Department of Mechanical and Aerospace Engineering

Analysis of Waste to Energy Technologies Suitable for Utilisation in Urban Areas in Sub-Saharan Africa: Case Study of Nairobi City, Kenya

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Abstract

Nairobi is faced with the challenge of managing municipal solid waste (MSW) generated from the production and consumption of goods and services in the domestic and commercial sectors. MSW disposal in the city mainly constitutes open dumping and burning of the waste with no regard for the environment. The situation is made even more serious by the growing population of urban dwellers. In addition, the growing population has led to an increase in demand for energy, in an already underserved environment. The population mostly affected by these challenges is the low-income category of urban dwellers living in informal parts of the city commonly referred to as slums. This situation is reflected in other cities in Sub-Saharan Africa.

There is however the potential to generate energy from the municipal solid waste generated through various biological and thermal treatment methods. This project investigates the viability of such technologies for integration in the solid waste management frameworks of African cities, with Nairobi as the case study.

A review of literature reveals that landfill gas capture with energy recovery (LFGE) best suits Sub-Saharan African cities due to the high organic content in the MSW generated and because the waste is usually not separated before disposal. A technical analysis shows that electricity generation would be the most convenient way to utilise the landfill gas captured, with generation capacity of at least 2.1MW, enough to serve at least 6,200 households in the nearby slum area. Financial and economic analyses show that it is possible for the city's municipal council to return its investment in one year.

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Abbreviations

CCN	City Council of Nairobi
DESA	United Nations Department of Economics and Social Affairs
DOC	Degradable Organic Carbon
EPA	Environmental Protection Agency
FiT	Feed-in Tariff
FOD	First Order Decay
GDP	Gross Domestic Product
GNI	Gross National Income
IEA	International Energy Agency
IPCC	Intergovernmental Panel on Climate Change
IRENA	International Renewable Energy Agency
IRR	Internal Rate of Return
ISWA	International Solid Waste Association
JICA	Japan International Cooperation Agency
KES	Kenyan Shillings
KNBS	Kenya National Bureau of Standards
LandGEM	Landfill Gas Emissions Model
LFG	Landfill Gas

LFGE	Landfill Gas to Energy
MSW	Municipal Solid Waste
NEMA	National Environmental Management Authority
NPV	Net Present Value
SDG	Sustainable Development Goal
SEPA	Scottish Environmental Protection Agency
SID	Society for International Development – East Africa
U.S.	United States
UNEP	United Nations Environmental Programme
UN-HABITAT	United Nations Human Settlements Programme
USAID	United States Agency for International Development

1 Introduction

1.1 Problem Statement

The world is developing into a global urban community. According to the United Nations, over three billion people now live in urban areas(DESA, 2011). This accounts for over 50% of the world's population (UN-HABITAT, 2016). With the increase in urban populations comes a growing pressure for provision of public services such as transport, energy access, water, sanitation and municipal solid waste management.

The global urban population has been growing steadily in the 20th and 21st centuries. Barney Cohen's analysis (Cohen, 2004), which is based on the United Nations and World Bank data, indicates a 2.4% growth from 1975 to 2000 and an expected 1.8% average growth rate from 2000 to 2030. Based on the graph below, the urban population in middle- and low-income regions, viz South Asia and Sub-Saharan Africa, is expected to more than double from the year 2000 to 2030. By 2030, 53% of Africa's population is expected to live in urban environments (Cohen, 2004). This is against a backdrop of low levels of industrialisation and income (White, Turpie and Letley, 2017).

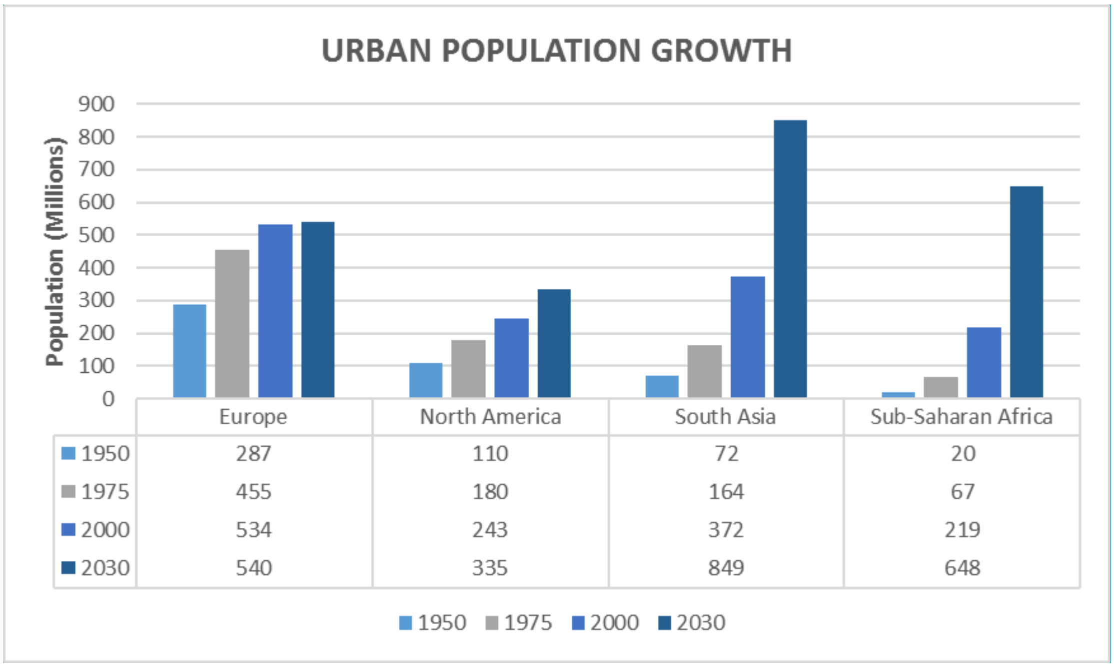


Figure 1: Growth in urban populations in selected regions since 1950[1]

It is estimated that cities currently consume 60% to 80% of primary energy produced, and generate up to 70% of global greenhouse gas (GHG) emissions (UN-HABITAT, 2016). This pressure is estimated to increase in the coming decades, with all the world's population projected to increase only in urban areas (DESA, 2011). The demand for energy will rise, putting a strain on the environment. Constant power outages and even living without grid connection are already a common experience for most African urban dwellers, particularly those living in or close to low-income areas of the cities. Most power systems are centralised, with limited capacity, unreliable fuel sources and transmission inadequacies, and can therefore not serve the ever-increasing urban population. The International Energy Agency (IEA, 2014, p. 30) describes Sub-Saharan Africa as "*the only region in the world where the number of people living without electricity is increasing, as rapid population growth is outpacing the many positive*

[1] Adapted from Cohen, 2004

efforts to provide access". Energy access is considered a key driver of industrialisation and economic development in cities and countries (Nkwetta *et al.*, 2007). As such, developing countries would need to find affordable and sustainable ways to produce energy for use in households and enterprises, particularly in urban areas such as cities.

In addition to the demand for energy, the continuous economic activities and consumption of goods in cities gives rise to generation of more waste, often referred to as municipal solid waste (MSW). The 2016 World Cities Report (UN-HABITAT, 2016) describes waste disposal as an all-time urban challenge, making it one of the most crucial responsibilities of a city's municipal council or authority. In low to middle income countries, cities use 30-50% of their annual budget on municipal solid waste management (UN-HABITAT, 2016). Yet, compared to developed countries, they remain behind when it comes to managing the waste that their urban dwellers generate. This has led to serious environmental and public health problems. It is possible to link the rate of solid waste generated to urban environmental issues. Local flooding caused by waste blocking drains, the spread of diseases from disease vectors such as rodents and insects, as well as water and air pollution from landfill leachate and methane respectively are some of the consequences of poor municipal solid waste management (UN-HABITAT, 2010a).

The generation of MSW however comes with an opportunity to utilise it as a renewable energy resource to meet the energy requirements of the ever-growing urban households, for lighting and cooking purposes. This project looks at potentially viable technologies that can utilise MSW to produce energy for use by urban households in developing countries such as Sub-Saharan Africa.

1.2 Project Aim and Objectives

The aim and objectives are as in the sections below. Though this project looks at a specific case study, the ultimate focus is on urban areas in Sub-Saharan Africa. It is therefore assumed that other urban areas in this region have similar characteristics to the case study under investigation.

1.2.1 Project Aim

To investigate the potential viability of waste to energy (WtE) technologies as a component in the municipal solid waste management value chain in urban areas in Sub-Saharan Africa.

1.2.2 Project Objectives

1. To determine the potential energy supply from MSW generated, using a case study of Nairobi, Kenya.
2. To determine the amount of MSW that could potentially be reduced by utilisation of the WtE technologies, using the case study.
3. To investigate the most viable WtE technologies to adopt in Nairobi, Kenya.

1.3 Methodology

This chapter introduces the problem being addressed by the analysis and breaks down the main objectives required to investigate the potential solution to the problem. **Chapter 2** gives a detailed account of literature reviewed about urbanisation and its link to sustainability and the environment, as well as MSW management and its role in meeting the energy demands of urban households in Sub-Saharan Africa. The chapter also investigates various WtE technologies as options for treating and disposing of MSW and their suitability for integration in MSW management frameworks in a Sub-Saharan Africa urban setting. It also clearly defines the terms urbanisation, urban areas, MSW, sustainability and other terms to further profile the scope of the project work.

Chapter 3 provides a summary background of the case study under investigation with respect to the issues discussed in the preceding chapter. **Chapter 4** gives an in-depth analysis of the case study with the aim of achieving objectives outlined in Chapter 1 and in connection to the findings from the literature review in Chapter 2. Microsoft Excel-based models are used to determine the best technical and financial options for the case study. The various methodologies for each phase of analysis are discussed in detail for each section. High level environmental and financial analysis of selected technologies and implementation methods to determine viability of likely implementation is also carried out.

Chapter 5 contains a comprehensive discussion of the findings from the analysis, as well as suggestions for improvements or alternatives where required. This chapter investigates the link between the analysis outputs and the project objectives. Finally, **Chapter 6** concludes the project by bringing out the key points found from the analysis in addition to identifying areas for further development.

1.4 Project Scope and Outline

Below is a summary of the scope of work carried out.

Case study area(s)

- Dandora dumpsite in Nairobi, Kenya

Type of waste considered

- Municipal solid waste (MSW) generated and disposed of at the Dandora dumpsite.
- Includes MSW generated by the domestic sector, the commercial sector and market places.
- Does not include sewage sludge or human waste.

Waste to energy (WtE) technology considered

- A literature review on thermal and biological WtE technologies utilising MSW is carried out as well as a general assessment of which technology or technologies would best suit the project's case study.
- It is based on this review that the most suitable WtE technologies are carried forward for further investigation on their technical, financial, economic and environmental viability.

Recipients of the energy supply

- Domestic households living near the Dandora dumpsite, in particular, the nearby Korogocho slum

Scope of viability analysis

- Technical viability in terms of potential for landfill gas to meet the energy needs of the surrounding community.
- Financial viability in terms of capital and annual operating and maintenance (O&M) costs. It does not cover energy cost savings by households from use of the energy supplied by the LFGE facility.

- Economic viability in terms of profitability of the LFGE project, as well as possible socio-economic benefits to the surrounding community.
- Environmental viability in terms of benefits and impact of the LFGE facility on the environment.
- The analysis does not cover transmission and distribution of energy to the consumers and the pre-treatment of MSW for use in the LFGE facility.
- Some high-level outline is provided on the MSW management and institutional framework in Nairobi

2 Literature Review

2.1 Urbanisation and Sustainable Development

2.1.1 Definition of Urbanisation and Urban Areas

The United Nations Population Fund (UNFPA, 2007, p. 6) defines urbanisation as "*the process of transition from a rural to a more urban society…urbanisation reflects on an increasing proportion of the population living in settlements defined as urban, primarily through net rural to urban migration*". Urban growth would therefore relate to an increase in the population living in urban areas.

There is no standardised definition of the term "urban" (Cohen, 2006; UNFPA, 2007). Definitions vary from country to country and even from period to period in some countries. This is because an area can be classified as urban by its administrative boundaries, its population, its population density, as well as its economic activities (Cohen, 2006; UNFPA, 2007). In addition, it is not easy to compare one urban area with another. What one country considers to be an urban area may be considered a rural area in another country. The National Geographic Society (National Geographic Society, no date) defines an urban area as a city and its surrounding area. It highlights the following features of an urban area:

- main economic activities are non-agricultural,
- a concentration of structures such as houses, buildings and transport networks, and
- can be a town, city or suburb.

This project specifically considers cities as urban areas and therefore uses the words "cities" and "urban areas" interchangeably.

The World Bank (World Bank, 2016b) explains that urbanisation can be caused by one of three main factors:

a. an "agricultural push" which generates excessive labour that migrates to urban environments seeking better employment,
b. an "industrial pull" where agricultural economies transform into industrial economies, therefore attracting rural labour to cities, and
c. "consumption cities" where economic growth is driven by exports and wealth from natural resources. In such cases, however, urbanisation tends to surpass economic development once a certain threshold is reached.

2.1.2 Urbanisation in World Cities

In 1987, Gro Harlem Brundtland, in his report to the World Commission on Environment and Development, "Our Common Future" (Brundtland, 1987), projected that almost half of the population would be living in cities by the start of the 21^{st} century. Today, this projection still holds true with over 50% of the world's population living in urban areas(Cohen, 2004; UNFPA, 2007; Hove, Ngwerume and Muchemwa, 2013; Sharma, 2016; UN-HABITAT, 2016). By 2014, 4 billion people in the world lived in urban areas (UN-HABITAT, 2016). This number is expected to grow to almost 6.3 billion by 2050 (Sharma, 2016). This growth rate is largely driven by the higher urban growth rates in Africa and Asia.

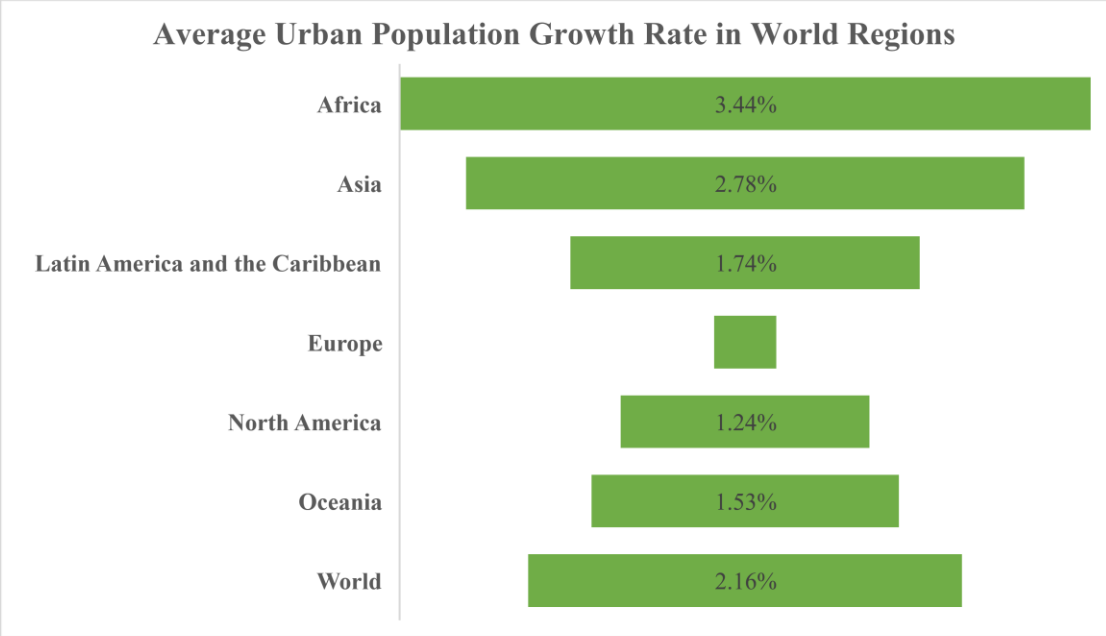


Figure 2: Average growth rate of urban population in the world from 1990 to 2015[2]

Out of the 6.3 billion people expected to live in urban areas in 2050, 5.2 billion of them (roughly 80%) will come from developing countries such as countries in Africa and Asia (UNFPA, 2007; DESA, 2011). This growth has been and will be mainly driven by the need for developing countries to compete on a global economic scale (UNFPA, 2007; Hove, Ngwerume and Muchemwa, 2013), rural-urban migration (Sharma, 2016), and natural increase in population within the urban areas (DESA, 2011). Sub-Saharan Africa has, over the past few decades, had the highest rate of urban population growth in the world, with an average annual urban growth rate of 5% (Hove, Ngwerume and Muchemwa, 2013). Its urban population is as large as that of North America, and its urban growth rate is expected to remain high over the next few decades (UNFPA, 2007). Rural-urban migrations will continue in developing countries as long as cities offer the hope of better standards of living. The situation is made dire by the fact that

[2] Adapted from UN-HABITAT, 2016

urbanisation in low-income areas like Africa is taking place against a backdrop of low levels of industrialisation and low rates of economic growth (UN-HABITAT, 2009).

2.1.3 Definition of Sustainable Development

Like urban areas, different countries have different interpretations of sustainable development. It depends on what stage each country or region is in terms of economic development. Developing countries, for example, view sustainable development from a social equity perspective, emphasizing more on equally providing basic needs to all citizens (Khatib, 2011). Developed countries are however beyond providing basic services to citizens, since equality is well underway if not already achieved. They are now considering the future of coming generations, and therefore interpret sustainable development in terms of the environment and environmental conservation for future use (Khatib, 2011).

The Brundtland Commission (Brundtland, 1987, chap. 1) defines sustainable development as "*development that meets the needs of the present without compromising the ability of future generations to meet their own needs*". This implies that long-term sustainability needs to be kept in mind with every stage of economic growth. Though other definitions of sustainable development exist, this is the most widely used definition, since it allows for the inclusion of both current equality issues and provisions for future generations.

Sustainable development also involves taking an integrated approach to social, environmental and economic concepts instead of treating them as isolated issues. As Bill Hopwood puts it, "*The concept of sustainable development is the result of the* *growing awareness of the global links between mounting environmental problems, socio-economic issues to do with poverty and inequality and concerns about a healthy future for humanity. It strongly links environmental and socio-economic issues*" (Hopwood, 2005, p. 39). In addition, the welfare of the people and the environment needs to take precedence when looking at development. Hove et.al. explain that "*sustainable development requires a careful cost-benefit analysis in order to craft development and environmental policies that will reinforce environmental protection while sustainably improving the welfare of local people*. (Hove, Ngwerume and Muchemwa, 2013, p. 3).

From these explanations, several features of sustainable development stand out:

- consideration of meeting the needs of future generations,
- taking a global approach to development,
- dealing with sustainable development as a cross-cutting issue in the social, environmental and economic aspects of society, and
- prioritising the environment and people's basic needs.

2.1.4 Urbanisation and the Environment

The literature review above on urbanisation and urban growth demonstrates an inevitability of urbanisation in every part of the world. Cities will continue to emerge and grow as the world develops into an urban society. In addition, cities are major drivers of economic transformation in any country. They provide the opportunity for better living standards, access to international investments and the global economy, as well as demographic transformation.

Although cities are advantageous, their emergence and the growing urban population puts a strain on the natural environment. Cities need natural resources for economic growth and for the general welfare of the inhabitants. In the book "Natural Resource and Environmental Economics", Perman et.al. identify four main services that the natural environment provides its human inhabitants (Perman *et al.*, 2003, chap. 2):

- a resource base to provide inputs for production of goods and services,
- a life support system for humans, plants and animals,
- a waste sink to assimilate waste generated and in most instances to clean up the ecological system, and
- a base for environmental amenities

They further explain that every economic activity has a material balance. Economic activities draw resources from the natural environment and return products to the environment, a concept similar to the law of conservation of mass.

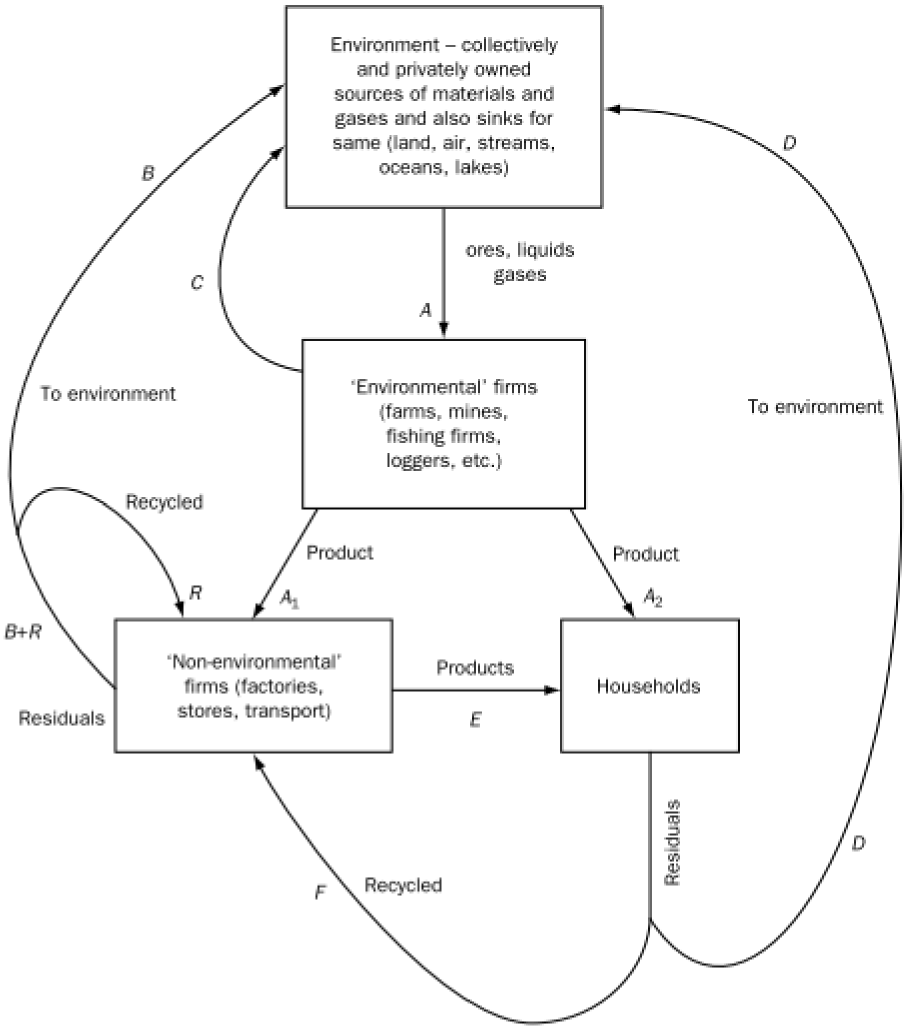


Figure 3: Interactions between the environment and economic activities[3]

As central points of economic growth, cities are a locus for the interactions between the environment and socio-economic activities both locally and internationally. White et.al. (White, Turpie and Letley, 2017) outline three major activities in urban areas that have a direct effect on the natural environment:

- consumption of natural resources,

[3] Source: Perman et. al, 2003

- transformation of the natural environment into a built environment, and
- generation of waste from urban activities.

These activities have a ripple effect not only on the environment but also on the local economy as shown in the figure below.

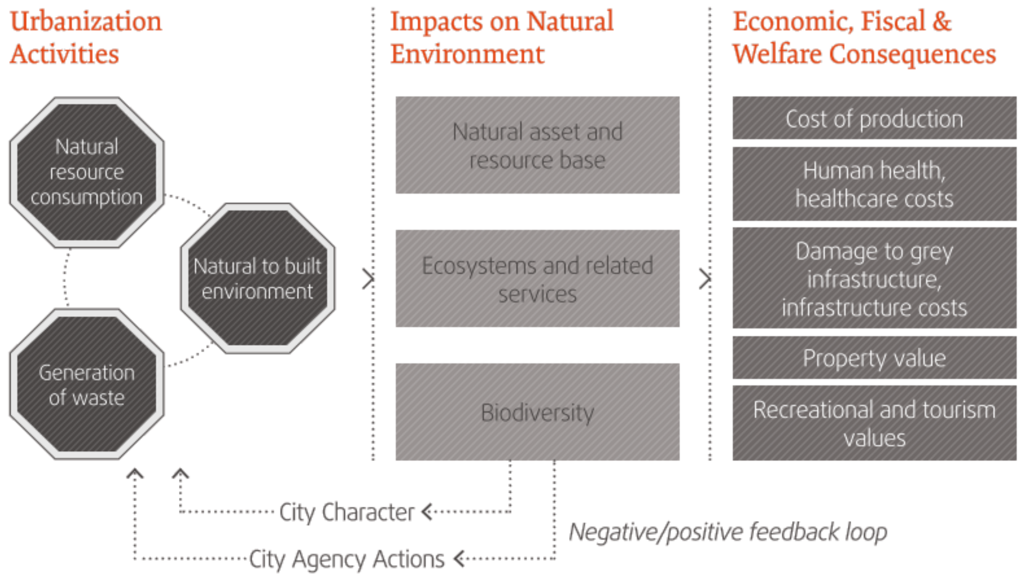


Figure 4: Urban activities and their overall impacts on the environment and the local economy[4]

One cannot therefore ignore the environment while looking at social or economic development. Governments and policy makers therefore need to prioritise the natural environment in urban planning.

[4] Source: White et.al, 2017

2.2 Municipal Solid Waste Management and Energy Access Challenges in Urban Areas in Developing Countries

2.2.1 Municipal Solid Waste Management Challenges

As demonstrated in the previous sections, cities play an important role in the economy of any country. The growth in production and consumption of goods and services leads to an increase in waste generated. It is estimated that as at 2012, cities generated a total of 1.3 billion tonnes of MSW annually, with this rate expected to increase to 2.2 billion tonnes by the year 2025 (Bhada-Tata and Hoornweg, 2012). Municipal solid waste management is generally considered a global urban issue since rural areas generate far less waste (Bhada-Tata and Hoornweg, 2012). It has such global significance that it is included in one of the targets in SDG 11 of the United Nations' Sustainable Development Goals. The United Nations Environment Programme goes on to consider it a "basic human right" (UNEP and ISWA, 2015, p. 2).

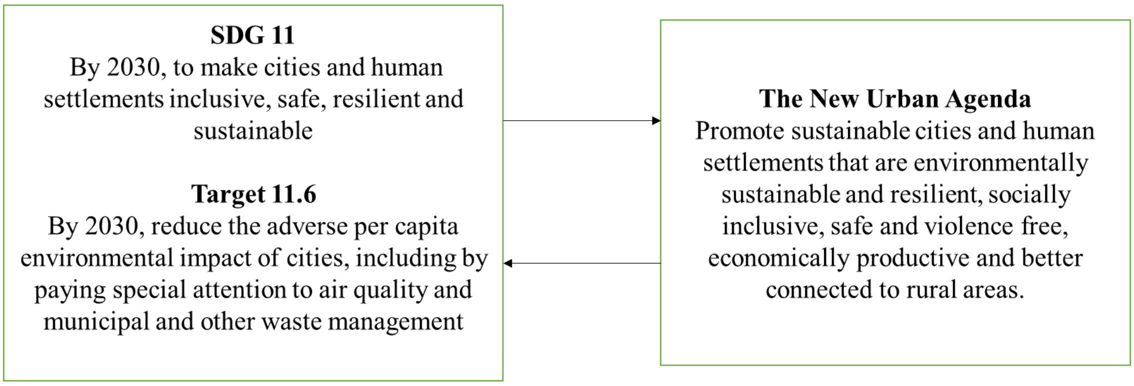


Figure 5: Waste management and its integration in SDGs and the New Urban Agenda[5]

[5] UN-HABITAT, 2016

Tackling pollution (air, water and MSW) is considered a foundation for all municipal services and other green urban development plans (Bhada-Tata and Hoornweg, 2012; White, Turpie and Letley, 2017). It is estimated that MSW management has the potential to reduce global greenhouse gas emissions by 10% to 15% (UNEP and ISWA, 2015). A city's ability to manage the waste generated is a good indication of how well it is run. In fact, a city administration that poorly manages the waste generated is often considered inefficient (UN-HABITAT, 2010a; ISWA, 2016).

