterns, collection sustainability, legal arrangement and the level of enforcement constitute impediment in various regions or countries. It is essential to understand within what context these technologies have been developed and implemented in countries, as well as the state of the MSW management system when the decision has to be made.

The composition of MSW in Africa does vary from place to place, depending on consumer attitude, income level, culture, etc. (UNEP, 2018). In view of the above observations, according to Ndola city (Zambia) waste stream composition, volume and energy content, this paper presented technological pathways that can improve Municipal Solid Waste management system. It is estimated that Zambia's landfills are mature still continuing to receive huge volume of waste (Sabo et al., 2020).

1.9 Objectives

1.9.1 General Objective

a) To determine the Viability of electricity generation from MSW in Ndola.

1.9.2 Specific Objectives

a) To Determine the composition of MSW and review disposal method used in Ndola;
b) To determine suitable technologies that can be used to generate electricity from MSW in Ndola by analysing Biomethanation and Incineration
c) To estimate electricity generation potential from MSW

d) To determine levelized cost of energy through analysis of Biomethanation and Incineration.

1.10 Research Questions

This study attempts to answer these questions:

i. Is the composition of MSW in Ndola Suitable enough to generate Electricity from Waste in Ndola
ii. Are the disposal methods used in Ndola suitable enough to be used in the generation of electricity from waste?
iii. What amount of electricity can we generate from Ndola's MSW?
iv. What is the suitable technology that can be used to generate electricity from MSW in Ndola using Levelized cost of energy technique?

1.11 Significance of the study

This study is significant for the following reasons. Firstly, the result derived from this study will provide sustainable insight into the growing energy crisis that is negatively affecting the economy of Zambia and the impasse in the management of municipal waste especially in Ndola and therefore the information from this study will bring to the attention of policymakers and stakeholders, in both the energy sector and waste management organisations the synergy of combining waste management practices and energy generation as a sustainable solution to Zambia's energy crisis.
This will intern revive the interest of the government and other stakeholders and private individuals about the opportunities in waste to energy generation in the country.
The findings of this study will also provide analytical insights that will contribute additional information to the current existing body of knowledge.

1.12 Definition of Concepts

Solid waste: is defined as the waste arising from human and animal activities that are normally solid and that are discarded as useless or unwanted (Pearvy et al, 1985);

Energy: is defined as the capacity or effort to create heat, light, or motion (capacity to do work). Energy is also used to generate power. Power is a measure of the rate at which energy flows in electrical systems and is measured in watts (W). A watt is a measure of energy flow (PMRC, 2013);

Municipal Solid Waste: is generally composed of electrical and electronic equipment (such as discarded computers, printers, mobile phones, TVs and refrigerators), construction and demolition waste, health-care waste, and waste from households, offices, shops, schools and industries, and agricultural residues; These include food waste, garden (yard) and park waste, paper and cardboard, wood, textiles, nappies (disposable diapers), rubber and leather, plastics, metal, glass (and pottery and china) and refuse such as ash, dirt, dust, soil and electronic waste (Guerrero et al., 2013; IPCC, 2007); and

Waste to energy: can simply be described as the concept or process of converting or generating energy from commercial and industrial waste, agricultural by-products, animal manure, as well as MSW, which are not recyclable (Ofori, 2016).

1.13 **Research limitation**

This research was limited to determining the viability of setting up a Waste to Energy plant in Ndola purposively with regard to time and resource required to deal with larger sample.

1.14 **Chapter Summary**

This Chapter outlines the research back ground and the rationale for the research. The present study tries to explain the challenges associated with municipal solid waste management and Zambia Power supply Constraints. The Chapter attempts to highlight on how a problem in Solid waste management can be viewed as a solution for energy shortages. The Chapter briefly reviews the waste to energy technologies used in different countries. The chapter also gives an outline of problems associated with municipal solid waste management and briefly looks into the twin problem of municipal solid waste and energy Shortages. The Chapter finally describes the Aims of the Study and presents the questions the present study tries to answer.

Chapter 2 : LITERATURE REVIEW

2.1 Introduction

This Chapter presents the outcomes of the review of existing literature on waste management system and waste to energy systems. The review of literature refers to the analysis of preceding research to the related topic, which constitutes the theoretical underpinnings of this study (Suter, 2012). The Literature further discusses Waste to Energy Technologies and the disposal methods used across the globe. The literature on Levelized Cost of Energy and models for methane generation are also reviewed

2.2 Description of Municipal Solid Waste Management

Solid waste management has overwhelmingly drawn the attention of a large number of officials, scholars and policy makers (African Development Bank, 2002). The high rate of population growth, the rapid pace of the global urbanisation and the economic expansion of developing countries are leading to increased and accelerating rates of municipal solid waste production (World Bank, 2012). The heterogeneity and complexity of MSW composition are causing great impediment in sustainable disposal of this massive amount of waste that also causes many economic losses, and poses drastic impacts on the environment and human health (Menikpura et al., 2012; Noya et al., 2018; D'Adamo et al., 2020. Mismanagement of waste associated with health and environmental issues have raised concerns among decisions makers, significant public resources are devoted to waste management in developing countries (Scarlat et al., 2015).

A study confirmed that more than 50 per cent of the total MSW generation in low-income countries is organic waste which is much more difficult to manage (Kaza et al., 2018). Alongside the increased dilemma of MSW generation and its sustainable management, global energy demand has also increased. Conventional energy resources are rapidly depleting and threatening energy security at a global scale (Gumisiriza et al., 2017; Soleymani and Rosentrater, 2017). Effective conversion of MSW is a sustainable innovative way of providing effective management solutions to close the gap between MSW and energy supply (Dlamini et al., 2018).

A review of existing literature such as the work of (World Bank, 2012) provides consolidated data on MSW generation, collection, composition, and disposal methods by country and by region. A projection on MSW generation and composition for the year 2025 was made to foster decision makers to prepare plans and budgets for solid waste management in the coming years by estimating global amounts and trends. Accuracy in MSW data along with waste production, collection sustainability are challenging in many developing countries. 40 per cent of waste is uncollected in

Africa (Agbelie et al., 2015). Moreover, lack of financial resources and breakdown of collection equipment inhibits waste collection data process (UN, 2015; Edema et al., 2012).

These setbacks have been hampering systematic and reliable information about waste generation and collection frequency which turns to slow down efforts in making policy to curtail the effect of excessive waste generation. Eawag, (2008), provides a snapshot on global MSW challenges: situation in developing countries. Findings revealed that there is a difference composition between MSW generated in high-income countries and the MSW generated in developing world. Data on MSW was for this study was obtained from international organisations, scientific journals, and unpublished reports and documents, covering the time period from 1997 to 2006. These sources attempted to render data concerning MSW in developing countries for the precise period of time mentioned above. Information drawn from the study is limited for a precise period of time and cannot be extrapolated, hence provided incomprehensible input on data accuracy. The developing world deals with fragmented, also waste generation quantification is due to socio-stratification, that impacts on the composition and the volume of waste production. This study remained silent on this point. In most developing countries, informal pickers play important role in waste collection (WIEGO, 2016). The informal sector was not rated in this study.

2.3 **Waste to Energy**

Waste-to-Energy (WtE) technologies consist of any waste treatment process that creates energy in the form of electricity, heat or transport fuels (e.g. diesel) from a waste source (World Energy Council, 2013).

These technologies can be applied at different scales and with varying complexity: the production of cooking gas in household digesters from organic waste, collection of methane gas from landfills, thermal treatment of waste in large scale incineration plants at the municipal level (often referred to as utility size), and co-processing of refuse derived fuel in cement plants or gasification (WIEGO, 2019).Waste to energy technologies apply to different waste streams, and have different functions and characteristics. The main literature distinguishes five main types of WtE technologies, also commonly known as conversion technologies, used for treating (municipal) waste internationally: a) incineration, b) co-processing, c) anaerobic digestion, d) landfill gas collection e) pyrolysis and gasification (Ibid, 2019).

When considering or discarding WtE technology, some factors should be analysed, because they play a role in WtE alternative, these are the nature (composition) and volume of the waste stream (GIZ, 2017). A key parameter is the energy content of the waste (that is, how well it burns). This is called the Lower Calorific Value (LCV) and is measured in Mega Joules/kg (MJ/kg). For instance if the average LCV of the waste burned in an incinerator is below 7 MJ/kg over a one-year period, then it should be regarded as an option (WIEGO, 2019).

2.4 **Review of Waste to Energy Technologies across the Globe**

World Energy Council, (2013), provides global status of energy technologies as a precious resource and fuel for the urban sustainable energy mix of tomorrow. It reviewed technical and economic considerations and market trends of different technologies. However, the inconsistency of the composition of MSW, as mentioned by several studies including seasonality, climate and changing consumption pattern from different regions of the globe, would heavily affect sustainable waste management policy system (Menikpura et al., 2012; Noya et al., 2018; D'Adamo et al., 2020); the complexity of the design of the treatment facilities that requires specific expertise or particular skillset, might vary around different regions (Farooq et al.,2021), and the air-polluting emissions still represent open issues for these technologies (Mendes et al., 2004; Zaman, 2009).

Farooq *et al*. (2021), reviewed different WtE technologies according to the conversion pathways, end-products, and their applications, and assessed statistical values of these technologies based on six different factors, viz., environmental performance, suitable waste fractions, capital and operational cost, efficiency, and complexity of the technology, the skillset of the labour, and favourable geographical location for the plant. This study developed a framework for the selection of suitable waste to energy technologies for a sustainable municipal solid waste management system. The recommended indicators, methods, and models in the proposed framework were selected after a detailed review of the literature published in well-known scientific journals, and reports of leading international organisations such as the World Bank, International Energy Agency (IEA), and International Labour Organisation (ILO).

The results of this review showed that biochemical and physiochemical WtE technologies are more favourable to convert organic waste, while thermochemical WtE technologies are suitable to process combustible fractions of organic and inorganic MSW. This study is credited for including territorial and technological aspect analysis of different waste to energy alternatives for any given country or region. However, the proposed framework is an effort toward the development of a policy that can help to design sustainable municipal waste management systems around the globe.

According to WIEGO, (2019), the technical Data on Municipal solid waste management has paid attention to the impact on livelihoods (especially those of informal waste workers) in municipalities particularly in emerging economies where new projects promoting incineration technology are proposed. In this publication, WIEGO (2019) aims to provide waste picker organisations, policymakers and practitioners with information about waste-to-energy initiatives. This is with a view to strengthen solid waste management models true to an inclusive circular economy. However WtE alternatives presented in this publication look specifically at the use of waste-to-energy systems in several countries in Europe. The framework conditions, which in most developing and emerging countries are essentially (structurally) different to those that have seen the rise of WtE projects in industrialised countries, where large waste-to-energy plants are an integral part of the waste management infrastructure (GIZ,2017).

Yuan *et al*. (2019), analysed the public perception of waste-to-energy in China. A questionnaire was carried in this research. The results revealed that the public showed a general concern with regard to environmental issues concerning WtE plants in China.

Respondents had an overall positive attitude towards waste-to-energy, but it varied according to the demographic details of residents, such as age, education, and income. Recognition level of the benefits was higher than the concern of associated risks. This study focused on Social acceptance for the development of WtE and was limited on China which has its specific social context and economic patterns; these factors might be contrary to other areas around the world, thus causing divergence of view about WtE acceptance

The waste informal sector, in developing countries plays a critical role in waste management system, and is present in all processes of the waste management chain. Considering waste to energy options, waste composition and volume of waste stream is cornerstone of any technological attempt on the part of municipalities, lack of separation of waste at sources along with scavenging devoicing waste from significant content values necessary for operation of WtE plants (ISWA, 2012).

Kumar *et al.* (2019), assessed the potential of WtE in India, including the possible technologies, job, and business opportunities and environmental influence. Also, the policies that encourage WtE industry are suggested along with a few recommendations for the course of action in the WtE sector that can support the investors, WtE project developers, suppliers, decision makers and the policymakers for further better management and planning.

This study provides an insight into the current one in terms of trends and characteristics of technologies in order to tackle waste mismanagement. This study lacks insight on economic feasibility of waste to energy facilities development and the variety sustainability of feedstock to support waste management system. Many waste management options were underscored by the study (waste to energy, business opportunities etc.) that might have diverged goals and utility. This study is of benefit for the current one because it highlights various waste minimisation and sustainable disposal options that have emerged from the literature around the globe. Potential waste disposal methods, including incineration, burning, landfilling, recycling, reuse, open dumping, pyrolysis, and shredding (Ogunmakinde et al.; 2019).

Soltani *et al*. (2016), also proposed a decision framework by incorporating environmental, economic, and social aspects only. They used Life Cycle Assessment (LCA) and life cycle cost analysis for environmental and economic evaluation, respectively, and developed a weighting scheme with the help of the MCDM analysis approach to aggregate the outcomes of environmental and economic evaluation. After that they used the Game Theory to involve the multiple stakeholders in the decision making and execution process, to avoid the issue of free riders in the WtE industry. The study focused on the waste management system of Vancouver, in Canada that represented only the developed world.

Another study by Ouda *et al.* (2015), reviewed the status of MSW management and energy sector of The Kingdom of Saudi Arabia (KSA) for the selection of best WtE options. Two scenarios were assessed: (1) incineration and (2) Refuse Derived Fuel (RDF) along with biomethanation from the year 2012 to 2035. Analytical hierarchical process method was used to develop a decision model by incorporating three criteria viz., merits and demerits of WtE technologies, technical and economical values of WtE technologies, Suitable WtE technology based on waste type. The scope of their study was only limited to a specific region (The Kingdom of Saudi Arabia). However, the decision to select between the two scenarios did not include the financial, social, and environmental analysis using life cycle assessment (LCA) tool.

A huge amount of data is required for the proper estimation of environmental performance and proposed socio-economic and technological indictors; therefore, the application of the proposed framework is highly sensitive to the availability and transparency of the data and the interests of governments, policymakers, and public and private sector investors. As exemplified by many literatures, data availability and reliability affect heavily decision making process in many developing countries (Asamoah et al., 2020; Agbelie et al., 2015).

The organic fraction in developing economies is often higher, 60 per cent (Hoornweg and Bhada-Tata, 2012). Organic fraction is underscored by many studies is be lower in caloric value (UN, 2017; Scarlat et al., 2015). WtE process intersects with the informal waste sector, it should be noted that in the informal waste sector, the main recyclable materials handled and commercialised are plastics, metals, glass, paper and cardboard, and, to a certain degree, textiles that contain high calorific value (WIEGO, 2019). These viable feedstocks are diverted in developing countries due to intensive activity of informal pickers in an environment less regulated, uncontrolled dumps and subject to lack of resources for effective waste management (Smith, 2018).

ISWA Guidelines: Waste to Energy in Low and Middle-Income Countries (2013), provided a strong focus on what needs to be done to make a WtE project successful, and emphasize on feasibility study phase. This guideline provides a viable step in WtE project development. However the influence of specific framework, legal arrangement and the level of enforcement in various settings or regions in developing countries, remain a challenge in technology development.

Scheutz *et al*. (2019), conducted a study to monitor methane emissions from three landfill sites, located in Sweden, using tracer gas dispersion technique, drone-based plume measurement, ground-based plume measurement and surface flux chambers at three landfill sites (one closed and two operational) located in Sweden. This study suggests that the most accurate, whole-site methane emission quantifications are performed using methods measuring plumes downwind of the landfill, such as tracer gas dispersion or UAV plume measurements. The scope of their study was limited to Sweden. The number of measurements needed, and the conditions under which measurements should be performed remains unsolved. Also, annual emission data from landfills was not measured and reported.

2.5 **Waste to Energy Technologies in Africa**

A study of (African Development Bank, 2002) focused on solid waste management options for Africa through a succinct analysis including waste generation and characterization, disposal methods, processing, collection and transportation, socio-economic and institutional policies of waste management. This study detailed review of solid waste management practices in major municipalities in Africa including: Cairo in Egypt, Nairobi in Kenya, and Accra in Ghana. This study provided a framework for decisions makers in the design of waste management projects or the integration of waste management concern into sanitation or urban development projects. This study focused on some African countries. Complexities in waste management in developing countries deserve a specific based solutions due to many aspects that might be taken into account, and hence these countries have different economic patterns, climate, and policy frameworks.

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 (Chimuka and Ogola, 2015).

A research conducted by Asamoah *et al*. (2019) assessed the potential for waste to energy generation in the Kumasi metropolis, the second-largest city in Ghana. It revealed that renewable energy from MSW carried great potential to solve the energy problem in sub-Saharan African cities and could be regarded as a technology that would ease the energy and environmental problems. However, there is evidence to indicate that several factors hindered waste to energy technology in Ghana; key among them was high capital cost, high operational cost and lack of governmental support and policy framework.

Moreover, many scholars pointed out difficulties in biogas plants management in Africa, 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 because biogas production plants have a short life-span (Akinbami et al. 2001; Omer and Fadalla 2003; Walekhwa, Mugisha, and Drake 2009).

Torreta and Forrenato (2009), analyses the environmental impacts due to unsustainable management of Municipal SW in developing countries, particularly risks associated with waste picking; open burning and open dumping for different waste streams. Opportunities for waste picking inclusion, within the formal SWM system, were also assessed.

The key argument is that there is a strong linkage between poor solid waste management and health or environmental issues. The rapid increase in population, economic growth, urbanisation and industrialisation improve the generation of Solid waste at global level, boosting environmental contamination when such SW is not managed. Indeed, in many developing countries waste is scattered in urban centres or disposed of in open dump sites. The lack of infrastructure for collection, transportation, treatment and final disposal, management planning, financial resources, know-how and public attitude reduces the chances of improvement, as pointed out also by other authors (Srivastava et al.;2015).

This study revealed the need to consider a sustainable way to deal with waste management; our main concern is that this study does not extend to incorporate waste characterisation or waste to energy potential assessment in its analysis. Inclusion of waste pickers, in a waste management system, needs a sound framework in order to prevent waste to energy facilities from being starved of sustainable waste stream provision rich in calorific value (paper, plastic, etc.). These are swept away in the process of circular economy requirement.

Palacio *et al*. (2018, reviews, existing knowledge on Municipal Solid Waste (MSW) management by analysing different energy recovery routes for MSW such as thermochemical and biochemical. Findings showed that depending on the size of the population, composition of waste, and products to be obtained (energy or chemical), more than one technology can be combined for a better energy usage of waste. However, this study fell short because it did not consider economic and environmental viewpoints into the analysis.

Adjibade and associates (2017, undertook a study entitled "Trends, status and potential generation of renewable energy from waste for sustainable development in Africa: An overview. This study focuses on the past and present status of energy in Nigeria and Africa at large and potential of renewable energy from organic wastes citing several case studies. This study is distanced itself from the current one, because it depicted trends, opportunities, challenges and innovations at regional level and in Nigeria, the current one was narrowed to Ndola, which has its own MSW infrastructure and socio-economic characteristics. Also, Scarlat *et al.* (2015) for example, highlight that in sub-Saharan African countries, technical expertise and specific repair and maintenance technology are often scarce and absent.

