The Potential of Grid Power Generation from Municipal Solid Waste for Nairobi City

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Abstract

The objective of this research is to minimize the environmental impact of municipal solid waste through the development of a waste to electricity Rankine cycle power plant to generate steam and electricity from municipal solid waste for Nairobi city as a solution to waste management challenges. Quantification of solid waste for the City was done to provide design data for sizing and selection of a solid mass burning boiler furnace. The study demonstrated that municipal solid waste can be used as fuel directly or as refuse derived fuel upon processing which enhances its properties for use in electricity production. The study proposes a power plant of capacity 12 MW processing 3000 tonnes of solid waste per day. The main elements of the plant are, a multi-fuel boiler, super heater, economizer, turbine, surface condenser and a cooling tower. The power plant can generate 72, 751,770 kWhrs of electricity annually. This will lead to avoided carbon emissions from fossil fuel power plants and hence make a contribution to the energy transition. Additionally waste to energy conversion reduces the weight of solid waste by 60 to 90% of the original weight making disposal easier. The electricity will be sold to the grid to generate revenue to improve solid waste management and other programs leading to sustainable environmental management for the city.

Keywords: condenser; waste to energy; cogeneration, multi-fuel power plant; multi-fuel boiler; economizer; condenser**;** municipal solid waste; solid Waste management.

1. Introduction

Energy recovery from waste or Waste-to-Energy (WtE) is an effective attractive value addition and waste management option for many countries. Various WtE technologies offer valuable energy, reduce the burden on the land in form of landfill disposal and mitigate greenhouse gas emissions by avoiding decomposition and substitution of fossil fuel generated power (Kabeyi & Oludolapo, 2020a, 2020b). Because of these benefits, the global market for WtE technologies has experienced substantial growth (World Energy Council, 2013) with now over 1200 operating plants across 40 countries (Ghosh, 2014).The Waste-to-energy power plants burn municipal solid waste (MSW) to generate steam in a boiler that is used to run a Rankine cycle steam turbine to generate (Qingbin et al., 2020). Municipal Solid Waste is a mixture of energy-rich materials like paper, plastics, yard waste, and products made from wood as well as noncombustible materials. For every 100 kg of MSW in the United States, about 85 kg can be burned as fuel to generate electricity (Barasa, 2020). The Waste-to-energy power reduce can reduce 2,000 kg of MSW to ash weighing about 300 kg to 600 kg, while the volume of MSW can be reduced about 87% (US Energy Department, 2020; Yap & Nixon, 2015).

The world urban population grew to reach 50% of the global population in 2015 and is expected to reach 70% of the world population by the year 2050 with developing countries accounting for most of this growth. Africa's urban population is expected to grow from 470 million in 2015 to 1.2 billion by 2050. This is expected to come along with significant challenges of municipal solid waste (MENR, 2017). According to the World Bank (2012) the rate of growth of solid waste will outpace the rate of urbanization. It is projected that municipal solid waste was to grow from 0.64 kg/person per day in 2002 to 1.2 kg/person per day in 2012 or 1.3 billion tons per year, and 1.42 kg per person per day or 2.2 billion tons by the year 2025.

Solid waste is the useless, unwanted products in the solid state derived from various activities of and discarded by society Waste is generated continuously in every single way from our daily activities (Conrad, 2012). Urbanization is associated with high population density, increased waste generation, and increased littering, increased pressure on limited and diminishing free land for disposal and environmental challenges (UNEP, 2005; Jumba, 2017). Municipal solid waste is the non-hazardous part of solid wastes generated by businesses, households with exception of industrial processes waste, building debris, construction wastes, offal, sludge (National Renewable Laboratory, 1995). Municipal solid waste (MSW) also called trash or garbage includes tires, furniture wastes, newspapers, plastics, containers, packaging materials (Center for Sustainable Systems, 2010).

Municipal solid waste management is a process which encompasses, planning, organization, engineering, administration, financial and legal dimensions and aspects related to municipal solid waste (Jumba, 2018). According to Munala & Moirongo (2011) municipal solid waste management refers to all activities and processes with respect to municipal solid waste namely waste collection, sorting, control, transport, processing and disposal in line with best principles including engineering, economics, conservation aesthetics, health and environmental considerations. The UN- Habitat (2011) noted that the main trouble with municipal solid waste management is the quantity and diversity of solid waste available. This makes the process complex and expensive (Hoornweg & Bhada-Tata, 2012). Excessive waste generation due to inefficient production, low product and service durability and unsustainable production and consumption (Kenya Republic, 2011). Integrated waste management involves waste reduction, source separation, recycling, waste reuse, material recovery and remain disposal through landfill (UNEP, 2011).