The term waste has a broad meaning. The Global Waste Management Outlook (UNEP and ISWA, 2015, p. 22) provides different interpretations of waste: the report's own definition of waste as "unwanted and discarded materials", the United Nation's Statistic Division's use of "residues" instead of waste and categorising the residues into "emissions to air, generation of wastewater and generation of wastes", and the Basel Convention's[6] definition of waste as "substances or objects which are disposed of or are intended to be disposed of or are required to be disposed of by the provisions of national law". Certain features from waste arise from these definitions:

1. it is a by-product of some human activity,
2. it is not considered valuable to the waste generator,
3. it has potential negative effects on the natural environment, and

[6] The Basel convention was developed at a conference in Switzerland in 1989 in response to a growing concern of worldwide disposal of hazardous waste which has serious public health impacts. It's scope however also covers other waste such as household waste and ash from incinerators. Source: http://www.basel.int/TheConvention/Overview/tabid/1271/Default.aspx

4. it requires to be disposed of.

Municipal solid waste (MSW) is often associated with waste generated in urban areas. The Intergovernmental Panel for Climate Change (IPCC) considers MSW "*as 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 other (e.g., ash, dirt, dust, soil, electronic waste)"* (Bhada-Tata and Hoornweg, 2012, p. 4). The Organisation for Economic Co-operation and Development (OECD) defines MSW as "*waste (that is) collected and treated by, or for municipalities. It covers waste from households, including bulky waste, similar waste from commerce and trade, office buildings, institutions and small businesses, yard and garden, street sweepings, contents of litter containers, and market cleansing*" (Bhada-Tata and Hoornweg, 2012, p. 5). MSW can therefore be categorised by source (households, businesses and institutions) or by waste type (organic and inorganic). In the context of this project, a greater emphasis has been placed on categorisation by source of MSW generation for easier technical analysis. In addition, the terms "waste" and "solid waste" used in this project all refer to municipal solid waste (MSW).

2.2.1.1 <u>The Hierarchy of Municipal Solid Waste Management</u>

Municipal solid waste management in different countries often depends on existing physical, financial and policy dispositions of their urban areas. However, some waste management practices are generally better than others from a public health and environmental point of view. The figure below, taken from the Global Waste Management Outlook report (UNEP and ISWA, 2015), demonstrates the generally accepted hierarchy of managing MSW, with prevention being the most ideal method of waste management and uncontrolled disposal being the most undesirable method. Waste to energy technologies can be considered part of the recycling and other recovery categories of the hierarchy.

Figure 6: MSW management hierarchy based on the Basel Convention[7]

While the first 6 practices are common in developed countries, developing countries are still practicing poor waste management practices such as open burning or waste and uncontrolled disposal Bhada- Tata et.al (2012). Developing countries do not as yet have an established institution to encourage waste re-use, reduction and recycling practices as is common in developed countries.

[7] Source: (UNEP and ISWA, 2015)

2.2.1.2 MSW Generation and Composition

There is a correlation between income levels and amount of waste generated particularly in developing countries. In the case of East Africa, for example, Okumu-Okot explains that due to less disposable income, lower income households tend to consume less and therefore generate less MSW compared to their higher income household counterparts that have more to spend on goods (Okumu-Okot, 2012). Bhada-Tata et.al. (2012) support this argument by stating that higher income levels lead to higher consumption of goods and services, which translates to generation of more MSW per capita. A study of the municipal solid waste management situation in Nairobi, Kenya (Kasozi and Harro, 2010) revealed that average MSW generated per capita ranged between 0.49kg/day in low income areas of the city to 0.65kg/day in high income areas of the city. Similar results of per capital waste generation were found in a study in Ghana, with MSW generation ranging between 0.49kg/capita/day in lower income households and 0.82 kg/capita/day in high-income households (Monney, Tiimub and Bagah, 2013). The situation is also the same from an international level. The table below provides a summary of estimated rates of MSW generated in several regions of the world.

Waste generated particularly in Sub-Saharan African areas mainly contains organic material, usually with a high moisture content (Kasozi and Harro, 2010; Okumu-Okot, 2012; Monney, Tiimub and Bagah, 2013; Rutz *et al.*, 2014).

Table 1: MSW generation in various regions of the world in 2012[8]

Region	Total estimated waste (million tonnes/year)	Per capita range (kg/capita/day)	Average per capita waste generation (kg/capita/day)
Sub-Saharan Africa	62	0.09-3	0.65
East Asia and the Pacific	270	0.44-4.3	0.9
Eastern and Central Asia	93	0.29-2.1	1.1
Latin America and the Caribbean	160	0.1-1.4	1.1
Middle East and North Africa	63	0.16-5.7	1.1

2.2.1.3 MSW Collection and Disposal

Local authorities such as city councils are usually responsible for the collection and disposal of waste, both in developed and developing countries. While almost all the waste generated is collected and disposed of properly in developed countries, only about 35% to 70% of MSW generated in urban areas in developing countries is collected (Okumu-Okot, 2012; Monney, Tiimub and Bagah, 2013). In addition, separation at the source, especially from the domestic sector, is not a common practice in urban areas in developing countries such as in Sub-Saharan Africa (World Energy Council, 2016; Mutz *et al.*, 2017). Waste is often only separated once it reaches the disposal destination.

There has been an improvement since the involvement of private collectors. However, collection from private companies seems to be concentrated in more affluent parts of the urban areas, where there is better road access and where households can afford to pay for the solid waste collection services (Okumu-Okot, 2012; Monney, Tiimub and Bagah, 2013). This has therefore led to open dumping or open burning of waste

[8] Source: Bhada-Tata and Hoomeg, 2012

especially in low income parts of these urban areas. This practice has become the most common method of disposing MSW in urban areas in developing countries (Okumu-Okot, 2012; Rutz *et al.*, 2014).

According to the International Solid Waste Association (ISWA), about 40% of the world's MSW is disposed of in dumpsites (ISWA, 2016). The Waste Atlas Partnership (Waste Atlas Partnership, 2014, p. 13) defines dumpsites, also commonly referred to as open dumps, as "*on-land throwing away areas, insufficiently managed, where solid waste is disposed of in an uncontrolled manner that does not protect the environment*". The International Solid Waste Association (ISWA) describes a dumpsite as "*a land disposal site where the indiscriminate deposit of solid waste takes place with either no, or at best very limited measures to control the operation and to protect the surrounding environment*" (ISWA, 2016). Based on these definitions, a dumpsite will typically have the following characteristics:

- uncontrolled and wide-scale dispersion of waste,
- waste remains uncovered and is not compacted,
- unsanitary conditions caused by improper operation as well as lack of monitoring and management of waste disposed, and
- adverse effects on the environment due to improper management of the waste.

These sites continue to grow in size and number as more and more people move to urban areas and as their consumption level rises (Waste Atlas Partnership, 2014).

It is worth noting that some African countries define their designated waste disposal areas as landfills (Waste Atlas Partnership, 2014), Kenya being one of them (UNEP, 2011). Unlike sanitary landfills which are engineered to monitor, control and regulate leachate from escaping into nearby soil or water bodies, as well as collection of landfill gas, these disposal areas are neither engineered, regulated nor sanitary. Developed countries in Europe, the UK and America have, over the past three decades, completely banned the use of dumpsites as a means of disposing solid waste for these reasons (ISWA, 2016).

Waste that has not been properly disposed of or treated poses serious impacts on the environment and is a potential hazard to the public's health. The following is a summary of some of the environmental and public health issues that arise from poorly disposed MSW (USAID, 2007; Bhada-Tata and Hoornweg, 2012; Waste Atlas Partnership, 2014):

- The rotting organic material provides a good breeding ground for rodents and insects, which act as disease vectors.
- During decomposition, the disposed waste releases some liquid and solid discharge known as leachate which contains toxic elements such as heavy metals like mercury and dioxins which, if not controlled, could leak into the soil and nearby water bodies, thus contaminating them.
- Dumping of waste into rivers and other natural habitats could potentially destroy the ecosystems existing in these areas, thereby endangering animals and plants.
- Methane gas, which has 21 times the global warming potential of carbon dioxide, is released from the anaerobic decomposition of the deeply buried

waste in the dumpsites. This therefore leads to air pollution which translates to poor air quality in the local environment.

- In addition, open fires caused by spontaneous combustion of the gas leads to smoke production, which is both a nuisance and harmful to the communities living in the surrounding area, due to emission of particulate matter, carbon monoxide and other toxic gases.
- The smoke, gas emission and the overall bad odour from the dumpsite degrades the quality of life in the areas close to it.
- MSW disposed in open areas can clog drains, leading to local flooding during rainy seasons as well as the spread of water borne diseases.

It is estimated that if nothing is done to close or upgrade open dumps around the world, they could contribute to 8-10% of global greenhouse gas emissions by 2025 (ISWA, 2016). These effects also lead to added environmental and public health costs. It would therefore ultimately be cheaper for city authorities to develop proper waste disposal systems. Closing or upgrading these dumpsites should therefore be considered priority especially in low- and middle-income countries, where the rate of urbanisation is growing faster than the rest of the world.

However, as hazardous as dumpsites are, they can also be a source of income for the informal sector. Many people living near the sites earn a living from "scavenging" through the dumpsites to find recyclable items that they can either sell to the formal recycling sector, or they can repurpose and on-sell. Consideration should be taken for this local economy whenever there are plans to close or upgrade the dumpsites. The graph below provides a picture of the estimated number of people that benefit from picking waste from of the biggest dumpsites in the world.

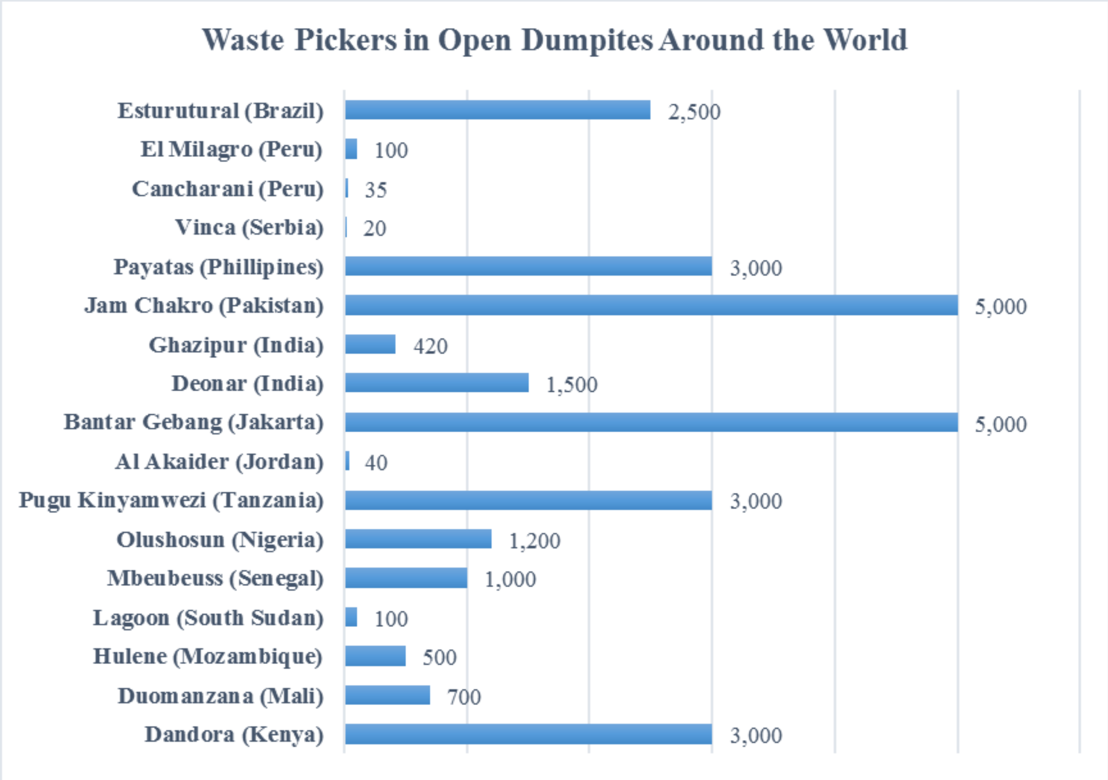


Figure 7: Number of waste pickers operating in some of the largest dumpsites in the world[9]

2.2.2 Energy Access Challenges

Low household income levels, inefficient and costly energy supply, weak energy networks, and constant power shortages are some of the energy access challenges that majority of urban dwellers face in developing countries, especially in Sub-Saharan Africa (Nkwetta *et al.*, 2007; IEA, 2014). Power utilities often do not run at optimal capacity due to poor maintenance and operation. Some of the main problems in energy supply include unreliable supply of fuel for energy for electricity production, low

[9] Derived from Waste Atlas Partnership, 2014

transmission capacity, poor grid operation, low power plant efficiency, frequent power outages and high fuel prices (IEA, 2014) The inefficiency and high costs of energy supply leads to many people seeking alternative and often inferior sources of fuel for cooking and lighting, which lead to higher expenditure on fuel due to poor conversion efficiency. The Africa Energy Outlook (IEA, 2014) for example highlights typical expenditures of 20-25% of household income on kerosene for lighting, even though it would cost 150 times more than incandescent lighting and 600 times more than compact fluorescent lighting. Average electricity consumption for a 5-person household in Sub-Saharan Africa is estimated to be between 500kWh to 600kWh per year, which translates to 100kWh to 120kWh per person per year (IEA, 2014).

Energy in Sub-Saharan Africa is prioritised for cooking and lighting. Most urban households in Sub-Saharan Africa use charcoal and kerosene for cooking, since they are easier to transport and have higher energy content compared to fuel wood, which is more commonly used in rural areas. The figure below provides a summary of the disparity in type of fuel used for cooking in rural and urban areas in Sub-Saharan Africa. There is an opportunity for the utilisation of waste for energy production in urban areas to replace charcoal, kerosene and/or fuel wood for cooking or lighting, or for electricity production, to boost the local grid.

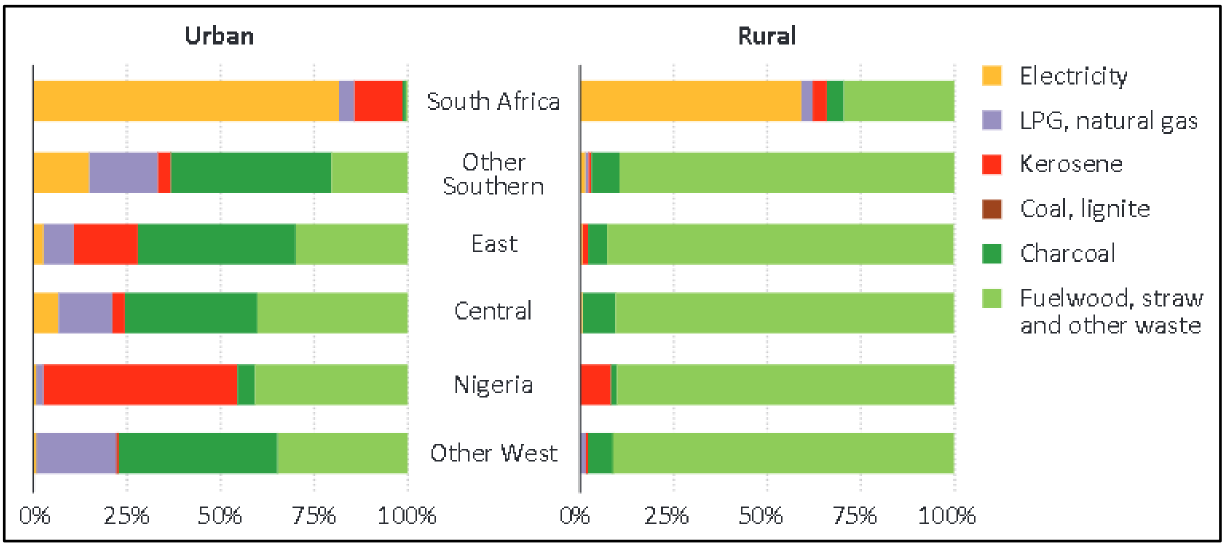


Figure 8: Percentage of fuel used for cooking in rural and urban parts of Sub-Saharan Africa[10]

2.3 Waste to Energy Technologies

Waste to Energy (WtE) technologies utilise waste generated in urban areas as a resource for production of energy. Waste is a product of human activities and can therefore be relied upon as a constant resource for energy production. As such, it can be categorised as a renewable source of energy.

There are 2 main ways of treating municipal solid waste for energy production, namely biological treatment and thermal treatment. Biological treatment involves the breakdown of the decomposable fraction of the waste by microorganisms to release energy, usually in form of methane gas. This can be carried out either through anaerobic digestion for biogas capture or through landfill gas capture. Thermal treatment involves the input of heat to release energy from the MSW. Energy products from thermal

[10] Source: 2014 Africa Energy Outlook

treatment can be solid, liquid, gaseous, or even in form of heat energy. This can be achieved through either incineration, pyrolysis or gasification.

2.3.1 Biological Treatment of MSW

This method of waste treatment requires that the composition of waste be organic to enable biological degradation and production of energy in form of methane gas (CH_4), which could either be used directly or utilised to produce electricity. The feedstock used for this could either be the organic fraction of MSW collected or waste buried in engineered landfills. The first type of feedstock undergoes anaerobic digestion to produce biogas while the second goes through bio-gasification to produce landfill gas, both of which contain CH_4.

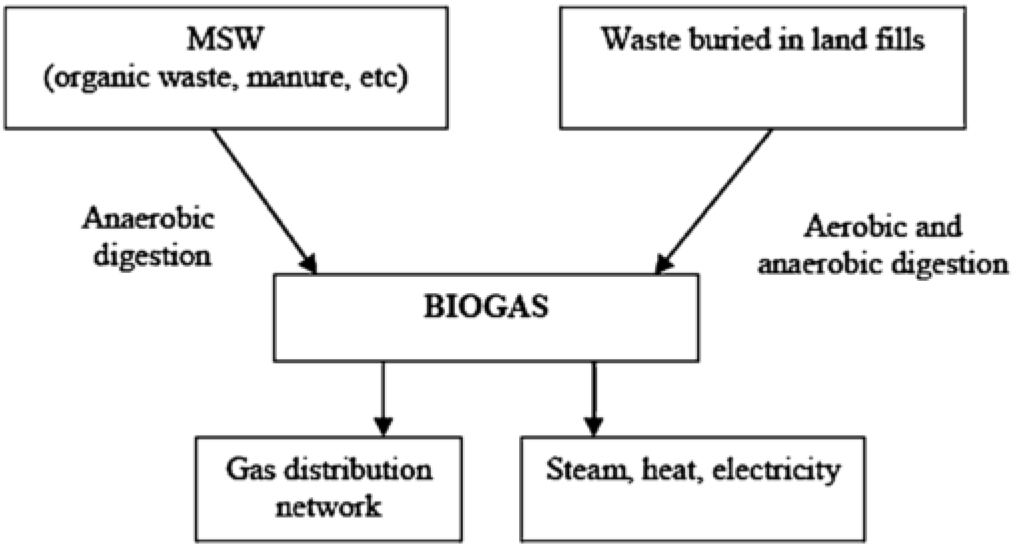


Figure 9: Biological MSW treatment options for energy recovery[11].

[11] (Pande and Bhaskarwar, 2012)

2.3.1.1 **Anaerobic Digestion**

This involves the decomposition of organic material under humid conditions by certain micro-organisms with no supply of oxygen (Sattler, 2011). It occurs in four main stages, usually in an anaerobic digester (Sattler, 2011; Pande and Bhaskarwar, 2012):

- **Hydrolysis** where complex polymers such as carbohydrates, proteins and lipids are broken down into less complex monomers such as amino acids, sugars and fatty acids and carbon dioxide (CO_2) and water are released.
- **Acidogenesis** where the monomers are further broken down into short chain / volatile fatty acids such as lactic acid and propionic acid.
- **Acetogenesis** where volatile fatty acids are decomposed into acetic acid and water and CO_2 are released.
- **Methanogenesis** where the acetic acid, CO_2 and hydrogen are converted to methane.

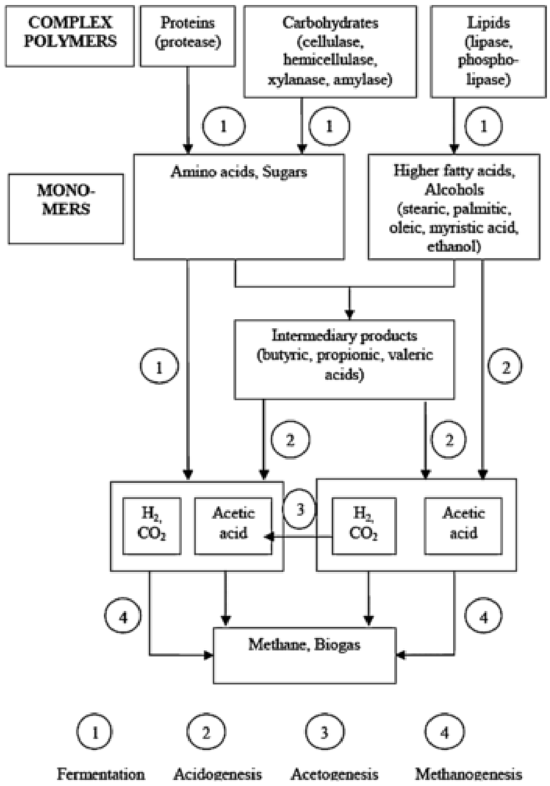


Figure 10: Anaerobic digestion process

A typical digestion cycle lasts 10 to 13 days (World Energy Council, 2016). The product of anaerobic digestion, often referred to as biogas, contains 65-70% of methane, 30-35% of carbon dioxide and traces of other gases such as hydrogen sulphide, and has a heating value of about 26MJ/m^3 (Pande and Bhaskarwar, 2012). In addition to the gas, some nutrient rich semi-solid residue is also produced, which can be stabilised and used as compost for agricultural purposes (World Energy Council, 2016).

2.3.1.2 **Bio-gasification**

This takes place in 2 main stages: aerobic decomposition and then anaerobic digestion. In the first stage of aerobic decomposition, bacteria already present in the waste convert the carbon content into carbon dioxide and water, in the presence of oxygen trapped within the spaces of the waste disposed (Townsend *et al.*, 2015b). Since this is an exothermic process, it leads to a rise in the temperature of the waste thereby creating a conducive environment for methanogenic organisms to act on the waste (Pande and Bhaskarwar, 2012). As more waste is disposed and compacted, oxygen levels are slowly depleted in the lower layers of the landfill, thereby creating an environment like that required for the anaerobic digestion, which is the second stage of this process, at which point the organic matter is broken down further to produce landfill gas, which has a lower heating value of 16.8MJ/m^3 (Ouedraogo, 2005).

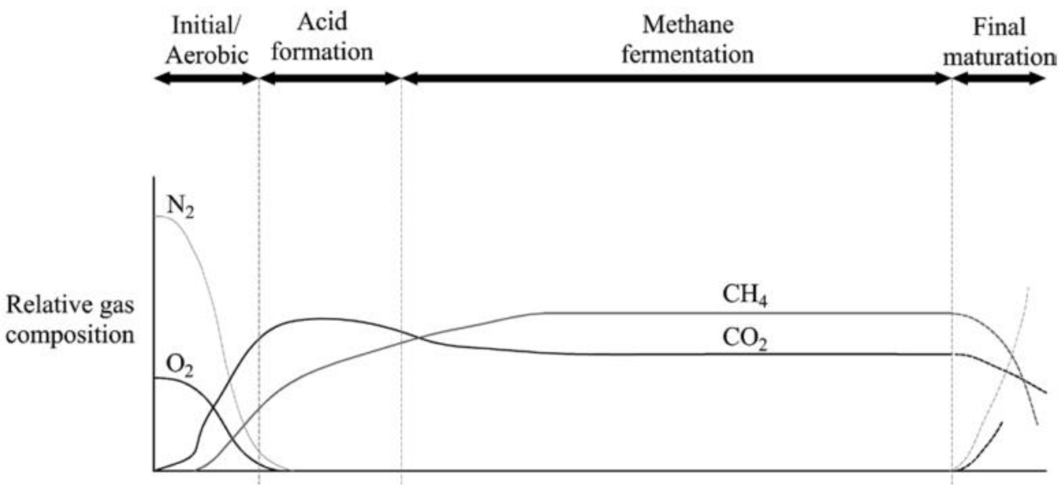


Figure 11: Summary of bio-gasification process for landfill gas production[12]

[12] (Townsend *et al.*, 2015b)

2.3.2 Thermal Treatment of MSW

For this method to be effective, the waste material needs to have a high energy content and low moisture content. This form of treatment involves high temperature conditions and, in some cases, high pressure conditions (Pande and Bhaskarwar, 2012). The energy products of thermal treatment can either be gaseous (for example methane), liquid (for example methanol or ethanol), solid (for example char) or heat. The 3 main technologies that utilise thermal treatment of MSW are incineration, pyrolysis and gasification.

2.3.2.1 <u>Incineration</u>

This involves the direct combustion of feedstock in an oxygen-rich environment at temperatures higher than 850^0C (Moustakas and Loizidou, 2010). During this process, the organic component of the waste is converted into CO_2 and water while the inorganic component is converted into ash. The main purpose of this process is to reduce the volume of waste and to make the waste chemically inert (Moustakas and Loizidou, 2010; Mutz *et al.*, 2017), but there is an opportunity to utilise the heat produced for space heating, production of steam or electricity production. Incineration can reduce waste by up to 90% by volume and 75% by weight (Moustakas and Loizidou, 2010). For the process to be self-sustaining and therefore effective, the net calorific value of the feedstock needs to be at least 7MJ/kg and at least 100,000 tonnes/year of supply of combustible waste is required (World Energy Council, 2016).