A study carried out by Tsunatu *et al*. (2015), investigates on alternative energy recovery from Municipal Solid Waste (MSW) in Jalingo Metropolis. The energy recovery of the biodegradable and non-biodegradable waste was considered for both the Thermo-chemical and Bio-chemical conversion processes. The findings revealed, approximately 18,144 tonnes/year of waste was generated and disposed, out of which 15,930.43 tonnes per year was available for conversion into energy with bio-chemical and thermo-chemical conversion processes producing 62,596.80 kW and 151,016.14 kW net power generation potential respectively. This study fail short in advancing insight about sustainability of waste production, because the relevance and efficiency of technological options depends on stability in consumption patterns, economic activity, packaging methods and material, and or compost and recycle markets, which is very much challenging in a fast paced changing world. A detailed Environmental Impact Assessment Analysis lacked in this study.

Dlamini *et al*. (2018) present, a review of the literature on WTE technologies and their implications on sustainable waste management in urban areas. The paper particularly contributes to the understanding of WtE technologies and its potential on Municipal Solid Waste Management (MSWM) in Johannesburg, South Africa. The deployment and use of landfill gas recovery, incineration and anaerobic digestion were considered to address a number of emerging challenges in waste management in Johannesburg, while generating electricity and mitigating GHG (Greenhouse Gas) emissions.

This study is narrowed in depicting trends and opportunities of adoption and implementation of WtE options for Johannesburg city, such patterns in waste management system in Johannesburg is quite challenging considering the diversity of waste stream presented by different areas in developing countries, other setbacks such as 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 on the adoption and implementation of modern WtE technological solutions in many developing countries.

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).

Africa Waste Management Outlook provides an introduction to solid waste generation and management in Africa as compared to global trends and patterns. It provides an overview of the drivers, pressures and impacts of waste on the continent, a comprehensive analysis of waste management on the African continent, including challenges and opportunities (UNEP, 2018).
One of the limitations of the Africa WMO is the lack of reliable, comprehensive and up-to-date waste data for Africa, which is a constraint to effective waste management on the continent (Bello et al, 2009). Another limitation is the scarcity of empirical data on the impacts of unsound waste management (e.g. exposure to hazardous substances) on human health and receiving environments. Of particular concern, are the risks to a large informal waste sector (DEA, 2012).

2.6 **Circular Economy**

The tremendous rise in Municipal Solid Waste (MSW), in the fast-growing cities of developing and emerging countries, has led to increasing public concerns with regards to the resultant health and environmental impacts (UN, 2015). Current global MSW generation levels are approximately 1.3 billion tonnes/year, and by the year 2025, these are expected to increase to approximately 2.2 billion tonnes/year. This represents a significant increase in per capita waste generation rates, from 1.20 to 1.42 kg per person per day, in the next fifteen years (UN, 2015).
One of the keys for a sustainable development of human society is the efficient use of resources. This is a particularly challenging task especially as resources and energy are inextricably linked in the Circular Economy (IEA, 2020). The concept of Circular Economy (CE), while not entirely new has recently gained importance in the agendas of policymakers, to address the aforementioned and other sustainability issues (Geissdoerfer et al., 2016). Municipal Solid Waste (MSW) is a manifestation of the unsustainable consumption of natural resources by humankind, which has led to, and continues, the depletion of natural capital and environmental degradation (Pallacio et al., 2018).
Implementation of a Circular Economy aims to minimise the impact of the economy on the environment and the climate, more specifically to minimise Green House Gas emissions, energy demand, pollutants release, and/or distribution of scarce resources (IEA, 2020; Asamoah et al., 2020).
The WtE supply chain provides a method for simultaneously addressing issues related to energy demand, waste management and emission of Green House Gases (GHG), achieving a circular economy system (Trindade et al., 2018; Chibinda, 2016). On a global scale, 70 percent of MSW is landfilled, 19 per cent is recycled, and only 11 percent is utilised in Waste-to-Energy (WtE) schemes, this occurs due to logistical and economic issues such as primary fossil energy scarcity

and landfill volume restrictions (Pallacio et al., 2018). It is important to note that turning waste to energy is a means for poverty alleviation in developing countries if the application of the circular economy is implemented. It is estimated that about trillion of dollars and close to 100,000 jobs can be added to the economy of any country that implements the circular economy concepts by turning waste as a resource for poverty alleviation by 2025 (Perella, 2011).

The cornerstone to the theory of circular economy is the principle that materials and products are kept as long as possible. This helps to minimise the need for the input of new material and energy, thereby reducing environmental pressure linked to the life-cycle of products, from resource extraction, through production and use to end-of-life (European Parliament, 2017).

2.7 The role of waste-to-energy in circular economy

As a part of the package EU Commission has issued a communication about the role of waste to-energy in the circular economy. It provides guidance for Member States to achieve a balance of waste-to-energy capacity, highlighting the role of the waste hierarchy which ranks waste management options according to their sustainability and gives top priority to preventing and recycling of waste. It helps optimizing their contribution to the Energy Union and exploiting the opportunities for cross-border partnerships where this is appropriate and in line with our environmental goals. (Sundqvist.2017)

2.8 Incineration and Recycling

2.8.1 Waste Hierarchy and MSW Composition

Municipal Solid Waste is commonly defined as waste composed of municipalities or other local authorities. It includes mainly domestic waste, commercial, and institutional wastes (World Bank, 2017). It can be classified as biodegradable waste, recyclable materials, inert waste, composite waste and waste plastics, domestic hazardous waste, and toxic waste (WIEGO, 2019). In the same line, according to Inter-governmental Panel on Climate Change (IPCC), MSW is composed of food waste (25– 70%), plastic, metal, glass, textiles, wood, rubber, leather, paper and others (World Bank, 2017).

Most WtE transformation processes require pre-treatment of MSW. The characteristics of the raw materials, within solid waste, are affected by several factors, which range from the storage method (influence of humidity), maturity (wide variety of waste within an excavated landfill), classification policies (which vary depending on the country), to name a few. Successful implementation of WtE conversion technologies depends considerably on the efficiency of the process, which, in turn, depends on the quality of the waste considered (Pallacio et al., 2019).

The waste hierarchy is the main principle at the cornerstone of the waste policy in Europe. It establishes the priority order Member States should apply when developing waste management legislation and policy. It envisions that waste should be in the first place prevented, then reused, recycled, processed for energy recovery, and finally disposed of.

Unfortunately, although waste prevention represents the top priority of the waste hierarchy, effective waste measures of this kind have rarely been yet developed by Member States. This delay in the implementation of the waste hierarchy principles is in part due to the lack of consistency among national waste policies: on the one hand, there are principles and other non-binding tools to promote more sustainability-oriented practices; on the other hand, Member States are free to subsidies the activity of burning mixed municipal waste, known as incineration. (Marco giacomazzi, 2017)

waste-to-energy is seeing to continue to have a role to play in an integrated approach to waste management, providing hygienic treatment of the remaining waste that is not suitable for sustainable recycling, and at the same time generating energy from it, rather than it being sent to a landfill Recycling and waste-to-energy are complementary to achieve lower landfill rates (Ella Stengler, 2015)

Zero-wasters say that a major problem with incineration is the long-term contracts that waste-to-energy plants sign with the cities that supply them with trash. Incinerators are extremely expensive to build as large, modern facilities in Europe cost $150 million to $230 million and to make a profit and repay investors, incinerator operators need a guaranteed stream of waste. The operators sign contracts with municipalities to provide a certain volume of waste over a long period of time, often 20 or 30 years, effectively committing municipalities to generating a certain amount of waste. Zero-waste advocates say this reduces the incentive to recycle more and waste less, which exists with landfills, where tipping fees can be high. (nate seltenrich ,2013)

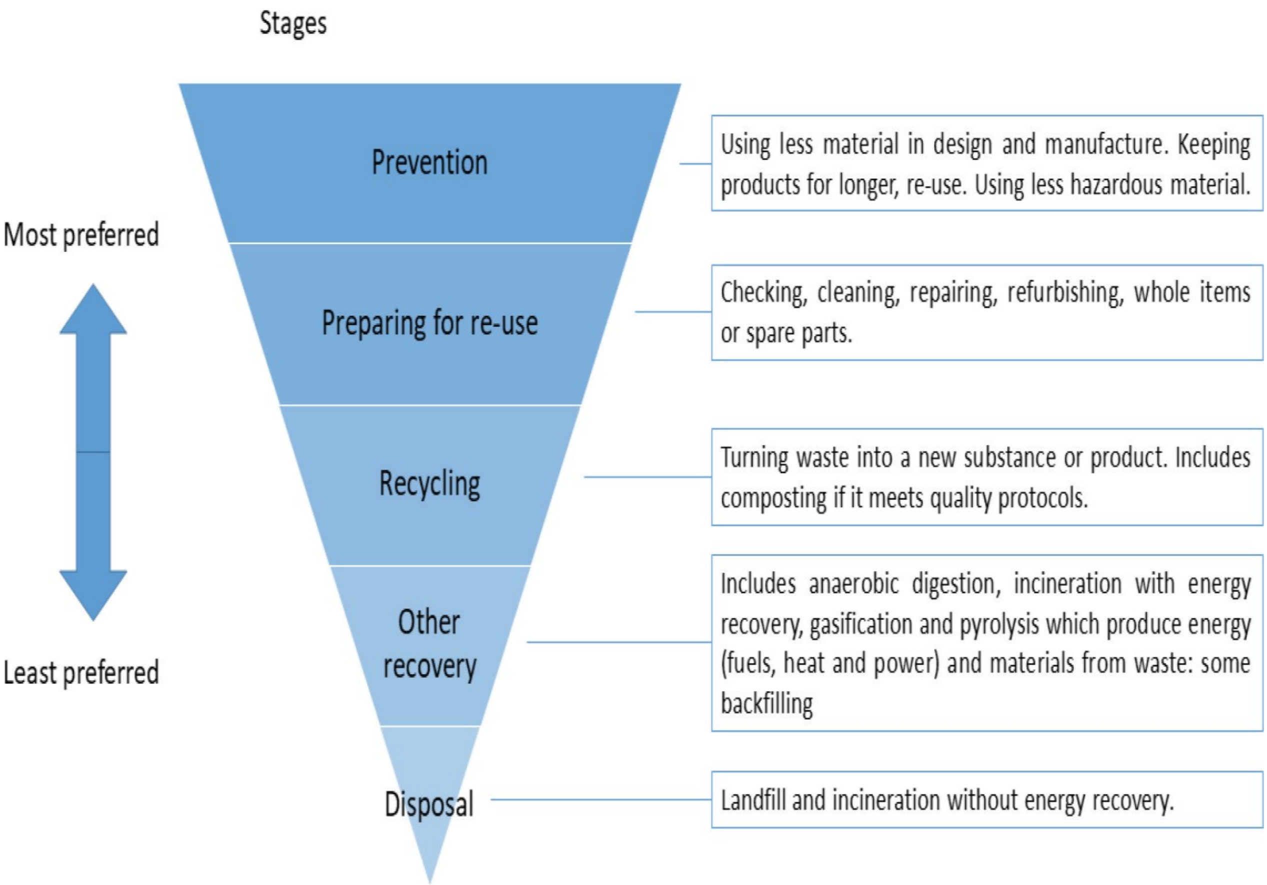

Figure 2. 1: Waste hierarchy, adapted from (DEFRA, 2011)

2.8.2 Energy used to collect, process and market recycled materials

Incinerating municipal solid waste (MSW) in an energy-from-waste (EFW) facility recovers a portion of each waste material's heat value as electrical energy. Recycling waste materials conserves energy by replacing virgin raw materials in manufacturing products, thereby reducing acquisition of virgin materials from the natural environment. At the same time, recycling removes materials, some of which have high intrinsic energy content (e.g., paper and plastic), from the stream of MSW available for EFW incineration. Thus, the question: Does recycling waste conserve more energy than incinerating waste generates? The analysis that follows shows that for 24 of 25 waste materials, recycling saves more energy than is produced by incinerating MSW in an EFW facility to generate electricity. This is because burning garbage to produce steam and spin turbines in EFW facilities captures only about 15% of a materials' intrinsic heat value. It is also because recycling saves substantial amounts of energy that would otherwise be expended extracting virgin materials from the natural environment and transforming them to produce goods that can also be manufactured from recycled waste materials. Furthermore, energy conserved by manufacturing with recycled materials rather than virgin materials exceeds incineration generated energy by enough to cover incremental energy used collecting and processing recycled materials, as well as energy needed for shipping recycled materials to markets. In fact, the estimates reported in this paper are consistent with customary practices in the recycling industry. For example, recycled glass or compost made from yard or food wastes have lower energy savings and are typically used near the community from which they are recycled. But recycled paper, plastics, and aluminium cans have higher energy savings and often are shipped great distances to manufacturers of recycled-content products.(Jeffrey Morris July 1995)

The energy conserved by recycling is three to five times as great on average as the energy generated by incinerating MSW in an Energy from Waste facility. Only for food, yard and wood waste is energy generated from incineration close to or greater than the energy conserved when waste materials are recycled. However, this comparison does not take into account the energy required to collect recyclable materials, clean and process them for market, and ship them to end users. At the same time, recycling diverts materials from the refuse stream and saves some of the energy necessary to collect and dispose of MSW. (Jeffrey Morris July 1995)

2.9 **Methods used to estimate potential of Energy from Waste**

Scarlat et al. (2015), carried out a study to assess, at the African level, the role which waste could play in providing energy to citizens and provides an estimate of the total potential of energy from waste incineration and from Landfill Gas (LFG). Data was collected after a detailed review of the literature published in well-known scientific journals, and reports of leading international organisations such as the World Bank.

The results showed an energy potential of all waste generated in Africa of 1125 PJ in 2012 and 2199 PJ in 2025. Nevertheless, if energy recovery through LFG is considered, about 155 PJ could be recovered in the year 2012 and 363 PJ in the year 2025 if waste actually collected, or projected to be collected, is considered. The electricity generation could reach 62.5 TWh in the year 2012 and 122.2 TWh in the year 2025, in case of full waste collection, compared with electricity consumption in Africa of 661.5 TWh in the year 2010. If waste actually collected is considered, these estimates decrease respectively to 34.1 TWh in the year 2012 and 83.8 TWh in the year 2025. The estimations provided in this study considered waste production and collection in urban areas only, production and collection of waste in rural areas was not assessed. Additionally, there are large variations from city to city in terms of waste generation and collection. Considering waste management system in developing countries, waste stream is being depleted from substances providing high calorific value (plastic, paper, glass, etc...) that led to shift attention on undertaking for technological options. The role of informal sector in Municipal Solid Waste management was not rated in terms of waste collection and disposal methods.

Surroop and Mohee, (2011), conducted a study in which they used the IPCC method for predicting the amount of landfill gas generated from the landfill, which could be used for power generation. Based on the flow rate of the landfill gas, it was found that the amount of power generated varied over time. It would initially increase until it reached a peak. In the case of the Mare Chicose landfill (Mauritius), the peak will be reached in the year 2012 and after this it would decrease. It was found that the amount of power produced in the year 2010 would be 50.50 GWh. The scope of their study was limited to predicting the amount of landfill gas generated from for the Mare Chicose landfill (Mauritius), costs and risks analysis approach to identify the most favourable WtE technology(s) among others (mass burn incineration, refused derived fuel incineration, gasification, anaerobic digestion) were not fully analysed.

Osra and associates (2021), carried a study in which MSW characterisation and the energy recovery of Makkah were determined. The Gas Generation Model (LandGEM) was used to evaluate energy recovery potential from solid waste from open dump site landfill and landfill gas generation potential and capacity were determined. The results estimate the methane potential of 83.52 m3 per tonne of waste from Kakia, collecting and dumping open site for Makkah. The unit of analysis was limited to Makkah where MSW collected in the city are high in organic matter averaging to 48 per cent which may be due to their high economic levels. Waste stream is specific to different regions, due to many factors including socio-economic and climate aspects. This study did not include analysis on other waste disposal methods and their impact on an effective LGF generation. Moreover, The Gas Generation Model (LandGEM) tailored for US was not appropriate in developing countries.

Despite the achievement in the implementation of WTE technologies in many countries of the world, there are challenges associated with WTE technologies. The major challenges include operating costs; public perception and acceptance, legislations and institutional frameworks associated with the regulation of the WTE technologies (UN, 2012; Asamoah et al., 2015; Chimuka and Ogola 2015). Researchers suggest 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 (World Bank, 2012).

Mudenda and et al (2018), undertook a study based on the requisite capacities of households for the adoption of renewable energy services in Zambia. The main findings revealed that there is a need for a broader, multidimensional understanding of access to renewable energy in order for deployment to be effective. A detailed analysis on WtE technologies was not provided by this study.

Sambo and associates (2020), focused on challenges sustainable solid waste management in Lusaka, in this study little was known about energy generation from waste.

In Ndola, the provincial capital of the Copperbelt province of Zambia, Edema *et al.* (2012), carried out a study with the aim of evaluating the methods of solid waste disposal, the level of access to solid waste management services, and Ndola residents' attitudes towards solid waste management. The findings showed that waste stream is mainly composed of food waste (50% of household waste in low density areas and 45% in medium density areas), while paper and textiles were the least abundant in the household wastes evaluated. The C: N ratios of the wastes collected ranged from 16.21 to 27.06 a range indicating that the waste was good material for use as compost. This study did not provide enough information about WtE technologies as part of integrated sustainable waste management system in Ndola.

2.10 **The Case for Waste to Energy in Zambia**

2.10.1**Zambia Electricity's Demand and Supply Constraints**

Zambia is situated in Southern Africa, it's a landlocked country with an estimated population of 16.9 million and a national Gross Domestic Product (GDP) of USD 22 billion (Lucas, 2016). Economically, Zambia attained a lower-middle-income status in the year 2011. Between the year 2003 and the year 2013, the average GDP growth rate was 6.3 per cent per annum (World Bank, 2015). However, with a GDP per capita of USD 1361, poverty remains a major challenge, with 60 per cent of the population below the poverty line and 42 per cent in extreme poverty (Lucas, 2016). Zambia's economy came under strain in 2015 and 2016, resulting in a sharp decrease in GDP growth from 4.9 per cent in the year 2014 to 2.8 per cent in the year 2015, due to external and domestic factors, including falling commodity prices (especially low copper prices), expensive borrowing on international markets and a weakening currency (World Bank, 2017). This situation was exacerbated by the electricity supply crisis triggered mainly by a drought in the 2014/2015 rainfall season, which caused blackouts of up to eight hours per day (Kesselring, 2017). Zambia's current power deficit, therefore, affects the ability of businesses, large and small to effectively function (ZIPAR, 2015). The most recent World Bank Enterprise survey, which predates the current load shedding, quantifies firms' average annual losses attributable to power outages. This data offers some intuition on the economic costs of electrical outages on firms' turnover. On average, firms were estimated to lose 7.5 per cent of their annual turnover (World Bank, 2017).

These electricity supply difficulties put severe pressure on the country's economic growth, with commerce and industry suffering substantial losses due to reduced production capacity (many manufacturers claimed to be running at only 30 to 40 per cent of production capacity during the worst parts of the electricity crisis) (World Bank, 2015).

The productive sector also acknowledged increased input costs, due to expensive back-up power and the changing of shifts (Samuel, 2016). As a strategic sector, mines were largely exempted from load-shedding, but were asked to reduce their electricity consumption by 30 percent in 2015 (Kesselring, 2017; Owen, 2016). The electricity supply crisis was therefore a substantial growth constraint for Zambia. Equally of importance is the environmental impact of load shedding. There has been increased demand for charcoal as a source of energy for cooking, a development likely to increase the rate of deforestation in Zambia and the adverse effects of climate change (ZIPAR, 2015).