The aim of this research is to minimize the environmental impact of municipal solid waste through the development of a waste to electricity Rankine cycle power plant to generate steam and electricity from municipal solid waste in Nairobi city as a solution to waste management challenges. The electricity generated will lead to avoided generation from fossil fuel sources which are polluting and contribute heavily to greenhouse gas emission from power generation (Kabeyi & Oludolapo, 2020c, 2020d) .

2.0. Problem Statement

Waste management procedures in developing countries is associated with occupational safety and health risks (Bleck & Wettberg, 2012). The huge influx of people into the city of Nairobi has led to increased waste generation and with several related challenges. One of the common feature in Nairobi City is uncollected solid waste in several parts of the city due to poor solid waste management system. A sore sight of piles of garbage with choking smell and scavenging vultures at Dandora dumpsite cannot go unnoticed dumpsite by anybody (UNEP, 2011). According to a study by JICA in 2010, Solid waste generated in Nairobi on a daily basis is about 3,000 to 4,016 tons. The collection rate is as low at 33% (JICA, 2010) which leaves about 2,690 tons uncollected. Solid waste. This compares quite unfavorably with cities having similar population like Addis Ababa in Ethiopia (Oyake-Ombis, 2018). UNEP commissioned a couple of studies showing dangerously high levels of heavy metals in the surrounding environment and in the body of local residents (Onyari, 2017). Dandora dumpsite was deemed full in 2001, yet it still receives unfiltered wastes of about 2000 tons of solid waste daily, including hazardous chemicals and hospital wastes. The dumpsite itself is a crime zone, mainly due to jobless hence youths idle in the area, youth who strike fear in the residents even in broad daylight (Jeremiah, 2018). To overcome this menacing problem, there is need to come up with environmental friendly sustainable solutions that will absorb the waste. Even with promotion of reuse and recycling, total solid waste dumped remains increasingly high (MENR, 2013). Authorities should develop policies and measures aimed at maintaining a clean environment, mitigate greenhouse gas emissions and facilitate sustainable development (Kabeyi & Oludolapo, 2020b).

Dandora dumpsite covers 43 hectares of land fully occupied by wastes which is an equivalent of 60 football pitches. The solid waste in this dumpsite has contaminating the groundwater for years and impacts over half a million residents living around the dumpsite. A 2007 study by UNEP that examined 328 children living close to the dumpsite uncovered that half had blood lead levels equal to or exceeding the poisoning threshold of 10 micrograms per deciliter of blood. Exposure to such high levels of lead is linked with damage to the nervous system and the brain. (MENR, 2017). Around one third of Nairobi's waste is transported to the only dumpsite, Dandora. About 200 trucks offload garbage at Dandora dumpsite daily (WEMAK, 2015). Figure 1 below summarizes the health conditions around the dumpsite.

Figure 1: A truck off; loading solid waste at the Dandora Dumpsite in Nairobi (MENR, 2017)

From figure one, it can be noted that the dumpsite is congested with muddy access while idle youth await arrival of fresh waste to scavenge for any valuables.

3.0. Waste to Energy Conversion

There exist different technologies of waste-to-energy systems, but the most common type used in the United States and China is the mass-burn system, where unprocessed MSW is burned am incinerator or furnace with a boiler and a generator for electricity generation. Another less common type of system processes MSW to remove most of incombustibles materials to produce refuse-derived fuel (RDF) (Qingbin et al., 2020; US Energy Department, 2020).