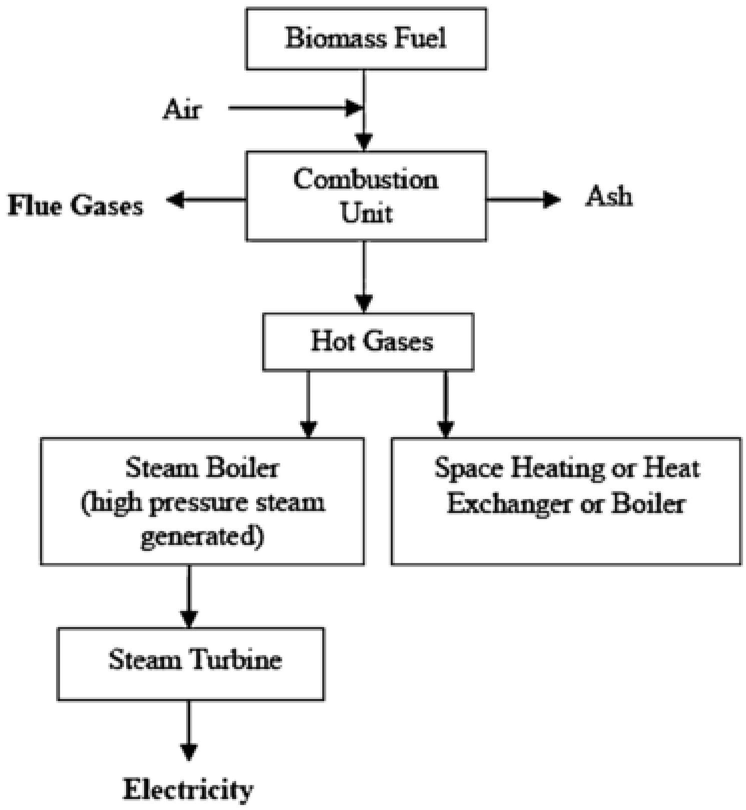


Figure 12: Waste incineration process[13]

2.3.2.2 <u>Pyrolysis</u>

This process involves the heating of the feedstock in the absence of oxygen. Products from pyrolysis include liquids (tar, oils and water), gases (CH4, carbon monoxide and carbon dioxide, synthetic gas) and solids (char) (Pande and Bhaskarwar, 2012; World Energy Council, 2016). Unlike incineration, pyrolysis is an endothermic process and therefore requires external heat supply (Pande and Bhaskarwar, 2012). The volatile matter in the feedstock is driven off leaving a synthetic gas (syngas) mainly composed of methane, carbon dioxide and hydrogen (Moustakas and Loizidou, 2010) and a

[13] (Moustakas and Loizidou, 2010)

carbon-rich solid known as char. The syngas produced has a net calorific value of 10-20MJ/m^3 (Moustakas and Loizidou, 2010).

2.3.2.3 Gasification

This process occurs at elevated temperatures in the presence of limited levels of oxygen to produce a synthetic gas, also known as syngas (Canzana, 2011; Pande and Bhaskarwar, 2012; World Energy Council, 2016). The syngas, mainly consisting of carbon dioxide, carbon monoxide and hydrogen can be used for production of high quality fuels and synthetic natural gas (World Energy Council, 2016).

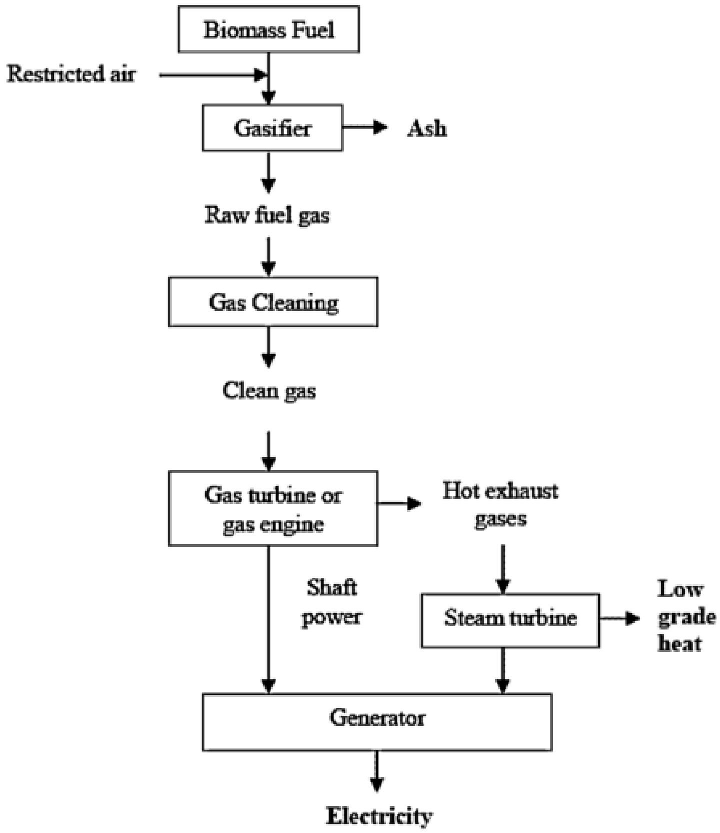


Figure 13: Gasification process for electricity generation[14]

[14] (Pande and Bhaskarwar, 2012)

2.3.3 Technology Suitability for Household Energy Supply

The choice of WtE technology to implement in an urban area will depend on the amount and nature of the waste disposed (World Energy Council, 2016), the level of demand for the energy produced as well as the availability of infrastructure. Financing and technical personnel, as well as a favourable policy framework also play a major role in successful implementation of a WtE project (Mutz *et al.*, 2017).

2.3.3.1 Characteristics of waste disposed in urban areas in Sub-Saharan Africa

Literature review on waste management in section 2.2 above highlights the following features of solid waste disposal in Sub-Saharan Africa:

- Inadequate waste collection services. Less than half of the waste generated in cities in Sub-Saharan Africa is disposed of at the designated disposal sites. The rest is either dumped in unauthorised areas or burned openly.
- Waste is not separated at the source. Some recyclable waste such as plastics and metals is recovered from some transfer stations and at disposal sites by waste pickers in the informal recycling sector, but a significant amount of the waste disposed of is mixed.
- Waste contains a high fraction of organic matter (over 50%) and a high moisture content.
- Once disposed of, waste is usually not treated further. Therefore, no compacting, homogenisation or covering takes place.

- Disposal areas are often not fenced to prevent trespassing by waste pickers or animal vectors. In addition, these disposal areas are often located near sensitive areas such as water bodies, forest edges and quarries (UN-HABITAT, 2010a).
- Most urban personnel handling and disposing the waste are not equipped with the technical skills required to operate complex disposal techniques (Mutz *et al.*, 2017).
- Majority of urban areas do not have air and water emission control standards.

The best WtE option should put these factors into consideration while minimising the costs involved in constructing and operating it. The technology needs to be considered as part of the entire solid waste management system rather than an independent system, so as to ensure a smooth flow of information and operation.

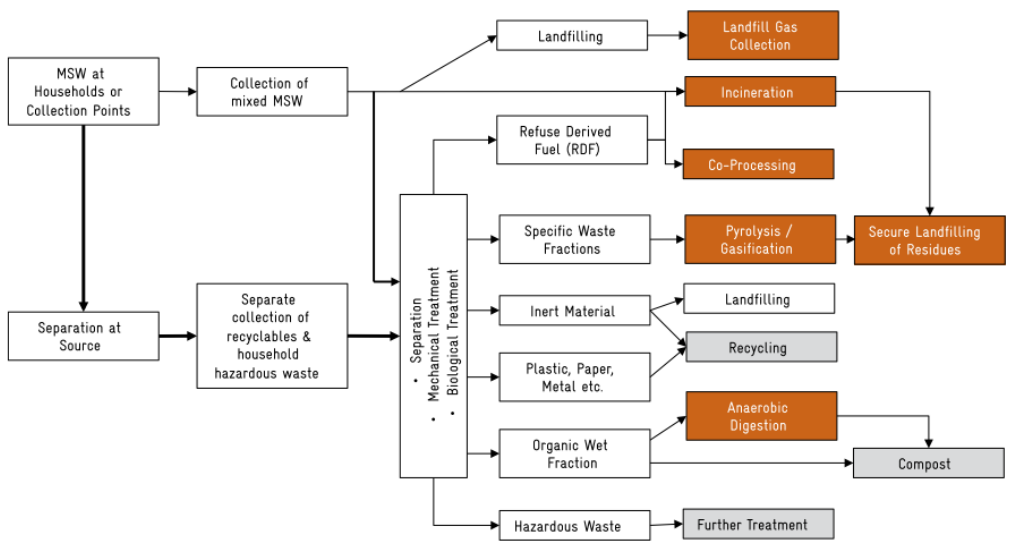


Figure 14: Example of WtE technology integration in a solid waste management framework[15]

[15] (Mutz *et al.*, 2017)

A summary of requirements, advantages and disadvantages of the different MSW treatment options is as shown in Table 2 below.**Error! Reference source not found.**

Table 2: Summary of WtE technologies, their operating parameters, energy products, advantages and disadvantages

Waste Treatment technology (Energy Products)	**Operating Parameters**	**End Uses**	**Advantages**	**Disadvantages**
BIOLOGICAL TREATMENT OPTIONS				
Anaerobic Digestion (Biogas)	30-40^{0}C for mesophilic digestion; 50-60^{0}C for thermophilic digestion (Sattler, 2011) High organic and moisture content in waste and an optimum pH level of 6.8-7.5 (Sattler, 2011; Mutz *et al.*, 2017). Consistent flow of well sorted and separated organic fraction of waste (Mutz *et al.*, 2017). Homogenisation of feedstock to meet required conditions of high organic content, small particle size and required moisture levels (World Energy Council, 2016) High Carbon – Nitrogen ratio (Sattler, 2011; Mutz *et al.*, 2017).	Cooking Space heating Electricity generation Transport fuel	Proven technology. Low cost of operation. Best method to handle food and garden waste in an environmentally friendly way (World Energy Council, 2016). Successful use of small-scale digesters in urban areas in African countries, especially for agricultural waste (Mutz *et al.*, 2017). Technical requirements of personnel not as stringent as other WtE options due to less complex operations. Less land area requirements: about 25m^2 per tonne of feedstock (Rawat *et al.*, 2016)	Operation is very sensitive to change in temperature and pH in the substrate. Large scale systems require a consistent supply of organic matter. The presence of inorganic or mixed feedstock reduces the performance of the digester and reduces the quality of the digestate for use as compost (Mutz *et al.*, 2017). Potential conflict if feedstock used can be utilised as food for livestock.

Waste Treatment technology (Energy Products)	Operating Parameters	End Uses	Advantages	Disadvantages
	Robust pipeline infrastructure for direct use of biogas by households for safety purposes. Households require the right cooking appliances for use of the biogas for cooking.			
Bio-gasification (landfill gas)	Mixed or sorted waste with high organic content. High moisture content Significant land requirement Leachate management Robust infrastructure to manage leachate, collect the gas and distribute it. For direct use, users need to have the right equipment e.g. gas cookers.	Cooking Heating Electricity production Combined heat and power (CHP) Transport fuel	Significant greenhouse gas reduction and improvement of local air quality (World Energy Council, 2016). Reliable renewable energy supply (30-50 years) (World Energy Council, 2016) Low cost of energy produced	Requires adequate land area for implementation. Any gas leakages could cause spontaneous explosions (Mutz *et al.*, 2017). Ground water contamination from un-collected leachate and bad odours if not well managed (Mutz *et al.*, 2017) For direct use of gas, the energy users must be nearby (U.S. EPA and ISWA, 2012)
THERMAL TREATMENT OPTIONS				
Incineration (heat energy)	850 – 1450^{0}C operating temperatures Mixed or sorted waste; organic and inorganic waste (Ouda and Raza, 2014) High energy content and low moisture content in feedstock Homogenisation of waste mix.	Space heating Use in boilers Electricity generation	Proven technology. Significant waste reduction.	High cost due to the pre-treatment of waste and measures to monitor and control emissions. Generation of high volume of air and water pollutants as flue gases (Ouda and Raza, 2014)

Waste Treatment technology (Energy Products)	**Operating Parameters**	**End Uses**	**Advantages**	**Disadvantages**
	Continuous flow of waste Pre-conditioning of waste required to reduce moisture content to 8-12% and to pelletise the feedstock (Pande and Bhaskarwar, 2012) Highly skilled technical personnel due to complexity of operation. Suitable demand for heat and power to increase plant efficiency (Mutz *et al.*, 2017).Therefore site specific.	Combined heat and power (CHP)	Up to 80% conversion efficiency for combined heat and power applications (Mutz *et al.*, 2017) Production of significant heat energy.	Requires proper disposal of solid residue (ash) from the combustion process (Mutz *et al.*, 2017) High capital and operating costs (Mutz *et al.*, 2017) Performance highly sensitive to seasonal changes in waste composition.
Pyrolysis (synthetic gas, bio-oil, char)	500-800^{0}C operating temperatures in the absence of oxygen (Moustakas and Loizidou, 2010; World Energy Council, 2016) Feedstock with high heating value required (World Energy Council, 2016) No metal or glass in waste. Waste therefore needs to be sorted prior to input (Moustakas and Loizidou, 2010) Mechanical treatment of feedstock required for homogenisation of	Electricity generation	No ash content produced (Moustakas and Loizidou, 2010). Less air emissions compared to incineration due to the absence of oxygen in the heating process (Moustakas and Loizidou, 2010) Suitable method for treating plastic waste (Rawat *et al.*, 2016)	Highly sensitive to feedstock composition. High costs involved in pre-treatment of feedstock and proper disposal of residue (Moustakas and Loizidou, 2010) Limited commercial scale application of pyrolysis at present (Moustakas and Loizidou, 2010; Mutz *et al.*, 2017)

Waste Treatment technology (Energy Products)	**Operating Parameters**	**End Uses**	**Advantages**	**Disadvantages**
	materials (World Energy Council, 2016) Highly skilled technical personnel due to complex operation. About 10 tonnes/day of supply required (World Energy Council, 2016)			
Gasification (Syngas)	500-1800^{0}C operating temperatures with limited supply of oxygen (Rawat *et al.*, 2016). Solid pre-sorted feedstock with high heat value required. Highly skilled technical personnel required due to complexity of operations. Robust pipeline for use as synthetic natural gas in households. Households also need to be equipped with the right equipment to use the gas.	Electricity generation High quality fuels and chemicals	Diverse utilisation of syngas. Can treat organic waste as well as plastic waste (Rawat *et al.*, 2016)	Low heating value of gas produced because it is diluted with nitrogen (Canzana, 2011). Still in development stage for commercial use. Significant cleaning of gas required for direct use therefore limiting it for large scale use (Moustakas and Loizidou, 2010; World Energy Council, 2016) Presence of heavy metals and organic pollutants in the residue (Matsakas *et al.*, 2017) High costs involved in cleaning syngas and pre-treatment of feedstock (World Energy Council, 2016; Matsakas *et al.*, 2017)

Waste Treatment technology (Energy Products)	Operating Parameters	End Uses	Advantages	Disadvantages
				Challenges in using heterogenous waste for gasification (World Energy Council, 2016; Mutz *et al.*, 2017) High capital costs (Moustakas and Loizidou, 2010)

From this breakdown, it is possible to narrow down the most suitable MSW treatment options for energy recovery as shown in the matrix below, which is based on the above characteristics and the decision support system developed by Mutz et al (2017).

Table 3: Decision matrix for most suitable WtE technologies for urban areas in Sub-Saharan Africa.

Key

Colour	Meaning
Green	Suitable
Yellow	Potential for use but more assessment required
White	Not suitable

Typical Characteristics	**Anaerobic Digestion**	**Landfill Gas Capture**	**Incineration**	**Pyrolysis**	**Gasification**
Somewhat systematic waste collection, but recycling is not well organised. There is a designated disposal site	Not suitable	Suitable	Potential for use but more assessment required	Not suitable	Not suitable
Waste is not separated at source and may contain some minerals and hazardous waste	Not suitable	Potential for use but more assessment required	Potential for use but more assessment required	Not suitable	Not suitable
High fraction of organic matter, high moisture content and heating value <7MJ/kg	Suitable	Suitable	Potential for use but more assessment required	Not suitable	Not suitable
Lower amounts of waste generated and disposed of in comparison to developing countries (approximaely up to 100,000 tonnes disposed a year)	Suitable	Suitable	Not suitable	Potential for use but more assessment required	Potential for use but more assessment required
Waste disposal personell have limited technical experience	Potential for use but more assessment required	Suitable	Not suitable	Not suitable	Not suitable
Safe disposal of residues may require longer transport distances	Not suitable	Suitable	Potential for use but more assessment required	Not suitable	Not suitable
Little to no heat demand for domestic use in surrounding areas. There is however the possibility of disposal sites being located close to a power transmission network	Potential for use but more assessment required	Suitable	Potential for use but more assessment required	Potential for use but more assessment required	Potential for use but more assessment required

Based on the typical characteristics of waste management practices in urban areas in Sub-Saharan Africa, landfill gas capture seems like the most suitable option for waste disposal and energy recovery. This project therefore investigates the viability of implementing a sanitary landfill with landfill gas to energy (LFGE) utilisation in a city in Sub-Saharan Africa for domestic use.

3 Case Study: Landfill Gas Technology for Nairobi, Kenya

3.1 Nairobi Background

3.1.1 Geography and Climate

Nairobi, the capital city of Kenya, is located at 1° 9’S, 1° 28’S and 36° 4’E, 37° 10’E, at the South-Eastern part of Kenya (UNEP and CCN, 2007). Being in the highland and agricultural part of Kenya, the city experiences two rainy seasons annually and temperate tropical climate. The table below provides a summary of Nairobi’s climate (UNEP and CCN, 2007).

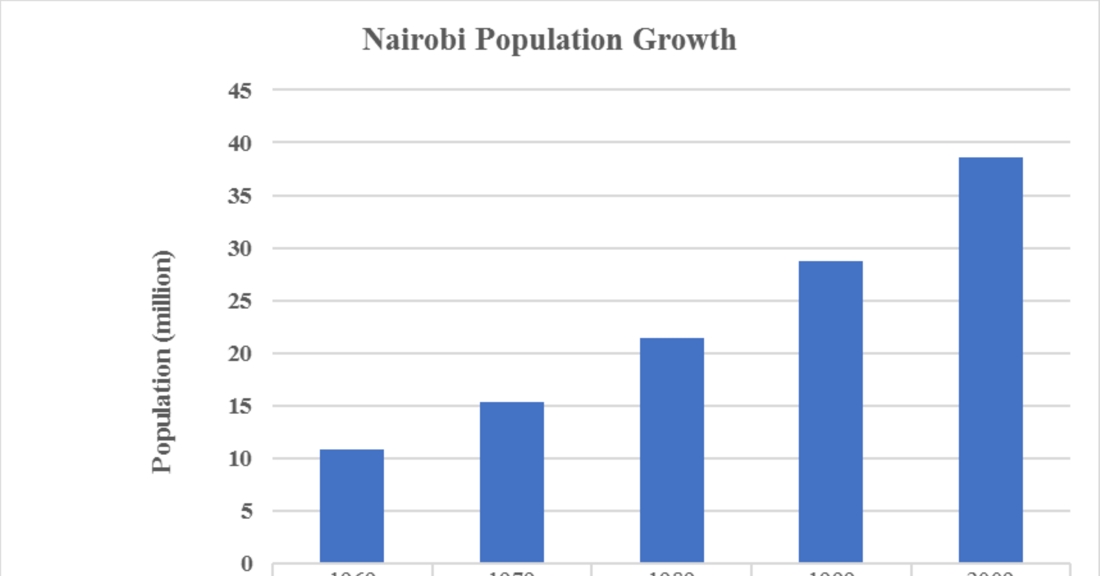
Table 4: Summary of Nairobi's climate

Rainy Season	Long rains – Between March and April Short rains – Between November and December
Mean annual rainfall	120mm[16]
Mean daily temperature	12^0C – 26^0C
Mean daily sunshine hours	9.5 hours

[16] From worldweatheronline.com www.worldweatheronline.com/nairobi-weather-averages/nairobi-area/ke.aspx

3.1.2 Population Growth

Nairobi is ranked the 14th largest city in Africa (KNBS, 2015) with an estimated population of 4 million in 2014 (KNBS, 2015; World Bank, 2016b), as well as the 5th fastest growing large city in Africa (UN-HABITAT, 2010b). The city's population, which accounts for 25% of Kenya's urban population, is expected to grow to 6 million by 2030 (World Bank, 2016b)



	1969	1979	1989	1999	2009
Population (million)	10.9	15.3	21.4	28.7	38.6

Figure 15: Historical population of Nairobi according to national census[17]

The average urban household size in Nairobi has been taken to be 4.4, based on the most recent national census carried out in 2009 (KNBS, 2015).

3.1.3 Socioeconomic Background

Due to its economic, political and financial prominence in East Africa, the city contributes to 60% of Kenya's wealth (KNBS, 2015). Despite this significance, about

[17] Source KNBS, 2015

1 million people in Nairobi live in low-income informal settlements commonly known as slums as seen in Appendix D (UN-HABITAT, 2010b). This accounts for 25% of Nairobi's population and about 350,000 households with low access to public services, either because they cannot afford them or because of poor delivery services and infrastructure in these areas.

3.1.4 Energy Access

With regards to cooking, kerosene is the most commonly used fuel in Nairobi (UNEP and CCN, 2007; KNBS and SID, 2013). According to the Kenya National Bureau of Statistics (KNBS and SID, 2013), 53.9% of households in Nairobi use kerosene as a primary source of fuel for cooking.

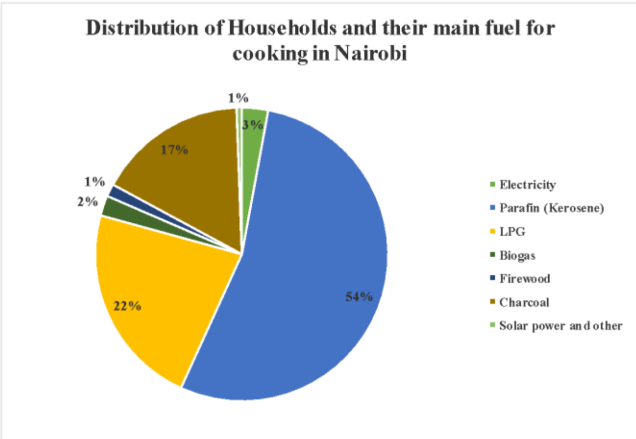


Figure 16: Percentage distribution of main cooking fuel among Nairobi households[18]

From the chart above, 70% of the households in Nairobi use either kerosene or charcoal as the main fuel for cooking. If considering an average household size of 4.4 in Nairobi as per the 2009 national census, and assuming a current total population of 4 million people, then that means about 640,000 households in Nairobi use kerosene or charcoal

[18] Adapted from KNBS and SID, 2013

as their main source of cooking fuel. The use of kerosene for lighting and cooking presents safety issues especially in informal settlements. Poor ventilation in houses, high population density and unsafe storage practice leads to the risk of fires starting and spreading in these areas (Karekezi, Kimani and Onguru, 2008).

About 72% of Nairobi households use electricity for lighting (KNBS and SID, 2013). This is mainly in areas with better road access and better electricity networks. This is followed by 13% of households who use lanterns and 12% who use kerosene fuelled tin lamps for lighting. Despite the relatively good access to electricity, people living in lower-income areas such as informal settlements get fewer hours of electricity compared to higher-income areas (World Bank, 2016b). Like in most African countries, electricity generation remains centralised and the capacity of the power utilities is not enough to service the growing populations (Nkwetta *et al.*, 2007). This has led to frequent black outs and power rationing.

Due to unreliability of electricity supply, households, particularly in the low-income parts of the city, have resorted to finding other means to meet their electricity requirements, such as using kerosene lamps, which ultimately becomes costlier. It also does not help that the cost of connection to the grid is too high for most families in the lower-income category to afford. This could in part be due to the centralised nature of power production which makes transmission costly for the power utilities.

3.1.5 Solid Waste Management in Nairobi

3.1.5.1 <u>Waste Generated</u>

There have been several studies on solid waste generated per capita in Nairobi over the past few years. The Japan International Cooperation Agency (JICA) has so far conducted two major surveys on solid waste generated in the city: one in 1998 and another in 2009. Kasozi & Harro (2010) conducted an independent survey of waste generated in 2010 and used historical data from various sources to develop projections of solid waste generation in Nairobi up to the year 2030. UNEP and the city council of Nairobi (UNEP and CCN, 2007) have also provided general figures. The table below summarises the findings from the various sources of literature.

Table 5: Summary of waste generation in Nairobi from historical surveys

	Waste Generated per Capita (kg/capita/day)	Total Waste Generated Daily (tonnes/day)
JICA 1998 survey (Kasozi and Harro, 2010)	0.59	1,580 (domestic and non-domestic)
UNEP and Nairobi City Council 2007 report (UNEP and CCN, 2007)	0.714	1,580 (domestic and non-domestic)
JICA 2010 survey (JICA, 2010)	0.36 – 0.62	1,848 (domestic and non-domestic)
Kasozi & Harro 2010 survey (Kasozi and Harro, 2010)	0.65	2,122 domestic waste 999 non-domestic waste

For the purposes of this project, figures from the 2010 JICA survey are used for analysis for the following reasons:

- It is the most recent and comprehensive account of solid waste generation and disposal in Nairobi.

- The survey was conducted over the course of one year and accounted for seasonal variability.
- The survey accounted for solid waste generated across all sectors in Nairobi, including residential, commercial and industrial sectors.
- It provides a relatively realistic projection of solid waste generation with population growth that closely matches literature reviewed on population growth in Nairobi.
- It provides a comprehensive analysis of waste categories and their weighted percentages.
- The results from the survey were used as a basis for developing Nairobi's Integrated Solid Waste Management Master Plan.

However, some reference is made to the situation analysis prepared by Kasozi and Harro (2010) to account for some modifications since the report provides a comprehensive critique on the solid waste management situation in Nairobi with reference to past surveys, including the JICA 2010 survey.

3.1.5.2 Waste Re-Used/Recycled

In 2007, UNEP reported that only 40% of the waste generated in the city was collected by city authorities (UNEP and CCN, 2007). The private sector collected about 20% of the waste, meaning that the remaining 40% was disposed of irregularly, either in unregulated open dumps or by burning it openly. Taking UNEP's estimation of 1,580 tonnes of waste generated per day as shown in Table 5 above, it would indicate that only 948 tonnes of waste were collected daily. The report does not however provide details on how this waste is disposed of and does not cover re-use and recycling of waste. This information is required to determine the residue waste that could potentially be used for waste-to-energy technologies. The Kasozi & Harro (2010) and JICA (2010) analyses provide a better picture of solid waste collection and recycling in Nairobi as shown in the tables below.

Table 6: 2009 flow of waste in Nairobi by recipients of waste[19]

Waste stream	Amount (tonnes/day)	Percentage of Total
Total Amount generated	**1,848**	**100%**
Amount reduced at source	0	0.0%
Amount recovered by junk collectors and dealers	63	3.4%
Organic portion recovered for composting	10	0.5%
Amount recovered at material recovery facilities and by the waste collection companies	6	0.3%
Amount recovered at the disposal site and other dumpsites	6	0.3%
Amount disposed of at disposal site and other dumpsites	**1,763**	**95.4%**

Table 7: 2009 flow of waste in Nairobi by type of waste [20]

Waste stream	Waste Generated (tonnes/day)	Waste Recovered (tonnes/day)	Waste recovered as percentage of waste stream
Total waste	**3,121**	**150**	**4.8%**
Food and garden waste	1,589	3	0.2%
Paper waste	546	44	8.1%
Plastic waste	502	25	5.0%

[19] Source: JICA's 2010 Preparatory report on integrated solid waste management in Nairobi.
[20] Source: Kasozi & Harro (2010) analysis.