Zambia has, 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 (ZEMA, 2011; Muller et al., 2017). The combination of these changes have soared levels of growth in electricity consumption and the level of demand. Energy generation in Zambia relies almost entirely on hydropower (96% out of a total installed generation capacity of 2.754 MW) while the country's electrification rate stands at approximately 20 per cent. Due to drought and subsequent poor rainfall, hydro-power generation was severely reduced in the year 2015, and this resulted in an estimated power capacity shortfall of about 1000 MW (ERB, 2015).

Seventy-five per cent of Zambia does not have access to electricity; to tackle this issue Government, through the Rural Electrification Master Plan (REM), has targeted to increase electrification rates to 66 per cent of households by the year 2030 of which, 90 per cent would be for urban areas while 51 per cent would be for rural areas. The National Energy Policy (2008), acknowledges the need to increase the share of renewable energy (apart from large hydro) in the electricity generation system (PMRC, 2013).

Despite the rapidly growing electricity demand by various consumers, there have been limited investments in expanding electricity generation capacity, with few efforts made to replace the aging electricity infrastructure.

What is also clear is that there is very little diversity in the energy generation mix. Since the year 2000, electricity demand in Zambia has been growing at an average of four per cent per year. The current annual energy deficit is estimated at 3500 GWh (World Bank, 2017), which leads to load management because the total energy demand exceeded internal generation capacity; shortages in energy supply are not showing slowdown years ahead (PMRC, 2013).

An assessment of hydropower in Southern Africa, including Zambia, simulated a reduction in annual average energy production of 21 per cent. Reservoir levels, behind the hydroelectric generation dams, are expected to decrease on an annual basis as a result of more frequent and prolonged drought conditions. This, combined with increased surface water evaporation, especially from upstream reservoirs and floodplains, could result in reduced energy generation capacity throughout Zambia (World Bank, 2010).

In order to keep up with the soaring energy demand, ZESCO had to employ emergency measures such as importing expensive power from the Southern African power Pool, as well as from Aggreko Mozambique (Owen, 2016), combined with the weakening Zambian currency. The Zambian government needed to provide ZESCO with about USD 340 million to cover emergency power costs in the year 2016 (World Bank, 2015).

Facing serious electricity supply deficit from recent droughts, the Government of the Republic of Zambia (GRZ) now actively seeks to improve conditions for private investment and to diversify its energy mix. This programmatic proposal will support GRZ by helping to catalyse private investment in the Renewable Energy (RE) sector, thereby accelerating the achievement of its electricity generation and diversification targets. This will essentially reduce the country's reliance on the energy imports which has been an added fiscal pressure at the time of power crisis (ZEMA, 2011; PMRC, 2013).

A key challenge facing the sector is that electricity tariff has been historically very low and cost effective (i.e. the tariff do not provide an attractive return to power producers) which places further pressure on the fiscal through support of the public utility (as government has to provide direct or indirect subsidies) and this makes it difficult to attract private sector investment in the power sector (IRENA, 2015; Owen, 2016).

The current power crisis presents investment opportunities in the energy subsector. Zambia has both the comparative and competitive advantage to venture into a generation mix using various energy sources. The country has abundant sunshine for solar energy; more than eighty identified hot springs for geothermal energy; small rivers in the Northern and the North-Western provinces for mini hydro plants; climate and arable land suitable for cultivating bio fuel crops such as maize corn and sugar cane; and potential for energy from wind at high altitudes (ZIPAR, 2015).

Table 2. 1: Installed generation capacity in Zambia. Source: (Ministry of Energy, 2016)

N°	Power Stations	Installed Capacity	Type of generation	Operator
1	Kafue Gorge	990	Hydro	ZESCO
2	Kariba North Bank	1080	Hydro	
3	Victoria Falls	108	Hydro	
4	Lusemfwa and Mulungushi	56	Hydro	Lusemfwa Hydro-Corp
5	Small Hydro-combined	25	Hydro	
6	Isolated Generation	8	Diesel	ZESCO
7	Gas Turbine (Stand by)	80	Diesel	
	Total	2177		Copperbelt Energy Corp

2.11 **Increasing waste generation**

The increase in the rate of MSW generation in Zambia, has been worsened by an increase in urbanisation, rapid population growth, rural-urban migration and industrial growth (ZEMA, 2011; Muller et al., 2017; Sabo et al., 2020). Zambia's waste generation rates were approximately 0.52 kg per person daily (UN-Habitat, 2010). According to Lusaka City Council, less than 20 per cent of Lusaka's urban waste was treated after disposal, there was an inherent risk of environmental susceptibilities, due to the failure to sort waste. Lusaka generates about 1,000 tonnes of solid waste daily (Lusaka City Council and Environmental Council of Zambia, 2008).

The challenge is that only about 300 tonnes of the waste is disposed off at the designated dumpsites and treated in a sustainable environmental manner (UN-Habitat 2010). Zambia Environmental Management Agency (2011), argues that despite the existence of a national SWM strategy, the growth of the urban population and increased economic activity had resulted in an accumulation of waste. Poor waste management has resulted in soaring major public health concern and decline environment health conditions in Zambia (Sabo et al., 2020), which has led local authorities and policy makers to focus attention in developing strategies for sustainable waste management system (NEP,2008).

The existing policy, legislative, regulatory, and accountability frameworks that govern solid waste management within Zambia are complex, opaque, and insufficient to catalyse investment and job creation within the waste management sector. At the national level, the Ministry of Lands, Natural Resources and Environmental Protection is responsibility for the formulation, implementation, monitoring and evaluation of policies on the environment, natural resources, and pollution control.

Through the Ministry, the Zambia Environmental Management Agency (ZEMA) assists other government Ministries and local authorities to regulate and advise on environmental protection measures. At a sub-national level, responsibility is further decentralised, with several departments within City or Municipal Councils mandated to oversee different aspects of Solid Waste management. While guided by national policies, these local authorities are responsible for developing their own by-laws around waste management (Muller et al., 2017).

Edema *et al.* (2012), described the changes in waste management in Ndola from the early 1980s to present. The city council was experiencing issues with old equipment and trucks used to collect waste frequently breaking down. Only one of four tipper trucks, and three of four skip loaders were operational at the start of the year 2017. The dumpsite bulldozer was also out of operation and a replacement was currently hired from the army. Other equipment included a compacting truck and a front-end loader. Vandalism or theft of 50l bins was common, most were broken or stolen. There was a lack of public sensitisation around waste management. Private companies used their own vehicles. There were seven companies servicing specific areas, but it was also possible for them to subcontract each other's services.

2.12 **Waste to Energy (WtE) Potential in Zambia**

Substantial amount of waste produced in Zambia, particularly in Ndola consists of biodegradable wet waste (Muller et al, 2017; Adema et al, 2012). Biodegradable waste has a good potential for generating biogas, which can serve as fuel, and can also be converted to energy as well as to compost which can improve soil health and lead to increased agriculture production (Asamoah et al., 2020; Agbelie et al., 2015). This waste must, therefore be processed either through incineration, biomethanation or composting technology for generating biogas, electricity or compost for use as nutrient and prevent such wastes reaching the landfill.

According to Babcock *et al*. (2012), LFG power represents one of the most readily available, cheap and relatively simple forms of WtE options. However, the carbon dioxide emissions from landfills per tonne of MSW processed are at least 1.2 t CO2, much higher than WtE plants. Considering all environmental performance criteria (energy, material, and land consumption, air and water emissions, risks), WtE is the most favourable solution. Waste to energy is the process of converting waste to energy in form of heat or electricity by using appropriate technology.

WtE facilities serve a dual role of waste disposal and energy production. Although the cost per MW of capacity may be greater than other renewable sources, the benefits of waste management, energy and metals recovery, and reduction of GHG emissions need to be considered. Moreover, due to space deficit in urban areas, WtE provides an effective way to reduce the volume of waste by approximately 90 percent and thereby lower the space needed for landfills (Ofori et al., 2013).

2.13 **WtE Opportunity in Africa**

Waste to energy is seen as efficient advanced waste management technologies that would support the overall objective of sustainable urban livable cities, such as landfill diversion, resource efficiency, energy recovery, greenhouse gas avoidance and a high level of public service (UNEP, 2018). Waste quantities are increasing in most growing African mega-cities, and there is significant availability of waste suitable for WtE treatment and energy recovery (Agbelie et al., 2015). Owing to the often large difference between less-affluent and highly affluent suburbs in African mega-cities, it is possible to source and mix the waste from the most suitable suburbs, urban centres and business districts to secure a calorific value in the range of 8 to11 MJ/kg, which is suitable for energy conversion by WtE. Typically, a suitable calorific value can be maintained, particularly if there is source separation and recovery of such things as paper, cardboard, plastic bottles and perhaps garden waste/kitchen waste in affluent suburbs (UNEP, 2018).

It is, therefore, possible, based on technical and objective criteria for most fast-growing African mega-cities to establish WtE facilities that can contribute to, much needed landfill diversion and electricity generation for the city, and support near-urban waste treatment. If the WtE facility can be located in or near (e.g. within 2 km of) industrial estates with energy-intensive industries that have large heating or cooling needs, it would further be possible to use more of the energy produced as an industrial process energy. The critical factor for making WtE technology a success is not the technology itself (UNEP, 2018).

2.14 **Waste to Energy Options in Municipal Solid Waste Management**

In the following section, an overview of widely used and implemented technologies for sustainable MSW management has been explained, namely; thermochemical technologies and biochemical technologies (WIEGO, 2019; Ouda and Raza, 2015). For each technology, some technical background information is given followed by the description of the technology, types of end-products and the application of these end-products. These technologies have different functions and applications in the municipal waste management system. The order of the technologies is based upon the perceived demand for advice on these technologies and does not imply any priority or applicability (GIZ, 2017). According to Bogner *et al*. (2007), existing waste-management practices can provide effective mitigation of GHG emissions from this sector: a wide range of mature, environmentally-effective technologies are available to mitigate emissions and provide public health, environmental protection, and sustainable development co-benefits. Collectively, these technologies can directly reduce GHG emissions (through landfill gas recovery, improved landfill practices, engineered wastewater management) or avoid significant GHG generation through controlled composting of organic waste, state-of-the-art incineration and expanded sanitation coverage.

Publications from different stakeholders describe in detail critical differences and particularities of WtE technologies. These documents include an analysis of necessary prerequisites such as market, policy, regulatory and financial sustainability issues (GIZ, 2017).

2.14.1 Thermochemical Technologies

Thermochemical conversion is a process through which thermal energy breaks down the molecular structure of MSW organic components and transforms larger molecules into smaller molecules. After that, supplementary oxygen is provided which combines with the hydrogen and carbon atoms released from the decayed larger waste molecules and produces more energy than it provided to break the complex molecular structure of MSW components. Thermochemical pathways use conversion pathways, and use very high temperature to convert waste feedstock MSW into heat, electricity, and other value added products (IEA, 2013). These technologies include incineration, pyrolysis, and gasification. In the following section, these thermochemical WtE technologies are briefly explained.

i. Incineration[u1]

Incineration is one the most essential part of MSW management in many countries worldwide (Agbelie et al, 2015). MSW incineration is a consistent form of thermal treatment technology that has evolved substantially over the years together with counter measures for air pollution and dioxins (Makarichi et al., 2018). Incineration is a well-established and the most commonly used WtE technology globally (Farooq et al., 2021).

Municipal solid waste incineration is the burning of mixed and (often) crude waste from households, commerce (and certain) constructions in a controlled process within a specific facility (called an incinerator) that has been designed and built for this purpose (WIEGO, 2019). The major goal of MSWI is to reduce MSW volume and mass and also make it chemically inert in a combustion process without the need of additional fuel (UNEP, 2020). Though a decrease in volume and a mass of 75 per cent can normally be attained, it is the remaining 25 per cent left over that is of concern and requires specialized attention. The left-over ashes in the form of slag (bottom ash) and fly ash require further treatment (GIZ, 2017).

The combustion of waste generates energy and heat, but the waste does not burn by itself. The ignitable materials in waste only burn when they reach a specific temperature (the necessary ignition temperature) and come into contact with oxygen, therefore undertaking an oxidation reaction. This (so-called) reaction temperature is between 850 and 1450ºC (WIEGO, 2019, IEA, 2013; GIZ, 2017). The burning process proceeds in the gas and solid phase, instantaneously freeing heat energy. Waste materials require a minimum calorific value (energy content, or how well it burns) to enable a thermal chain reaction and self-supporting combustion (autothermic combustion).

If this minimum value is not met, supplementary fuels are required to initiate (and continue) the incineration process. This means that there should be a continuous and large supply (feedstock) of waste to be burned and this feedstock should have enough materials with high calorific values (i.e. paper, cardboard, plastics and textile content). If this is not guaranteed on a permanent and long-term basis, the additional fuel consumption will lead to (unforeseen) high operational costs to avoid the ovens having to be shut down (IEA, 2013).

The process efficiency of incineration is 25-30% (Ouda and Raza, 2015). According to (Chakraborty et al., 2013) around 65-80% of energy stored in organic materials can be recovered in the form of heat that can be used in other power producing facilities based on thermal supplies.(According to World Bank, 1999) incineration pathway is intended to treat characteristically mixed and largely untreated domestic waste and certain industrial and commercial wastes.

A key parameter is the energy content, the so-called lower calorific value (LCV) in MJ/kg. To ensure autothermic combustion of the waste LCV should not be below 7 MJ/kg on average over a year (for comparison: The LCV of 1 kg fuel oil is about 40 MJ/kg). In developing countries the LCV of unsorted MSW is often below this threshold due to a dominant organic content with high moisture and a significant level of inert waste fractions such as ash or sand (GIZ, 2017).

The end product of incineration is hot combusted gases mainly composed of nitrogen, carbon dioxide, flue gas, oxygen and non-combustible materials (Tan et al., 2015). To minimize the air pollutants emissions, most con- temporary incinerators use an extensive pollutant/emissions control system. Solid residue known as slag is detached from the bottom of the furnace, typically into a quench tank. Slag can be combined with fly ash and incorporated into cement or other similar building materials, or simply landfill if its characteristics are appropriate although the capital cost of incineration is lower in comparison to other WTE technologies (Arena, 2015). Incineration technology is complex, capital intensive, repair and maintenance sensitive, and requires highly skilled staff for operation and management (WIEGO, 2019).

As it turns out, countries with the highest rates of garbage incineration Denmark, Norway, and Sweden, for example, all incinerate at least 50 percent of their waste as an alternative to waste management, also tend to have high rates of recycling and composting of organic materials and food waste. But zero-wasters argue that were it not for large-scale incineration, these environmentally conscious countries would have even higher rates of recycling. Germany, for example, incinerates 37 percent of its waste and recycles 45 percent — a considerably better recycling rate than the 30-plus percent of Scandinavian countries. (Nate Seltenrich 2013)

Energy from waste is an important waste management method in Sweden, especially incineration of waste. In the last 5 year-period, the incineration of municipal solid waste in Sweden has been 2.2 – 2.3 million tonnes annually, which corresponds to approximately 48 – 51% of the municipal waste. The incineration plants also use other waste fuels: the total amount of incinerated waste in "municipal incinerator plants" were about 5.8 million tonnes in 2015, of which 2.3 million tonnes were Swedish municipal waste, about 1.5 million tonnes were imported municipal waste or sorting residues from municipal waste, and the rest were Swedish industrial wastes. The incineration plants produced 14.7 TWh of district heating and 2.3 TWh of electricity. That means that close to 23% of the district heating in Sweden is produced from in municipal waste incineration plants. (Jan-Olov Sundqvist).Europe and Sweden offers a good example of how Incineration can be used for waste management.

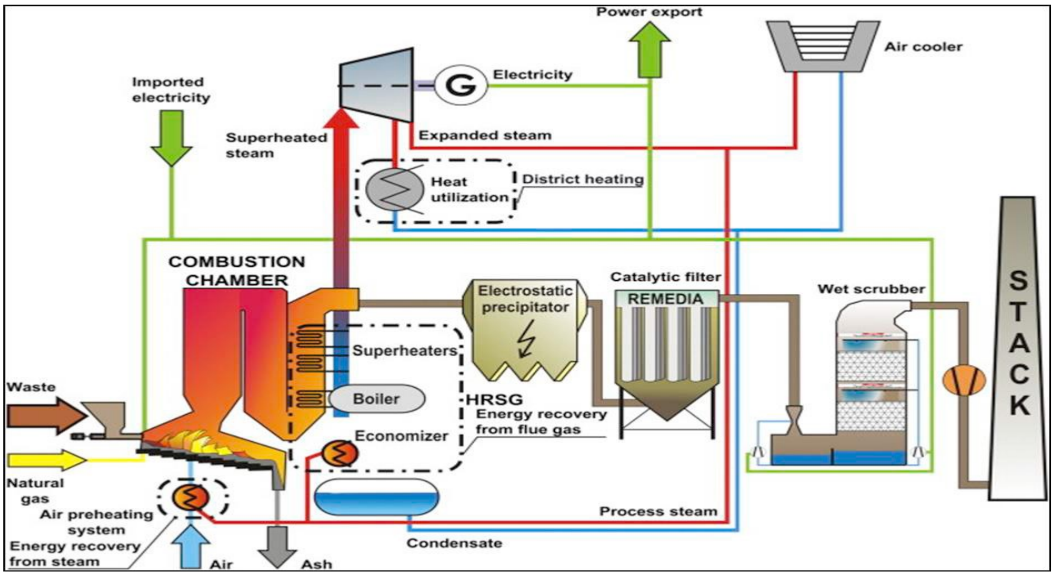

Figure 2. 2: Incineration plant to produce electricity and heat from MSW.(Kilkovsky et al., 2014)

ii. Pyrolysis

Pyrolysis is a thermal process that is realised in the absence of oxygen. According to Ouda *et al.* (2016), the pyrolysis process can recover up to 80 per cent of the energy from the carbonaceous fraction of MSW. Within pyrolysis pathway, three different reactions are available depending on temperature, heating rate, particle size, and residence time. These reactions are slow, fast, and flash pyrolysis (Qazi et al., 2018). The heat values of pyrolysis gas typically lie between 5 and 15 MJ/m³ based on municipal waste. In a broader sense, “pyrolysis” is a generic term including a number of different technology combinations (GIZ, 2017).