Domestic waste contributes 68% of the total waste generated in Nairobi; while non-domestic waste from industrial area, markets, roads & other activities contributing a combined total of about 32% of the total waste generated, broken down as follows; Industrial: 14 %; roads: 8 %; hospitals: 2 %; markets: 1 %; and 7 % from other sources (MENR, 2017). The National Solid Waste Management Strategy developed by the National Environment Management Authority (NEMA) reported that, Nairobi generated 2400 tons of waste per day. Of these, 80 percent are collected, 20 percent is uncollected and 45 percent of the waste is recovered. (MENR, 2017, World Bank, 2012). The continued increase in Kenya's urban population has made it difficult to manage solid waste leading just less than 40% being collected and dumped in open dumpsites (David Conrad, 2012) MENR, 2017). This is a danger to health due to waste contamination of soil and water with hazardous material which end up in the food chain and water cycle. It is only by institutional and policy adherence to the hierarchy that emphasizes weight reduction, reuse and recycling that waste to energy conversions gets priority in municipal waste solid waste management (Kokalj, & Samec, 2019).

Waste to Energy (WtE) is the generic term given to a process by which the energy stored in waste is extracted in the form of electricity, heat and/or a fuel for use in a de-centralized energy generation plant. Energy recovery from waste can solve two problems at once: treating non-recyclable and non-reusable amounts of waste; and generating a significant amount of energy that can be included in the energy production mix in order to satisfy the consumers' need(*World Energy Resources*, 2016) The high rate of population growth, the rapid pace of the global urbanization and the economic expansion of developing countries are leading to increased and accelerating rates of solid waste production(Barasa, 2019; World bank Bank, 2012) The choice of waste to energy conversion technology depends on the nature and volume of the incoming waste stream. The energy content largely determines how much energy, can be extracted from it. A number of technologies are commercially available and have been deployed. These represent a number of fundamentally different technologies under two main groups: e.g. biological processing of biodegradable waste and thermal technology of residual waste, including direct combustion (incineration) and Advanced Conversion technologies (ACT - gasification and pyrolysis(Union, 2000)The benefit of waste to heat is massive reduction in weight of the solid waste by 60 to 90% of the original weight besides steam and power generation capability (Fobi, 2002, Salvapalo et al, 2007, Khamala & Aganda, 2013). The waste to heat pathways are broadly classified into thermal incineration, gasification and pyrolysis anaerobic digestion is a biochemical pathway. The incineration process converts waste into ash, flue gas, and hea(R. Lew, 2018) Incineration is only applicable only when the lower calorific value (LHV) of the feedstock is on the average over 7 MJ/kg and should never fall below 6 MJ/kg in any season (Lewis, 2018; World Energy Council, 2013).

Moving grate incineration is one of the most efficient technology for a large-scale mixed MSW treatment because it is the only thermal technology able to treat over 3,000 tons of mixed MSW per day. It also seems to be considerably cheaper than conventional technologies(Rachael Lew, 2018) Moving grate can be used in a wide range of composition and physicochemical properties of processed solid waste. The thermal systems used in the Waste to Energy/heat power plants have an efficiency of about 20 (Khan, 2010) Through cogeneration, efficiency can be improved to around 40% or more("Clarke Energy," 2015) In this approach application of heat and power is adopted.

3.1. Municipal solid fuel as fuel for power generation

The heterogeneous nature of composition of MSW makes it difficult for traditional technologies of fuel combustion and processing (Muthuraman & Reddy, 2013). Presence of garbage in municipal solid waste reduces its calorific value to as low as 800 kca/kg. If the waste is processed, a study on Indian MSW showed that the energy content will vary from 3000-4000 kJ/Kg which is comparable to Indian coal (Muthuraman & Reddy, 2013). In another study on characteristics of refused-derived fuel (RDF), it was established that Gross calorific values (GCVs) varied between 14.6 and 40.2KJ/g. The calorific value significantly increases when the composition of plastics is high, presenting 33.6 ± 0.5, 40.2 ± 1.0, and 28.6 ± 0.4 for non-packaging hard plastics, packaging foils, and packaging polyethylene terephthalate (PET), respectively. Total chlorine contents are less than 4 mg/g, except for non-packaging hard plastics. Cadmium contents of organic kitchen waste (KW) and non-packaging hard plastics (HP) respectively are below the detection limit and the lead content of kitchen waste is also below it. This results show that MSW can be used as refused derived fuel and conversion can be done through various conversion technologies (Nam-Chol, & Kim, 2017).