Glass waste, metal waste and other	484	78	16.1%
Total waste disposed of at disposal site and other dumpsites		**2,971**	**95.2%**

The above tables indicate that only about 5% of waste generated in Nairobi is re-used or recycled on average, with the remaining being disposed of either at a designated disposal site or at unauthorised sites.

3.1.5.3 <u>Waste Collected and Disposed</u>

Solid waste in Nairobi is collected by both the city council and private collectors. Almost all waste collection services are concentrated in high- and middle-income areas of the city, where road networks make it easier to transport the waste, and households can better afford the services (World Bank, 2016). Due to lack of standardised guidelines on waste collection and transfer, the private collectors mostly operate in affluent areas and have control of the waste collection fees. The Nairobi City Council, which is mandated to provide public services such as MSW management in the city of Nairobi, does not monitor the collection, transfer and disposal of waste by these private collectors, so some take advantage by dumping the waste they collect in illegal areas, or burn the waste in open fields, therefore contributing to the waste management problem.

Nairobi has only one designated disposal site known as the Dandora dumpsite, located about 7.5km from the city centre. As the name suggests, this disposal site is not a sanitary landfill, but rather an open field where waste is dumped without further treatment or control. According to JICA (JICA, 2010), the dumpsite received a minimum of 473 tonnes of waste a day and a maximum of 906 tonnes a day in the year

2009. No accurate records of waste received at the dumpsite exist before 2006 since this is the year when a weigh-bridge was installed at the site (JICA, 2010). Details on the dumpsite are provided in the next section.

One of the main causes of air pollution in the city is open burning of waste especially in informal settlements (UNEP and CCN, 2007). Moreover, the city currently does not have an air quality monitoring and management system (UNEP and CCN, 2007), making environmental degradation a growing policy concern especially with the growth in population.

3.2 The Dandora Dumpsite

Located just 7.5km from the city centre, Dandora has been Nairobi's official waste disposal site since 1981 and has accumulated over 1 million cubic meters of waste since then (UNEP and CCN, 2007). The dumpsite is located close to one of Nairobi's slum areas known as Korogocho slums which is home to about 41,900 people (about 12,900 households) (UN-HABITAT, 2010b).Only 34.8% of the household population in Korogocho has access to electricity (KNBS and SID, 2013).

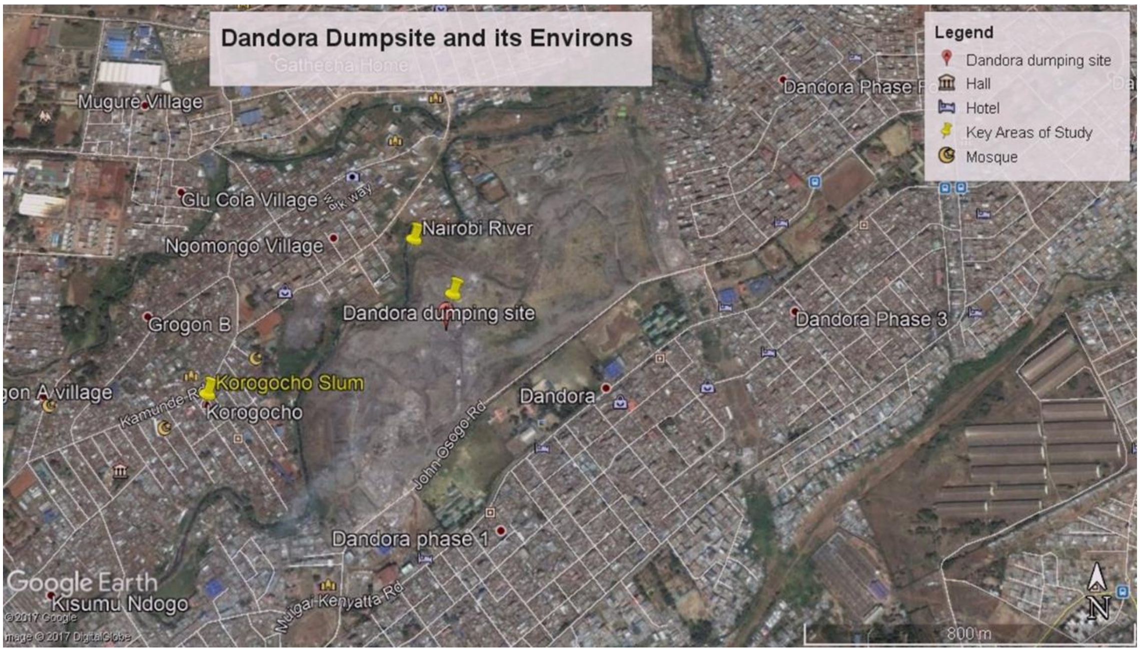


Figure 17: Dandora dumpsite and its environs[21]

Figure 18:Location of Dandora dumpsite with respect to Nairobi City[22]

[21] Google Earth Pro
[22] Source: UNEP and CCN (2007)

As at 2010, the site received approximately 830 tonnes a day of the waste collected in the city. This falls within the estimates reported by JICA in 2010, based on their analysis of waste measured and recorded by the city council between 2006 and 2009. The dumpsite is claimed to have reached its capacity in 2001, but is still being used to dispose of MSW generated from various sources in the city (Concern Worldwide, 2015). The 2014 Waste Atlas report (Waste Atlas Partnership, 2014) rates Dandora Dumpsite as one of the 50 largest and therefore most hazardous dumpsites in the world while Concern Worldwide terms it a violation of human rights (Concern Worldwide, 2015). Based on the figures in the table below, the dumpsite received over 3.5 million tonnes of waste between 1981 and 2009.

Table 8: Amount of waste disposed of at the Dandora dumpsite between 1981 and 2009[23]

Waste received by Dandora dumpsite (tonnes/year)	Amount (tonnes/year)	Percentage received over total generated
1981-2005[24]	166,667	
2006	145,000	21%
2007	187,000	28%
2008	193,000	29%
2009	222,000	33%

The fact that this disposal site is not an engineered sanitary landfill, and since it is situated close to the Nairobi river, it poses serious hazards to the environment. People living near this area, particularly women and children, are exposed to health risks such as stillbirths, low birth weight, leukaemia and other types of cancer (UNEP, 2011). In

[23] Adapted from JICA, 2010

[24] Estimates add up to 2,800,000 tonnes as reported in JICA (2010). Estimates based on analysis, by the authors, of population change, demographic distribution and existing records over the years

addition, methane gas emission and open fires from its spontaneous combustion pollute the air. The soil and the nearby Nairobi River, which flows to one of the major rivers in Kenya known as Athi River, are also contaminated by leachate from the dumpsite. A United Nations study found that about 50% of the children living in settlements near the dumpsite had respiratory conditions and higher toxic levels of heavy metals in their blood than the accepted international limits (Waste Atlas Partnership, 2014). The dumpsite is also greatly affecting the aesthetics of the surrounding areas. The ash produced from existing small-scale incinerators (usually waste from sensitive sources like hospitals) are usually disposed at this dumpsite (UNEP and CCN, 2007), which is a potential hazard to those working in the area and to nearby water bodies.

Figure 19: A snapshot of part of Dandora dumpsite[25]

The dumpsite however also acts as a source of income to over 3,000 informal waste pickers (Waste Atlas Partnership, 2014). These waste pickers, some who often reside

[25] Google Maps

in the areas near the dumpsite, collect recyclable materials from the dumpsite and sell them to formal recycling companies and dealers (Kasozi and Harro, 2010).

The city council and the national government recognise that waste-to-energy technologies have the potential to benefit the urban poor through improved energy access, improved means of solid waste disposal and increased income through collection, treatment and disposal of the waste (UNEP and CCN, 2007; National Environment Management Authority, 2015).

3.2.1 Possible options for closing the dumpsite

The International Solid Waste Association (ISWA, 2016) highlights three different methods of closing a dumpsite:

- The upgrade method that involves capping the existing waste, installing a landfill gas collection system as well as a leachate collection system. For this method to work, the dumpsite must have sufficient space adjacent to it to design and engineer a sanitary landfill for disposal of any other incoming waste.
- The in-place method that involves covering the entire dumpsite with top soil and possibly installing a gas collection system depending on the estimated gas generation volume and the type and age of the waste. This method is most commonly used in areas where there is not enough space in the dumpsite for further disposal of waste and no room for the construction of an engineered sanitary landfill, and areas looking to rehabilitate an open dump. This method seeks to reduce exposure of waste to elements such as rodents, insects and other

disease vectors, to minimise waste disturbance by the wind, to reduce bad odour, and to prevent infiltration of rainfall thus reducing leachate formation.

- The removal of waste method that involves transferring all the waste from a dumpsite into another disposal site, typically a sanitary landfill, with possible waste recovery of recyclable material. This is a costly method is not commonly practised.

This project assumes that there are currently no alternative sites suitable for waste disposal in Nairobi, that the Dandora dumpsite will continue to be used as the designated disposal site for the years to come, and that there is sufficient room in the dumpsite to construct a sanitary landfill. With this in mind, the upgrade method is selected.

4 Data Analysis

This section describes the method used to conduct an analysis on the potential energy output from waste disposed of in the Dandora dumpsite, and its possible contribution to household energy demand in Nairobi. It assumes a business as usual approach in which the solid waste management situation in Nairobi does not change and the dumpsite continues to receive the same average amount of waste during the project lifetime. The flow of analysis is broken down as below.

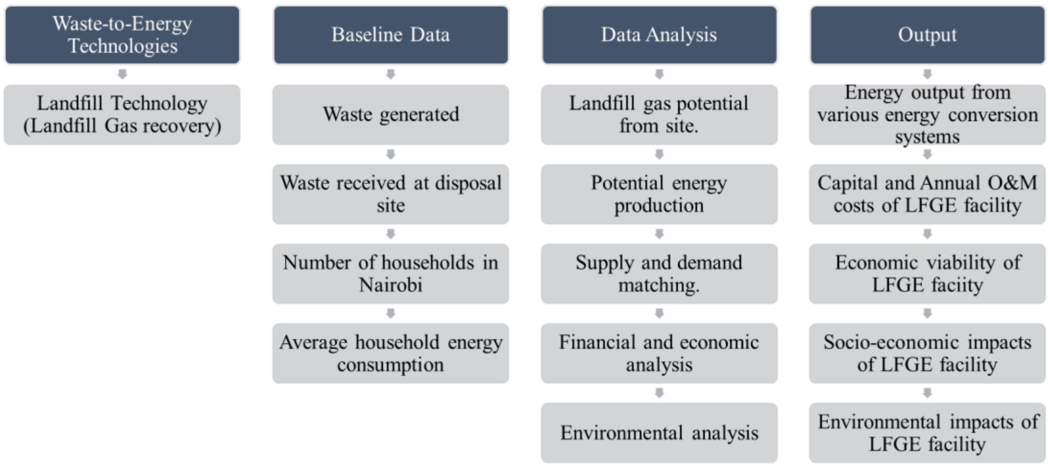


Figure 20: Outline of analysis process

4.1 Data Inputs and Data Analysis Methodologies

4.1.1 Methodology for Choice of Energy Supply for Domestic Use.

Based on the literature review ins section 2.3.3, landfill gas capture is the most promising technology for a dumpsite such as Dandora dumpsite. It is however necessary to determine its suitability for direct use by the households or for electricity production. LFG can be used to generate electricity through internal combustion engines, gas turbines or steam turbines. It can also be upgraded to cleaner fuel for cooking and space heating requirements in households.

Kasozi and Harro (2010) explain that while bio-fuel use for cooking would be the most ideal form of domestic energy supply from waste in Nairobi, it is not currently practical mainly due to its cost implications. First, the LFG would need to be cleaned and purified to meet the standards of natural gas which is almost entirely methane. Since LFG contains at least 50% of methane, the gas would need to be scrubbed to remove CO_2, water, hydrogen sulphide and other impurities present (World Bank, 2016a), then either pressurised and distributed through a gas pipeline or liquefied and compressed into cylinders as liquefied natural gas (LNG). The costs involved in purifying the LFG, pipeline distributing it per unit length, and/or pressurising it, would be very high. Second, Nairobi does not have a natural gas pipeline connecting into domestic dwellings. Nairobi residents that use gas for cooking normally have LPG cylinders. Either an entire distribution piping, metering and control system would need to be installed, or LFG compression standards would need to be created. A network would then need to be established for distributors and end-users, and strict monitoring and control systems would need to be instituted to ensure the safety of the gas pipelines or cylinders and the gas quality for use. For example, CO_2 freezes at a temperature higher than CH_4 during liquefaction while oxygen levels above 0.5% could lead to explosions (U.S. EPA, 2017b) This would also have high cost implications.

Third, the retail price of the LNG or piped LFG would need to be competitive with that of LPG for it to be marketable. The high cost of cleaning, packaging and distribution may make it more costly and therefore not marketable in a city like Nairobi (World

Bank, 2016a), unless there are incentives in place to encourage domestic users to purchase it. In addition, the demand for the gas for cooking would need to be high enough to justify the construction and operation costs. The fourth and most crucial aspect of LFG supply for domestic use would be changing the cooking behaviour of domestic users. As seen in the Nairobi background review, most households, particularly in low income areas, use kerosene and charcoal to cook. They therefore would not have the appropriate stoves and kitchen layouts to use LFG. They would need to invest in the right equipment to accommodate LFG use, which may be financially challenging. LFG use for cooking would therefore only be feasible if there is an established market in the East African region.

Electricity on the other hand is already an established source of energy in the city with infrastructure in place for transmission and distribution. It also requires minimum behaviour changes for use. In addition, there is an opportunity for decentralised generation from LFG to meet the electrical needs of the households near the disposal site and reduce pressure on the centralised generating utilities (Kasozi and Harro, 2010). It is for these reasons that this project investigates the viability of utilising LFG for electricity generation.

The analysis assumes that a sanitary landfill is already in place and that the first year of operation is 2017. Consequently, in this chapter, the Dandora dumpsite is referred to as "Dandora landfill" or, in simpler terms, "the landfill". The methodology for each level of analysis is explained further below, including input parameters, equations and tools/models.

4.1.2 Baseline Data

Due to time and resource constraints, secondary data is used for this project. Below is a summary of baseline data used throughout the analysis and its sources and justification. A more detailed account of how the data is used for the analysis can be found in the Section 4.2 below.

4.1.2.1 Baseline Data on Population and Demographics

Table 9:Nairobi household population, demographics and electricity consumption baseline data

Demographics	**Estimates**	**Notes**
Average household size	4.4 persons	Based on 2009 national census (KNBS, 2015). Household size assumed to be constant between 2009 and 2017.
Estimated % of low income population.	52%	Estimates taken from the JICA 2010 preparatory report on Nairobi's Solid Waste Management (JICA, 2010). Estimates assumed to be constant from 2010 to 2017.
Estimated % of middle income population.	35%	
Estimated % of high income population.	13%	
Nairobi Population Projections from 2009 National Census to 2017[26]		
Year	**Population**	
2010	3,144,918	2010 – 2014 projections taken from the 2015 Nairobi County Statistical Abstract (KNBS, 2015)
2011	3,351,315	
2012	3,563,473	
2013	3,781,394	
2014	4,004,400	
2015	4,216,119	2015 – 2017 projections made using the FORECAST.ETS function on Microsoft Excel[27]
2016	4,431,410	
2017	4,646,701	

[26] See Appendix G for breakdown of population according to income level.

[27] The function uses historical data to calculate or predict future values, as a continuation of historical values. It does this by utilising the exponential smoothing algorithm. More details on the function can be

Average Household Electrical Consumption		
Low-income household consumption (kWh/year)	768	Details in Section 4.2.1 below
Middle-income household consumption (kWh/year)	1,948	
High-income household consumption(kWh/year)	3,762	
Average consumption (kWh/year)	2,159	

4.1.2.2 Baseline Data on Waste Composition

Table 10: Composition of waste generated in Nairobi and corresponding weighted ratios[28]

Waste Type	Weighted Ratio (%)
Organic Waste	**82.21%**
Food and garden waste	69.69%
Paper	9.43%
Rubber and Leather	0.27%
Textiles	0.72%
Lumber and Logs	0.36%
Other organic waste	1.74%
Plastic	**9.42%**
Glass, Metal and Other	**8.37%**
Glass	3.15%
Metal	2.28%
Dirt, Ash, Stone, Sand	2.51%
Other	0.43%
TOTAL	**100.00%**

The table above indicates that MSW in Nairobi mainly consists of food and garden waste which has a high organic carbon content, making it suitable for landfill gas capture.

found on https://support.office.com/en-us/article/FORECAST-ETS-function-15389b8b-677e-4fbd-bd95-21d464333f41?ui=en-US&rs=en-US&ad=US

[28] Based on JICA (2010) estimates

4.1.2.3 <u>Baseline Data on Dandora Dumpsite</u>

Table 11: Dandora dumpsite baseline data

Parameters	Details	Notes
Total Area (ha)	46	(UNEP and CCN, 2007; JICA, 2010)
Distance from city centre (km)	7.5	(JICA, 2010)
Cumulative capacity of waste since 1981 (tonnes)	5,800,564	See Appendix G on determining waste disposed of at dumpsite.
Average waste received per day (% of total generated)	27% - 33%	(JICA, 2010; Kasozi and Harro, 2010)
Amount of organic fraction in waste (% of total disposed)	70%	Assumption based on waste composition.

4.1.3 Methodology for Analysis of Viability of LFGE in Dandora Dumpsite

As mentioned earlier, this project looks at the viability of producing electricity from landfill gas captured from the disposal site, referred to here as landfill gas to energy (LFGE) technology. Two main systems are considered: utilising internal combustion engines or using gas turbines. The analysis for potential power generation and supply follows the steps summarised below. An account of the methodologies used for each step is as detailed in the sub-sections that follow.

Table 12: Steps employed in the viability analysis of LFGE for Dandora dumpsite

Step	Detail	Purpose
1. Household average electricity consumption.	Determining how much electricity a household in Nairobi would consume for selected common household appliances.	To determine technical viability through supply-demand matching.
2. Potential LFG emission from the site.	Estimating how much LFG would be available for electricity generation.	To determine LFG utilisation per year and corresponding power generation potential for

Step	Detail	Purpose
		each electric conversion system.
3. Power Generation Potential	Estimating how much electricity from the landfill would be available for supply to domestic consumers in Nairobi.	To determine the most technically viable electricity conversion system option for Dandora dumpsite. For supply and demand matching. For Financial, economic and environmental viability analysis per conversion system.
4. Financial and socio-economic analysis.	Analysis of capital costs, operation costs, and return on investment from a LFGE plant.	To assess the overall financial and economic viability of a LFGE plant in Dandora disposal site. To assess most financially viable conversion system option to implement. To determine the social implications of the LFGE facility.
5. Environmental Analysis	Analysis of pollutants that could possibly be emitted from the LFGE facility. Analysis of environmental benefits of implementing the LFGE facility.	To determine the most environmentally friendly way to implement the LFGE plant.

4.1.3.1 <u>Household Average Electricity Consumption</u>

The end-use method is used to determine average household electricity demand in Nairobi. This method emphasises on the utilisation of electricity for various household activities such as cooking, lighting and heating (Magambo, 2010; Nzia, 2013) and therefore provides a realistic picture of household electricity demand.

Nzia (2013) explains that the end-use method depends on 2 main factors: the activity (the energy service) and the energy intensity (amount of energy used per activity). The energy demand for a certain end-use *i* is determined by

$$E_D = P_i * N_i * H_i$$

Equation 1[29]

Where:

E_D = Electrical demand of an activity/appliance (kWh)

P_i = Power rating of appliance used (kW)

N_i = Number of households using the appliance

H_i = Number of hours of use (hours)

A summation of demand from all end-uses provides the overall electrical demand across all households. From here it is possible to compute an average consumption for all households. The number of households utilising a certain appliance for an activity depends on the penetration level of the appliance per income group. This is determined by:

$$N_i = S_i * HH$$

Equation 2

[29] Adapted from (Magambo and Kiremu, 2010; Nzia, 2013)

Where

S_i = Penetration level of appliance (%)

HH = Number of households per income group.

4.1.3.2 Potential Landfill Gas (LFG) Capture from the Dumpsite.

The value of LFG for energy production is found in its methane gas (CH_4) concentration. LFG, usually produced over 30-50 years, will typically contain 45-55% of CH_4 with the rest mainly being carbon dioxide. (Mutz *et al.*, 2017). Both these gases, if not captured and utilised, have a significant contribution to global warming. The 2006 Intergovernmental Panel on Climate Change (IPCC) guidelines provides two main methods of estimating LFG produced in a landfill, namely, the mass balance method and the first order decay (FOD) method.

The mass balance method assumes that CH_4 is released within the same year that waste is disposed at the site (Froiland and Pipatti, 2006). This means that for a given year, no residual gas is carried forward to the next year. This method computes CH_4 emission as:

$$Methane\ emissions = \left(MSW_T \times MSW_F \times MCF \times DOC \times DOC_F \times F \times \frac{16}{12} - R\right) \times (1 - OX)$$

Equation 3[30]

Where:

MSW_T= Total MSW generated (Tonnes/year)

[30] Source: (Froiland and Pipatti, 2006)

MSW_F= Fraction of MSW disposed of at the disposal site (tonnes/year)

MCF= Methane correction factor (expressed as a fraction)

DOC= Degradable organic carbon (kg of carbon/ kg of solid waste)

DOC_F= Fraction of DOC dissimilated

F= Fraction of CH_4 in landfill gas

R= Recovered CH_4

$\frac{16}{12}$= Conversion of Carbon to CH_4

OX= Oxidation factor[31]

This method is simple and requires only a limited set of data. The only two figures required are 1) the amount of waste that is eventually disposed of at the disposal site (MSW_F) and 2) The amount of landfill gas recovered, where documentation is available, in which case only MSW_F is needed for areas where LFG capture is not carried out or recorded. The IPCC guidelines provide default values as well as recommendations for the other terms of the equation for different solid waste management practices and different climatic conditions (Froiland and Pipatti, 2006). While this method is simple, it does not include a time factor and therefore does not account for variations in waste composition and amount over time, which affect CH_4 production (Froiland and Pipatti, 2006; Dowling *et al.*, 2012). It can only be used in cases where the amount and composition of the waste disposed is constant throughout, which is not possible in an urban area, due to the dynamic nature of population growth,

[31] CH_4 is recovered is usually less than the amount produced. Some of it is oxidised at the surface. This is accounted for by the oxidation factor.

shifts in income levels change in consumption behaviour per capita over time and seasonal variations of waste composition.

The First Order Decay (FOD) method assumes that CH_4 is formed slowly over the years from the degradable organic carbon (DOC). This means that CH_4 will continue to be formed if some DOC is present in the waste. The amount produced reduces as the fraction of DOC continues to be consumed by the bacteria in the waste (Coburn *et al.*, 2006). The method introduces a time factor to the decay of the waste, therefore providing more realistic results of CH_4 production from disposed waste. For a year, the amount of CH4 emissions can be computed as:

$$CH_4\ Emissions = \left[\sum_x CH_4\ generated_{x,T} - R_T\right].(1 - OX_T)$$

Equation 4[32]

Where:

T	= inventory year
CH_4 emissions	= CH_4 emitted in year T (tonnes)
X	= waste type/material
R_T	= CH4 recovered in year T (tonnes)
OX_T	= oxidation factor in year T

The general First Order Decay equation for landfill gas emissions is given by:

[32] Source: (Coburn *et al.*, 2006)

$$Q = L_0 R(e^{-kc} - e^{-kt})$$

Equation 5[33]

Where:

Q = methane generated in a specific year (m^3/year)

L_0 = methane generation potential (m^3/Mg[34] of waste)

R = average amount of waste received by disposal site per year during its active life (Mg/year)

k = a constant of methane generation rate ($year^{-1}$)

c = time since the disposal site was closed (years)

t = time since the disposal site was opened (years)

For this project, the FOD method is used to estimate potential methane emissions from landfill gas captured from the disposal site. The United States' Environmental Protection Agency's (EPA) Landfill Gas Emissions Model (LandGEM) is used to estimate potential LFG available from the dumpsite, since it uses the FOD method, and because it is internationally recognised and has been used in various feasibility studies in developing countries including Africa (Wilfried Nguz Mbav *et al.*, 2010; Dowling *et al.*, 2012; Mbav, Chowdhury and Chowdhury, 2012; Kumar *et al.*, 2014; Majdinasab, Zhang and Yuan, 2017). LandGEM uses a Microsoft Excel interface to estimate emissions from landfills. These emissions include landfill gas, CH_4, CO_2 and non-methane organic compounds (Alexander, Burklin and Singleton, 2005). The model

[33] Sources: (Froiland and Pipatti, 2006; Dowling *et al.*, 2012)
[34] 1 Mg = 1 metric tonne this project uses metric tonnes as the main unit of weight.

utilises the following key FOD equation in its analysis, which is similar to the IPCC guideline's equation:

$$Q = \sum_{i=1}^{n} \sum_{j=0.1}^{1} kL_0 \left(\frac{M_i}{10}\right) e^{-kt_{i,j}}$$

Equation 6[35]

Where:

Q = annual methane generation in a specific year i

i = one-year time increment

n = number of years between the reference year and the year the landfill opened

j = 0.1-year time increment

k = a constant of methane generation rate ($year^{-1}$)

L_0 = methane generation potential (m3/ Mg of waste)

M_i = mass of waste received by the disposal site in year i (Mg)

t_{ij} = age of the j^{th} section of waste M_i accepted in year i (decimal years e.g. 2.1 years).

The model provides some guidance on some default values such as landfill capacity, methane generation constant (k) and methane generation potential (L_0), but in the context of the United States' regulations and requirements. It however allows for input of user defined values, allowing users outside of the U.S. to use the model. With this regard, this project uses the Tier 1 default values (for countries such as Kenya that do

[35] Source (Alexander, Burklin and Singleton, 2005)

not have good documentation of waste management practice) suggested by the 2006 IPCC guidelines to get results that better reflect the nature of Dandora dumpsite and the MSW management practice in Nairobi.