The three pyrolysis operating parameters reactions are also different. The following parameters represent respectively temperature for slow, fast and flash pyrolysis 500–950, 850–1,250, 1,050–1,300◦C; residence time 450–550 s, 0.5–10 s, < 0.5 s; particle size 5–50mm, < 1mm, < 0.2mm; and heating rate 0.1– 1, 10–200, 200–1,000◦C/s, respectively. A fluidised bed reactor is the most pyrolysis pathway used for pyrolysis (Balat et al., 2009; Jahirul et al., 2012; Shahnazari et al., 2020). The end product of pyrolysis is gaseous, liquid, and solid fuels (char) as a result of converting the carbonaceous fractions of MSW. Different types of fuels are produced for all three (slow, fast, and flash) pyrolysis reactions due to different operating parameters. The percentage share of liquid, solid, and gaseous fuels production for slow pyrolysis is 30, 35, 35 per cent; for fast pyrolysis is 50, 20, 30%; and for flash pyrolysis is 75, 12, 13 per cent, respectively (Balat et al., 2009; Jahirul et al., 2012; Qazi et al., 2018b).End products deriving from pyrolysis pathway (gaseous, liquid, and solid) considering all three types of fuels have properties very similar to fossil-based fuels (Ouda et al., 2016). Pyrolysis gas is very rich in ethylene that can be used for alcohol/gasoline production. All three pyrolysis fuels can be used for heat and power generation purposes directly (Balat et al., 2009; Marshall et al., 2014; Qazi et al., 2018)

The impetus to apply pyrolytic technologies to municipal waste feedstocks grew out of concern for the mounting MSW problem, including diminishing landfill space and groundwater contamination and ·environmental problems associated with early MSW incineration efforts One of the major reasons for interest in pyrolysis in the United States stems from our dependence on liquid fuels, or, in general, on fuels that are storable, economically transportable, and that can readily substitute for conventional fuels. Pyrolysis is one of the few technologies that offers the potential for the production of "high density" alternative fuels. (Nrel October 1992)

This shows that considerable MSW weight reduction can be achieved through pyrolysis and this is a means of MSW management. Pyrolysis especially at high temperatures, not only reduces volume significantly, but also eliminates the original odour of the source materials (Yoshida, 2000; Shinogi and Kanri, 2003).

Waste Management by Pyrolysis

Dozens of pyrolysis plants successfully operate in different countries including USA, China, Japan, Germany, and Spain (splainexts.ecomsystem, 2022)

Japan built pilot, demonstration and commercial scale pyrolysis plants during the late 1960s, 1970s and early 1980s. Pyrolysis appears especially attractive for managing Japanese MSW (NREL, 1992)

In Europe Denmark is widely using pyrolysis to convert waste into energy especially plastic waste. Japan is also the country that is using pyrolysis for converting waste into plastic.

iii. Gasification[u2]

Gasification is an indirect combustion process, where an exothermic reaction occurs in the reactor when carbon reacts with oxygen to produce energy to drive the reaction, temperature, pressure and oxygen concentrations are the main parameters that affect the gasification process (Ouda et al., 2016). It occurs at a very high temperature of around 800◦C. End products through gasification route are very high (up to 85%). However, gasification efficiency depends on several parameter, involving temperature, feedstock particle size, moisture content, and gasification agent.

The temperature in the gasifier should be between 500 and 1,000◦C, the feedstock particles should be very small and uniform in size, the moisture content should be below 15% (Qazi et al., 2018). There are many reactors design suitable for gasification with an overall efficiency around 17% (Bridgwater, 2002). Many studies underscored the following: rotary kiln, updraft fixed bed reactor, downdraft fixed bed reactor, bubbling fluidized bed reactor, entrained flow bed reactor, plasma reactor, vertical shaft, and moving grate furnace (Arena, 2012; Moya et al., 2017).

An effective and efficient gasification pathway deals with small and uniform in size feedstock particles with moisture content below 15 per cent (Qazi et al., 2018b). Gasification process converts plastics and combustible organic fractions of MSW into clean and very useful syngas or synthesis gas. According to Ouda *et al*. (2016 and Qazi *et al*. (2018), syngas, contains these elements carbon monoxide (CO) and Hydrogen (H2), CO and H2, smaller amounts of carbon dioxide (CO2), water vapour (H2O), nitrogen (N2), and methane (CH4).

The clean syngas produced in the gasification process can be used directly in a gas turbine to produce combined heat and power (CHP) or can be used as valuable transportation fuels. Moreover, it can also be used as secondary raw material in fertilizers and chemical industries (Ouda et al., 2016; Moya et al., 2017; Qazi et al., 2018).

Faced with the costly problem of waste disposal and the need for more energy, a growing number of countries are turning to gasification, a time-tested and environmentally-sound way of converting the energy in MSW into useful products such as electricity, fertilizers, transportation fuels and chemicals. On average, conventional waste-to-energy plants that use mass-burn incineration can convert one ton of MSW to about 550 kilowatt-hours of electricity. With gasification technology, one ton of MSW can be used to produce up to 1,000 kilowatt-hours of electricity, a much more efficient and cleaner way to utilize this source of energy. Gasification can help the world both manage its waste and produce the energy and products needed to fuel economic growth.

Gasification converts MSW to a usable synthesis gas, or syngas. Gasification is a unique process that transforms a carbon-based material, such as MSW or biomass, into other forms of energy without actually burning it. Instead, gasification converts the solid and liquid waste materials into a gas through a chemical reaction. This reaction combines those carbon-based materials (known as feedstocks) with small amounts of air or oxygen (but not enough to burn the materials), breaking them down into simple molecules, primarily a mixture of carbon monoxide and hydrogen. (Naresh Bhatt, 2021)

Gasification is a versatile technology also regarding circular economy; waste streams could be used for production of value added products. Furthermore, a synergy with other technologies could be provided to boost the amount of products and to increase the process efficiency. And last, but not least, the gasification could be very beneficial for the environment, e.g. as technology converting biomass into biofuels and biochemical as well as a carbon storage decreasing in this way a footprint.(IEA Bioenergy,2022)

Although the technology of gasification has been in use for over 200 years, gasification of MSW is still in its early stages of development. Despite the fact that gasification technology is, in potential more energy efficient than and can be financially competitive with other waste management options, such as WTE, implementation of thermal MSW gasification technologies has only recently started to gain momentum. Instead, coal gasification is being applied worldwide to produce 'town gas' for heating, cooking and lighting (Jenkins, 2007). Although MSW gasification can be considered a viable technology, i.e. the individual processes described have been proven to work well, combining the steps needed for electricity generation is rather new and not yet mature yet (AES, 2004). Only recently, MSW gasification has been further paid attention to by implementing facilities that produce either steam or electricity. With rising costs of landfills in Europe due – among others – to higher taxes for landfilling, the 'gasification' option has become more interesting and several plants are operational in various European countries already. These are mostly fluidized bed type facilities built over the last ten years (Jenkins, 2007).

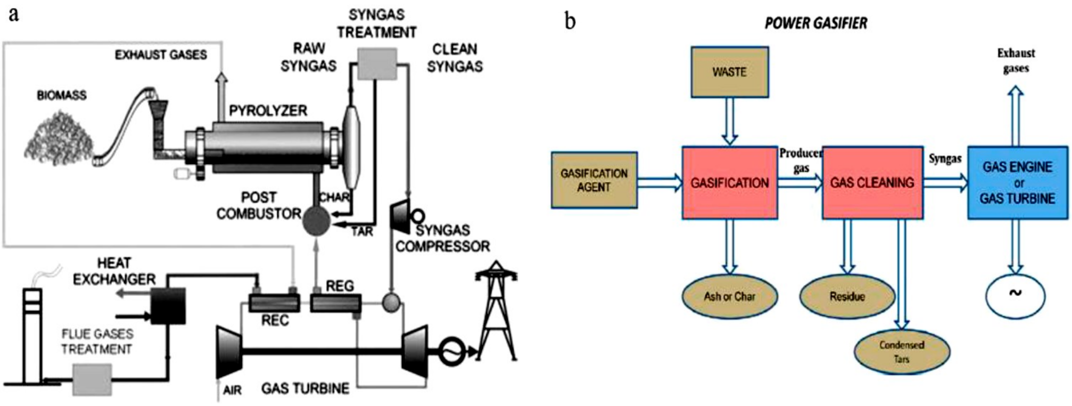

Figure 2. 3: Representation of (a) Pyrolysis process (b) gasification technology based on configuration power (D'Alessandro et al., 2013)

iv. Plasma Arc Gasification

Plasma arc gasification converts the waste and organic materials into syngas or synthesis gas and solid slag using plasma generated by an electrically powered plasma torch (Belgiorno et al., 2003). The quality of waste decomposition through plasma depends upon plasma density and its temperature (Quiros, 2004). Plasma is known as the fourth state of matter with hot ionised gases produced by electrical discharge at very high temperature (2000-5000 °C) (Tavares et al., 2011). An inert gas, such as argon, is normally used in the plasma torch. The waste is heated, melted and then vaporised at these extreme conditions. The complex molecules are dissociated into individual atoms in gas ousphase by breakage of molecular bonds. The efficiency of this technology is reported as being around 32 per cent (Heberlein et al., 2008). Plasma arc gasification for MSW is most prominent in those countries where space for constructing landfill is limited, like in Japan. In Europe, this technology is used at limited scale. The operating plants have the capacity to handle up to130 tonnes of MSW per day.

Waste Management by Plasma Gasification

Plasma gasification refers to a range of techniques that utilize plasma torches or plasma arcs to generate extreme temperatures that are particularly effective for highly efficient gasification. Solid waste contains organic content metallic particles, inorganic contents. Plasma gasification proves to be one of the most efficient methods for treating all type of solid waste without segregating them. It involves pulverizing of solid waste through crusher's thereby increasing surface area for pyrolysis. The bundles of pulverized solid waste are charged into plasma gasifier furnace using conveyer belt arrangement. The plasma produced by high intensity current (approx. 60 Volt & 350 Amp) (8) electrodes produces temperature approximately 10000 degree Fahrenheit which break downs solid waste into elemental form. The major advantage of using pyrolysis process is that the metallic particles do not evaporate as in the case of combustion where oxygen is employed which forms metal oxide which is fatal to further proceeding of the process. (Ghaziabad, 2012)

Over the past 15 years, South Korea has been actively pursuing a sustainable waste management strategy, since municipalities are not allowed to export waste outside of their respective jurisdictions, plants range in size from 25 ton/day to over 500 tons/day. There are currently 7 plants on 6 sites using gasification technology in South Korea, with the first plant in operation since 2001. Synopsis of the technology: Curbside Municipal Solid Waste (MSW) is rough shredded and fed into the primary chamber through an air lock. The gasification occurs in the low temperature negative pressurized primary chamber where the MSW goes through drying, pyrolysis and gasification stages. The resulting syn-gas is filtered through the char bed into a secondary chamber where combustion takes place, producing a hot inert flue gas. A Heat Recovery Steam Generator (boiler) is used to recover the thermal energy from the flue gas. The char at the bottom of the primary chamber is oxidized, creating the heat for the gasification process. The air pollution control system is located after the Boiler and consists of carbon and lime injection followed by a bag filter. (Sung Chun Kim, 2009)

2.14.2 Summary of Country reports on bioenergy

With the end of 2021 the IEA Bioenergy published Country reports on bioenergy, included are 25 countries worldwide and the EU28. This summary report together with the separate country reports, was prepared from IEA statistical data, combined with data and information provided by the IEA Bioenergy Executive Committee and its Tasks. All individual country reports were reviewed by the national delegates to the IEA Bioenergy Executive Committee, who have approved the content. The highlights regarding renewables and bioenergy in different sectors are summarized below:

- Bioenergy plays a role in the three main energy sectors: electricity, fuel/heat consumption and transport energy consumption. Particularly for heat and transport bioenergy/biofuels are the dominant renewable energy types.
- The main growth of renewable electricity in the past decade has been in wind power, followed by solar power and biomass-based power. In Denmark, Finland and Estonia, bioenergy represents more than 15% of electricity production (predominantly through combined heat and power - CHP), followed by the UK, Sweden, Germany and Brazil. In other countries, typical levels of biomass-based electricity are 2-5%.

- For most countries solid biomass is the dominant fuel to produce bioelectricity. However, in Germany, Italy and Croatia bioelectricity is mainly produced from biogas. In Switzerland renewable MSW is the dominant fuel for bioelectricity.
- The main support systems for renewable power have been feed-in tariff systems and obligations connected with tradable green certificates. Recently there is a trend to work with tender systems on a competitive basis. A point of attention is that, apart from the production cost per MWh, policy actions also need to reflect the multiple benefits of using bioenergy for electricity, including rural development, waste management and dispatch ability.
- In most of the analysed countries fossil fuels still dominate in fuel/heat provision, typically exceeding 75% of total fuel/heat provision. Biomass is the dominant type of renewable heat. The most important progress in renewable heat has been made in countries with important shares of district heating (Denmark, Estonia, Sweden, Finland), particularly through the replacement of fossil fuels by biomass for centralised heat production.
- The main support systems for renewable heat have been subsidies for renewable heat projects and financial support for domestic renewable heat instalment. Several countries (particularly in Scandinavia) have implemented a CO2 tax on fossil fuels which was an important driver for industries (and heat producers) to move from fossil fuels to bioenergy.
- Fossil fuels still represent over 95% of transport energy in most countries. This reflects the challenge to displace fossil fuels in the transport sector. Brazil and Sweden have achieved a renewable energy share in transport of 25% and 21%, respectively, with Norway and Finland also reaching more than 10%. Most other countries have renewable shares of 4 to 6% or lower.
- Biodiesel (including an increasing share of HVO) and bioethanol are the dominant biofuel types. Bioethanol is mainly important in countries with high shares of gasoline cars (Brazil, USA, Canada)

2.14.3 **Biochemical Technologies**

A biochemical technology converts organic waste to energy in the form of gaseous or liquid biofuels by using biological agents or micro-organisms such as yeast. Anaerobic digestion and fermentation are the WtE technologies that follow the biochemical conversion pathway (Ouda et al., 2016; Qaziet al., 2018).

i. Anaerobic Digestion/Biomethanation

Biomethanation is an anaerobic process by which organic waste is microbiologically converted into energy in the form of biogas and organic fertilizer. The microbes involved in different stages (acidogenesis, acetogenesis, and methanogenesis) of the anaerobic digestion process are very sensitive to pH level, and need specific conditions to grow and boost the yield of end products. Therefore, this process takes place in special reactors that operate at specific conditions that include well maintained temperature and pH level. Efficiency of this technology is about 25-30 per cent (Chiu et al. 2016; Bajpai, 2017; Qazi et al. 2018).

The organic feedstock is mixed well and kept in the digester for five to ten days and during this time the anaerobic digestion process takes place in four different phases, viz., hydrolysis, acidogenesis, acetogenesis, and methanogenesis (Weedermann et al., 2013; Mutz et al., 2017).

The pH level should be maintained between 6.7 and 7 according to the microbes used in the corresponding stage of the process while there are three different ranges for temperature, viz., <25◦C (psychrophilic), 35–48◦C (mesophilic), and >50◦C (thermophilic) conditions. Mostly, mesophilic or thermophilic conditions are preferred because they are economical. The process naturally occurs at the landfill sites but works more efficiently in controlled conditions (Ouda and Reza, 2015). Anaerobic digester largely necessitates untainted organic waste stream (restaurant, vegetable market, or source-segregated waste) at consistent and sufficient volume to function properly. The process produces biogas and a liquid or after drying, a solid fertilizer. The biogas can be used to generate heat or electricity (World Bank, 2018).

The effective efficiency of this technology is around 25 per cent (Metro Waste Authority, 2013). The glaring disadvantage of using this process is the space requirement 1.61-6.45 m2/tonnes. The waste collected for this technique has to be properly covered for the anaerobic processes to take place and cannot be opened for the next few years, making that space unavailable for the next few years (Gotmare et al., 2011). This fact has limited its application in urban areas. There are different types of reactors for different types of feedstock. For food waste, continuously stirred tank reactors are preferred, while for other types of organic waste, plug-flow and batch reactors are used (Mutz et al., 2017). There are three different end products generated from the anaerobic digestion process. The main product is biogas which contains 50– 80 per cent methane (CH_4), 20–50% carbon dioxide (CO_2), and small traces of sulphide and ammonia. The other two products that are generated along with biogas, are fibre and liquid digestate (Vindis et al., 2009; Sitorus et al., 2013; Chiu et al., 2016; Mutz et al., 2017; Qazi et al., 2018).

The biogas produced in the anaerobic digestion process can be used to replace natural gas in CHP generation. However, the efficiency of heat and power production from biogas is around 5.5–7.5 kWh/m3 which is less as compared to natural gas. This is because the calorific value of biogas is about two-third that of natural gas (Mutz et al., 2017; Qazi et al., 2018). The liquid digestate and fiber produced in the anaerobic digestion process can be used as secondary raw material in the fertilizers industry (Qazi et al., 2018).

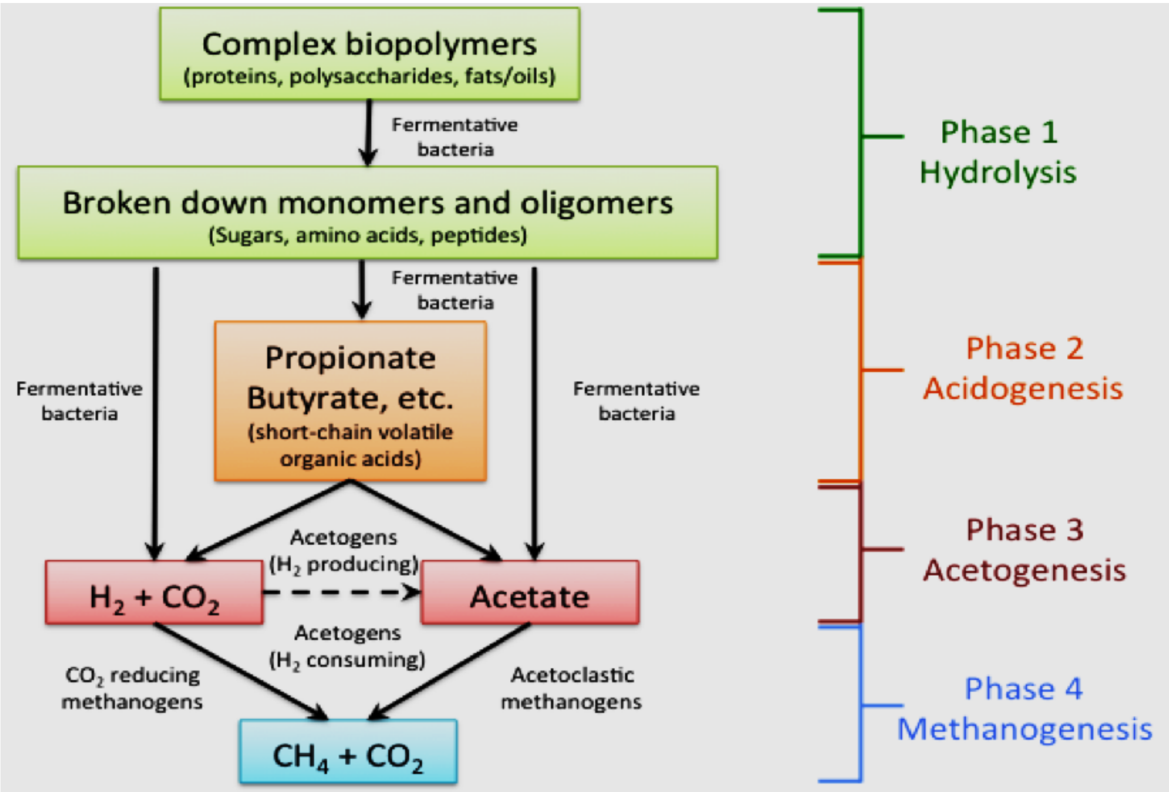

Figure 2. 4: Stages involved in production of biogas using anaerobic digestion. (Tickson et.al, 2008).

Europe has been producing 191 TWh combined worth of biogas and biomethane in their quest to manage waste, a figure bound to quadruple by 2030. European countries have depended on Bioenergy as clean, renewable energy during those long winters. Germany has the highest number of biomethane plants at 232, followed by France and the United Kingdom. We have rounded up some big names in the European biogas market who are making a mark.