3.2. Composition of Nairobi's MSW.

In the analysis of MSW as a fuel in waste to energy conversion, important parameters are the moisture content, composition, density calorific value. Bulk density influences costs involved in collection, storage and tipping. The bulk density in most developing countries varies fromm120kg/m^3 to 540kg/m^3 while calorific value generally varies between 1.578 MJ/kg to 20 MJ/kg based on studies carried out in Ghana, Senegal and Malaysia (Khamala & Aganda, 2013, Moses, 2019). A study on composition of waste in Nairobi city gave the following results on average basis in Table 1 and Table 2 , while the composition of the municipal (residential) solid waste in Nairobi is depicted in Figure 2;

Table 1: Composition of MSW in Nairobi (Khamala & Aganda, 2013).

MSW CONSTITUENT	COMPOSITION
Plastics	14.15
Organic or food waste (Putrescibles)	59.33
Inorganics (bottles, metals and others	7.74
Leather & Textiles (LT)	7.53
papers	12.65
Total	**100%**

Table 1 shows that organic waste constitute the largest portion of MSW in Nairobi with about 59.33% while leather and plastics is the list.

Table 2: The Nairobi waste compositions, 1985 – 2010 (Allison et al, 2009)

CONSTITUENT	COMPOSISTION
Plastics	13.8%,
Organic or food waste (Putrescible)	58.8%
Inorganics (bottles, metals and others	8.30%
Leather & Textiles (LT)	7.80%.
papers	11.30%,
Total	**100%**

Table 2 shows that organic or food waste constitute the highest composistion in municipal solid waste while leather and textile is the least component of the Nairobi's MSW.

Figure 2 below shows the composistion of domestic municipal solid waste.

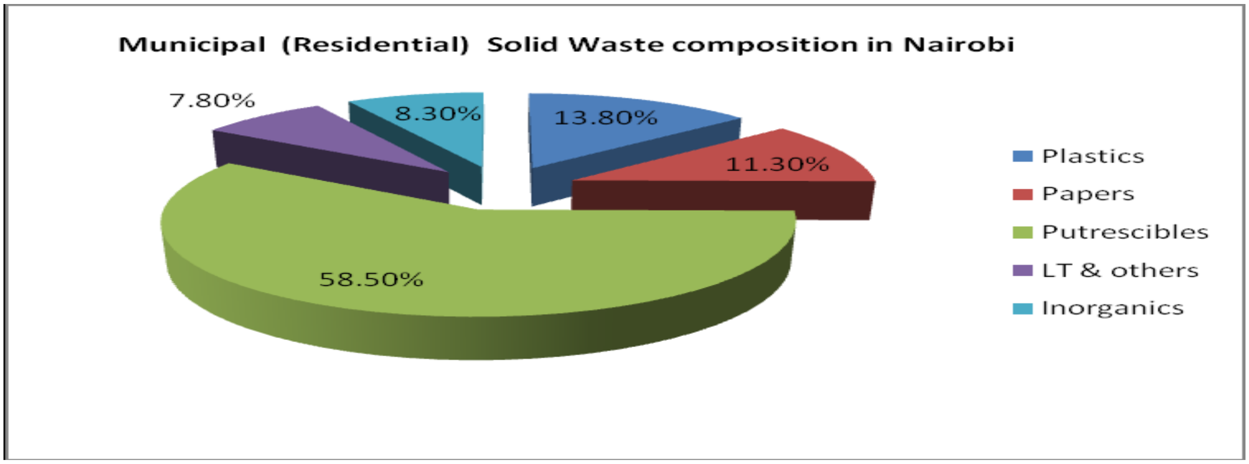

Figure 2: Composition of the MSW f 1995 and 2010 (Allison Kasozi, Harro von Blottnitz, 2009).

From figure 2, it is noted that putrescible or food waste are the main constituents of domestic solid waste is Nairobi. Other materials are plastics, paper, leather & textiles and inorganics.

3.3. Moisture content of Nairobi's MSW.

The moisture content of MSW significantly affects its combustion characteristics and the heat value. The contents varies with type of waste and the season or weather. In the study by Khamala & Aganda (2013), it was observed that the moisture content of the MSW in Nairobi varied from a low of 63.2% and a high of 75.0% giving a weighted average of 68.9% as moisture content.

3.4. Density of Nairobi's MSW

The mass density of the MSW in Nairobi varies from 296 kg/M^3 to 282 kg/m^3 and average of 289 kg/m^3 (Khamala & Aganda, 2013). These compares unfavorably with the 410 to 546 kg/m^3 sampled in Ghana in (Fobil, et al, 2005), but more favorable and less varied compared to 120-330 kg/m^3 sampled in Kuala Lampur in (Sivapalan, et al, 2002). It should however be noted that the properties tend to vary from time to time based on peoples consumption trends and items consumed.