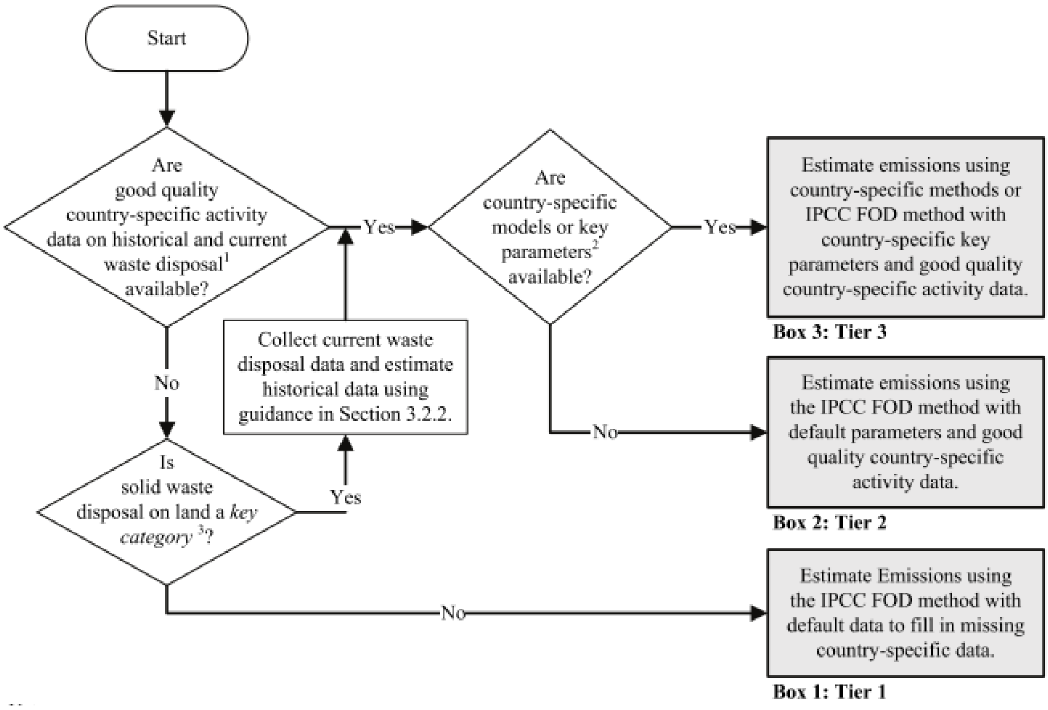


Figure 21: IPCC flow chart for choice of default values to use per Tier[36]

The table below provides a summary of inputs used for LandGEM.

Table 13: Input parameters used in LandGEM

Parameters	Values	Notes
Landfill Open Year	1981	Year that Dandora dumpsite was opened.
Landfill Current Year	2021	The landfill allowed to receive waste for 40 years from year of opening.
Methane generation rate (k)	0.065	From IPCC 2006 guidelines (Coburn *et al.*, 2006, p. 3.17). Nairobi taken to have dry tropical climate and waste handled taken to be bulk.

[36] (Coburn *et al.*, 2006)

Methane generation potential (L0)	100	IPCC 2006 guideline recommendations between below 100m^3 and 200m (Froiland and Pipatti, 2006)
Methane content (% by volume)	50	Same default value used in LandGEM
Waste density (tonnes/m^3)	0.3	As per JICA (2010) report
Average dumpsite capacity (m^3)	1,820,000	As per JICA (2010) report: total area is 46ha (460,000m^2), of which 440,000m^2 is a shallow landfill of average 3m depth and the remaining 20,000m^2 is an old quarry of average 25m depth. This brings the total capacity to [(20,000x25) + (440,000x3)] = 1,820,000m^3
Waste Design Capacity (tonnes)	655,200	(Average dumpsite capacity x waste density) + 20% allowance.
Average Annual Temperature (^{0}C)	19	From UNEP and CCN 2007 report
Average Annual Rainfall (mm)	120	

4.1.3.3 Power Generation Potential and Financial Analysis.

The methodology used by the LFGcost-Web model is adopted to estimate the installed capacity of LFGE systems and how much it would cost to construct and operate them. This model, developed by the United States EPA for the Landfill Methane Outreach Program (LMOP), is a Microsoft Excel based tool designed to help landfill owners, operators, policy makers and other stakeholders estimate costs of running a sanitary landfill as well as the cost of utilising the LFG. The LFGcost-Web version 3.2 model, updated in May 2017 (which is the version referenced for this analysis) covers an extensive range of LFG utilisation options which are: collection and flare systems, direct use (e.g. for boilers), compressed natural gas production, leachate evaporation, electricity generation (from gas turbines, internal combustion engines, microturbines and combined heat and power application options), boiler retrofits and high heat processing units (U.S. EPA, 2017a).

The model utilises the FOD Equation 6 to estimate LFG produced and utilised. It is therefore possible to transfer LFG emission outputs from LandGEM for use in the LFGcost-Web model. It also offers a good range of electricity generation options to analyse.

Standard turbine-generator sets	Greater than 3 MW
Standard reciprocating engine-generator sets	800 kW and greater
Microturbine-generator sets	30 to 750 kW
Small reciprocating engine-generator sets	100 kW to 1 MW
CHP reciprocating engine-generator sets	800 kW and greater
CHP turbine-generator sets	Greater than 3 MW
CHP microturbine-generator sets	30 to 300 kW

Figure 22 Range of electricity generation options analysed in LFGcost-Web model[37]

The model has the following positives:

- It is easy to navigate through and uses simple methods of computation.
- It provides a wide range of LFG utilisation options for cost analysis and therefore allowing users to analyse various LFG utilisation scenarios.
- It is updated regularly, with default values being updated to reflect the most recent LFG market analysis in the U.S.
- It comes with a user's manual which provides further guidance on the equations, assumptions and terms used in the model.

The model however has some drawbacks in the context of this project's case study:

[37] Extracted from the LFGcost-Web model.

- This model is designed for use by stakeholders in the U.S only and therefore the allowance for customising parameters for used outside the U.S, for example changing units of measurements from imperial units to metric units, is limited. It also contains many features, such as credits and taxes, that may only apply to the U.S and not to other countries.
- Since this model is designed to analyse a wide range of LFG utilisation options, it may contain too much information for users looking to analyse a specific LFG use rather than a wider range of uses, e.g. electricity generation through ICEs or gas turbines as is the case in this project.
- Most default assumptions and features such as electricity prices and interest rates are set for use in the U.S. They would therefore not apply to a Kenyan setting since electricity prices and interest rates are higher.
- A user would need to save a different file each time they analysed different scenarios of the same technology. This would make comparisons challenging.
- The model is designed to analyse projects with a lifetime of 10 to 15 years. It is therefore not applicable to this case study whose lifetime is 20 years.

To deal with these drawbacks, a Microsoft Excel workbook is developed based on the LFGcost-Web model methodology, but with adjustments to fit the case study's criteria. The workbook utilises the same technical and financial equations used in the LFGcost-Web model, but with reference to the Kenyan context and only for ICE and gas turbine systems. Inputs and key calculations used are as below. All imperial units of measure are converted into metric units of measure.

Table 14: Input parameters for technical, financial and economic analysis of a LFGE plant in Dandora disposal site.

Parameter	Values/Equation	Notes/Reference
LFG Utilisation in LFGE Plant		
LFG produced		Outputs per year, transferred from LandGEM model.
Actual LFG utilised (m^3/year)	$LFG\ emission(\frac{m^3}{year}) \times collection\ efficiency\ \times availability\ factor$	70% assumed collection efficiency [38] 90% assumed availability factor[39]
Power Generation Potential		
Project lifetime (years)	• 20 years	(Mbav, Chowdhury and Chowdhury, 2012)
Year of construction	• 2016	
First year of operation	• 2017	
System operating schedule (h)	• 7,884 hours	90% of 8760 hours in a year.
Electricity conversion systems	• Standard internal combustion engines (800kW and above) • Standard gas turbines (3,000kW and above)	LFGcost-Web has no provisions for lower gas turbine capacities. No literature was found for costs and technical requirements for smaller gas turbines.
Parasitic loss efficiency	• 93% for ICEs • 88% for gas turbines	LFGcost-Web guidelines (U.S. EPA, 2017a)

[38] Can be between 65% and 85% (Ouedraogo, 2005; Mutz *et al.*, 2017)
[39] LFGcost-Web default value is 93%. 90% assumed for Nairobi to account for technical inefficiencies and irregularities in domestic consumption.

Parameter	Values/Equation	Notes/Reference
		2% and 6% losses from the ICEs and turbines respectively (Mbav, Chowdhury and Chowdhury, 2012). The remaining losses attributed to compression, treatment and interconnecting systems.
LFG lower heating value (kJ/m^3)	• 16,800 kJ/m^3	(Ouedraogo, 2005)
Net electricity generated per year (kWh)	$\left(\frac{LFG\ heating\ value(\frac{kJ}{m^3})}{Fuel\ use\ rate(\frac{kJ}{kWh})}\right) \times Parasitic\ loss\ efficiency \times actual\ LFG\ utilised(\frac{m^3}{year})$	(U.S. EPA, 2017a)
Fuel use rate (kJ/kWh generated)	• 11,869 kJ/kWh for ICEs • 13,716 kJ/kWh for gas turbines	Requirements for the conversion systems selected (U.S. EPA, 2017a). Rates converted from BTU/kWh to kJ/kWh.
Installed capacity (kW)	$\frac{(Maximum\ net\ electricity\ generated\ over\ the\ projects\ lifetime(kWh))}{system\ operating\ schedule\ (h) \times parasitic\ loss\ efficiency}$	

Parameter	Values/Equation	Notes/Reference
Number of potential customers served.		Outputs for both ICE and gas turbine systems are based on average household electricity consumption of 2,702kWh/year, which translates to about 225.2kWh per month.
Financial and Economic Analysis		
Loan lifetime (years)	• 10 years	LFGcost-Web model assumption.
Project ownership options	• Fully owned by a private company • Fully owned by the Nairobi City Council (the municipal council)	General assumptions made for analysis of public sector vs private sector project financing.
Electricity sales arrangement	• Direct sale to customers • Sale to the national grid through a Feed-in Tariff (FiT)	Municipal owned facilities only sell directly to the customers. Privately owned facilities can choose between direct sale to customers and FiT arrangements. Unit electricity prices for each option are based on existing policy schedules (Regulus Limited, no date; Ministry of Energy, 2012; Energy Regulatory Commission, 2013)
Project financing method	• Sale of electricity generated • Municipal bonds for municipal owned projects (for capital costs) • Commercial loans for privately owned projects (for capital costs)	Debt financing method selected for the analysis for simplicity.

Parameter	Values/Equation	Notes/Reference
		The analysis does not account for any equity, subsidies, grants, super-funds or off-sets available as sources of financing or revenue.
Electricity prices ($/kWh)	• 0.1 $/kWh FiT for capacities between 500kW and 10,000kW[40] • 0.2 $/kWh for direct sale to domestic consumers between 51kWh and 1,500kWh consumption.[41]	
Key financial indicators analysed	• Net present value, NPV ($) • Simple payback period (years) • Break even (years) • Internal rate of return, IRR (%)	To determine the most financially viable option in terms of privately owned vs municipal owned and direct sale vs FiT arrangements (for privately owned plants). Equations based on guidance from the LFGcost-Web model user's manual (U.S. EPA, 2017a)

[40] (Ministry of Energy, 2012)

[41] Based on the 2013 schedule of tariffs for electricity consumption in Kenya(Energy Regulatory Commission, 2013). Note, surcharges vary from month to month, therefore January 2017 electricity prices used (Regulus Limited, no date)

4.2 Analysis Outputs

4.2.1 Technical Analysis

4.2.1.1 Household Average Electricity Consumption

Not enough data exists either in published literature or official energy supply sources in Nairobi to develop a comprehensive load profile for typical households in city. It is worth noting that Kenya is still in the process of standardising power ratings of electrical appliances and setting energy efficiency policies for power utilities and consumers (IEA, 2014). This section therefore attempts to develop a general outline of energy consumption of typical households in Nairobi as per their income group. The 2 main sources of information used are reports by Magambo (2010) and Nzia (2013) as shown in Appendix F . These two accounts:

- are the most recent literature that could be found on household energy use in Nairobi,
- analyse electrical consumption as a measure of income,
- provide a good record of actual power ratings of electrical appliances used in Nairobi households as well as penetration levels of these appliances per income group, and
- adjust average consumption based on actual consumption

For this project, 6 major end-uses are considered as shown in Table 15 below, because they are found to be the most common activities across all household income levels.

Table 15: End-use considerations for household energy demand calculations in Nairobi

End-Use	Appliances
Lighting	Incandescent lamps, compact fluorescent lamps
Cooking	Electric cookers
Water Heating	Instant shower heaters, immersion water heaters, electric kettles
Refrigeration	Refrigerators
Entertainment	Radios, televisions, mobile phones, home theatre systems, DVD players, PCs
Laundry	Ironing boxes

Table 16 below provides general information on number of rooms in a typical house in Nairobi per income level, based on Magambo's (2010) description of typical middle-class houses in Nairobi and from personal observations.

Table 16: Typical number of rooms per house per income level in Nairobi

Room	Low Income	Middle Income	High Income
Living room	1	1	1
Kitchen	1	1	1
Pantry/store	0	1	1
Dining area	0	1	1
Bedroom	1	2	4
Toilet and Bathroom	1	1	2
Guest room (SQ)	0	0	1
Garage	0	1	1
Corridor	1	1	2
Total	**5**	**9**	**14**

This information is then used to estimate number of electrical appliances required per room for each category highlighted in Table 15 above.

Table 17 below provides details of average use of selected electrical appliances in a typical household in Nairobi per year. Details of load ratings and average use in a day/week/year can be found in Appendix F .

Table 17: Average use of household electrical appliances per year

	Equipment	**Average Use per Year (kWh)**
Lighting	Incandescent lamps	45.50
	CFLs	36.40
Cooking	Electric cookers	309.40
Water heating	Immersion heaters	136.50
	Instant shower heaters	955.50
	Electric kettles	136.50
Refrigeration	Large refrigetators	500.00
	Medium refrigerators	250.00
	Small refrigerators	90.00
Laundry	Iron boxes	195.00
Entertainment	Mobile phone chargers	1.82
	Television sets	145.60
	DVD players	14.56
	Music systems	76.44
	Desktop computer	145.60
	Laptops	36.40

Using the figures from the tables above, and the penetration levels from Nzia's (2013) report as a guide to determine which appliances or equipment are most commonly used per income group, average household electricity consumption per income level can then be determined. Results from the analysis (see Appendix G), household electrical demand as per the selected end-uses is 788kWh/year for low-income households, 2,877kWh/year for middle-income households and 4,441kWh/year for high-income households, which brings average electrical demand across all income groups to 2,702kWh/household/year.

Some assumptions are made in computing these figures:

1. The same power rating is used for each appliance across all income levels.

2. All households require only one light bulb per room.
3. The number of mobile phone chargers increase by 1 as the income level increases, to indicate an increase in the number of mobile phones per household. It is therefore assumed that each low-income household has 1 mobile phone, each middle-income household has 2 mobile phones and each high-income household has 3 mobile phones.
4. Television sets, desktop computers and laptops are considered luxury items and therefore only 1 appliance for each household in the low- and middle-income houses, and 2 in high-income houses are considered. It is however possible that some middle-income and high-income households would typically have more, depending on the household size.
5. For equipment with competing services (e.g. immersion heater and instant shower heater, refrigerators and lighting), the one with the higher penetration percentage is selected for the household as it would be more popular in that income group. The others are then put as zero. In a case where there is a 50% penetration for each appliance, it is assumed that each household will have an equal number of each appliance, for example, the incandescent and compact fluorescent lights (CFL) in middle-income households.
6. Any appliance with 10% or less penetration level is put as zero since it is not common in that income group.

4.2.1.2 Landfill Gas Capture for Electricity Generation

When LandGEM is prompted to calculate a year of landfill closure, the initial outputs from waste disposed of at the dumpsite between 1981 and 2017 show that the dumpsite should have been closed by the year 2001, after which no more waste is received by the landfill. This is because the model computes the waste closure year from the waste design capacity, the waste acceptance rates entered per year and the opening year entered.

Since this input does not provide an output for the 2017, the year of landfill closure is set to 2021 to allow for use of the landfill for 40 years[42]. With this change, the model assumes that waste received in the disposal site between 2018 and 2021 remains the same as the last entry of 2017 (see Appendix H for input figures used for waste disposed in the disposal site).

INPUT REVIEW **Landfill Name or Identifier:** Dandora Dumpsite

LANDFILL CHARACTERISTICS		
Landfill Open Year	**1981**	
Landfill Closure Year (with 80-year limit)	**2021**	
Actual Closure Year (without limit)	***2021***	
Have Model Calculate Closure Year?	**No**	
Waste Design Capacity	**655,200**	*megagrams*
MODEL PARAMETERS		
Methane Generation Rate, k	**0.065**	*$year^{-1}$*
Potential Methane Generation Capacity, L_o	**100**	*m^3/Mg*
NMOC Concentration	**4,000**	*ppmv as hexane*
Methane Content	**50**	*% by volume*
GASES / POLLUTANTS SELECTED		
Gas / Pollutant #1:	**Total landfill gas**	
Gas / Pollutant #2:	**Methane**	
Gas / Pollutant #3:	**Carbon dioxide**	
Gas / Pollutant #4:	**NMOC**	

Figure 23: Revised input parameters on LandGEM

It is also worth noting that the LandGEM model assumes that no LFG is produced during the year of opening of the landfill (see Appendix I). This could be because there is a delay time between waste disposal and full production of CH_4. A six month to one

[42] From (Mutz *et al.*, 2017), landfill gas can be produced in a site for 30-50 years.

year grace period from opening of the landfill is often allowed to account for the various stages of decomposition detailed in the literature review section (Coburn *et al.*, 2006).

From the model, the disposal site would continue to produce LFG up to the year 2121, reaching peak production in 2021 after which LFG production decreases since no more waste is disposed of at the site.

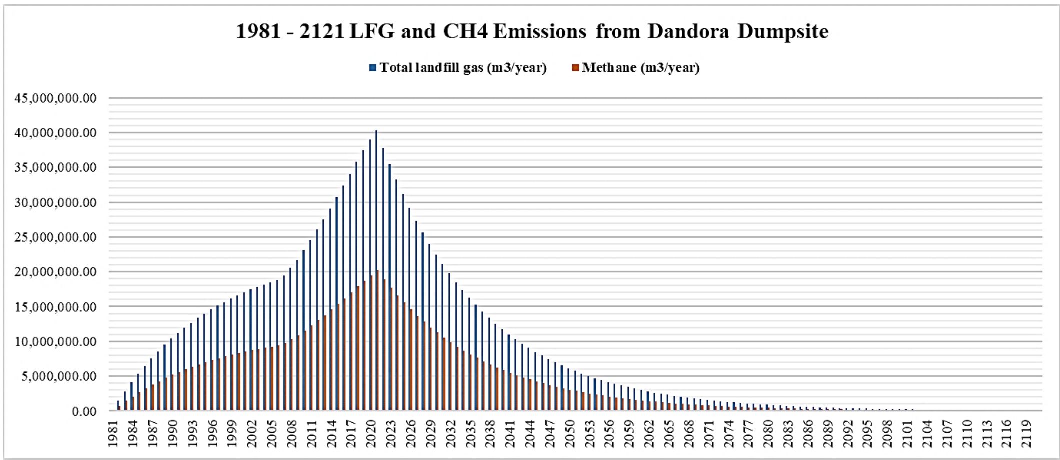


Figure 24: LandGEM results of LFG production from Dandora

The LFGE project is assumed to generate electricity for 20 years from 2017. The amount of power produced per year will depend on the amount of LFG collected at the site, which depends on the amount of LFG emissions during this period.

4.2.1.3 <u>Power Generation Potential from LFG Captured</u>

The next step is to design the LFGE facility by determining the amount of LFG that can be utilised for electricity generation, and the subsequent installed capacity of the energy conversion systems to be utilised. This step is carried out using the Microsoft Excel workbook created, based on the LFGcost-Web version 3.2 model methodology.

An LFGE plant/facility/project can be designed based on minimum, average or maximum gas flow rate. The flow rates considered help to determine the size of the conversion system to use since LFG flow rates change with time and with waste used (U.S. EPA, 2017b). It is also a key factor to consider when planning for any future expansion of the utility. The LFG collection facility for this case study is designed based on average flow rate of LFG, which is normalised over the course of the project lifetime. This allows for a steadier flow of gas over the project's life and leaves room for expansion should the municipal council or project developer choose to do so.

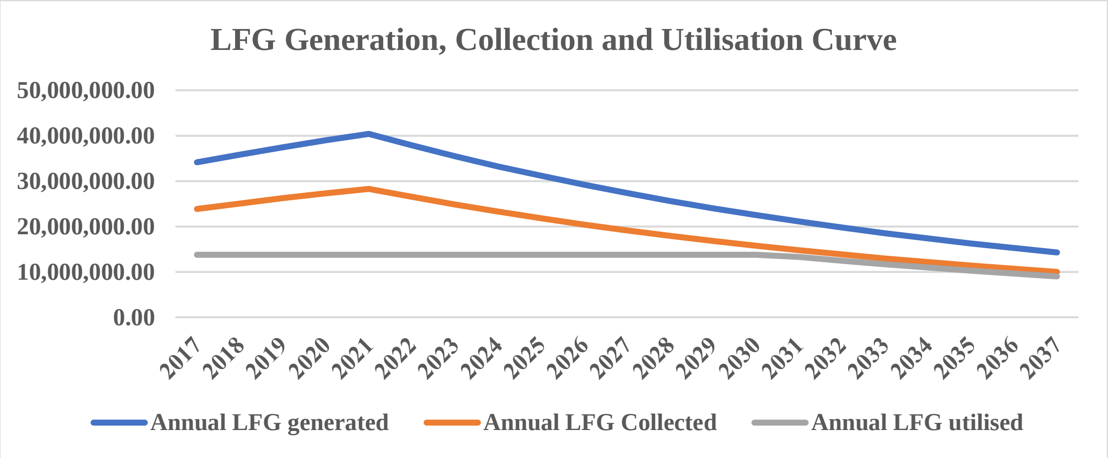


Figure 25: LFG generation, collection and utilisation curve

As can be seen from the graph above, not all the LFG produced is utilised. A 70%[43] collection efficiency and 90% availability factor is applied to account for problems with collection equipment for the former and downtime due to scheduled maintenance, problems with energy production equipment or irregularities in consumption for the latter (U.S. EPA, 2017a).

The actual LFG utilised is determined by

[43] Collection efficiency can range between 65% and 85% (Ouedraogo, 2005; Mutz *et al.*, 2017). The LFGcost-Web model uses a collection efficiency of 85%.

$$LFG_i = LFG_{e,i} \times \eta_c \times AF$$

Equation 7

Where:

LFG_i= Actual LFG utilised in year i (m^3)

LFG_{ei}= LFG emissions from landfill in year i (m^3)

η_c= collection efficiency (%)

AF= Availability factor (%)

Once LFG utilised for each year is calculated, the next step is to determine the installation capacities of viable energy conversion systems. Three conversion systems are considered: internal combustion engines (ICEs), gas turbines, and microturbines. Each system requires a specific standard gas flow rate for efficient operation. The table below provides flow requirements for the three different systems.

Table 18: Gas flow requirements for different energy systems for LFGE utilities[44].

System	Capacity Range	LFG flow requirements (m3/h)	Notes
ICEs	800kW – 3MW	510 – 1,870 m^3/h at 50% methane content.	Can be used for a wide range or electricity output. It is possible to align multiple ICEs for projects larger than 3MW.
Gas turbines	1MW->10MW	At least 2,200m^3/h to produce at least 3MW of power	More economical for large scale utilities.
Microturbines	30kW – 250kW	30 – 340m^3/h per microturbine.	Suitable for small scale projects that with < 1MW capacity.

[44] (U.S. EPA and ISWA, 2012; U.S. EPA, 2017b)

ICE and gas turbine systems are considered for this case study since gas utilisation rates are estimated to range between 1,026m^3/h and 1,571m^3/h from the analysis. The potential installed capacity of each system is then computed using the equation below.

$$P_s = \frac{E_{max}}{OS \times \eta_p}$$

Equation 8[45]

Where:

P_s= ICE or gas turbine capacity (kW)

E_{max}= Maximum net electricity generated over the project lifetime from the normalised average LFG utilised (kWh).

OS= System operating schedule, which is AF x 8760 hours in a year (h)

η_p= Parasitic loss efficiency (%)

The net electricity generated per year is determined by the equation highlighted in Table 14 above. The following is a summary of inputs used and outputs from the analysis for Dandora landfill:

Table 19: Summary of inputs and outputs from analysis of potential power output from Dandora landfill

Parameters	ICE	Gas Turbine	Notes
Inputs			
System operating schedule	7,884 hours		70% of 860 hours in a year
LFG lower heating value	16,800kJ/m^3		

[45] Based in LFGcost-Web model methodology

Parameters	ICE	Gas Turbine	Notes
Average domestic consumption in Nairobi	2,702 kWh/year 225 kWh/month		From analysis outputs in section 4.1.3.1 above.
Fuel use rate	11,869 kJ/kWh	13,716 kJ/kWh	Based on LFGcost-Web model guidelines.
Parasitic loss efficiency	93%	88%	(U.S. EPA, 2017b) 2% loss attributed to ICEs and 6% to gas turbines (Mbav, Chowdhury and Chowdhury, 2012). Other losses distributed among the compression, treatment and interconnection systems.
Outputs			
System Capacity	2,470 kW	2,138 kW	
Approximate number of households serviced.	7,207	6,237	

The installed capacities of ICE and gas turbine systems translate to 19.47GWh/year and 16.85GWh/year respectively for a 90% availability factor. This would be enough to meet the demand of at least 7,207 households from ICE system supply and at least 6,237 households from gas turbine system supply, assuming an average electricity demand of 2,702kWh/year per household.

As mentioned in section 3.2 above, Dandora dumpsite is located close to Korogocho, one of Nairobi's slums. The slum is home to approximately 12,900 households (UN-HABITAT, 2010b), about 34.8% of whom do not have access to electricity (KNBS and

SID, 2013). This translates to about 8,400 households. Assuming an average household consumption of 2,702kWh a year, the electricity generated would be enough to service at least 86% of the 8,400 households from an ICE system and at least 74% of the 8,400 households from a gas turbine system. Considering that Korogocho is a low-income area, demand is likely to be closer to or within the low-income demand category of 788kWh/year, in which case up to twice number of households in Korogocho could potentially be serviced. This could therefore leave room for supply to small scale businesses in the area or similar households in neighbouring low-income areas.

4.2.2 Financial and Economic Analysis

For a LFGE facility to be considered financially viable, there must be demand for the energy produced and the product must be sold at a competitive price compared to other energy resources (U.S. EPA and ISWA, 2012). This case study assumes that there is demand for electricity in areas surrounding Dandora dumpsite, such as Korogocho slum.

Financial viability is assessed for two types of LFGE facilities, based on forms of ownership: a landfill fully owned and operated by the municipal council and a landfill fully owned and operated by a private company. For both cases, the LFGE land is assumed to belong to the municipal council. In addition, the main source of financing for capital costs is taken to be debt either through municipal bonds or through commercial debt, depending on the nature of LFGE ownership. The table below provides a summary of project ownership, financing and electricity sales arrangements considered for analysis.

Table 20: Electricity sales and financing arrangements for LFGE project at Dandora dumpsite.

Parameter	**Municipal Owned**	**Privately Owned**	**Notes**
Electricity sale arrangements	Direct sale to consumers.	Direct sale to consumers. Sale to national grid through feed-in tariff (FiT)	Electricity prices assumed to follow the guidelines of Kenya's 2013 schedule of tariffs for direct sale and revised 2012 FiT policy or sale to the national grid.
Financing options	Municipal bonds	Commercial loan	

The financial analysis carried out for the case study follows same principles similar to those of the LFGcost-Web model, but with adjustments for the Kenyan environment. The analysis considers debt financing and sale of electricity as the only 2 sources of financing available for the project owners. The following key indicators and assumptions are made for the case study.