The city of Madrid produces more than a million tons of urban waste per year. Valdemingómez Technology Park treats over 90% of the organic matter from the waste that enters its processing plant. Out of this waste, it generates 207,013 MWh of electricity, enough for the consumption of 59,367 homes. And that is just 76% of the Bioenergy it produces. They have been using the rest of it for running the facility itself. It claims to have effectively saved 1,130,768 t of greenhouse gas emissions. (Prospero events group 2022)

Waste Management by biomethanation

Waste management by Biomethanation has been greatly implement in Europe, the analysis of the data collected shows that the number of biomethane plants in Europe has increased by 51% in 2 years, from 483 in 2018 to 729 in 2020. There are currently 18 countries producing biomethane in Europe. Germany has the highest share of biomethane plants (232), followed by France (131) and the UK (80).(EBA,2020).

On Jan. 26.2018, Canada inaugurated a biomethanation plant in Saint-Hyacinthe, Quebec. The facility processes waste into renewable natural gas (RNG) that is fed into grid of Energy, a natural gas distributor in Quebec.

The facility is the largest of its kind in Canada and is the first municipal biomethanation project in Quebec Canada. (Erin Voegele, 2018)

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One of the largest biogas plants constructed in Europe, the Nature Energy Korskro plant will produce 37 million Nm3 of biogas per year. Nature Energy operates the plant in Korskro and had consulted with the Portuguese company EFACEC regarding its design, construction, and installation.

The biogas plant will take in 708,000 Tons/Year of biomass and produce a fertile slurry of 521,000 tons. The company claims to be the largest biogas producer in Denmark with over 12 biogas facilities in the country and one in a foreign land. They plan to establish more large-scale biogas plants in Denmark. (Prosperoevents, 2022)

ii. Fermentation

Except the methanogenesis stage, fermentation process also comprises almost all the stages similar to anaerobic digestion using microbes for the decomposition of organic materials in an oxygen-free environment (Qazi et al., 2018b). According to Moukamnerd et al. (2013 and Kumar and Samadder (2017), this metabolic process is carried out in non-sterilised conditions by using yeast or bacteria to convert sugar into alcohol. Liquid biofuel rather than biogas is derived from the fermentation process and it ends at acetogenesis where diluted alcohol is formed which is separated from the fermentation digestate by performing an additional step known as distillation (Qazi et al., 2018).

Scholars have agreed on two different pathways to perform the fermentation process which include continuous or batch process. For instance, according to Abreu-Cavalheiro and Monteiro (2013) in the continuous process, fermentation is carried out by keeping a balance between feedstock load and discharge rate which means that the same amount of feedstock is loaded into the reactor, as the quantity discharged.

Therefore, the initial investment and capital and operation costs for continuous fermentation process, are relatively lower as compared to the batch process because it needs smaller reactor volumes to use larger amounts of feedstock. On the other hand, the batch process produces a larger quantity of end product as compared to the continuous process. Moreover, the payback period is also shorter for a batch fermentation reactor (normally 1 year) as compared to continuous fermentation (Lopes et al., 2016). The main output from the fermentation process is ethanol (Qazi et al., 2018b). After performing the distillation process by using advanced technology such as a molecular sieve, 99.99 per cent pure fuel-grade biofuel (ethanol) can be obtained (Farooq et al., 2020).

Fermentation process yields other end products such as Carbon Dioxide (CO2), distilled-dried grains (DDGs), and stillage (wastewater) are also obtained as by-products from the fermentation process (Sorapipatana and Yoosin, 2011). The ethanol produced by the fermentation process can be used to replace gasoline as a transportation fuel. Carbon Dioxide produced during the fermentation process can be liquefied and sold as dry ice to confectionaries or processed food industries to generate extra revenue (Farooq et al., 2020). DDGs can be used as a raw material in the cattle feed industry, while stillage can be processed further in an anaerobic digestion plant to produce biogas (Sorapipatana and Yoosin, 2011).

2.14.4 **Physiochemical Technologies**

This is the most famous WtE technology that follows the physicochemical conversion pathway is transesterification which produces biodiesel.

i. **Transesterification**

Transesterification is the process that converts the fat fractions of food waste in the MSW stream specifically Used Cooking Oils (UCO) and animal fats into biodiesel (Shahnazari et al., 2020; Li et al., 2012; Shahzad et al., 2017). It’s the most famous WtE technology that follows the physicochemical conversion pathway. The fat fractions include UCO from restaurants and households, and also the indigestible parts of animals (blood, fat, and internal organs) from slaughterhouses. Transesterification process is performed using collected UCO which is then screened and dehydrated to remove impurities and moisture. On the other hand, slaughterhouse waste is also processed in a rendering facility, where the inedible animal parts are converted into fat with one more value-added product as meat and bone meal.

The processed fat then undergoes transesterification reaction with monoalkyl alcohols, viz., ethyl, or methyl alcohol in the presence of acid or base catalyst to produce biodiesel. Potassium hydroxide (KOH) or carbonic acid (H2CO3) are the commonly used catalysts in transesterification reaction (Gardy et al., 2014; Nizami et al., 2016).

The selection of catalysts depends on the amount of Free Fatty Acids (FFA) in the feedstock. Normally, FFA content in rendered animal fat is up to 20 per cent while it is just 15 per cent in the UCO. The reaction time for alkane-catalysed reaction is faster (half an hour) as compared to the acid-catalysed (1–8 h) (Sharma et al., 2008; Thamsiriroj and Murphy, 2010). However, the yield of end products from the acid-catalysed transesterification process is higher as compared to alkane-catalysed but the reactor has to stay under a corrosive environment for a longer period that can end up in higher maintenance costs.

The solution to this problem is that the transesterification process can be performed in two steps to handle feedstock with higher FFA content. In the first step, an acid catalyst can be applied to an esterification reaction to convert the FFA into biodiesel. After that alkane catalyst can be applied through transesterification reaction to convert remaining triglycerides into biodiesel (Gerpen, 2005). Biodiesel is produced as the main end product from the transesterification process while glycerol is also produced as a by-product. The quality and quantity of produced biodiesel depend on the amount of unsaturated fatty acids present in the feedstock.

The higher the amount of unsaturated fatty acids in the feedstock, the higher is the quality and quantity of produced biodiesel. While in the case of higher concentration of saturated fatty acids in feedstock, both the quality and yield of biodiesel are low (Shahzad et al., 2017). The biodiesel produced from UCO and animal fat can replace petrochemical diesel and can be used as vehicle fuel (Li et al., 2012). Moreover, both biodiesel and the glycerol that is produced as a by-product can be used for electricity production because their Higher Heating Values (HHV) are very high at 40.17 MJ/kg and 19 MJ/kg, respectively. The meat and bones meal obtained from the rendering process, can be used as a raw material in the livestock feed industry or can be burnt for energy recovery as well (Shahzad et al., 2017).

2.15 **Methane Production from Landfills**

According to IPCC (1996), on national level, two methods viz. default method and first order decay methods are recommended for estimating LFG. The IPCC Guidelines describe two main methods:

Firstly, the default IPCC methodology that is based on the theoretical gas yield (a mass balance equation). Secondly, theoretical first order kinetic methodologies, through which the IPCC Guidelines introduces the "First Order Decay model" (FOD).

The main difference between the two methods is that method A does not reflect the time variation in SW disposal and the degradation process as it assumes that all potential methane is released the year the SW is disposed.

The timing of the actual emissions is reflected in method B. Only if the yearly amounts and composition of waste disposed as well as disposal practices have been nearly constant for long periods, the method A will produce fairly good estimates of the yearly emissions. Increasing amounts of waste disposed will lead to an overestimation, and decreasing amounts correspondingly to underestimation, of yearly emissions. Method B gives a more accurate estimate of the yearly emissions. Many countries may, however, have problems getting the necessary data and information (historical data on SW disposal, rate constant for the decay) to establish the proper basis for emission inventories with acceptable accuracy. (Source)

Among the available methods, the simplest one for the estimation of methane emissions from landfills is based on mass balance approach, i.e. the default methodology. This method was being used in the revised IPCC (1995) guidelines as the default methodology for estimating methane emissions from solid waste disposal sites. The detailed methodology for estimation of methane emissions, from solid waste disposal sites, is explained in further detail below. A number of empirical constants, like methane correction factor, DOC, dissimilated organic fraction converted into LFG, have been considered while developing the default methodology and accordingly the emissions are calculated. Though IPCC has claimed that the default methodology provides reasonable annual estimate of actual emissions and this has been widely used in the situations where detailed data is not available, but it may not provide realistic estimate because it is assumed that all potential methane is released during the same year the waste is disposed off.

2.16 **Use of Landfill Gas**

Landfill Gas consists of 45 to 55 per cent methane gas and is therefore suitable as a fuel for heat or power generation, combined heat and power generation or as fuel for transportation. The rest is mainly Carbon Dioxide. The yield of LFG depends on a number of factors: Composition of the waste; how fresh waste is placed and compacted; level of compacting and height of the individual layers; water content in the landfill; climate; technical features for capturing the methane gas in the SLF (GIZ, 2017).

The methane in LFG is formed by the anaerobic digestion of organic matter in the landfill body which can be seen as an over-dimensioned bioreactor. In order to reduce greenhouse gas emissions from landfill sites into the atmosphere, capturing of methane gas is essential (World Bank, 1999). This is possible through LFG capture; however significant losses occur in the start-up phase of a landfill site, before the methane capturing system is installed and in operation. The yield of LFG depends on a number of factors: Composition of the waste; how fresh waste is placed and compacted; level of compacting and height of the individual layers; water content in the landfill; climate; technical features for capturing the methane gas in the SLF. LFG capture projects require a high content of reactive organic waste in the body of the landfill.

A high content of mineral waste or slow digesting organics (e.g. wood) reduce the yield. United States Environmental protection Agency estimates a collection efficiencies range from 60 to 85per cent. However, many SLF in developing countries reach a capturing rate of hardly 50 per cent due to reduced technical standards and cost limitations.

Comparing the amount of gas actually captured and collected in relation to the total gas emitted from a SLF over its entire lifespan, the efficiency rate drops further to less than 20-30 per cent. Audits of the gas collection system should be undertaken annually to assess the efficiency of the system. Landfill Gas collection is seen as an opportunity for existing landfills rather than for new WtE projects. Landfill Gas capture can mitigate some of the climate impacts of SLF, however the low efficiency rate of gas capturing over the entire life span of shows the difficulty of mitigating climate impacts of SLF.

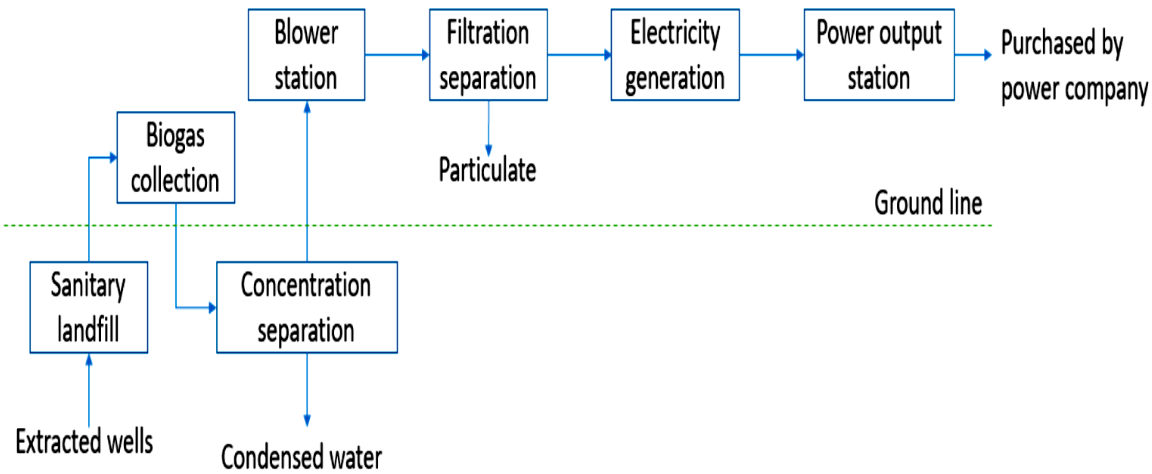

Figure 2. 5: Flow diagram of electricity Generation from Landfill Sites (Source: Tsai, 2007)

2.17 **Economic Evaluation of Technologies**

The technique used in evaluating the technologies was Levelized Cost of Energy. The LCOE of renewable energy technologies differs by technology, country and project, centred on the renewable energy resource, capital and operating costs and the efficiency/performance of the technology (Farooq et al., 2021; Qazi et al., 2018; Soltani et al., 2016, IRENA, 2012). The LCOE of renewable energy technologies is a widely used measure by which renewable energy technologies can be evaluated for modelling or policy development purposes (IRENA, 2012).

The approach used in the analysis presented here is based on a Discounted Cash Flow (DCF) analysis. The LCOE is the price of electricity required for a project where revenues would equal costs, including making a return on the capital invested equal to the discount rate, expressed in Net Present Value terms (Daniel et al., 2012). According to Nordi, (2015), this means that future costs and outputs are discounted, when compared to costs and outputs today. This is sometimes called a life-cycle cost.

The Levelized cost estimates do not consider revenue streams available to generators (e.g. from sale of electricity or revenues from other sources), with the exception of heat revenues for CHP plant which are included so that the estimates reflect the cost of electricity generation only (Fennell et.al, 2013).

Levelized costs relays only to those costs accumulating to the owner or operator of the generation asset as shown in figure below, it does not cover wider costs that may in part fall to others, such as the full cost of system balancing and network investment, or air quality impacts.

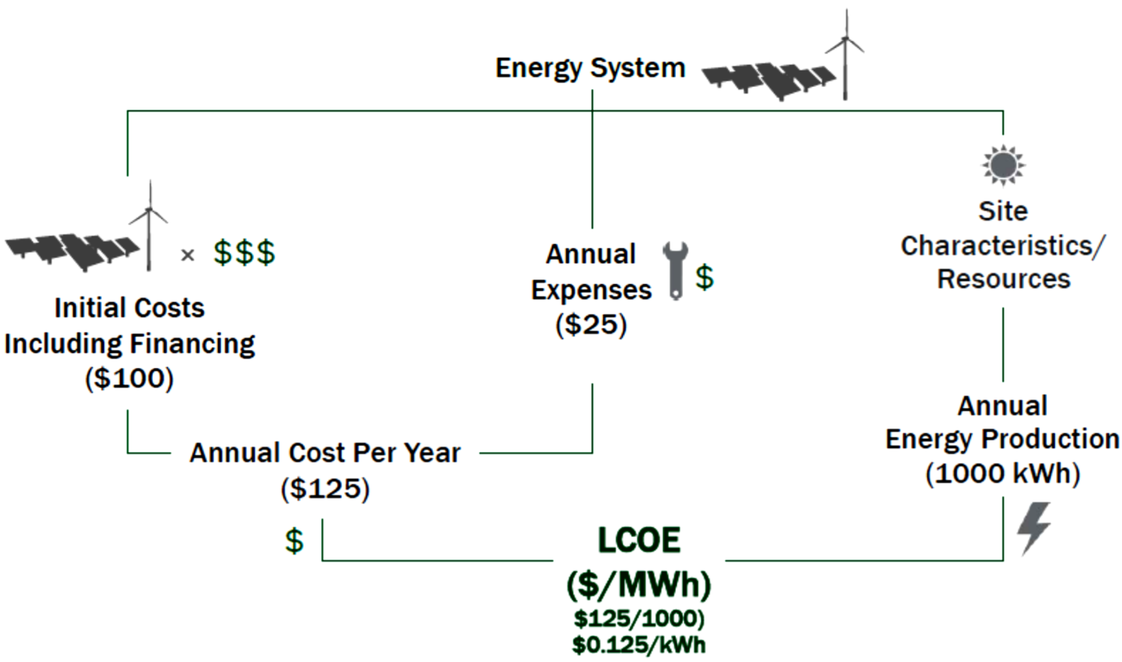

Figure 2. 6: Flow Diagram of Levelized Cost of Energy Calculation Modelling Source: (Mirko, 2011).

When assessing different capacity expansion options to meet a specific, well Characterised need identified by a power producer or regulatory body, LCOE can provide a screening tool that simultaneously considers fixed and variable costs in a single metric (Fennell et.al, 2013). However, even in this narrow application; care must be taken not to over-sell the usefulness and importance of a metric that doesn't consider a host of other important economic and technical evaluation factors (Nordi, 2015).The Levelized Cost of Electricity Generation is the discounted lifetime cost of ownership and use of a generation asset, converted into an equivalent unit of cost of generation in Particular country currency per MWh (Nordi, 2015).

2.18 **Operation and Maintenance Expenditure (OPEX)**

Operation and maintenance (O&M) refers to the fixed and variable costs associated with the operation of biomass-fired power generation plants. Fixed O&M costs can be expressed as a percentage of capital costs. For biomass power plants, they typically range from 1% to 6% of the initial CAPEX per year. Fixed O&M costs consist of labour, scheduled maintenance, routine component/equipment replacement (for boilers, gasifiers, feedstock handling equipment, etc.), insurance, etc. The larger the plant, the lower the specific (per kW) fixed O&M costs, because of the impact of economies of scale, particularly for the labour required. Variable O&M costs depend on the output of the system and are usually expressed as a value per unit of output (USD/kWh). They include non-biomass fuels costs, ash disposal, unplanned maintenance, equipment replacement and incremental servicing costs. The data available will often combine fixed and variable O&M costs into one number so a breakdown between fixed and variable O&M costs is often not available. (us doe, 2007; us ePa, 2009; and MoTT Macdonald, 2011)

2.19 **Chapter Summary on Literature Review**

The Review suggest that conditions for solid waste management in developed nations are essentially different to those in developing nations. In developed nations WtE plants is an integral part of Waste management infrastructure. The Chapter also reviews advanced Economic patterns, Waste management infrastructure, Social and economic patterns in developed nations and developing nations. The complex of waste management in developing nations is indicative of a specific based solutions due to aspects such as policy frame work, lack of solid waste management etc. The Review on the literature indicates that effective Conversion of municipal solid waste into energy is an effective way of waste management disposal. The literature supports that there is a huge gap in how municipal solid waste is managed between developed nations and developing nations. The Challenges faced due massive Waste Generation is looked at as a solution for increased energy mix with focus on a Circular economy in developed countries. Effective conversion of MSW is a sustainable innovative way of providing effective management solutions to close the gap between MSW and energy supply (Dlamini et al., 2018).

The literature further review intense activity of informal waste pickers who usually divert most of the solid waste disposed into land fill sites.

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 (Chimuka and Ogola, 2015).

The literature shows that in many developing nations the studies conducted have not included Waste to Energy as a solution to Waste management. Different studies conducted have not characterized municipal solid waste in providing insight into waste to energy viability in developing nations.

The literature also reviews different methods of estimating Energy potential from waste and a comparisons of Waste to Energy plants is made in the chapter.

Based on comparisons of different ways of converting WtE and massive Generation of waste due to population growth, the study is indicative of massive potential of Waste to Energy plants in Zambia, particularly Ndola.

Chapter 3 : RESEARCH METHODOLOGY

3.1 Introduction

This chapter presents the following: research design, the population of the study, the sample and sampling techniques, instruments for data collection and method, data analysis and presentation. It evaluated the energy recovery potential for electricity generation using various conversion technologies.