3.5. Calorific value of municipal solid waste

The mean calorific value of MSW for Nairobi was computed in Khamala & Aganda (2013) as a low of 12.36 MJ/kg and a high of 18.36 MJ/kg and average of 15.70 MJ/kg for the dominant organic components and average of 12.48 MJ/kg. This compares unfavorably with the mean calorific value of coal taken as 23.25 MJ/kg hence we expect less power out per unit mass from the MSW in Nairobi city (Khamala & Aganda, 2013).

4.0 Overview of the MSW Power Plant Design

4.1. Waste-to-energy plants make steam and electricity

MSW is usually burnt at special waste-to-energy plants that use the heat from the flue gases generate steam for generating electricity by running a steam turbine (Kabeyi & Oludolapo, 2020), with potential for process heat application (Kabeyi, 2020). In 2018, 68 U.S. power plants generating 14 billion kWhrs of electricity burnt 29.5 million tons of combustible MSW. Biomass materials content accounted for 64% of the weight of burnt MSW and about 51% of these electricity produced with the remainder being non biomass sources, mainly plastics. Many large landfills also generate electricity by using the methane gas by decomposing biomass in landfills (EIA, 2019). Burning waste generates steam, hot water and electricity and also reduces the amount of material that would probably be buried in landfills by about 87% by volume. An example of a solid waste cogeneration plant is shown in Figure 3 below. During thermal treatment the energy content is released and the volume and weight of waste reduced by approximately 90% (EIA, 2019). Generally, a MSW cogeneration plant operates 90%-95% of the time with 5% taking care scheduled/planned maintenance and unplanned events also called forced plant outage (EIA, 2019: Kabeyi, 2020).
Figure 3 below illustrates a mass burn waste to electricity power plant.