Table 21: Inputs and assumptions made for financial analysis of LFGE project options in Dandora[46]

Feature	**LFGcost-Web model value**	**Case study value**	**Notes**
Key Indicators Analysed			
• Net Present Value (NPV) in \$ • Simple payback period in years • Years to achieve break even • Internal rate of return (IRR) as a percentage			
Financial Assumptions Made			
Electricity prices (\$/kWh)	0.06	0.20 (direct sale) 0.1 (FiT)	Prices determined from Kenya electricity tariff policies.
Annual electricity price escalation rates (%)	1	2	Assumption based on analysis of annual electricity price changes from 2010 to 2017.

[46] LFGcost-Web model values taken from the default values used in the model (U.S. EPA, 2017a)

Feature	LFGcost-Web model value	Case study value	Notes
Loan lifetime (years)	10	10	Typical loan period for large scale projects.
Loan interest rate (%)	6%	10%	General assumption that loan interest rates in Kenya will be higher than in the U.S due to the comparative economic status of the country.
Down payment for loan	20% (commercial) 0% (municipal bond)	Same as LFGcost-Web model value	
Discount rate (cost of capital) (%)	8% (commercial loan) 5% (municipal bond)	10% (commercial loan) 5% (municipal bond)	(IRENA, 2012)
Marginal corporate tax rate (%)	35% (privately owned) 0% (municipal owned)	35% (privately owned) 0% (municipal owned)	Rates assumed to be the same for companies in both countries.
General inflation rate (%)	2.5%	2.9%	Based on 2017 global estimate made in the latest Kenya economic survey (KNBS, 2017).
Equipment inflation rate (%)	2%	2%	Assumed to be the same for both countries.

The first step in the analysis is to determine the respective capital and annual costs of both an ICE system and a gas turbine system. Costs calculated include direct costs of purchasing equipment, costs related to design, engineering and administration, costs associated with preliminary assessments and surveys, and decommissioning costs (U.S. EPA, 2017a). They do not cover the cost of treating the waste to make it appropriate for landfilling, as well as transmission and distribution of the electricity generated to the consumers. They also do not cover any land leases in cases where the private company owns the LFGE facility. The analysis shows that the total capital cost of an ICE system is $4,840,192 and the annual cost is 0.025 $/kWh generated. The respective costs of a gas turbine are $5,601,914 and 0.014$/kWh.

Next, an analysis of the cash flows, NPV, payback period, break-even point and IRR is carried out for each scenario highlighted in Table 20 above. The following results are achieved.

Table 22: Outputs from key financial and economic indicators for different LFGE project options in Dandora landfill[47]

LFGE Project	NPV ($)	Payback period (years)	Break Even point (years)	IRR (%)
ICE – Privately owned (direct sale)	$262,870	0	1	98%
ICE – Privately owned (FiT)	$112,635	4	6	27%
ICE – Municipal owned	$1,054,879	0	1	407%
Gas turbine – Privately owned (direct sale)	$232,881	2	1	65%
Gas turbine – Privately owned (FiT)	$109,860	7	1	19%
Gas turbine – Municipal owned	$921,143	0	1	284%

Next, a socio-economic impact analysis of implementing the LFGE project in Dandora area is carried out. This is mainly through a literature review of the social-economic benefits achieved in areas where LFGE projects have been successfully implemented.

[47] Payback period is the amount of time that would take the project to pay back capital investment, while the break-even point represents the number of years it would take for the project to start making profit, where costs equal revenues. NPV is the present value of current and future cash flows (costs minus revenues) over the project's lifetime. Higher NPV values are more attractive.

The United States LFGE project development handbook (U.S. EPA, 2017b) highlights the following socio-economic benefits based on LFGE projects implemented in the United States:

Table 23: Socio-economic benefits of implementing a landfill gas to energy project in an urban area

For the owner(s)
• Revenue from sale of electricity • Revenues from carbon trading (depending on the arrangement of ownership)
For the end users
• Availability of reliable electricity supply at affordable rates.
For the surrounding community
• Improved living conditions due to reduced emissions, odour elimination and leachate management. • Job creation in LFGE facilities e.g. during construction of LFGE facility, in sorting stations, waste compacting, gas collection and utility operation. • Enhancement of the recycling market due to better waste handling techniques such as segregation of MSW before landfilling. • Increased economic activities as a ripple effect of the LFGE facility e.g. manufacture and sale of locally sourced construction materials and spare parts for the facility, food and lodging businesses for the workers at the LFGE site, emergence of new businesses as a result of increased income levels of the community, and an increase in small scale businesses in the areas supplied by electricity from the LFGE facility.

4.2.3 Environmental Analysis

This section provides an outline of potential emissions from LFGE implementation, their sources and possible ways of minimising or controlling them. The information is mainly based on review of standards and guidelines provided by various environmental regulatory bodies such as the U.S. EPA and the Scottish Environmental Protection Agency (SEPA).

LFGE projects have the potential to reduce the amount of CH_4 emitted into the atmosphere. The United States Environmental Protection Agency highlights the following environmental benefits of LFGE projects (U.S. EPA, 2017b):

- Direct GHG reduction through the collection of 60-90% of methane generated, and the conversion of the methane to CO_2 and water when utilised for electricity or heat generation.
- Replacing fossil fuel use (natural gas, coal etc.) for the same level of energy requirements, thereby indirectly reducing GHG emissions from fossil fuels.
- Improvement of local air quality. For example, the destruction or conversion of non-methane organic compounds present in the LFG during collection and use, or the emission avoidance of air pollutants (sulphur dioxide, nitrogen oxide and particulate matter) that would have been emitted if fossil fuels were used.
- Reduction of odours from accumulation of sulphides in the disposed MSW.
- Safety improvement by minimising migration of gas to air pockets that could spontaneously explode.

If not properly managed and monitored, LFGE facilities could lead to some emissions, though their concentrations tend to be much lower than those from raw landfill gas from an open dump. The Scottish Environmental Protection Agency (SEPA and Environmental Agency, 2004) identifies 2 main types of emissions from LFGE facilities which are point source emissions and utilisation emissions, discussed in the sections below.

4.2.3.1 Point Source Emissions

These are emissions that escape from leakages in collection systems and leachate produced in the landfill. They mainly consist of methane, carbon dioxide and non-methane organic compounds present in the collected LFG. The figure below shows possible emissions from leakages in the Dandora dumpsite.

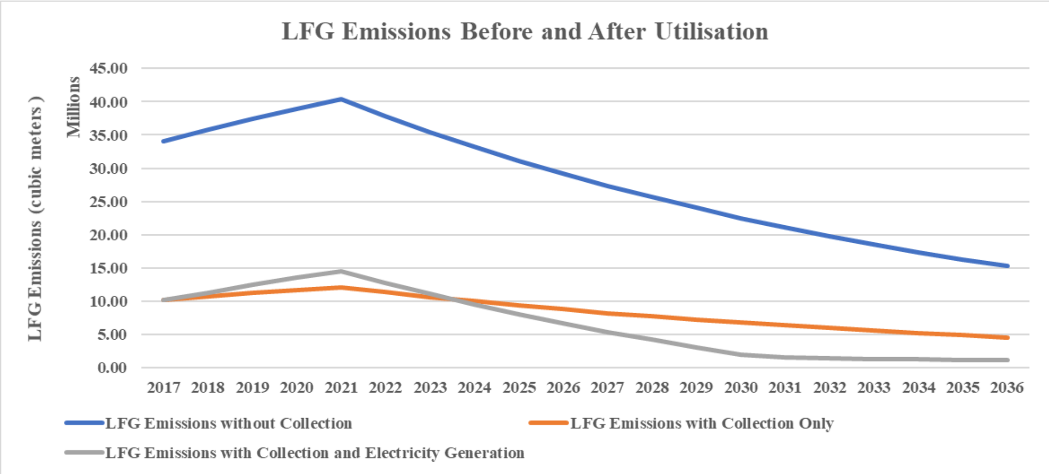


Figure 26: Estimates of LFG emissions from Dandora LFGE facility due to leakages and collection inefficiencies.

The most significant emissions from the LFG are methane and carbon dioxide. Methane in particular has 25 times more global warming potential than carbon dioxide over a 100 year period (IPCC, 2007; U.S. EPA, 2017b). With an approximate life span of 12 years (U.S. EPA, 2017b), this gas is potent and can have substantial impacts on the environment and air quality The best way to minimise these types of emissions is through regular monitoring and routine maintenance.

4.2.3.2 Utilisation Emissions

These emissions are produced from the utilisation of LFG for energy production or from flaring of the collected LFG. During the combustion process, the LFG is used as the fuel and about 21% of oxygen, usually from air, is injected into the system to oxidise it (SEPA and Environmental Agency, 2004). Lower concentrations of oxygen could lead to incomplete combustion of the LFG resulting in formation of several pollutants. The table below provides a summary of potential emissions from electricity generation through the combustion of LFG, the sources, potential effects on the environment and equipment and possible methods of minimisation.

Table 24:Utilisation Emissions from LFGE facilities and potential effects[48].

Emissions	Sources	Effects	Potential minimisation
Carbon dioxide (CO_2)	Product of complete combustion of LFG (lower concentrations than in raw LFG).	A GHG contributing to global warming if in large concentrations.	Membrane separation or molecular sieve (U.S. EPA, 2017b) Emissions too low to significantly affect the environment.
Carbon monoxide (CO)	Incomplete combustion of LFG. Can be used as a measure of system combustion efficiency.	Reduction of air quality	Complete combustion of LFG to form carbon dioxide.
Nitrogen oxides (NO_x)	Nitrogenous compounds in the LFG. Nitrogen present in the injected air. Flue gas reactions at high temperatures. NO_x concentration is higher in more	Acid rain Corrosion of plant and equipment	Lower operating temperatures. Control of oxygen levels during combustion.

[48] Most points sourced from (SEPA and Environmental Agency, 2004)

Emissions	Sources	Effects	Potential minimisation
	efficient electrical systems.		
Particulate matter	Products of LFG combustion. May contain carbon from incomplete combustion of LFG as well as corrosive metal salts.	Highly abrasive to plant equipment. Respiratory problems for workers.	Filtering system Proper sorting and homogenisation of waste to reduce particle size.
Sulphur oxides and hydrogen sulphide	Oxidation of sulphur contained in sulphurous compounds in the LFG. Higher concentrations for landfills accepting construction and demolition materials (U.S. EPA, 2017b)	Sulphuric acid formation when in contact with moisture. Hydrogen sulphide is corrosive to plant equipment.	Absorption/scrubbing (U.S. EPA, 2017b)
Non-methane volatile organic compounds (NMVOC)	Incomplete combustion. Flue gas reactions. Residue unburnt LFG	Some compounds are thought to be carcinogenic (Terraza and Willumsen, 2009).	Molecular sieve or membrane separation.
Hydrogen chloride and hydrogen fluoride	Products of complete combustion of LFG.	Corrosive to plant equipment.	
Siloxanes	Household and industrial products (U.S. EPA, 2017b).	Formation of silicon dioxide which is deposited in the ICE or gas turbine during combustion, leading to lower performance	Adsorption or liquid scrubbing (U.S. EPA, 2017b)

Emissions	Sources	Effects	Potential minimisation
		efficiency and high maintenance costs.	
Leachate	Semi-solid sludge produced from anaerobic digestion of the MSW in the landfill. May contain heavy metals and dioxins.	Soil, surface water and ground water contamination.	Proper landfill slope design for collection of leachate (Townsend *et al.*, 2015b) Landfill bottom lining (U.S. EPA and ISWA, 2012) Leachate recirculation into landfill to increase MSW moisture content (Townsend *et al.*, 2015b) Leachate evaporation (U.S. EPA and ISWA, 2012) .

Aside from the above discussed emissions, constant monitoring of oxygen levels in LFGE facilities is required to prevent any spontaneous explosion. A less than 5% oxygen concentration level is often recommended, with constant monitoring to ensure that sub-surface temperatures are not too high (Terraza and Willumsen, 2009; U.S. EPA and ISWA, 2012). In addition, a landfill will continue to emit LFG even after the end of the project (see Appendix I below). Measures therefore need to be taken to continue monitoring and treating the gas emitted. A landfill gas flaring system could be implemented to capture and burn any excessive LFG not utilised during plant operation and after project decommissioning, therefore preventing it from going into the atmosphere. After project closure, the landfill should be capped with impermeable material to prevent water entry and disturbance from natural elements such as the wind (Townsend *et al.*, 2015b).

5 Discussion

5.1 Technical Outputs

5.1.1 LFG Potential for Energy Supply in Dandora Area

A potential LFG collection rate ranging from 1,026m^3/h to 1,571m^3/h from the current MSW disposed at Dandora dumpsite over a 20-year period makes it a useful resource for renewable energy production. This is augmented by the fact that 62% of the households in the nearby Korogocho slum require electricity. From a technical perspective, LFG capture appears to have good potential for electricity generation in Nairobi. It is estimated that a 2.5MW plant capacity using internal combustion engines can produce enough electricity to serve about 7,200 households whose average consumption per year is 2,702kWh. A 2.1MW gas turbine system would serve about 6,200 households with this same average consumption per year. Since Korogocho is a low-income area, majority of the households would have average electricity consumptions that are closer to 788kWh/year on selected household appliances. In this case the ICE system would generate enough electricity to power at least 24,712 households within the low-income electricity consumption group, and the gas turbine would generate enough electricity to supply 21,391 households. This is more than enough for Korogocho households and could be used to also power some small-scale businesses in the area.

It is worth noting that these estimates are based on the 33% of total MSW generated that is disposed of at Dandora dumpsite with an assumed methane composition of 50% in the waste. As shown in section 4.1.2.2 above, about 70% of Nairobi's MSW is composed of organic matter from food and garden waste. A proximate and ultimate analysis of the various waste components of the MSW would likely show higher methane content in the waste. A more structured and active MSW collection and management framework in Nairobi has the potential to increase the amount (in volume and weight) of the MSW disposed in Dandora, thereby increasing amount of LFG produced and collected, and consequently increasing the electricity generation capacity by the LFGE plant. Mechanical and/or biological treatment of waste prior to disposal by recovering any recyclable material, sorting out non-organic fractions of MSW and homogenising remaining MSW to be landfilled would greatly improve the quality of the MSW used for landfilling thereby increasing LFG production rates.

5.1.2 Improvement of LFG Production

Landfill gas can be considered a renewable source of energy due to consistency of waste supply. The electricity generated depends on the amount of LFG collected per hour which depends on the amount and quality of the waste used. There are 2 main terms in the first order decay equation ($Q = L_0 R(e^{-kc} - e^{-kt})$) that account for amount of LFG produced: the methane generation rate constant, k, and the methane generation potential, L_0. The methane generation rate constant is an indicator of the rate at which the organic content in the waste is decaying. The rate of decay depends on the moisture content of the waste, the temperature and pH of operation and the nutrients available for methane producing bacteria (U.S. EPA, 2017b).

Moisture content has the highest influence on the decay rate. Since methane bacteria thrive in moist environments, sufficient water in the waste accelerates their activity, leading to an increase in LFG generation (Townsend *et al.*, 2015b; U.S. EPA, 2017b).

Higher moisture content in the waste therefore leads to higher methane generation, hence a higher k value. A 40% moisture content in waste is considered suitable for accelerated rate of methane generation (U.S. EPA, 2017b). Waste disposed of in a landfill would normally not have enough moisture for accelerated decomposition of the organic fraction of waste, but it is possible to increase the moisture content. One common method is recirculating leachate produced back to the landfill (Ouedraogo, 2005; Townsend *et al.*, 2015b; U.S. EPA, 2017b). This type of landfill is then known as a leachate recirculation landfill and serves to not only increase waste moisture content, but also prevents ground water and soil contamination from leachate run-off. It would also be worth considering the possibility of adding sewage sludge in a controlled manner as a source of moisture addition to the waste. It may also have the added advantage of adding nutrients necessary to keep the decomposing bacteria active, but this is subject to further investigation.

Landfill temperatures range between 30-60^{0}C for typical landfills, but would be lower for landfills in colder regions or shallow landfills (U.S. EPA, 2017b). Except for these 2 cases, temperature in a landfill does not have a significant effect on k since temperatures in deeper layers are often not affected by external elements and would therefore remain constant.

The methane generation potential, L_0, mainly depends on the organic content in the waste, measured based on the dry weight rather than the wet weight (Terraza and Willumsen, 2009; U.S. EPA, 2017b). Higher organic content leads to a higher methane generation potential. The default L_0 value used by LandGEM is 170m^3/tonne to represent a conventional landfill, but this can be adjusted to a lower level for less organic content and a higher level for a higher organic content. L_0 values range from 56 – 198 m^3/tonne of waste (Alexander, Burklin and Singleton, 2005; U.S. EPA, 2017b). Source separation of organic waste, mechanical and biological pre-treatment of MSW received at the landfill and particle size reduction of MSW to be disposed would play a significant role in improving the methane generation potential from the waste. A higher methane content would lead to an increase in the heating value of the LFG collected and a consequent increase in net electricity generated per year.

5.1.3 Energy Conversion Systems

Using ICEs for electricity production appears to be the most technically viable option since it allows for generation of more electricity due to a higher conversion efficiency and a lower parasitic load requirement. The higher parasitic load of gas turbine systems is usually due to the high gas pressure (165 psi = 11.38 bar) requirements for electricity generation, so more power is needed to compress the LFG collected (U.S. EPA, 2017b).

The conversion efficiency of the ICE could be increased by cogeneration to recover heat (combined heat and power), but this largely depends on the year-round demand for heat at the facility or in nearby areas. The efficiency of gas turbines increases with an increase in installed capacity, so it would be more economical to operate gas turbine capacities of at least 3MW (U.S. EPA and ISWA, 2012; U.S. EPA, 2017b).

One advantage of interest that ICEs have over gas turbines is the ability to install or remove smaller engine capacities to match the amount of LFG emitted and collected over time ((U.S. EPA and ISWA, 2012). In addition, since Nairobi is in a developing country, ICEs and ICE maintenance services would be more readily available locally than gas turbine (Terraza and Willumsen, 2009).

5.2 Financial and Economic Outputs

5.2.1 Costs per Energy Conversion System

The financial analysis shows that the ICE system would have lower capital costs of $4.8 million compared to $5.6 million for the gas turbine system. However, the annual costs of operation and maintenance for the ICE system would be $0.011 higher per kWh of electricity generated. This corresponds to existing literature comparing ICE costs and gas turbine costs (U.S. EPA and ISWA, 2012; U.S. EPA, 2017b).

The higher O&M costs for the ICE system could be attributed the gas quality requirements(U.S. EPA, 2017b). ICEs are more sensitive to corrosion and impurities than gas turbines, so more work would be required in removing impurities such as siloxanes an hydrogen sulphide from the gas before it is used for electricity generation (U.S. EPA, 2017b).

The total costs for implementing and operating a gas turbine system rely on economies of scale. Larger capacities usually cost less per kWh generated due to an increase in system efficiency. It would therefore be more economical to operate a gas turbine where gas flow rates allow for production of at least 3MW of power (U.S. EPA, 2017b). A LFGE facility using ICEs would therefore better suit Dandora dumpsite. This would also allow for addition of modular units in case the amount of gas collected increases over time due to increased MSW generation resulting from population growth, as well as improved MSW collection and disposal in the city.

5.2.2 LFGE Project Ownership

As seen in the financial and economic analysis, landfill ownership plays a major role in determining the financial viability of a LFGE facility. The type of project ownership largely influences the type of financing available for a LFGE project as well as the cash flows of the project. LFGE projects owned and operated by private companies will usually be liable to paying corporate tax from revenues earned. Municipal owned projects do not have this obligations since revenues are earned by the local government. In addition, a municipal council has the advantage of access to cheaper forms of LFGE financing. Further, private developers would generally be required to contribute their own funds as part of the capital costs. This is the down payment, which is usually a percentage of the total capital costs (U.S. EPA, 2017a). Cash in-flows for municipal owned LFGE projects would therefore be higher.

In this case study, marginal tax rates for a privately owned LFGE are assumed to be at 35% of taxable income. Out of the 6 project scenarios considered, the municipal owned ICE system financed using municipal bonds appears to be the most attractive with a net present value of over $1 million and only 1 year needed to break even.

Literature indicates different forms of financing available for privately and privately owned LFGE projects. The World Bank and the United States Environmental Protection Agency highlight 4 main sources of financing for LFGE projects in developing countries (World Bank, 2016a; U.S. EPA, 2017b):

- Revenues from the direct sale of LFG as a natural gas substitute, sale of the heat produced from LFG, sale of electricity generated from the LFGE plant, or off-sets from using the energy on-site.

- Public sector financing through bonds, development aid, direct investment from the municipal council's own funds, tariffs, taxes and subsidies.
- Environmental valuation where the project benefits from environmentally focussed funding like environmental funds, grants, results based financing, carbon off-sets and environmental pension funds.
- Private sector investments such as commercial loans, equity, public-private partnerships and other niche credit services.

While municipal bonds and own funds are the most attractive and cheapest sources of capital investment for a municipal owned LFGE project, they are often either not fully established or not sufficient for developing countries such as Kenya (World Bank, 2016a). It would therefore be more advantageous for the municipal council to access commercial loans through financial intermediaries such as development banks, in which case the project structure would follow that of a privately owned, direct sale LFGE project. If considering this option, then the best fit for Dandora dumpsite would be that similar to the privately-owned ICE (direct sale) LFGE project as seen in the comparison table below. The loan requirements such as interest rates, project discount rates and down payments would however likely be lower.

Table 25: Commercial funding options for a municipal owned LFGE project.

LFGE Project	NPV ($)	Payback period (years)	Break Even point (years)	IRR (%)
ICE – Privately owned (direct sale)	$262,870	0	1	98%
Gas turbine – Privately owned (direct sale)	$232,881	2	1	65%

It is also possible to consider a public-private partnership arrangement as a way of sharing the project risks and to acquire experienced personnel since the municipal council personnel may not have the proper technical capacity to operate a LFGE facility (World Bank, 2016a). The municipal council, which in this case owns the land containing the landfill, could partner with a project developer who would finance, construct and operate the landfill for a specified length of time before transferring operation back to the municipal council. The municipal council could in return receive part of the revenue from sale of electricity or from other revenue streams from the LFG collected, based on agreed upon rates. Such an arrangement is referred to as a Design-Build-Finance-Operate (DBFO) public-private partnership arrangement (World Bank, 2016a). It would however only work if there are economic incentives such as subsidies, tax reductions or special electricity prices from LFGE supply, to keep the project profitable enough for a private developer.

An interesting source of financing to consider for both the private and the municipal owned LFGE projects would be carbon financing through voluntary or compliance carbon markets. An LFGE project gets revenue from the carbon emissions reduced or avoided, often referred to as carbon offsets (World Bank, 2016a). In this form of financing, the carbon emissions reduced from collecting or utilising the LFG emitted in the landfill are measures and verified. The owner of the landfill receives carbon credits, with one credit representing one metric tonne of carbon dioxide or its equivalent for other GHGs such as methane(World Bank, 2016a). The owner can then sell the credits in the carbon market. Carbon financing is so far one of the most popular means of financing LFGE projects in the world (World Bank, 2016a). Though revenues from the carbon market may not be enough to cover capital costs, they would make a significant contribution to reducing project risks in operation, thereby making an LFGE project bankable. It is also worth noting that carbon financing is results based, so revenues are received only when carbon emissions reduction targets are met (World Bank, 2016a).

Other ways to increasing revenues and raise funds for operation of the LFGE facility include setting up a tipping fee system to charge for disposal according to type and amount of MSW received. A sorting and materials recovery system would also raise more revenues through the sale of recyclable materials. The proceeds from these activities could be used to set up a type of fund that could be used for further developments in the future.

Finally, while not covered in the scope of this project, it is necessary for the municipal council or project developer to consider the additional costs of setting up a pre-treatment facility to separate MSW suitable for landfilling as well as homogenising it through mechanical or biological treatment to make it suitable for landfilling. Furthermore, it may be necessary to look into the cost of electricity transmission and distribution network to supply to the consumers.

5.2.3 Direct Sale vs FiT

The table below, showing outputs of the economic analysis, indicate that direct sale to consumers is the most favourable option due to higher revenues. Revenues received through direct sale however include surcharges made to consumers for the administration of other local and national electricity programmes. For simplicity of analysis, it is assumed that the 35% marginal tax rate for privately owned LFGE projects includes the transfer of these surcharges from revenues received to the local and national government.

Table 26: Comparison of economic viability by type of electricity sale arrangement.

LFGE Project	NPV ($)	Payback period (years)	Break Even point (years)	IRR (%)
ICE – Privately owned (direct sale)	$262,870	0	1	98%
ICE – Privately owned (FiT)	$112,635	4	6	27%
ICE – Municipal owned	$1,054,879	0	1	407%
Gas turbine – Privately owned (direct sale)	$232,881	2	1	65%
Gas turbine – Privately owned (FiT)	$109,860	7	1	19%
Gas turbine – Municipal owned	$921,143	0	1	284%

The FiT rate set at 0.1$/kWh for biomass sources in Kenya's feed-in tariff policy is low compared to 0.20 $/kWh charges for distribution to domestic consumers. This contributes to lower revenues per kWh of electricity sold. The municipal owned LFGE project using ICEs would therefore be the most financially viable option here.

Overall, it would be more viable for the municipal council to own and operate the LFGE project, due to access to cheaper financing options and increased revenues from direct sale of electricity to consumers. Using internal combustion engines for electricity generation would also be a cheaper and more convenient technical option compared to a gas turbine system.

5.2.4 Socio-Economic Impact of Upgrading Dandora Dumpsite into a LFGE Facility

A key factor to consider when upgrading Dandora dumpsite into a sanitary landfill is the socio-economic impact this would have on the community surrounding the area. Figure 7 in section 2.2.1.3 shows that about 3,000 people, most of whom live close to the dumpsite, earn a living from sorting through the waste deposited at the dumpsite and selling it to the informal recycling market in Nairobi. Some forethought on the role of waste pickers in the operation of a sanitary landfill is therefore crucial, for the project to be considered acceptable by its nearby beneficiaries. A report by Concern Worldwide shows that waste pickers would be against any plans to close or upgrade the dumpsite if they are not integrated into the new system (Concern Worldwide, 2015). A “viable economic alternative” for the waste pickers (Concern Worldwide, 2015, p. 24) should therefore be identified and integrated into the new plans to upgrade the dumpsite. Some suggestions on how to integrate waste pickers into an upgraded sanitary landfill with electricity generation include:

- Creating MSW materials recovery and sorting centres near the landfill and employing waste pickers to manage the sorting process.
- Formalising the waste recycling sector and setting up a market for the recyclable MSW.
- Encouraging the creation of refuse derived fuels such as briquettes from recycled materials and selling them to the local market.
- Allocating a certain percentage of jobs at the LFGE facility to the local community.

- Capacity building on entrepreneurship to encourage local community members to utilise the electricity supplied by the LFGE for local businesses.