3.2 Research Design

This study focused on assessing WtE potential in Ndola. It was a cross sectional study. A cross sectional study was used because the researcher was limited with time and did not wish to focus on change over a long time and this is according to Creswell, (2014) has advised when researchers intend to undertake cross sectional studies. Moreover, the researcher was in a position to describe events and then organise and tabulate the data to the actual reality on the ground. Because of the nature of the study, a quantitative approach was used. According to Creswell (2014), if the problem calls for the identification of factors that influence an outcome; the utility of an intervention or understanding the best predictors of outcomes, then a quantitative approach is most suitable.

3.3 Study Area

Ndola is the third Largest City in Zambia with regard to Size and Population with an estimated population of 475194 as indicated by data in the Census 2010.Ndola is located in the Northern Region of Zambia abut 10km from the boarder of the Democratic Republic of Congo. Ndola Climate boasts of Dry and Rainy Season. The Dry Season comes with hot and cold months. The Main Economic activity of Ndola includes Mining with the focus on Industrialisation.

The site of the study was chosen purposively because Ndola town had witnessed a rapid and unplanned development with significant population growth which resulted in the increased Municipal solid waste generation. Ndola is endowed with a large number of commercial and industrial activities leading to increased waste production and insufficient infrastructure for collection of MSW (ZEMA, 2011; Muller al., 2017). The municipal administration of Ndola started to use the Kaloko dump site, which has an area of 7.84 hectare (Maps.app.goo.gl) located at 15 km away from the city centre in the south-western direction.

3.4 Source of Data

Primary and secondary sources of data were used in this study. Primary data was collected from sampled respondents using questionnaires and interview guide. Secondary data was collected from journals, reports, and other pertinent documents were consulted as well. These documents were obtained from Ndola City Council and research institutions such as the Univerrsity of Zambia (UNZA).

3.5 Population of Study

The study population comprised staff and management employees of Ndola City Council (NCC), independent collectors and Residential housing units depicting High income, low income and medium income areas. Therefore, the target population of the study was 118 individuals comprising of seven individuals from NCC Management, 28 individuals working at the landfill site known as crew members, and 83 independent collectors and 110 housing units from Kansenshi, Pamozi and Twapia.

3.6 Determination of Sampling Size

Ndola District is divided into constituencies and each constituency into wards. Stratified sampling design was used in order to spread the sample over geographic sub areas and population sub groups. A total of 90 households from different wards in Ndola were selected. The wards were picked randomly as 40 houses for high cost ward being Kansenshi ward and Kanini ward, 25 houses for Middle income cost being Pamozi and low income cost being 25 house hold being Twapia Ward. (Central Statistical Office Zambia 2016).

According to Mugenda (2003), a sampling frame is a comprehensive list of all sampling units, which a sample can be selected (Cooper and Schindler, 2008). In this study, the Kish (1965) approach was used in determining the sample size. The approach is most appropriate when there is an available sample frame as it is in the case of this study. The generic formula for this approach is

$$n = \frac{N}{1+N(e^2)} \tag{3.1}$$

Where n is the sample size, N is the population size, and e is the level of precision. The study uses a 95 per cent confidence interval (e = 0.05). For the population (sampling frame) of 118, the sample size is determined as;

$$\text{n} = \frac{118}{1+118\ (\ 0.0025)} = 95 \tag{3.2}$$

The level of precision ***e*** or reasonable certainty, sometimes called sampling error, is the range in which the true value of the population is estimated to be. This range is often expressed in percentage points, (e.g., ± 5 percent). In other words, this means that, if a 95 per cent confidence level is selected, 95 per cent of the samples will have the true population value within the range of precision specified earlier. There is always a chance that the sample one obtains does not represent the true population value.

The Table below shows the areas where the different samples were collected in Ndola and the number of samples collected for each sampling frame.

Table 3. 1Size Sample and amount of Waste collected as of population Census 2010

House Hold Waste	Number of samples selected	Number of house hold sampled
High Cost	320	40
Medium Cost	125	25
Low Cost Sampled	120	25
Total house Hold Sampled	565	90

3.7 **Source Separation and Sorting.**

Determination of waste composition was done by Source separation of organic content (food and Yard Waste) and non-organic content (Plastic and Paper) and Sorting was conducted at house hold level. Source Separation and sorting was further done at the Research Site in order to determine waste composition and characterisation and to remove doubt in terms of waste separation Compliance.

Four Polythene bags labelled Plastic and paper, Food waste, Garden Waste, and other types of waste were given to each house hold and the waste was collected for 14 days. The first seven days was during the first week of the month from the 6th June 2022 to 13th June 2022 and the second week was in the last week of the month from 24th June 2022 to 30th June 2022. This was done in order to monitor the impact of a salary on the waste generation rate per house hold.

3.8 **Sampling Technique**

In selecting respondents for the study, multistage or clustering procedure was used as sampling design. In multistage sampling, or multistage cluster sampling, you draw a sample from a population using smaller and smaller groups at each stage.

This method is often used to collect data from a large, geographically spread group of people in national surveys, for example. You take advantage of hierarchical groupings (e.g., from state to city to neighbourhood) to create a sample that's less expensive and time-consuming to collect data from.

The selection of Ndola was done purposively. Ndola is the second largest city of Zambia with a high level of commercial and industrial activities resulting to large volumes of waste generation. Ndola was considered as one town that was divided into different Social strata where different clusters were identified and individual household samples were randomly picked where the questionnaire was administered.

The individuals (staff) and Management from NCC under Health Department were selected by way of the census, as the numbers were relatively small (28 and 7 respectively). The individual waste collectors in Ndola were, however, selected using convenient sampling, as they were scattered across the town, and therefore, difficult to gather.

3.9 Data Collection Tool and Data Analysis

Two main instruments developed by the researcher were used in data collection, namely, a questionnaire and an interview guide. The choice of the questionnaire for the purpose of this study was reinforced by its potential benefit. The major benefit is the need to eliminate biasness and to guarantee anonymity for the respondents. To avoid biasness the questionnaire was structured in such a way as to avoid complex and confusing questions. The researcher was there to guide the respondents on question than they did not understand to avoid drop outs. The researcher had a face to face interview with the respondents in order to get prompt answers.

After revision of the data collection instrument; the whole study sample was subjected to the data collection instrument. A number of methods were used to improve returns like response rate, such as drop and pick later method. To ensure cooperation and a high response rate, a cover letter was provided, which stated the purpose of the study and of what importance it would be to the respondents. Data collected for the study was analysed using the Statistical Package for the Social Sciences (SPSS) version 22.0, Microsoft excel and Mathematical models.

3.10 Disposal Methods used and Determination of Waste Characterisation

Information on the types and amounts of waste is important in assessing the waste composition in the Municipal solid waste. MSW characterization studies are used to assist in the planning, policy development, and infrastructure sizing decisions for various facets of an integrated and sustainable waste management program.

For this study it is essential that waste composition is undertaken in order to enable us select a suitable technology to convert waste to energy for the mixture of organic and inorganic content.

Identifying the composition and characteristics of MWS is substantial for selection of adequate treatment method to recover energy from the heterogeneous mixture of organic and inorganic municipal solid waste.

There are basically two most widely used methods for the waste characterization. These are the material flow method and site-sampling via sorting and weighing refuse by category (Martin *et al.* 1995). The sampling and sorting method is the more prevalent of the two. A standard method for determining waste composition by sorting has been published and is used widely ASTM D 5231-92 (ASTM 1999).

This Study applied sampling and sorting method for Waste composition.

3.11 **Waste Weighing of Sorted Waste for Waste composition**

The sorted waste was collected using a Heice Van to the main sorting centre. The sorted wastes were weighed using a Plat form STGL-PC30 scale of maximum capacity 30kg. Plastic sheets were placed on the floor to ease sorting, segregation and weighing. The wastes sorted by households were further segregated into various sub-fractions including paper and plastic segregation and analysed by their weight as well as the percentage composition as described by Pichtel (2005). The fine particles were sieved from the waste to help ease the sorting and also reduce the fractions which could otherwise be identified as inert.

3.12 **Determination of Moisture Content**

The samples were prepared at the research site and in duplicate by weighing 1kg and 0.5kg of the domestic solid waste in a petri dish. The dish was placed in a Sterling Hot Air oven at 110^0C for one hour after which it was placed in the desiccator to cool and then re-weighed. The procedure was repeated until a constant average weight was recorded. Moisture content of the sample was then calculated as:

$$\%\ \text{moisture} = \frac{loss\ in\ weight\ \ * 100}{weight\ of\ sample} \tag{3.3}$$

3.13 **Energy Potential Generation from Waste**

The potential of electricity generation from MSW in Ndola was assessed in three stages:

- Characterisation of MSW and disposal method used in Ndola;
- Determination of the potential of electricity generation from MSW in Ndola;
- Determination of the suitable technology that can be used to generate energy from MSW in Ndola.

3.14 **Estimation of methane: Biomethanation Process**

3.14.1 **Methods for Estimating Methane Production from Landfills**

The default method was used to estimate the methane emissions from landfill site. Among the available methods, the simplest one for the estimation of methane emissions from landfills is based on mass balance approach, i.e. the default methodology. This method was being used in the revised IPCC (1995) guidelines as the default methodology for estimating methane emissions from solid waste disposal sites. The detailed methodology for estimation of methane emissions, from solid waste disposal sites, is explained in further detail below. A number of empirical constants, like methane correction factor, DOC, dissimilated organic fraction converted into LFG, have been considered while developing the default methodology and accordingly the emissions are calculated. Though IPCC has claimed that the default methodology provides reasonable annual estimate of actual emissions and this has been widely used in the situations where detailed data is not available, but it may not provide realistic estimate because it is assumed that all potential methane is released during the same year the waste is disposed off.

3.14.2**IPCC Model / IPCC Default Method**

According to IPCC Guidelines, the formula for calculating GHG emission from solid waste landfills is as follows (IPCC, 1995).

$$Methane\ emissions\left(\frac{Gg}{yr}\right) = \left(MSWT * MSWF * MCF * DOC * DOCF * F * \frac{16}{12} - R\right) * (1 - OX) \qquad (3.4)$$

Where:

- E_{CH4} is Methane emission from landfills
- MSW_T is Total MSW generated (Gg/yr).
- MSW_F is Percentage of urban waste actually land filled; in this paper MSW equals the quantity of urban waste sent to landfills, so MSW_F = 70 per cent. The remaining 30 per cent is assumed to be lost due to recycling, waste burning at source as well as at disposal site, waste thrown into the drains and waste not reaching the landfills due to inefficient solid waste management system
- MCF = methane correction factor (fraction) = Three default values ranging from 1.0 to 0.4 are included, depending on the site management and with 0.6 as general default value Source: IPCC,2006
- DOC = degradable organic carbon (fraction) (kg C/ kg SW) = Content of degradable organic carbon in the waste, recommended to be 15% by IPCC.

- DOCF: fraction DOC dissimilated = Percentage of actually decomposed DOC in the waste (recommended to be 77% by IPCC)
- F = fraction of CH4 in landfill gas (IPCC default is 0.5) 16/12 = conversion of C to CH4 R = recovered CH4 (Gg/yr)
- OX = oxidation factor (fraction – IPCC default is 0).

The method assumes that all the potential CH4 emissions are released during the same year the waste is disposed off. The method is simple and emission calculations require only input of a limited set of parameters, for which the IPCC Guidelines provide default values, where country-specific quantities and data are not available.

3.14.3 Heat to power generation potential calculation by biomethanation process

The biomethanation process is preferred for organic waste stream with moisture content to allow for microbial activity. The typical conversion efficiency for this process is taken as 30% (Churney et al., 1989). The values for the total landfill gas (LFG) generation are taken for IPCC default model. The power recovery (PRP) and net power generation potential (NPRP) is given by (Eqs. (3.5) and (3.6)). The values for the LFG generation were taken from IPCC default model.

$$PRP = \frac{\left(\text{Total Methane Generation}\left(\frac{M}{day}^{3}\right)*\text{NCV}*365.25\right)}{0.042*1000*24} \quad (3.5)$$

$$NPRP = \left(\frac{\text{Total Methane Generation}\left(\frac{M^3}{Day}\right)*\text{NCV}*\eta*365.25}{1000}\right) \quad (3.6)$$

Where NCV is the Net Calorific Value of LFG and lies in the range 0.194-0.242 kW/m3 and ɳ is the efficiency for the bio-chemical process.0.242KW/m3 was Chosen for this study. (Chakraborty et al., 2013).

3.15 Power Recovery Potential using Incineration

In order to evaluate the Waste to Energy potential from municipal solid waste using Incineration WOIMA model was used to calculate the LHV at a moisture content of 26 percent. The input parameters to the WOIMA model include the Moisture content of MSW, Geographical location of the landfill site, the percentage composition of MSW (Organic Waste, Paper waste, Plastic waste, Metal waste). In this study, the Waste to Energy potential from incineration was obtained by the equation below, equation is the expression used to calculate an estimate of the electric power that can be obtained by incineration. The percentage of incineration efficiency varies between 25 to 30 per cent according to literature (Ouda et al., 2013) . In this study, a 25 percent efficiency was used and Dry Waste without moisture content was considered.

The calculation of energy recovery potential using incineration route was obtained using the following equations:

1. $$Energy\ Recovery\ Potential\left(\frac{GWh}{day}\right) = \frac{\left(DryWaste\left(\frac{tons}{day}\right)*LHVofwaste\left(\frac{kWh}{kg}\right)\right)}{1000} \quad (3.7)$$
2. $$\left(Power\ Generation\ Potential(MW)\frac{Drywaste\left(\frac{kg}{s}\right)*LHVofwaste\frac{KW}{kg}}{1000}\right) \quad (3.8)$$
3. Net power Generation Potential(MW) =η*Power Generation Potential (3.9)

Woima waste Fuel LHV estimation is a tool used to evaluate the calorific value of the solid waste management. Understanding your fuel characteristics is the cornerstone of a successful waste-to-energy project. The key is defining the LHV or Lower Heating Value of the waste fuel as it determines the feasible technical solution for the waste fuel. Net Calorific Value (NCV) is the energy content of the waste. The moisture, or water content, naturally, contains no energy. Thus, the waste fuel feedstock requirement is larger by the moisture content percentage, e.g. 50% moisture means that the feedstock is doubled compared to 0% moisture content fuel defined by such terms as Higher Heating Value (HHV) or Gross Calorific Value (GCV)

3.16 **Levelized Cost of Energy Determination**

In this study LCOE was utilised in the assessment process and a suitable technology selection for Ndola. The LCOE is a vigorous method that helps with technology selection and decision support for electricity projects and expanding electricity portfolios. This method involved sound analysis of the following technologies anaerobic digestion and incineration. According to Nordi (2015), the main components of the Levelized cost calculation are:

1. The development cost of a project which includes achieving planning permission and compliance with regulatory requirements.
2. The capital cost of bringing a plant to operation.
3. On-going fixed and variable costs of operating a renewable generator and keeping it available for generation.
4. Fuel costs or gate fees and related technical assumptions such as fuel efficiency.
5. Availability: defined as the maximum potential time that a generation plant is available to produce electricity annually. The factor will vary depending on how the plant is operated

and the amount of downtime required for maintenance. For example, the expected availability of a gasification plant is 99 percent, allowing for maintenance downtime and parts replacement.

6. Load factor: defined as the ratio of average annual output to its total potential output if a plant was to operate at full capacity over its lifetime.
7. Pre-development, construction and operational time periods.

The following equations were considered by the present study:

$$Lev\ cost = \frac{Fixed\ Charge\ factor * capital\ costs + fixed\ O\&M}{annual\ expected\ generation\ hours} + variable\ O\&M + fuel \tag{3.10}$$

Where

Annual Expected Gen=Capacity Factor*8760

$$Fixed\ Charge = Discount\ rate\ \frac{Discount\ Rate}{(1+Discount\ Rate)^{financial\ life}} \tag{3.11}$$

3.16.1 Key assumptions

The discount rate used to represent the average cost of capital for bioenergy power generation is assumed to be 10%. The LCOE of a bioenergy plant is generally sensitive to the discount rate used; however, it is generally less sensitive to the discount rate than wind, hydropower and solar due to the impact of the bioenergy fuel costs. The economic life of biomass plants is assumed to be 20 to 25 years. Minor equipment refurbishment and replacement is included in O&M costs.

Biomass-fired power plants are assumed to operate at an 85% capacity factor although the generation of a specific power plant will depend on its design and feedstock availability, quality and cost over the year. Power plants designed to take advantage of low-cost agricultural residues may experience periods in which insufficient feedstock is available or periods where the necessary transportation costs to get similar or equivalent feedstock from other markets are too expensive.
The table below shows waste to energy technologies that have been considered for the viability of setting up a waste to energy plant. The table is also indicative of the Investment cost and maintenance cost of the technologies. The life span and efficiency of the two technologies are also indicated.

Table 3. 2**:** Levelized cost of energy inputs for WtE technologies.

Waste to energy technologies	**(Biomethanation)**	**Incineration**
INVESTMENT COST (million USD)	138	250
MAINTENANCE COST (fixed) (% Inv Cost)	10	15
MAINTENANCE COST (variable) (% Inv Cost)	5	12
LIFESPAN (Years)	30	30
CAPACITY (MW)	100	100
EFFICIENCY (%)	80	85

Source :(Nordi, 2015).

The LCOE metric's limitations must be highlighted, understood, and taken into account when using it, so that accurate analysis and due diligence are performed when making decisions that have widespread economic, social, and environmental impacts in the long run.

3.16.2 Sensitivity of LCOE to assumptions

Levelized Cost of Energy of renewable energy can be highly sensitive to input assumptions. Different assumptions can change LCOE by 50 per cent or more. Some of the key assumptions are:

a) Capacity factor (performance);
b) Weighted Cost of capital (WACC);
c) Capital cost; and
d) Important to select assumptions in a consistent manner across technologies.

Chapter 4 : RESULTS and DISCUSSIONS

4.1 Introduction

This chapter presents the analysed data as well as the interpretation of the data. The data presentation and interpretation depicts the demographic characteristics of the respondents, waste disposal methods, waste characteristics and routes, scenarios through which energy potential was assessed as well as evaluation of waste to energy technologies.

4.2 Demographic Characteristics of the Respondents

The demographic characteristics of the respondents collected and analysed (presented in table 4.1). With regard to the specific roles respondents play along the waste management chain, 63.2 per cent of the respondents represented independent collectors involved in waste collection; 29.5 per cent crew members played a role of collecting and disposed waste at landfill and 7.4 per cent played management or administrative roles in waste management in the city of Ndola. 110 housing units across Ndola representing High cost, Medium Cost and Low Cost played house representation in the City of Ndola.

Regarding educational background with regard to the respondents who played Ndola City Council and Independent Waste Collectors, the review showed that 87.4 per cent of respondents had low formal education, only 1.1 per cent of respondents had master's degree, whereas 9.5per cent had certificate. The results clearly show a significant numbers of respondents with low formal education, this group was mainly the independent collectors and crew members. As far as gender was concerned, the questionnaire responses showed that 94.7 per cent of respondents were men and 5.3 per cent of the respondents were women. The results show that the majority of people involved in waste management were men in Ndola. Moreover, a review of the questionnaire responses showed that 85.3 percent of the respondents had worked in the waste management for a period of between six and ten years, 5.3 per cent of the respondents had worked for a period of between eleven and fifteen years while 9.5 per cent of the respondents had worked in the waste management for a period of five or less years.