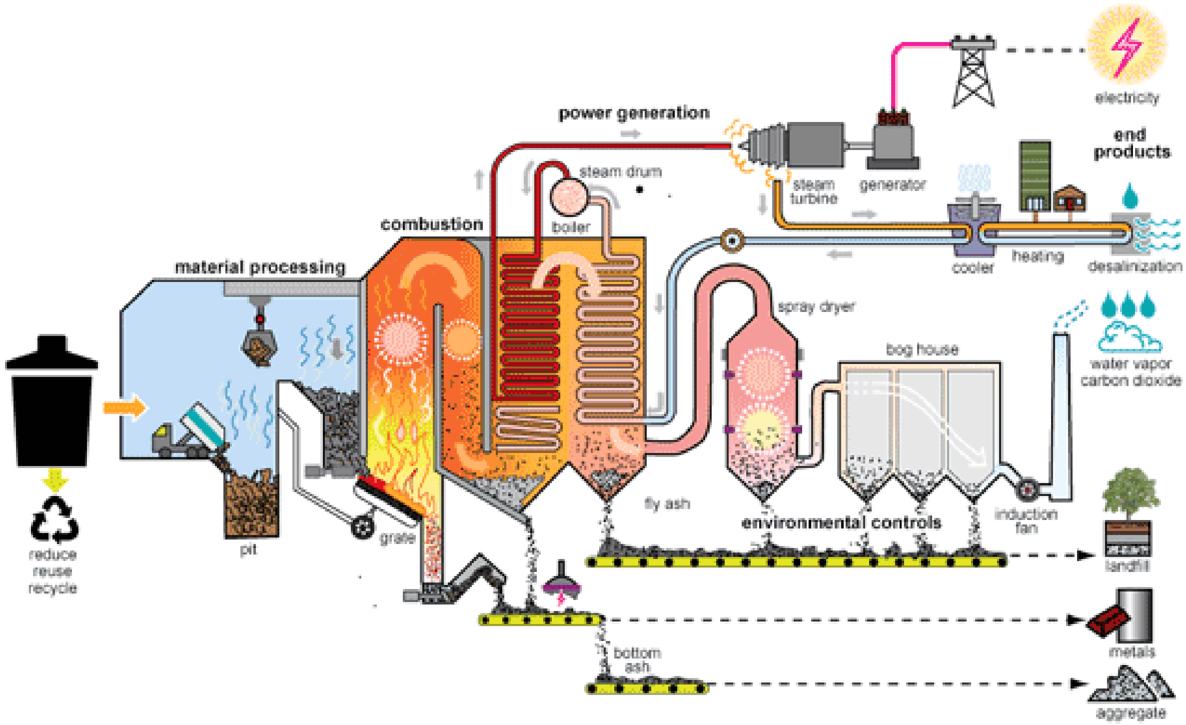

Figure 3: Model of solid waste cogeneration plant (Khamala & Aganda, 2013).
From figure 3 is a model of a municipal solid waste power plant with main elements being tipping feed chute, moving grate boiler, electrostatic precipitator, the stack, fans, turbine other elements. The first step shows that before the incineration in mass boiler, the waste should be subjected to reduce, reuse and recycle options of solid waste management.

The process of generating electricity in a mass-burn waste-to-energy plant has seven stages:

1. Waste is dumped from garbage trucks into a large pit for temporary storage and preparation.
2. The MSW is grabbed and dumped in a combustion chamber.
3. The MSW is burned, releasing heat and flue gases which are transmitted by means of a draught to the chimney/stack with heat exchangers installed along the path.
4. The heat is transferred from the flue gases to water and converted to into steam in a boiler.
5. The generated steam which is at high-pressure and temperature as well as dry is piped to Rankine cycle steam turbines steam turns the blades of a turbine generator to produce electricity.
6. An exhaust cleaning system removes pollutants from the combustion gas before it is released through a smoke stack to the environment.
7. Ash deposits are collected from the boiler and the air pollution control system for disposal (US Energy Department, Nordi, et al, 2017, Kabeyi, 2019).

4.2. Moving grate

The grate resembles a staircase where the grate bars are alternately placed horizontally and vertically. The grate bars are mounted on shafts and as the grate bars of one axle interferes with the bars of the adjoining axle, a continuous grate carpet is formed. The grate is placed at a 26^0C inclination from the horizontal. The grate should be designed in a way that it can accommodate the heat released by combustion. The calculation of the calorific value is as shown below;

$$H_{low,overall} = \frac{M_1}{100} \times H_{low,1} + \frac{M_2}{100} \times H_{low,2} + \frac{M_3}{100} \times H_{low,3}$$

Where; H_{low} – Lower calorific value of each type of waste
M – The percentage weight of wet MSW

4.3. Boiler system design

Water tube boiler with feed water is maintained at a minimum of 125ºC to 130ºC will be used. The design of the boiler and combustion chamber addresses the need to cool the flue gas temperature to approximately 650ºC before it reaches the heat transfer surfaces of the boiler. A boiler efficiency of up to approximately 80 percent can be achieved. There are three major heat exchanger components in the boiler; evaporator, economizer and a super heater. The feed water is at first preheated sensibly in the economizer in liquid phase at a certain pressure. Figure 4 is a schematic diagram of the proposed steam boiler system (Kabeyi, 2020).

And equipemnt.

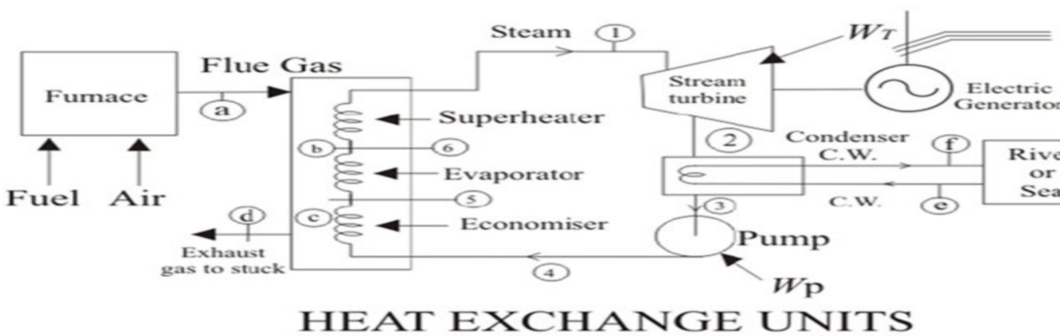

Figure 4: Components the boiler system (Kabeyi, 2020).