5.3 Environmental Outputs

5.3.1 Point Source vs Utilisation Emissions

The environmental analysis in section 4.2.3 above highlights some of the potential emissions from LFG collection and utilisation as well as their sources and possible methods of minimisation. The more impactful emissions appear to be those borne from the utilisation of LFG for electricity generation. Nitrous oxides, sulphate compounds, hydrogen chlorides and fluorides, particulate matter and siloxanes all emanate either from the combustion process of electricity production or from the reaction of flue gases. This largely depends on the conversion efficiency of the system used for electricity combustion. Since the conversion technologies are the same as those used in conventional power systems such as natural gas power plants, mature methods of emission treatment and minimisation exist as outlined in table Table 24 in section 4.2.3 above. ICEs are recorded to be less environmentally friendly than gas turbines due to higher nitrogen oxides emissions resulting from their higher operating temperatures and higher combustion efficiencies (SEPA and Environmental Agency, 2004; World Bank, 2016a; U.S. EPA, 2017b).

5.3.2 Post Closure Utilisation of Landfill Area

As mentioned in the environmental analysis section, LFG will continue to be emitted even after the end of the project. There exist several ways of accelerating LFG production during the project period, such increasing moisture levels of the compacted

MSW. However, this does not guarantee that all the LFG will have been used up by the end of the project. One possible way of dealing with this challenge would be to install a capture and flare system to burn any excess LFG not utilised by the LFGE facility, and to capture any LFG emissions after decommissioning of the LFG facility.

A landfill will typically be situated in a relatively remote part of the city with a lot of space. Depending on the climatic conditions of the area, there is an opportunity to rehabilitate the landfill area into a renewable energy park since the landfill area is already fitted with electricity generating equipment (Townsend *et al.*, 2015a). Two common technologies are wind and solar PV. Solar PV technology would more likely suit the Dandora dumpsite, post landfill closure, since Kenya has a good solar resource, being in a dry tropical climatic region.

6 Conclusion

This project is set to achieve three main objectives, 1) to determine the potential energy supply from MSW generated, using a case study of Nairobi, Kenya, 2) to determine the amount of MSW that could potentially be reduced by utilisation of the WtE technologies, using the case study, and 3) to investigate the most viable WtE technologies to adopt in Nairobi, Kenya. These three objectives then lead to the project aim which is to investigate the potential viability of waste to energy (WtE) technologies as a component in the municipal solid waste management value chain in urban areas in Sub-Saharan Africa. This section summarises some points that come across from both the project objectives and the project aim. It also outlines some further developments for future consideration.

6.1 Summary Points from Project Aim and Objectives

In connection to the project objectives, the following points can be made:

- Based on the current MSW management framework in Nairobi, a landfill gas to energy system would best suit the city. The 70% organic content in the MSW also makes it a good candidate for gas collection through landfilling.
- Though LFG production for use in domestic cooking and heating is an attractive option to replace charcoal and kerosene, Nairobi's current infrastructure and policy environment is not sufficient to accommodate such use. Electricity production seems to be the most viable option now, but this could change as the city continues to grow in population and as demand for energy grows.

- The amount of waste currently present in the Dandora dumpsite in Nairobi has the potential to generate at least 19.47GWh of electricity per year from internal combustion engines and 16.85GWh per year from gas turbines, at a 90% availability factor. This would be enough to supply at least 60% of households in the nearby Korogocho slum if average consumption was at 2,702kWh/year, and more than twice the number if the average consumption was within the low-income level consumption of 788kWh/year.
- This electricity generating potential is only from the MSW received at Dandora dumpsite, which is approximated at only 830 tonnes per day, 33% of total MSW generated in the city. If MSW collection and transfer activities were improved, the amount of waste received by the dumpsite would be higher, which would translate into treatment and disposal of more MSW with the additional benefit of more electricity generated.
- From a financial and environmental point of view, a municipal owned and operated LFGE facility appears to be the most profitable option. However, the municipal council may not have enough finances to cover the capital costs, in which case seeking commercial debt from development banks, trading of carbon credits in the carbon market and public-private-partnerships are options to consider.
- Internal combustion engines are the most viable conversion systems to use for the LFGE facility compared to gas turbines. This is because their capital costs are lower, they operate at higher efficiency, they are more readily available in the Kenyan market, and smaller modular capacities can be added or removed to

match electricity generation with LFG supply. Some further investment would however be needed to control and minimise utilisation emissions.

- Upgrading the Dandora dumpsite to a sanitary landfill creates an opportunity to formalise the recycling sector in Nairobi and develop a local market for recyclable materials and refuse derived fuels. The LFGE facility would also have a positive effect on the local community's economy.

In connection to the project aim, a similar approach can be taken for other cities in Sub-Saharan Africa since most have similar MSW characteristics and similar MSW management challenges as Kenya. However, as seen in the literature review and data analysis, WtE technologies very much depend on the MSW composition, the amount generated and the enabling environment in terms of policies, regulations, institutional structure and local culture. All these need to be considered when evaluating the most suitable WtE technology for a city in Sub-Saharan Africa.

6.2 Further Development

On a wider scale, WtE technology suitability in Sub-Saharan Africa will largely depend on the MSW generation and management in a city. Table 3 in section 2.3.3 above shows a decision matrix on what WtE technologies work best for an African city. While landfill gas technologies appear to be the most suitable, there is still room for implementation of incineration and anaerobic digestion technologies, with some further improvements on the MSW management stream. For example, improving the MSW collection and transfer system and encouraging source separation of waste would increase the quantity and quality of the organic waste stream, making anaerobic digestion (with possible composting) an ideal choice of organic waste treatment. In addition, more waste suitable for incineration (such as paper, fabric and other dry materials with a high calorific value) would be collected and sorted for treatment through incineration. Landfilling would then be implemented as a final disposal method for residues from both these technologies. It is therefore worth assessing the viability of combining different types of waste treatment and disposal options to maximise energy recovery.

Other considerations for further development include:

- Assessing best practice in documentation of waste generation, collection and disposal practices in urban areas in Sub-Saharan Africa, as well as changes in waste composition with time, so as to make informed decisions on most suitable WtE technologies to employ.
- Utilising anaerobic digestion as a pre-treatment option for landfill gas technology.
- Assessing the effectiveness of using sewage sludge as a source of moisture addition to the waste to increase the rate of organic waste decomposition in the landfill.
- An In-depth review of enabling environments such as policy framework, infrastructure and finance for the implementation of LFGE technologies in Sub-Saharan African cities
- Assessing the viability of utilising LFG for domestic use in cooking and heating in urban areas in Sub-Saharan Africa.
- Investigating whether LFGE implementation for domestic use would bring any energy cost savings to the consumers.

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Appendices

Appendix A <u>Relevant Maps</u>

Figure 27: Map of Sub-Saharan Africa[49]

[49] Source: http://worldmap.org/region.php?region=Sub-Saharan%20Africa

Kenya

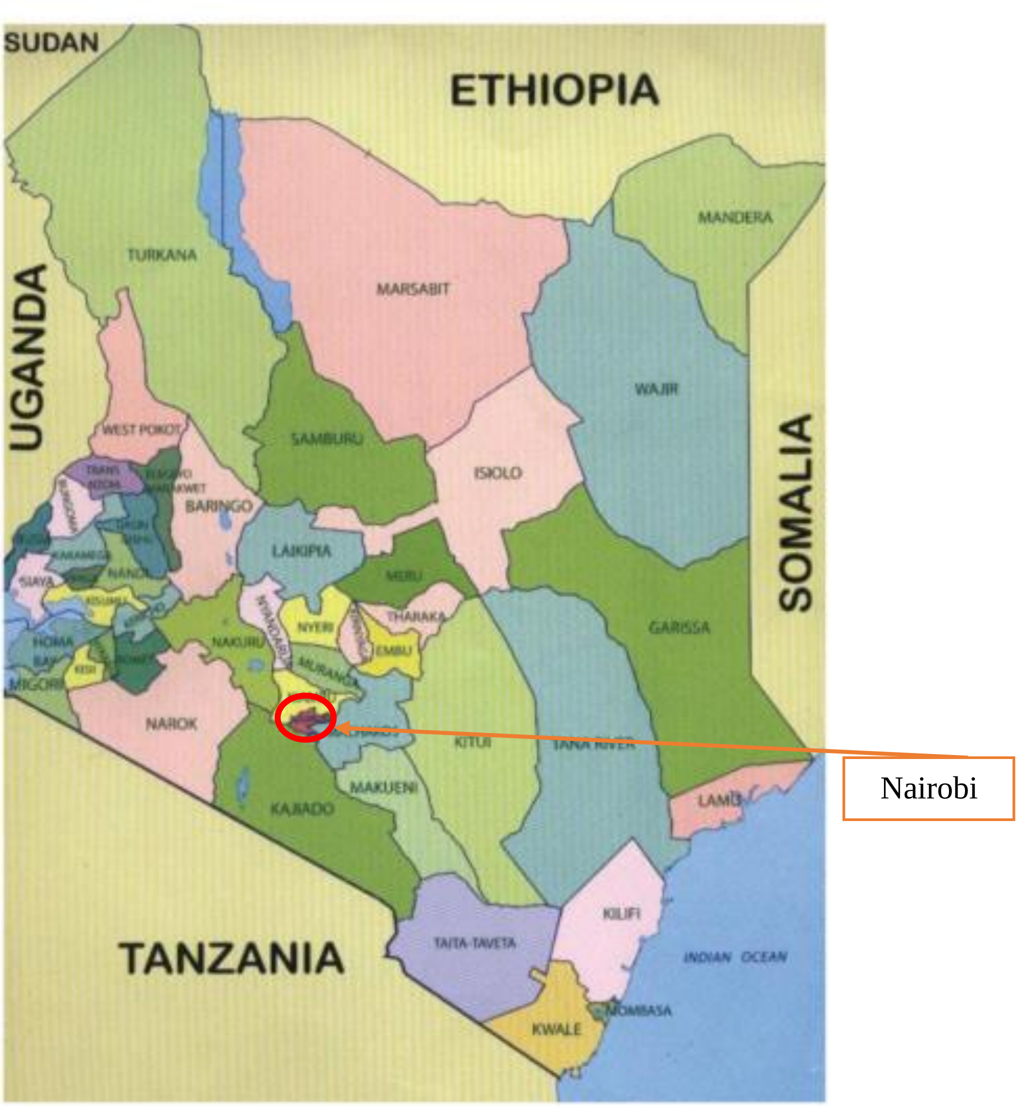

Figure 28: Map of Kenya[50]

[50] (Republic of Kenya, Ministry of land, 2016)

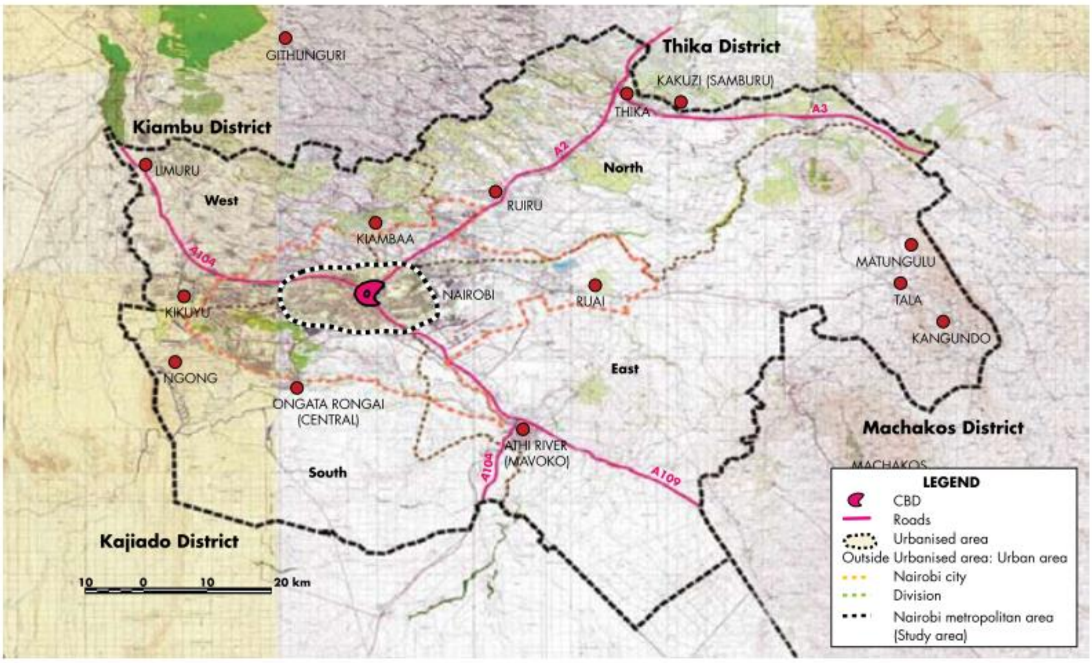

Figure 29: Map of Nairobi metropolitan area[51]

[51] (UNEP and CCN, 2007)

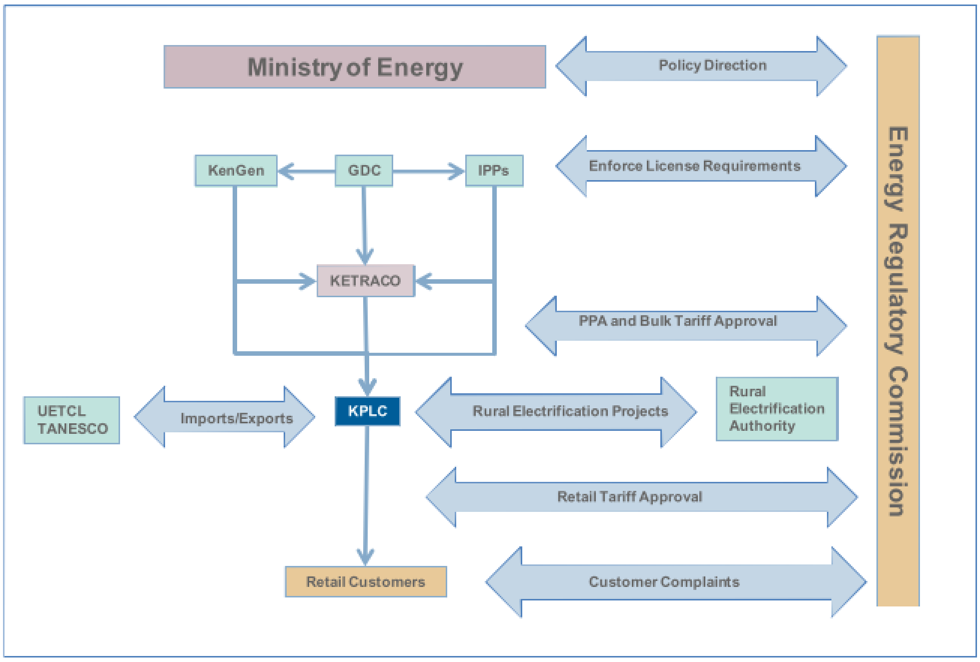

Figure 30: Outline of Kenya's electricity sector[52]

[52] (Parsons Brinckerhoff, 2013)

Appendix B World Urban Population Growth Rate

Table 27: Average urban growth rate of world regions between 1990 and 2015

Region	**1995 - 2000**	**2000-2005**	**2005-2010**	**2010-2015**	**Average**
Africa	3.25%	3.42%	3.55%	3.55%	**3.44%**
Asia	2.79%	3.05%	2.79%	2.50%	**2.78%**
Latin America and the Caribbean	2.19%	1.76%	1.55%	1.45%	**1.74%**
Europe	0.10%	0.34%	0.34%	0.33%	**0.31%**
North America	1.63%	1.15%	1.15%	1.04%	**1.24%**
Oceania	1.43%	1.49%	1.78%	1.44%	**1.53%**
World	**2.13%**	**2.27%**	**2.20%**	**2.05%**	**2.16%**

Source: (UN-HABITAT, 2016)

Appendix C Access to Electricity in Africa

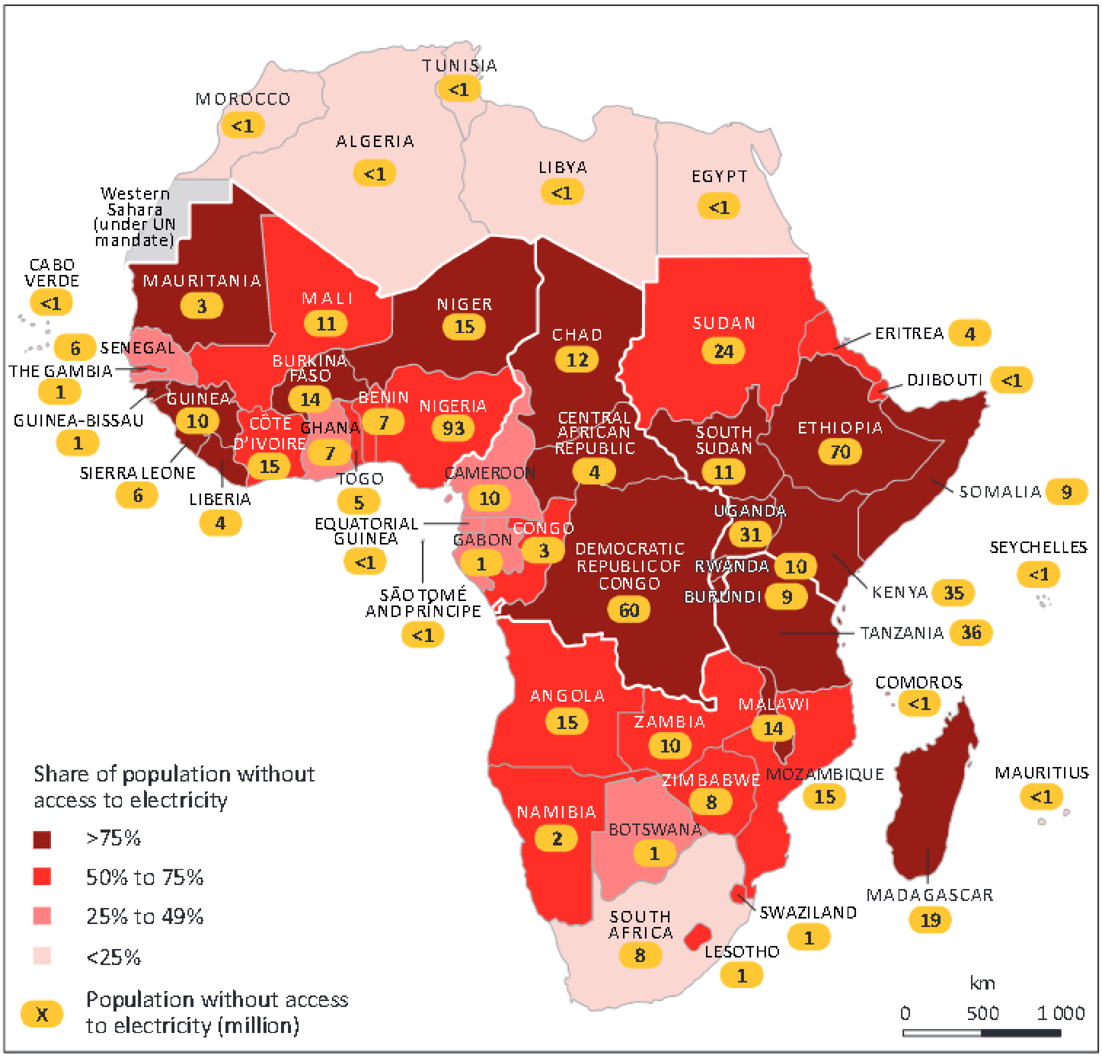

Figure 31: Percentage of population without access to electricity in Africa as at 2012[53]

[53] (IEA, 2014)

Appendix D Nairobi Slum Population

Area	Total Population ('000)	Households ('00(
Kibera	383.9	121.9
Embakasi	183.7	66.6
Huruma	106.3	34
Mathare	177.3	60.8
Kangemi	640.2	21.7
Korogocho	41.9	12.9
Viwandani	71.4	27.7
Kahawa	16.4	5.1
Total	1621.1	350.7

Figure 32: Population in Nairobi living in informal settlements[54]

[54] Adapted from (UN-HABITAT, 2010b)

Appendix E Kerosene and LPG prices in Kenya

Year	Month	Kerosene	Kerosen	LPG	LPG2
		KES	USD	KES	USD
2012	January	87.96	0.8796	3149.63	31.4963
	March	84.99	0.8499	2882.5	28.825
	June	84.05	0.8405	2772.94	27.7294
	September	80.51	0.8051	2628.06	26.2806
	December	87.29	0.8729	2604.55	26.0455
2013	January	84.71	0.8471	2630.73	26.3073
	March	89.39	0.8939	2662.61	26.6261
	June	82.38	0.8238	2573.75	25.7375
	September	86.47	0.8647	2836.67	28.3667
	December	83.99	0.8399	2877	28.77
2014	January	85.98	0.8598	2995.22	29.9522
	March	84.82	0.8482	3094.16	30.9416
	June	84.04	0.8404	3074.57	30.7457
	September	82.55	0.8255	3111.74	31.1174
	December	72.3	0.723	3018.45	30.1845
2015	January	66.53	0.6653	2954.36	29.5436
	March	56.71	0.5671	2629.56	26.2956
	June	62.73	0.6273	2387.04	23.8704
	September	53.52	0.5352	2393.85	23.9385
	December	54.23	0.5423	2369.46	23.6946
2016	January	47.11	0.4711	2343.86	23.4386
	March	43.13	0.4313	2277.48	22.7748
	June	59.1	0.591	2231.38	22.3138
	September	60.08	0.6008	2029.12	20.2912
	December	64.52	0.6452	1983.06	19.8306
	AVERAGE PRICE	**73.1636**	**0.731636**	**2660.47**	**26.6047**

Figure 19: 2012-2016 kerosene and LPG prices in Kenya[55]

[55] Adapted from (KNBS, 2017)

Appendix F Data Used to Determine Average Household Consumption in Nairobi

Table 28: Load ratings per usage category

		Load Rating (kW)	**Source**
Lighting	Incandescent lamps	0.025	(Magambo, 2010, p. 81)
	CFLs	0.02	
Cooking	Electric cookers	1.7	(Nzia, 2013, pp. 82–83)
Water heating	Immersion heaters	1.5	
	Instant shower heaters	3.5	
	Electric kettles	1.5	
Refrigeration[56]	Large refrigerators	0.5	((Nzia, 2013, pp. 82–83))
	Medium refrigerators	0.25	
	Small refrigerators	0.09	
Laundry	Iron boxes	1.5	(Nzia, 2013, pp. 82-83)
Entertainment	Mobile phone chargers	0.005	
	Television sets	0.1	(Magambo, 2010, p.46)
	DVD players	0.04	(Nzia, 2013, pp. 82-83)
	Music Systems	0.07	
	Desktop computer	0.2	(Magambo, 2010, p. 46)
	Laptops	0.22	(Nzia, 2013, pp. 82-83)

[56] Consumption for refrigerators recorded as kWh/cycle, where the cycle is 1 year.

Table 29: Typical ratings of appliances used in Nairobi households[57]

Appliance Description	Ownership (%)	Usage (%)	Quantity / Household	Load Rating (W)	Daily Usage (hrs/day)
Lights - Incandescent Lamps	53	53	12	651	4
Lights - CFL Lamps	47	47	11	192	4
Refrigerator	95	95	1	200	8
TV	90	90	1	100	6
Video/DVD Player	84	79	1	15	6
HiFi Music System	79	68	1	10	6
Iron Box	95	95	1	1000	0.5
Cooker	79	11	1	3000	0.25
Water Heater (Geyser/Instant)	68	21	1	3000	1
Kettle	42	42	1	1000	0.5
PC desktop	58	53	1	200	1
PC Laptop	58	42	1	50	1
Hair Drier	26	21	1	1000	0.15
Booster Pump	16	16	1	400	0.25
Microwave	16	16	1	1000	0.25
Shaver	16	16	1	10	0.25
Fan – Cooling	11	5	1	100	0.75
Electric Room Heater (coil)	26	0	1	1000	0

[57] (Magambo, 2010)

Table 30: Average power ratings of household electrical appliances and frequency of usage[58]

Appliance	Unit	Consolidated KWh/ cycle	Average power rating W	No. hours use day	Hours of use week	Hours of use month	Standard unit yearly cons in kWh
Air conditioning system			3000			135	4,860.00
Fan			2000			12.5	300.00
Dishwasher (cycle)	cy	1.2		1.00			438.00
Washing Machine(cycle)	cy	1.5			2		156.00
Built in oven			2000			3	72.00
Deep fryer			1200			1.5	93.60
Electric Cooker			1700			3	61.20
Extractor hood			300	0.30			32.85
Microwave oven			700	0.20			51.10
Rice cooker			500			1	26.00
Computer (CPU)			100	2.7			100.00
Computer monitor			50	2.7			50.00
Computer Printer			400			0.5	2.40
Computer Scanner			35			0.5	1.00
DVD Player			40	2.50			35.00
Home Theater System			70	2.7			70.00
House telephone	yr	10					10.00
Laptop			220	2.7			220.00
Mobile charger(s)			5	0.33			0.61
Satellite Decoder	yr	125					125.00
Stereo	yr	75					75.00
Television set	yr	220					220.00
TV Set –top box	yr	133					133.00
VCD Player	yr	50					50.00
VCR Player	yr	50					50.00
Video Game Console	yr	30					30.00
Gym Equipment			500		4		104.00
Jaccuzi - spa			1300		1.5		101.40
Sauna or steam			5000		1.5		390.00
Swimming pool			1000	12.00			108.00
Electric shaver			20	0.10			1.00
Hair dryers			1000		0.5		26.00
Vacuum cleaner			1000	0.30			90.00
Fan heaters			25			270	81.00
Iron Box			1500		2.5		195.00
Lighting HI			620	4			904.00
Lighting MI			240	4			352.00

58 (Nzia, 2013)

Appliance	Unit	Consolidated KWh/ cycle	Average power rating W	No. hours use day	Hours of use week	Hours of use month	Standard unit yearly cons in kWh
Lighting LI			105	3.5			135.00
Rechargeable torch			40	1.00			14.60
freezer large	yr	600					600.00
freezer medium	yr	400			0.166667		400.00
freezer small	yr	125					125.00
Refrigerator large	yr	500					500.00
Refrigerator medium	yr	250					250.00
Refrigerator small	yr	90					90.00
Geyser heater	yr	1000					1,000.00
Immersion heater			1500	0.25			136.88
Instant shower heater			3500	0.50			638.75
Blender/Juicer			350	0.03			4.26
Bread Toaster			800	0.10			29.20
Coffee maker			800	0.50			146.00
Electric kettle			1500	0.25			136.88
Water dispenser			580	2.00			423.40
Water booster pump(s)			500	0.50			91.25

Table 31: Penetration levels of electrical equipment and appliances among Nairobi households[59][60]

Appliance	Urban HI	Urban MI	Urban LI	Rural HI	Rural MI	Rural LI
	% Access Levels (penetration)					
Air conditioning system	5%	1%	0%	0%	0%	0%
Fan	17%	13%	3%	6%	0%	0%
Dishwasher (cycle)	12%	0%	0%	0%	0%	0%
Washing Machine(cycle)	49%	2%	0%	3%	0%	0%
Built in oven	29%	3%	0%	3%	0%	0%
Deep fryer	25%	5%	0%	3%	0%	0%
Electric Cooker	61%	9%	0%	16%	0%	0%
Extractor hood	5%	1%	0%	0%	0%	0%
Microwave oven	85%	33%	0%	9%	9%	0%
Rice cooker	29%	6%	0%	0%	0%	0%
Computer (CPU)	56%	20%	0%	0%	0%	0%
Computer monitor	54%	21%	3%	6%	9%	0%