The Table below shows the demographic characteristics of the respondents that were interviewed

Table 4. 1: Demographic characteristics of respondents

Characteristics	Option/response	Frequency	(%)
Organisation	Ndola City Council		
	Health Officers	6	6.2
	Administrative	1	1.1
	Crew members	28	29.5
	Independent collectors	60	63.2
Position/Role	Management/administrative	7	7.4
	Crew members	28	29.5
	Independent collectors	60	63.2
Length of service (Yrs)	5 or less years	9	9.5
	6-10 years	81	85.3
	11-15 years	5	5.3
Educational background	5 to 12	83	87.4
	Certificate	8	9.5
	Diploma	3	3.2
	Postgraduate	1	1.1
Genre	Men	90	94.7
	Women	5	5.3

Source: (Field work, 2021

4.3 **Disposal Methods Used and Waste Characteristics in Ndola**

4.3.1 **Determination of Waste characterisation**

Waste composition for Zambia is presented in Table 4.2 along with moisture content. The MSW for Ndola include 37% Food Waste 14 % paper and Plastic % 34 Yard waste and 15 % other Waste. The Yard and Food Waste are taken as the organic content suitable for Biomethanation process with the moisture content of 25%.

The characteristics of waste collected in Ndola, as identified in the study, comprises of organic waste (food and kitchen waste and green waste), Paper/Glass which are recyclable materials (paper, Garden (leaves, branches), and other Waste (cardboard, glass, bottles, jars and tin cans, debris waste, electrical appliances)

The Chart below indicated Ndola's Waste Composition

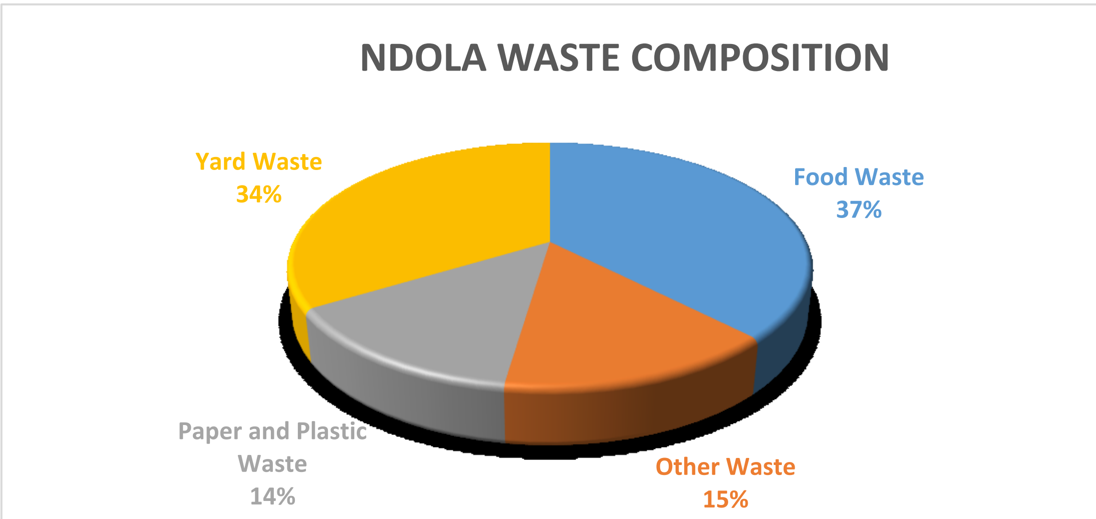

Figure 4. 1: Ndola Waste composition Chart

The Study showed that biodegradable waste was very high in Ndola waste stream coming up at 71% while Paper and plastic was at 14 percent. The finding is in line with many studies that found a large proportion of biodegradable and recyclable waste in Africa (Agbelie, 2015; Edema, 2012). The results generally reflected results from past studies on the characteristics of waste in Ndola and in Zambia in general (Edema et al, 2012; Mudenda et al., 2018; Sambo et al, 2020), biodegradable waste, including food and other organic materials, have been identified to constitute the largest portion of the total MSW in Zambia.

The Table below indicates Ndola's Waste Characterisation high cost, medium cost and low cost areas

Table 4. 2: Waste Characteristics Ndola

Waste Type	High Cost per kg	High Cost %	Low Cost per kg	Low Cost %	Medium Cost per kg	Med Cost %	Overall Average %
Food Waste	1.34	52%	0.51	27%	0.80	34%	38%
Other Waste	0.23	9%	0.42	22%	0.30	13%	15%
Paper and Plastic Waste	0.30	12%	0.17	9%	0.49	21%	14%
Yard Waste	0.69	27%	0.80	42%	0.76	32%	34%
Total	**2.58**	**100%**	**1.92**	**100%**	**2.37**	**100%**	**100%**
Average	**0.64**		**0.48**		**0.594**		**0.57**

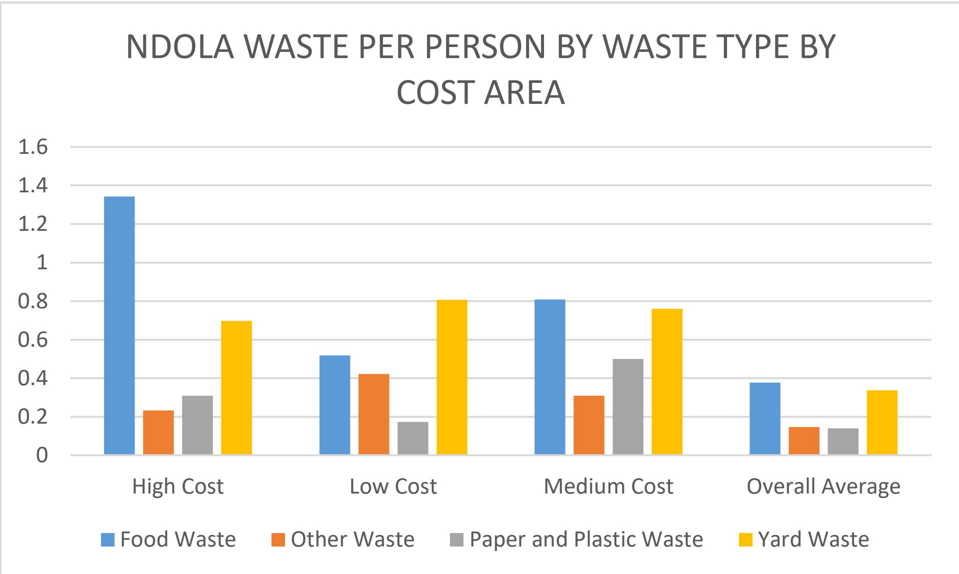

Figure 4. 2: Ndola Waste per person Chart

4.3.2 Disposal Methods Used in Ndola

In the study the respondents were asked to indicate on how is Waste disposed of in Ndola by choosing from six disposal methods namely Burning, recycling, disposed of in landfill, left at any place of convenience and compositing. The results from the analysis of responses gathered are presented in Table 4.3.

As the results show, 63.7 per cent of the respondents strongly agree with disposing waste in Landfill Site as waste disposal method in Ndola. From the point of view of respondents, the majority of waste disposed in landfill site was organic waste. Respondent also agreed that 15 percent of the waste is Recycled and 9 percent of the waste is disposed by burning. 10 percent of the respondents confirmed that 10 percent of the waste in disposed by leaving it at any place of convenience, respondents indicated that 3% of the waste is disposed by composting.

The Chart below shows the waste disposal methods used in Ndola in accordance with the findings.

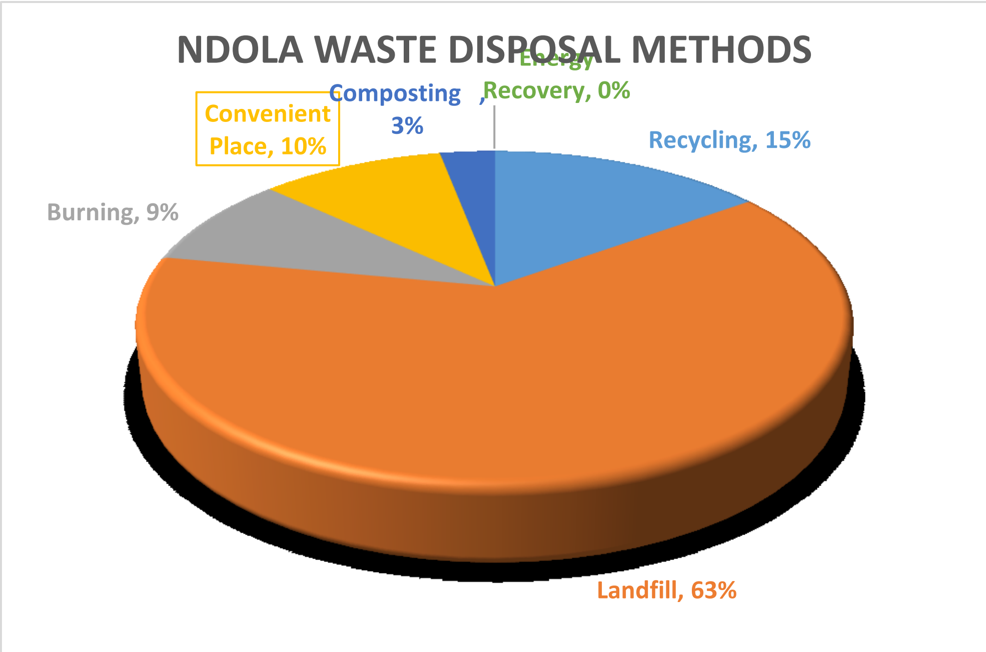

Figure 4. 3: Ndola Waste Disposal Methods

The table below indicate the disposal methods used in Ndola and the outcome of the respondents.

Table 4. 3: Waste disposal methods used in Ndola

Disposal methods	**No. Respondents**	**Percentage**
Recycling	18	15%
Landfill	76	63%
Burning	10	9%
Convenient Place	12	10%
Composting	4	3%
Energy Recovery	0	0%
Total	**120**	**100%**

4.4 **Key types of Waste Generated**.

Out of 130 house hold contacted for waste separation 10 of them failed to have the waste separated even though the households were interviewed. In High income Areas the majority of the Waste was food waste accounting for 1.34kg per person compromising nshima, rice and vegetables and the second was yard waste being 0.69 accounting for mainly leaves and branches and Thirdly Paper and Plastic accounting for 0.3kg of waste. Other waste was coming last at 0.23kg per person comprising mainly cardboard, glass etc.

In the Middle income Areas the majority of waste Food waste accounting for 0.8kg per person followed by Yard waste being 0.79kg per person and thirdly paper and plastic waste accounting for 0.49kg per person followed by other waste accounting for 0.3kg per person.

In low Income Areas the Predominance waste was Yard Waste accounting for 0.8kg per person, followed by food waste accounting for 0.51 kg per person. The third part of waste in Ndola low income area was other waste accounting for 0.42 kg and lastly paper and plastic standing at 0.17kg per person.

The overall average waste generated per person in Ndola was found to be 0.64kg per person in High income areas, followed by 0.59kg per person for Middle income areas and lastly 0.48 kg per person in Low income areas.

The waste generated per person in Ndola was found to be therefore 0.57kg per person in this study.

4.5 **Estimated solid waste volume generated in Ndola.**

Annual waste disposal rates are critically important model inputs that strongly influence projected LFG generation (Global Methane Initiative, 2012). The year 2015 was chosen as the starting year for forecasting. The MSW production rate was calculated to be 0.57 kg/capita/day obtained from Waste from selected homes in Nodlo. Per capita generation is the rate of waste generation per individual in a given population with units of kg/day. The Zambia census of the year 2010, estimates the population of Ndola to 475,194 people and will grow at a rate of 1.9 per cent from the year 2015 to the year 2035. The population growth is projected to maintain its trend of 1.9 per cent, which is the average growth of population in Ndola, for year up to the year 2035, the total MSW generation is forecasted accordingly. From the per person rate of waste generation the daily MSW generated in Ndola was estimated to be 276,007 metric tonnes in the starting year which was 2015 and 366,046 metric tonnes in the year 2035. The study projected annual waste generation of 100,742,529 metric tonnes of waste in the year 2015 and 126,271,726 metric tonnes of waste in the year 2035

The estimated solid waste volume generated from 2015 to 2035 and the population trends is summarized in table 4.3.

Table 4. 4: MSW generated per year in Ndola.

Year	Population* (estimate based on the growth rate of 1.9%)	*Daily waste generation (Metric tonnes)	Projected annual waste generation per kg
2015	484,222.68	276,007	100,742,529
2016	493,422.21	281,251	102,656,491
2017	502,797.01	286,594	104,606,918
2018	512,350.15	292,040	106,594,449
2019	522,085.80	297,589	108,619,951
2020	532,005.43	303,243	110,683,730
2021	542,114.53	309,005	112,786,928
2022	552,415.70	314,877	114,930,086
2023	562,912.59	320,860	117,113,964
2024	573,607.92	326,957	119,339,128
2025	584,506.47	333,169	121,606,571
2026	595,612.09	339,499	123,917,095
2027	606,929.71	345,950	126,271,726
2028	618,461.37	352,523	128,670,888
2029	630,212.13	359,221	131,115,634
2030	642,186.16	366,046	133,606,831
2031	654,388.69	373,002	136,145,567
2032	666,822.07	380,089	138,732,332
2033	679,492.68	387,311	141,368,452
2034	692,403.04	394,670	144,054,452
2035	705,559.69	402,169	146,791,694

Source: (Field work 2021)

Source: (Field work 2021)

The picture is indicative of the Field work at kaloko dump site

Source: (Field work 2021)

The Table below summarises the Total annual MSW generation by population whose waste goes landfill site.

Table 4. 5: Total Annual MSW disposed to SWD sites (Gg MSW) (2015 to 2035)

Year	Population Whose Waste goes to SWDs	MSW Generation rate (kg/cap/day)	Fraction of MSW disposed to SWDs Site	Total Annual MSW disposed to SWDSs (Gg/yr.)
2015	484,222.68	0.57	0.7	70.51977
2016	493,422.21	0.57	0.7	71.85954355
2017	502,797.01	0.57	0.7	73.22484255
2018	512,350.15	0.57	0.7	74.6161141
2019	522,085.80	0.57	0.7	76.03396548
2020	532,005.43	0.57	0.7	77.4786108
2021	542,114.53	0.57	0.7	78.95084958
2022	552,415.70	0.57	0.7	80.45106047
2023	562,912.59	0.57	0.7	81.97977504
2024	573,607.92	0.57	0.7	83.53738943
2025	584,506.47	0.57	0.7	85.12459976
2026	595,612.09	0.57	0.7	86.74196673
2027	606,929.71	0.57	0.7	88.39020832
2028	618,461.37	0.57	0.7	90.06962162
2029	630,212.13	0.57	0.7	91.78094355
2030	642,186.16	0.57	0.7	93.52478141
2031	654,388.69	0.57	0.7	95.30189687
2032	666,822.07	0.57	0.7	97.11263216
2033	679,492.68	0.57	0.7	98.95791645
2034	692,403.04	0.57	0.7	100.8381167
2035	705,559.69	0.57	0.7	102.7541855

4.6 **Biomethanation Production Potential**

4.6.1 Methane production: Net annual CH4 emission (Gg/yr.) (2015 to 2035)

I. Estimating Methane Production Potential from Landfills

For the estimation of Methane production from Ndola landfill site, user specified input are used in the LandGEM Modem. Biomethanation for this study is applied and takes the organic content of waste as input to the LandGEM model

The potential methane emission from MSW disposed at the Ndola landfill, from the year 2015 to the year 2035, as computed by the default methodology taking the values of methane correction factor as 0.6, fraction of DOC in MSW taken as 0.15, fraction of DOC which actually degrades as 0.77, fraction of carbon released as methane as 0.5, conversion ratio as 16/12, potential methane generation rate as 0.08 and realised methane generation rate per unit of waste as 0.05. The methane emission for different population ranges from 20.2Gg in the year 2015 to 29Gg in the year 2035 as demonstrated in Table 4.6. Based on values generated in line with the volume of generated methane form MSW in Ndola landfill, taking into account the population increase, the current study assumed that it was appropriate to install methane capturing facilities. Values clearly demonstrated an increase in methane production from the year 2015 to the year 2035. The assumption made in the default methodology was that the potential methane is emitted in the same years from the year 2015 to the year 2035 for which the solid wastes were deposited yearly. Because of the high methane content, Landfill Gas (LFG) fugitive emissions were a major threat to the environment (Lizik et al., 2013; Jung et al., 2011.

The current study assumed that, the percentage of MSW sent to landfills was 70 percent based on the LandGEM default Method. The remaining 30 per cent was assumed to be lost due to recycling, waste burning at source as well as at disposal site, waste thrown into the drains and waste not reaching the landfills due to inappropriate solid waste management system.

The Table below summarises the annual methane generation potential in Giga gram per year and in cubic meter per year. The Table is also indicative of the Power recovery potential in MW from Biomethanation.

Table 4. 6: Methane and Power Recovery potential from municipal solid waste

Year	Projected annual waste generation	*Annual Methane Generation Potential (Gg/yr.)	*Annual Methane Generation Potential in M^3/yr.	Daily Methane Generation Potential in M3/yr.	Power Recovery Potential (Megawatts') MW
2015	100,742,529	22.0991048	39308.2618	107.693868	7.57046225
2016	102,656,491	22.5189558	40055.0618	109.739895	7.71429006
2017	104,606,918	22.9468058	40816.0899	111.824904	7.86085809
2018	106,594,449	23.382795	41591.5955	113.949577	8.01021436
2019	108,619,951	23.8271136	42381.9167	116.11484	8.16242402
2020	110,683,730	24.2798287	43187.1731	118.321022	8.31751008
2021	112,786,928	24.7411909	44007.8102	120.569343	8.47555833
2022	114,930,086	25.2113188	44844.0391	122.860381	8.63660945
2023	117,113,964	25.6903791	45696.1564	125.194949	8.80072054
2024	119,339,128	26.1784961	46564.3829	127.573652	8.96793413
2025	121,606,571	26.6758874	47449.106	129.997551	9.13832484
2026	123,917,095	27.1827291	48350.6387	132.467503	9.31195295
2027	126,271,726	27.6992461	49269.3812	134.984606	9.48889555
2028	128,670,888	28.2255316	50205.4992	137.549313	9.66918451
2029	131,115,634	28.7618166	51159.4033	140.162749	9.85289895
2030	133,606,831	29.3082911	52131.432	142.825841	10.040104
2031	136,145,567	29.8651938	53122.0096	145.539752	10.2308815
2032	138,732,332	30.4326323	54131.3275	148.305007	10.4252682
2033	141,368,452	31.0108975	55159.903	151.123022	10.6233637
2034	144,054,452	31.6001044	56207.9409	153.994359	10.8252076
2035	146,791,694	32.2005519	57275.9727	156.920473	11.0309021

4.7 **Power Recovery and Net Power Recovery Potential from Biomethanation: (MW)**

The results for Power Generation potential from biomethanation process for the period from 2015 to 2035 is shown in table 4.6. The Minimum total Methane production from Landfill is estimated to be 39308.2618 M^3/yr. in the year 2015 giving a Net Power Generation Potential of 7.57MW and the Maximum Methane Generation Potential was estimated to be 57275.9727M^3/yr. in the year 2015 giving a Net Power Generation Potential of 11.03MW

The results of equations for power recovery are indicative of potential for Power recovery Potential and Net Power recovery potential from Ndola MSW disposal from Landfill. There was an increase in MSW generated due to increase in population as indicated in Table 4.6. The increase in MSW resulted in the increase in Power Recovery Potential from 7.57MW in 2015 to 11MW in 2035 as indicated in Table 4.6.

The actual Power Recovery Potential and Net Power Recovery Potential from Biomethanation was computed as below. PRP is the Power Recovery Potential and NPRP is the Net Power Recovery Potential.

The biomethanation process is preferred for organic waste stream with moisture content to allow for microbial activity. The typical conversion efficiency for this process is taken as 30% [Gotmare *et. al.*, 2011]. The values for the total land fill gas (LFG) generation are taken from IPCC default method.

The NCV is the Net Calorific Value of LFG and lies in the range 0.194-0.242 kW/m3 and η is the efficiency for the bio-chemical process.

4.8 Power Generation Potential by Incineration

The results for Power Generation potential from Incineration process for the period from 2015 to 2035 is shown in Table 4.7. The results are indicative of a systematic increase in Net Power Generation Potential and energy Generation Potential due to the continuous increase in Waste Generation as indicated in the Table below. The dry matter content was considered by removing the 25% moisture content from the Waste.

The Power Generation Potential increased from 21.56MW in 2015 to 31.14MW in 2035. Conversely the Net Power Generation Potential increased from 21.56MW in the year 2015 to 31.42MW in the year 2035.The Energy Recovery Potential also increased from 0.518 GWh in the year 2015 to 0.75 GWh in the year 2035.

The Table below summarises Power Generation potential, Net Power Generation Potential and Energy recovery potential from Incineration.

Table 4. 7: Power Generation, Net Power Generation and Energy Recovery Potential

Year	Population* (estimate based on the growth rate of 1.9%)	*Daily waste generation (Metric tons)	Dry Matter content at 25% Moisture content	Power Generation Potential(PRP) MW	Net Power Generation Potential (NPRP)MW	Energy Recovery Potential in GWH
2015	484,222.68	276	207	21.56304122	5.39	0.517512989
2016	493,422.21	281	211	21.97270779	5.49	0.527344987
2017	502,797.01	287	215	22.39017935	5.60	0.537364304
2018	512,350.15	292	219	22.81559262	5.70	0.547574223
2019	522,085.80	298	223	23.24913328	5.81	0.557979199
2020	532,005.43	303	227	23.6908668	5.92	0.568580803
2021	542,114.53	309	232	24.14103766	6.04	0.579384904
2022	552,415.70	315	236	24.59976164	6.15	0.590394279
2023	562,912.59	321	241	25.06720127	6.27	0.601612831
2024	573,607.92	327	245	25.54347769	6.39	0.613043465
2025	584,506.47	333	250	26.02880374	6.51	0.62469129
2026	595,612.09	339	255	26.52335088	6.63	0.636560421
2027	606,929.71	346	259	27.02733865	6.76	0.648656128
2028	618,461.37	353	264	27.54085788	6.89	0.660980589
2029	630,212.13	359	269	28.06413391	7.02	0.673539214
2030	642,186.16	366	275	28.59735244	7.15	0.686336459
2031	654,388.69	373	280	29.14074635	7.29	0.699377912
2032	666,822.07	380	285	29.6944203	7.42	0.712666087
2033	679,492.68	387	290	30.25865841	7.56	0.726207802
2034	692,403.04	395	296	30.83357288	7.71	0.740005749
2035	705,559.69	402	302	31.41945495	7.85	0.754066919

4.9 **LCOE calculations**

The cost analysis used in this study to compare WTE technologies was obtained through levelized Cost of Energy of the Three Scenarios.

The Incineration process is the most widely used waste to energy technology in the world incorporating both Heat recovery and Electricity Generation. The Incineration process has a high capital and investment cost compared to Biomethanation. The higher efficiency allow for daily through put and labour skill requirements of incineration plants makes it more favourable use in most countries. The levelized Cost of electricity for incineration was found to be \$0.015/kwh and the levelized cost of electricity for Biomethanation was found to be at \$0.00755/kWh

Biomethanation process has the lowest Annual Investment cost of \$138, 000, 000 for 100MW capacity plant and operational and Maintenance cost (Variable and Fixed) of 20 percent of Investment cost. Biomethanation process is likely to offer ideal economical solution for problems associated with Waste Management in the City of Ndola. It is also important to note that the majority of the waste ends up in landfill sites offering a favourable generation of Methane as a source of energy. This is the effective technology with organic waste standing at 71%, moisture content at 25% key ingredient for Biomethanation process.

4.9.1 **Biomethanation/Anaerobic Digestion**

LCOE inputs:

Investment cost = \$138, 000, 000

Operation and maintenance cost (fixed) = 10 percent investment cost

Operations and maintenance cost (variable) = 5 percent investment cost

Lifespan = 30 years

Plant capacity = 100MW (2,400MWh/day)

Annual run time = 8760hours

Plant efficiency = 80 percent

LCOE = Inv Cost + O & M (fixed) + O & M (variable)/ (Total expected energy production per year by efficiency by Lifespan)

LCOE = (\$138, 000,000 + \$13, 800,000 + \$ 6, 900,000)/ (2400MWh/d * 365d/yr * 0.8 * 30yr)

LCOE = (\$158, 700, 000/21, 024, 000MWh)

LCOE = \$7.55/MWh

LCOE = \$0.00755/kWh

4.9.2 Incineration

LCOE inputs:

Investment cost = \$250, 000, 000

Operation and maintenance cost (fixed) = 15 per cent investment cost

Operations and maintenance cost (variable) = 12 per cent investment cost

Lifespan = 30 years

Plant capacity = 100MW (2,400MWh/day)

Annual run time = 8760 hours

Plant efficiency = 80 per cent

LCOE = Inv Cost + O & M (fixed) + O & M (variable)/ (Total expected energy production per year by efficiency by Lifespan)

LCOE = (\$250,000,000 + \$37,500,000 + \$30,000,000)/ (2400MWh/d * 365d/yr. * 0.8 * 30yr)

LCOE = (\$317, 500, 000/21, 024, 000MWh)

LCOE = \$15.102/MWh

LCOE = \$0.01510/kWh

4.10 Discussion of the Findings

This study indicated a variation of Waste disposal methods used in Ndola from Recycling 15% disposed at any place of convenience 10 % burning 10%, landfilling 63%, and composting 3% .The study showed a high incline towards landfilling as a disposal methods which makes Biomethanation a more favourable WtE method to be applied.

The Study showed a high activity of waste pickers that are mainly picking recyclable waste. The 15% recyclable waste has high energy content substrate. This abundant presence of plastic and paper in developing countries waste stream, has raised concern about recycling and circular economy, noticing an important participation of waste pickers in this particular industry (WIEGO, 2016)

The same recyclable materials are what is needed for Incineration plant. This makes Incineration deprived of key input as they are picked by waste pickers

The MSW studied in this study depicted waste composition of Organic Content 71% paper and plastic 14 % and other waste 15%. The study also found moisture content of 25%. The high organic content and high moisture content provides important feedstocks for Biomethanation.

The High organic content of MSW depicted in this study further favours Biomethanation process for WtE.

This study underscored that waste management is the privilege field of people with low educational back ground in Ndola standing at 87.4% who have not attained grade 12 certificate. The Study underscored high content of Waste burned 10 percent and Waste disposed at any place of convenience 3%. This is due to lack of infrastructure, proper transportation, and Waste management practice in the city of Ndola. The current study is supported by a study which stated that the lack of infrastructure for collection, transportation, treatment and final disposal of waste, management planning, financial resources, know-how and public attitude reduces the chances of improvement in Waste management. (Srivastava et al; 2015).

The current study established an increase in methane emission from 22.1Gg/yr. in the year 2015 to 31.6Gg/yr. in the year 2035 due to population increase resulting from urbanisation as demonstrated in table 4.6. This has a potential to harness and to overcome energy downturn in Zambia, particularly in Ndola.

The finding of this Study was in line with (Chander Kumar Singh 2018) who stated that Economic development drives the population to move to cities where basic infrastructure and amenities are available. This diversion of the population subsequently leads to changes in the overall lifestyle and living standards and thereby increases the per capita generation of MSW. We found that the higher the population density, the more MSW was generated. The power Generated from Biomethanation increase from 7.57MW in the year 2015 to 10.82MW in the year 2035

Municipal Solid Waste (MSW) in Ndola contains organic as well as inorganic matter as evidenced in table 4.2. The potential of energy recovery through incineration route is quite appreciable according to findings, many studies around the world have valued incineration as ambitious technology in reducing waste volume as well as reduction of land field spaces in urban areas by producing energy (Avinash A. Patil and Kulkarni; 2015; Solano; 2002).

The current Study found an increase in Power Generation Potential from 21.56MW in the year 2015 to 31.42MW in the year 2035. The study considered an incineration efficiency of 25% which resulted in the Net Power Generation potential of 5.49MW in the year 2015 and 7.85MW in the year 2035. The increase was due to the increase in Waste Generation Rate resulting from Population Growth at a rate of 1.9 percent per annum. Although incineration is viable with regard to mentioned studies, an incineration plant involves heavy investments and high operating costs (Ouda et al; 2015) and is deprived of high energy content feedstock due to the law of waste pickers.

The most Suitable Technology was also evaluated on the basis of, Levelized cost of energy, availability of Degradable organic waste Stream, higher efficiency, lowest annual capital and operational cost.

The levelized cost of energy for incineration was found to be \$0.015/kwh. The investment and operational and maintenance test for incineration was found to be higher than for biomethanation. The levelized Cost of energy for Biomethanation was found to \$0.00755/kWh.

Chapter 5 : CONCLUSION AND RECOMMENDATIONS

5.1 CONCLUSION

This chapter discussed the findings of the study on waste to energy assessment potential in Ndola. It also outlined recommendations.

The Study shows with higher efficiency and lowest capital and operational cost, biomethanation is the preferred Technology than incineration. The contribution of this paper to the academic world is to expand and broaden existing information on Municipal Solid Waste (MSW) management by analysing different energy recovery routes for MSW. The main aspects related to the composition of waste were addressed, as well as the technological routes for thermochemical and biochemical energy usage. Within the thermochemical route, incineration was used as technology for energy recovery of waste, with generation of electricity and heat and also a decrease in the volume of the produced waste. The biological route referred to the utilisation of the organic fraction of MSW, as biomethanation or anaerobic processes enabled the production of biogas using LFG recovery.

Waste to energy (WtE) has gained recognition across the world as an appropriate and sustainable waste disposal method; an alternative to massive waste generation and its management witnessed during the last two decades in Zambia. WtE can be used as an opportunity to harness energy burgeons experienced in Ndola. Additionally, LFG recovery is a potential option to generate renewable energy which has not yet been exploited to its full potential in Ndola. Furthermore, incineration if well managed environmentally could be a sustainable solution to the dual impediment of energy shortage and waste mismanagement.

Currently, 100,742,529 kilo joules of waste is generated per year in Ndola and this mass would increase to approximately 138,732,332 kilo joules per year by 2035. This quantity of municipal waste could be seen as an opportunity to harness WtE potential to produce energy or heat as well as exploring or fostering composting, recycling materials. The findings of the study did not fall short to harness WtE potential in Ndola, it revealed a higher organic fraction presents in Ndola waste stream (71%) along with a huge volume of waste produced daily (276,007kg in 3015 and 380,089kg in 2035).Further figures obtained following levelized cost of energy calculations demonstrated by different technological options: Anaerobic digestion stands for $7.55/MWh While incineration referred to $15.102/MWh. The annual average projection of waste generation in Ndola by the year 2035 is estimated to 138,732,332kg.

However, Ndola City has been experiencing unprecedented challenges in waste management due to impediments in collection, transport and disposal of waste as evidenced by *Zambia daily mail*, Vol 26, N°017, 2022 "The failure to collect garbage by the companies has resulted in accumulation of the rubbish in the central business districts, especially in major cities like Lusaka, Ndola and

Kitwe". In view of findings WtE is a viable and sustainable solution to the twin impediments which has plagued Ndola City such as increasing volume of waste generated, and energy shortage. The present study paved the way in considering the construction of methane capturing facilities in order to respond to Zambia 2030 agenda in terms of energy generation.

5.2 RECOMMENDATIONS

There is need to develop and implement a comprehensive waste management system in Ndola, in order to tackle in an effective and efficient way of increasing waste generation and energy shortage. This recommendation will assist decision makers, municipal authorities, advocates and representative, non-governmental organisations, and community and neighbourhood organisations in assessing diverse management options including the limits and risks of the various WtE technologies for effective planning, efficient investments in waste management. This approach should consider the following: Accurate waste generation data, well-managed waste collection, appropriate waste disposal methods and waste separation and composition.

5.2.1 Specific Recommendations

A. Policy Recommendations

The government, through the management bodies of municipal solid waste, should develop a solid waste planning and policy enforcement development that should provide basic training support to personnel and other stakeholders in the WtE management sector. For example, they should ensure that the council workers and informal waste pickers have access to basic trainings and challenges in the WtE sector, develop and implement policy that will harmonize integrated waste management system in Ndola by considering informal pickers interests and the need of sustainable waste management

B. Institutional Recommendations

It is highly recommended that the waste management bodies undertake the following measures to foster waste management system:

1. Supporting and focusing on initiatives/mechanisms that facilitate provision of reliable, comprehensive and up-to-date waste data for Ndola which is a must to effective waste management;
2. Implementing an industrial Weighbridge at kaloko dumpsite for effective weighing.
3. Enforcing regulations already enacted on effective and efficient waste management within the country;

4. Developing and implementing sound waste collection system with distributed responsibilities and control of all waste types;
5. Considering and privileging environmentally safe disposal of waste including different waste streams;
6. Partnering with higher learning institutions in order to stimulate studies/researches in waste sector especially in areas where municipal authorities are lacking expertise or pressing issues within the waste sector, etc.…;
7. Encouraging or fostering training in waste management among council workers including other stakeholders, especially informal waste sector for an effective waste management system;
8. Integrating informal waste pickers in waste management system in Ndola because they play a critical role in waste management in Ndola;
9. Enforcing serious measures against mass burning within the community and dumpsites around the city ;
10. Implementing a sound sustainable disposal of biomedical waste which is generally buried at dumpsites in Ndola.

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Appendix A: Certification of Ethical Clearance

THE UNIVERSITY OF ZAMBIA
DIRECTORATE OF RESEARCH AND GRADUATE STUDIES

Great East Road Campus | P.O. Box 32379 | Lusaka10101 | Tel: +260-211-290 258/291 777
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APPROVAL OF STUDY

IORG No. 0005376
HSSREC IRB No. 00006465

23rd March, 2022

REF NO. NASREC-2022-MAR-004

Wildie Mutelo
The University of Zambia
School of Engineering
Department of Mechanical Engineering
P.O. Box 32379
LUSAKA

Dear Mr. Mutelo,

RE: "WASTE TO ENERGY POTENTIAL ASSESSMENT: A CASE STUDY FOR NDOLA"

Reference is made to your protocol dated as captioned above. NASREC resolved to approve this study and your participation as Principal Investigator for a period of one year.

Review Type	**Ordinary Review**	**Approval No. NASREC-2022-MAR-004**
Approval and Expiry Date	Approval Date: 23rd March, 2022	Expiry Date: 22nd March, 2023
Protocol Version and Date	Version - Nil.	22nd March, 2023
Information Sheet, Consent Forms and Dates	• English.	To be provided
Consent form ID and Date	Version - Nil	To be provided
Recruitment Materials	Nil	Nil
Other Study Documents	Questionnaire.	

Specific conditions will apply to this approval. As Principal Investigator it is your responsibility to ensure that the contents of this letter are adhered to. If these are not adhered to, the approval may be suspended. Should the study be suspended, study sponsors and other regulatory authorities will be informed.

Conditions of Approval

- No participant may be involved in any study procedure prior to the study approval or after the expiration date.

- All unanticipated or Serious Adverse Events (SAEs) must be reported to NASREC within 5 days.

- All protocol modifications must be approved by NASREC prior to implementation unless they are intended to reduce risk (but must still be reported for approval). Modifications will include any change of investigator/s or site address.

- All protocol deviations must be reported to NASREC within 5 working days.
- All recruitment materials must be approved by NASREC prior to being used.

- Principal investigators are responsible for initiating Continuing Review proceedings. NASREC will only approve a study for a period of 12 months.

- It is the responsibility of the PI to renew his/her ethics approval through a renewal application to NASREC.

- Where the PI desires to extend the study after expiry of the study period, documents for study extension must be received by NASREC at least 30 days before the expiry date. This is for the purpose of facilitating the review process. Documents received within 30 days after expiry will be labelled "late submissions" and will incur a penaltyfee of K500.00. No study shall be renewed whose documents are submitted for renewal 30 days after expiry of the certificate.

- Every 6 (six) months a progress report form supplied by The University of Zambia Natural and Applied Sciences Research Ethics Committee as an IRB must be filled in and submitted to us. There is a penalty of K500.00 for failure to submit the report.

- When closing a project, the PI is responsible for notifying, in writing or using the Research Ethics and Management Online (REMO),both NASREC

- and the National Health Research Authority (NHRA) when ethics certification is no longer required for a project.

- In order to close an approved study, a Closing Report must be submitted in writing or through the REMO system. A Closing Report should be filed when data collection has ended and the study team will no longer be using human participants or animals or secondary data or have any direct or indirect contact with the research participants or animals for the study.

- Filing a closing report (rather than just letting your approval lapse) is important as it assists NASREC in efficiently tracking and reporting on projects. Note that some funding agencies and sponsors require a notice of closure from the IRB which had approved the study and can only be generated after the Closing Report has been filed.

- A reprint of this letter shall be done at a fee.

- All protocol modifications must be approved by NASREC by way of an application for an amendment prior to implementation unless they are intended to reduce risk (but must still be reported for approval). Modifications will include any change of investigator/s or site address or methodology and methods. Many modifications entail minimal risk adjustments to a protocol and/or consent form and can be made on an Expedited basis (via the IRB Chair). Some examples are: format changes, correcting spelling errors, adding key personnel, minor changes to questionnaires, recruiting and changes, and so forth. Other, more substantive changes, especially those that may alter the risk-benefit ratio, may require Full Board review. In all cases, except where noted above regarding subject safety, any changes to any protocol document or procedure must first be approved by NASREC before they can be implemented.

Should you have any questions regarding anything indicated in this letter, please do not hesitate to get in touch with us at the above indicated address.

On behalf of NASREC, we would like to wish you all the success as you carry out your study.

Yours faithfully,

Dr. E. M. Mwanaumo

CHAIRPERSON
THE UNIVERSITY OF ZAMBIA NATURAL AND APPLIED SCIENCES RESEARCH ETHICS COMMITTEE - IRB

cc: Director, Directorate of Research and Graduate Studies
Assistant Director (Research), Directorate of Research and Graduate Studies
Assistant Registrar (Research), Directorate of Research and Graduate Studies

APPENDIX B: CERTIFICATE OF PUBLICATION

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AUTHOR CERTIFICATE

THIS IS TO CERTIFY THAT THE MANUSCRIPT, ENTITLED

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(March 2023)

AUTHORED BY

Wildie. Mutelo

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