[59] HI = High income, MI = Middle income, LI = Low income
[60] (Nzia, 2013, pp. 38–40)

Appliance	Urban HI	Urban MI	Urban LI	Rural HI	Rural MI	Rural LI
Computer Printer	42%	9%	0%	0%	4%	0%
Computer Scanner	29%	4%	0%	0%	0%	0%
DVD Player	85%	79%	65%	63%	63%	0%
Home Theater System	29%	32%	16%	3%	2%	6%
House telephone	27%	4%	0%	6%	6%	0%
Laptop	86%	35%	0%	9%	6%	0%
Mobile charger(s)	100%	100%	100%	100%	100%	100%
Satellite Decoder	58%	11%	0%	16%	13%	0%
Stereo	54%	45%	48%	38%	50%	31%
Television set	98%	93%	90%	78%	83%	19%
TV Set -top box	3%	9%	0%	3%	6%	0%
VCD Player	27%	17%	6%	6%	11%	0%
VCR Player	19%	8%	3%	0%	4%	0%
Video Game Console	0%	0%	0%	0%	0%	0%
Gym Equipment	7%	1%	0%	0%	0%	0%
Jacuzzi - spa	2%	0%	0%	0%	0%	0%
Sauna or steam	3%	0%	0%	0%	0%	0%
Swimming pool	12%	0%	0%	0%	0%	0%
Electric shaver	32%	9%	3%	0%	4%	0%
Hair dryers	34%	8%	3%	6%	2%	0%
Vacuum cleaner	36%	3%	0%	0%	0%	0%
Fan heaters	15%	2%	0%	0%	0%	0%
Iron Box	98%	96%	84%	59%	70%	19%
Lighting HI	100%	0%	0%	100%	0%	0%
Lighting MI	0%	100%	0%	0%	100%	0%
Lighting LI	0%	0%	100%	0%	0%	100%
Rechargeable torch	49%	31%	29%	56%	41%	0%
freezer large	19%	1%	0%	0%	2%	0%
freezer medium	20%	8%	0%	0%	2%	0%
freezer small	8%	2%	0%	3%	0%	0%
Refrigerator large	58%	18%	0%	3%	6%	0%
Refrigerator medium	47%	36%	6%	25%	19%	0%
Refrigerator small	5%	7%	6%	6%	4%	0%
Geyser heater	44%	3%	0%	0%	0%	0%
Immersion heater	14%	20%	16%	6%	13%	0%
Instant shower heater	69%	38%	0%	9%	0%	0%
Blender/Juicer	80%	28%	6%	19%	7%	0%
Bread Toaster	66%	25%	0%	6%	2%	0%
Coffee maker	29%	3%	0%	0%	0%	0%

Appliance	Urban HI	Urban MI	Urban LI	Rural HI	Rural MI	Rural LI
Electric kettle	73%	23%	6%	6%	4%	0%
Water dispenser	44%	13%	0%	3%	0%	0%
Water booster pump(s)	46%	7%	0%	6%	0%	0%

Table 32: Typical load ratings and quantity of electrical appliances per household per income group in Nairobi

		Load Rating (kW)	Low income	Middle Income	High Income
Lighting	Incandescent lamps	0.025	5	12	28
	CFLs	0.02	5	12	28
Cooking	Electric cookers	1.7	1	1	1
Water heating	Immersion heaters	1.5	1	1	1
	Instant shower heaters	3.5	1	1	2
	Electric kettles	1.5	1	1	1
Refrigeration	Large refrigetators		1	1	1
	Medium refrigerators		1	1	1
	Small refrigerators		1	1	1
Laundry	Iron boxes	1.5	1	1	1
Entertinment	Mobile phone chargers	0.005	1	2	3
	Television sets		1	1	2
	DVD players	0.04	1	1	2
	Music Systemns	0.07	1	1	2
	Desktop computer	0.1	1	1	2
	Laptops	0.22	1	1	2
	TOTAL		**24**	**39**	**78**

For this table, it is assumed that:

1. The same power rating is used for each appliance across all income levels.
2. All low-income households require only one lamp per room. Middle-income households use one lamp per room except for typically larger rooms like the living room, the master bedroom and the bathroom, which have 2 lamps. All rooms in high-income houses have 2 lamps each.
3. The number of mobile phone chargers increase by 1 as the income level increases, to indicate an increase in the number of mobile phones per household. It is therefore assumed that each low-income household has 1 mobile phone, each middle-income household has 2 mobile phones and each high-income household has 3 mobile phones.
4. Aside from mobile phone chargers, all other appliances in the entertainment category are considered luxury items and therefore only a minimum of 1 appliance for each household in the low- and middle-income houses, and a minimum of 2 in high-income houses is considered. It is however possible that some middle-income and high-income households would typically have more.

Appendix G Outputs of Household Average Electrical Demand.

Table 33: Average electrical demand: low-income households

		LOW INCOME HOUSEHOLDS		
	Equipment	Quantity per HH	Average % Penetration (Low-Income)	Average Electrical Demand (Low-Income) kWh/year
Lighting	Incandescent lamps	0	10%	0.00
	CFLs	5	80%	182.00
Cooking	Electric cookers	0	0%	0.00
Water heating	Immersion heaters	1	16%	136.50
	Instant shower heaters	0	0%	0.00
	Electric kettles	0	6%	0.00
Refrigeration	Large refrigetators	0	0%	0.00
	Medium refrigerators	0	6%	0.00
	Small refrigerators	0	6%	0.00
Laundry	Iron boxes	1	84%	195.00
Entertainment	Mobile phone chargers	1	100%	1.82
	Television sets	1	90%	145.60
	DVD players	1	65%	14.56
	Music systems	1	16%	76.44
	Desktop computer	0	3%	0.00
	Laptops	1	0%	36.40
	TOTAL			**788.32**

Table 34: Average electrical demand: middle-income households

		MIDDLE INCOME HOUSEHOLDS		
	Equipment	Quantity per HH	Average % Penetration (Middle-Income)	Average Electrical Demand (Middle-Income) kWh/Year
Lighting	Incandescent lamps	4	50%	182.00
	CFLs	4	50%	145.60
Cooking	Electric cookers	0	9%	0.00
Water heating	Immersion heaters	0	20%	0.00
	Instant shower heaters	1	38%	955.50
	Electric kettles	1	23%	136.50
Refrigeration	Large refrigetators	1	18%	500.00
	Medium refrigerators	1	36%	250.00
	Small refrigerators	1	7%	90.00
Laundry	Iron boxes	1	96%	195.00
Entertainment	Mobile phone chargers	2	100%	3.64
	Television sets	1	93%	145.60
	DVD players	1	79%	14.56
	Music systems	1	32%	76.44
	Desktop computer	1	21%	145.60
	Laptops	1	35%	36.40
	TOTAL			**2,876.84**

Table 35:Average electrical demand: high-income households

		HIGH INCOME HOUSEHOLDS		
	Equipment	**Quantity per HH**	**Average % Penetration (High-Income)**	**Average Electrical Demand (High-Income) kWh/Year**
Lighting	Incandescent lamps	14	80%	637.00
	CFLs	0	10%	0.00
Cooking	Electric cookers	1	61%	309.40
Water heating	Immersion heaters	0	14%	0.00
	Instant shower heaters	2	69%	1,911.00
	Electric kettles	1	73%	136.50
Refrigeration	Large refrigetators	1	58%	500.00
	Medium refrigerators	0	47%	0.00
	Small refrigerators	0	5%	0.00
Laundry	Iron boxes	1	98%	195.00
Entertainment	Mobile phone chargers	3	100%	5.46
	Television sets	2	98%	291.20
	DVD players	1	85%	14.56
	Music systems	1	29%	76.44
	Desktop computer	2	54%	291.20
	Laptops	2	86%	72.80
	TOTAL			**4,440.56**

Appendix H Determination of Waste Disposed of at the Dandora Dumpsite

Population growth plays a significant role in waste generation in a city (Ouedraogo, 2005). The higher the population, the greater the amount of waste generated. It is therefore important to account for population growth when estimating or projecting MSW generated in a city.

There is no comprehensive documentation on waste generated in Nairobi and corresponding figures of waste amount disposed of at the designated dumpsite since its year of opening in 1981. Estimates are therefore made in steps using the available information as a general guide. These steps are broken down according to timeline, from 1981 to 2017 and can be summarised as below:

Table 36: Dealing with missing data for waste disposed in Dandora Dumpsite

Timeline	Details Known	Details unknown	Action to be taken
1981 - 2005	Cumulative capacity of waste in dumpsite.	Population per year.	Use the cumulative capacity of waste to compute a general average amount of waste received by the dumpsite per year.
2006 - 2009	Actual average amounts of waste recorded in dumpsite per year. Population per year Percentage waste disposed of at disposal site 2009 waste generated per income group, commercial establishment and market.	None	Use average waste amounts recorded as is.

	2009 population distribution 2009 percentage waste disposed of		
2010 - 2014	Population projections	Actual population per year Actual average waste disposed of per year	Use 2010-2014 population projections, 2009 average waste generated per source, and 2009 percentage waste disposed of at dumpsite to estimate amount of waste disposed of at dumpsite per year.
2015-2017	None		Do a simple estimation of population projections then follow the same methodology as in 2010-2014 timeline.

The following assumptions are made in this computation:

- No change in consumption and waste generation patterns by sources (residential, commercial and market) since 2009.
- No change in population demographics 2010 and 2017. Therefore, percentages of low-, middle- and high-income population remains unchanged.
- No change in the number of commercial establishments and markets since 2009
- A simple projection of population between 2015-2017 is done using the Microsoft Excel's FORECAST.ETS function.
- Unit generation by each source has accounted for seasonal variability.
- Waste disposed at dumpsite follows the business as usual scenario since 2009, therefore remains at 33% of total waste generated.

- Since only about 5% of waste generated in Nairobi is recycled or re-used, it is assumed that this 5% has already been accounted for in the remaining 67% of waste not disposed of at the dumpsite.

Step 1: 1981-2005 estimates based on JICA 2010 report

Table 37: Estimation of waste disposed of at Dandora dumpsite between 1981 and 2005

Estimated cumulative capacity in dumpsite between 1981 and 2005 (tonnes) [61]	2,800,000
Average waste amount disposed per year between 1981 and 2005 (tonnes/year)	116,667

Step 2: 2006-2009 figures as recorded from actual measurements by the city council and reported in JICA 2010 report.

Table 38: Actual average waste amount disposed at Dandora dumpsite as weighed by city council[62]

2006	145,000
2007	187,000
2008	193,000
2009	220,000

Step 3: 2010 – 2017 figures estimated based on:

- Population projections for this period (2010-2014 projections taken from 2015 KNBS statistical abstract of Nairobi; 2015-2017 projections made from Excel's FORECAST.ETS function).

[61] This is before the weigh bridge was installed. Estimates done by JICA (2010) based on population change since 1981, demographics and consumption levels.
[62] As recorded in (JICA, 2010), after installation of weigh bridge

- Estimations of population distribution based on JICA 2010 report

The JICA (2010) report estimates the 2009 population distribution in Nairobi to be 52% low income, 35% middle income and 13% high income. Assuming no change in this distribution, the following estimations are made for each income group from 2010 to 2017.

Table 39: Projections on Nairobi's population and population distribution between 2010 and 2017[63]

Year	Total Population	Low-income population	Middle-income population	High-income population
2010	3,144,918	1,630,640	1,103,237	411,041
2011	3,351,315	1,737,657	1,175,641	438,017
2012	3,563,473	1,847,661	1,250,066	465,746
2013	3,781,394	1,960,653	1,326,513	494,228
2014	4,004,400	2,076,281	1,404,744	523,375
2015	4,216,119	2,186,058	1,479,015	551,047
2016	4,431,410	2,297,686	1,554,539	579,185
2017	4,646,701	2,409,314	1,630,063	607,324

- Estimations on total waste generated per type of source (see assumptions above)

[63] 2010-2014 projections taken from 2015 Nairobi Statistical Abstract (KNBS, 2015); 2015-2017 projections generated using the FORECAST.ETS function in Excel. NB: 2015-2017 projections are only a general assumption and are created for the purposes of deriving waste disposed to use in the LandGEM software.

	Unit	2010 Unit Generation (kg/day)	Quantity	Total Generation (kg/day)	Total Generation (tonnes/year)
Residential Waste				**1,365,221**	**498,306**
Low income population	person	0.36	1,630,640	587,030	214,266
Middle income population	person	0.474	1,103,237	522,934	190,871
High income population	person	0.621	411,041	255,256	93,169
Commercial Waste				**439,979**	**160,592**
Shops	establishment	0.5	47,941	23,971	8,749
Restaurants	establishment	38	1,582	60,116	21,942
Hotels (standard)	establishment	350	140	49,000	17,885
Hotels (lodgings)	establishment	100	586	58,600	21,389
Public facilities	establishment	137	500	68,500	25,003
Schools	establishment	32	2,847	91,104	33,253
Industrial Plants	establishment	150	501	75,150	27,430
Other	establishment	0.5	27,077	13,539	4,942
Market Waste	**market**	**2045**	**44**	**89,980**	**32,843**
TOTAL WASTE GENERATED				**1,895,180**	**691,741**

	Unit	2011 Unit Generation (kg/day)	Quantity	Total Generation (kg/day)	Total Generation (tonnes/year)
Residential Waste				**1,454,819**	**531,009**
Low income population	person	0.36	1,737,657	625,556	228,328
Middle income population	person	0.474	1,175,641	557,254	203,398
High income population	person	0.621	438,017	272,008	99,283
Commercial Waste				**439,979**	**160,592**
Shops	establishment	0.5	47,941	23,971	8,749
Restaurants	establishment	38	1,582	60,116	21,942
Hotels (standard)	establishment	350	140	49,000	17,885
Hotels (lodgings)	establishment	100	586	58,600	21,389
Public facilities	establishment	137	500	68,500	25,003
Schools	establishment	32	2,847	91,104	33,253
Industrial Plants	establishment	150	501	75,150	27,430
Other	establishment	0.5	27,077	13,539	4,942
Market Waste	**market**	**2045**	**44**	**89,980**	**32,843**
TOTAL WASTE GENERATED				**1,984,778**	**724,444**

	Unit	2012 Unit Generation (kg/day)	Quantity	Total Generation (kg/day)	Total Generation (tonnes/year)
Residential Waste				**1,546,918**	**564,625**
Low income population	person	0.36	1,847,661	665,158	242,783
Middle income population	person	0.474	1,250,066	592,531	216,274
High income population	person	0.621	465,746	289,228	105,568
Commercial Waste				**439,979**	**160,592**
Shops	establishment	0.5	47,941	23,971	8,749
Restaurants	establishment	38	1,582	60,116	21,942
Hotels (standard)	establishment	350	140	49,000	17,885
Hotels (lodgings)	establishment	100	586	58,600	21,389
Public facilities	establishment	137	500	68,500	25,003
Schools	establishment	32	2,847	91,104	33,253
Industrial Plants	establishment	150	501	75,150	27,430
Other	establishment	0.5	27,077	13,539	4,942
Market Waste	**market**	**2045**	**44**	**89,980**	**32,843**
TOTAL WASTE GENERATED				**2,076,877**	**758,060**

	Unit	2013			
		Unit Generation (kg/day)	Quantity	Total Generation (kg/day)	Total Generation (tonnes/year)
Residential Waste				**1,641,518**	**599,154**
Low income population	person	0.36	1,960,653	705,835	257,630
Middle income population	person	0.474	1,326,513	628,767	229,500
High income population	person	0.621	494,228	306,916	112,024
Commercial Waste				**439,979**	**160,592**
Shops	establishment	0.5	47,941	23,971	8,749
Restaurants	establishment	38	1,582	60,116	21,942
Hotels (standard)	establishment	350	140	49,000	17,885
Hotels (lodgings)	establishment	100	586	58,600	21,389
Public facilities	establishment	137	500	68,500	25,003
Schools	establishment	32	2,847	91,104	33,253
Industrial Plants	establishment	150	501	75,150	27,430
Other	establishment	0.5	27,077	13,539	4,942
Market Waste	**market**	**2045**	**44**	**89,980**	**32,843**
TOTAL WASTE GENERATED				**2,171,477**	**792,589**

	Unit	2014			
		Unit Generation (kg/day)	Quantity	Total Generation (kg/day)	Total Generation (tonnes/year)
Residential Waste				**1,738,326**	**634,489**
Low income population	person	0.36	2,076,281	747,461	272,823
Middle income population	person	0.474	1,404,744	665,848	243,035
High income population	person	0.621	523,375	325,016	118,631
Commercial Waste				**439,979**	**160,592**
Shops	establishment	0.5	47,941	23,971	8,749
Restaurants	establishment	38	1,582	60,116	21,942
Hotels (standard)	establishment	350	140	49,000	17,885
Hotels (lodgings)	establishment	100	586	58,600	21,389
Public facilities	establishment	137	500	68,500	25,003
Schools	establishment	32	2,847	91,104	33,253
Industrial Plants	establishment	150	501	75,150	27,430
Other	establishment	0.5	27,077	13,539	4,942
Market Waste	**market**	**2045**	**44**	**89,980**	**32,843**
TOTAL WASTE GENERATED				**2,268,285**	**827,924**

	Unit	2015			
		Unit Generation (kg/day)	Quantity	Total Generation (kg/day)	Total Generation (tonnes/year)
Residential Waste				**1,830,234**	**668,035**
Low income population	person	0.36	2,186,058	786,981	287,248
Middle income population	person	0.474	1,479,015	701,053	255,884
High income population	person	0.621	551,047	342,200	124,903
Commercial Waste				**439,979**	**160,592**
Shops	establishment	0.5	47,941	23,971	8,749
Restaurants	establishment	38	1,582	60,116	21,942
Hotels (standard)	establishment	350	140	49,000	17,885
Hotels (lodgings)	establishment	100	586	58,600	21,389
Public facilities	establishment	137	500	68,500	25,003
Schools	establishment	32	2,847	91,104	33,253
Industrial Plants	establishment	150	501	75,150	27,430
Other	establishment	0.5	27,077	13,539	4,942
Market Waste	**market**	**2045**	**44**	**89,980**	**32,843**
TOTAL WASTE GENERATED				**2,360,193**	**861,470**

		2016			
	Unit	Unit Generation (kg/day)	Quantity	Total Generation (kg/day)	Total Generation (tonnes/year)
Residential Waste				**1,923,692**	**702,148**
Low income population	person	0.36	2,297,686	827,167	301,916
Middle income population	person	0.474	1,554,539	736,851	268,951
High income population	person	0.621	579,185	359,674	131,281
Commercial Waste				**439,979**	**160,592**
Shops	establishment	0.5	47,941	23,971	8,749
Restaurants	establishment	38	1,582	60,116	21,942
Hotels (standard)	establishment	350	140	49,000	17,885
Hotels (lodgings)	establishment	100	586	58,600	21,389
Public facilities	establishment	137	500	68,500	25,003
Schools	establishment	32	2,847	91,104	33,253
Industrial Plants	establishment	150	501	75,150	27,430
Other	establishment	0.5	27,077	13,539	4,942
Market Waste	**market**	**2045**	**44**	**89,980**	**32,843**
TOTAL WASTE GENERATED				**2,453,651**	**895,583**

		2017			
	Unit	Unit Generation (kg/day)	Quantity	Total Generation (kg/day)	Total Generation (tonnes/year)
Residential Waste				**2,017,151**	**736,260**
Low income population	person	0.36	2,409,314	867,353	316,584
Middle income population	person	0.474	1,630,063	772,650	282,017
High income population	person	0.621	607,324	377,148	137,659
Commercial Waste				**439,979**	**160,592**
Shops	establishment	0.5	47,941	23,971	8,749
Restaurants	establishment	38	1,582	60,116	21,942
Hotels (standard)	establishment	350	140	49,000	17,885
Hotels (lodgings)	establishment	100	586	58,600	21,389
Public facilities	establishment	137	500	68,500	25,003
Schools	establishment	32	2,847	91,104	33,253
Industrial Plants	establishment	150	501	75,150	27,430
Other	establishment	0.5	27,077	13,539	4,942
Market Waste	**market**	**2045**	**44**	**89,980**	**32,843**
TOTAL WASTE GENERATED				**2,547,110**	**929,695**

- Estimations of waste disposed of at dumpsite based in calculated weighted percentage as at 2010 (33% assumed disposal rate)

Percentage of total waste	33%	
Year	Total Waste Generated (tonnes/year)	Estimated amount disposed at dumpsite (tonnes/year)
2010	691,741	228,274
2011	724,444	239,066
2012	758,060	250,160
2013	792,589	261,554
2014	827,924	273,215
2015	861,470	284,285
2016	895,583	295,542
2017	929,695	306,799

Step 4: Consolidating waste disposed at dumpsite from 1981 to 2017

Table 40: Inputs of waste estimates in Dandora dumpsite used in LandGEM

Year	Waste disposed (tonnes/year)
1981	116,667
1982	116,667
1983	116,667
1984	116,667
1985	116,667
1986	116,667
1987	116,667
1988	116,667
1989	116,667
1990	116,667
1991	116,667
1992	116,667
1993	116,667
1994	116,667
1995	116,667
1996	116,667
1997	116,667
1998	116,667
1999	116,667
2000	116,667
2001	116,667
2002	116,667
2003	116,667
2004	116,667
2005	116,667
2006	145,000
2007	187,000
2008	193,000
2009	220,000
2010	228,274
2011	239,066
2012	250,160
2013	261,554
2014	273,215
2015	284,285
2016	295,542
2017	306,799
Total	**5,800,564**

Appendix I Landfill Gas and CH_4 Emission from Dandora Dumpsite

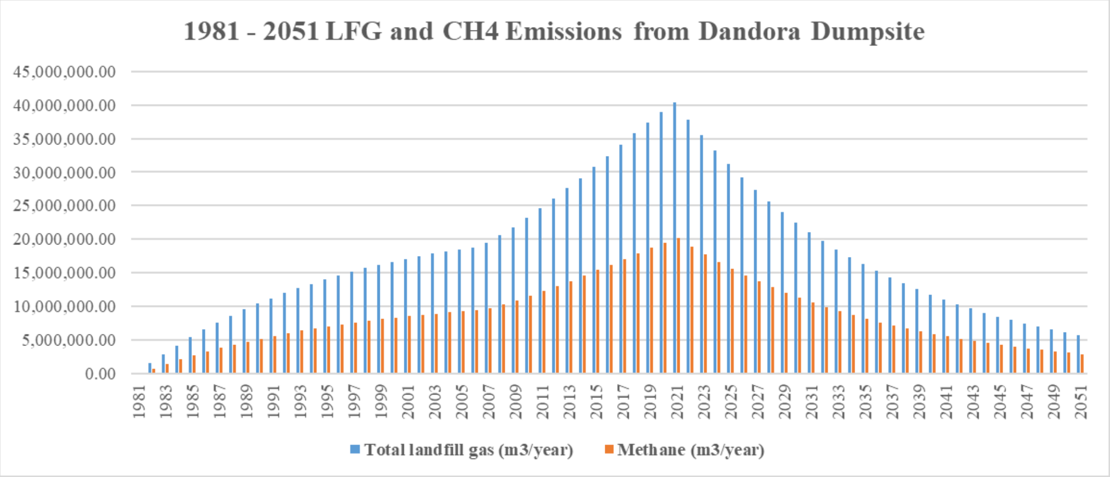

Figure 33: 1981-2051 LFG and methane emissions results from LandGEM

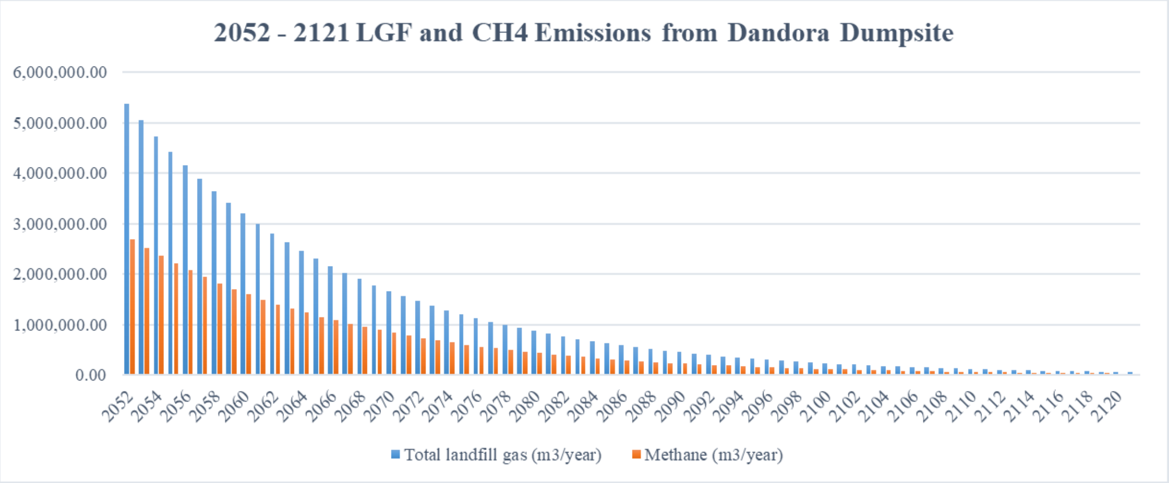

Figure 34: 2052 - 2121 LFG and methane emissions results from LandGEM

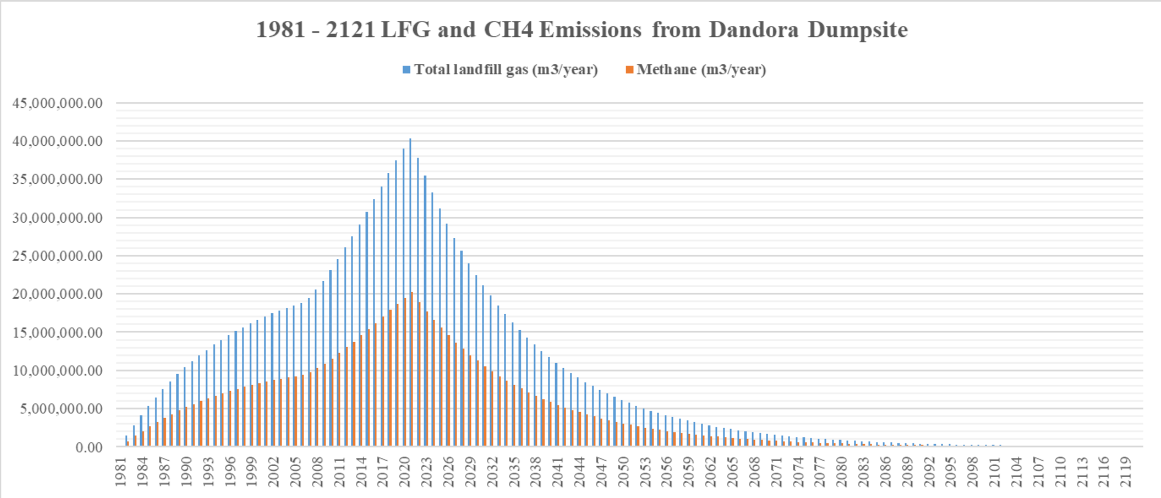

Figure 35: 1981 to 2121 LFG and methane emissions results from LandGEM