From figure 4, it is noted that heat in flue gases is used to heat water in the boiler to generate superheated steam. To realize this, it is equipped with the evaporator, super heater and economizer. Steam is then used to run a turbine which is coupled to a generator to generate electricity for export to the public grid. Combustion air is supplied with the aid of fans and the stack which provides the draught and exist for flue gases disposal to the atmosphere. Some electricity is used in the power plant to supply power to motors and other machines. The waste heat or steam can be used for other heating applications like drying.

Q economizer = $h_5 - h_4$
Q evaporator = $h_6 - h_5$
Q super heater = $h_1 - h_6$

In a steam boiler, the economizer is a heat exchanger device that recovers residual heat from the flue gases. The recovered heat is used to preheat the boiler feed water that will eventually be converted to superheated water. The flue gases are cooled to approximately 160^{0}C to 220^{0}C in the economizer before being passed on to the flue gas cleaning system. The maximum operating temperature of an economizer tubes lies below 399^{0}C.

Super heater is a coil type heat exchanger, which converts saturated steam into a superheated steam generated by a boiler. Super heater only utilizes sensible heat to superheat the steam in order to increase its enthalpy. In order to achieve this, the saturated steam is allowed to pass through the tubes of a super heater exposed to the flue gas. Superheating of steam generally increases the plant efficiency. The temperature of the flue gas that enters into the super heater may vary from approximately 650 to 900^{0}C. The super heater tube metal temperatures are generally in the range of 370 to 540^{0}C, depending on the steam temperature, along with other factors. The tube metal temperatures of the water wall, although depending on the operating pressure of the boiler along with other factors, are generally in the range of 260 to 315^{0}C.

4.4. Steam turbine design and selection

Incoming high-pressure steam from the boiler is expanded to a lower pressure level in the steam turbine. The thermal energy of high-pressure steam is converted to kinetic energy through nozzles and then to mechanical energy through rotating blades. The steam turbine consists of moving set of adjacent plates called buckets or rotor blades installed within a casing and a stationary set of blades called nozzles. The rate of change of momentum across the blades produces the torque required to drive the shaft. Condensing turbine is the primary type of turbine adopted for the conventional WtE utilities. This is because it is more efficient than both back pressure and extraction turbines in power generation (Kabeyi, 2020).

4.4.1 Flue gas recirculation

Flue gas recycling can increase efficiency and lower emissions through cooling the flue gases without the demand for more air. The recycled flue gas is injected the same way as the secondary air and is used for cooling and effective mixing of combustion products. The result is a higher total thermal efficiency of the plant and a reduction in NO_x emissions.

4.4.2. Condenser

This is a device where the steam from the exhaust of the turbine is condensed into liquid water. The Surface condenser is selected for the WtE due to its ability to increase the thermal efficiency of the plant and its suitability for higher capacity. Its condensate can be used as the boiler feed water. Cooling water of poor quality can be used to cool the steam because there is no direct contact between the steam and the cooling water.

4.4.3. Cooling Tower

A cooling tower is used to cool the hot water so that the cooled water can be reutilized in the condenser again. The cooling towers are useful when there is a scarcity of both water and land. Cooling towers are generally hyperbolic in shape.

4.4.4. Feed Pump

This device is used to pump the feed water to the boiler at very high pressures for steam generation. Its pressure range from 6-10% more than the boiler steam pressure.

4.4.5. Air Preheater

It heats the air before it is supplied to the combustion chamber by use of heat of the flue gas. Supply of preheated air influences the furnace temperature and accelerates the combustion of the MSW. The air preheater is set to recover some of the heat escaping the economizer since it cannot utilize all the heat.

4.4.6. Dry Scrubber and Flue gas chimney

Its main goal is to expel the harmful gases that results from the waste to energy process plant. The main exhausts of this process are Sulphur (IV) Oxide, Carbon (IV) Oxide and Nitrogen (IV) Oxide. The dry scrubber is lined with Calcium hydroxide, which reacts with the acid gases. This compound reacts with the harmful flue gases and makes sure that the gases released are not harmful to the environment. Reactions of the flue gases and Calcium hydroxide forms the following products;

$Ca(OH)_{2(s)} + SO_{2\,(g)} \longrightarrow CaSO_{3(s)} + H_2O_{\,(l)}$

$Ca(OH)_{2(s)} + 4NO_{2\,(g)} + O_{2\,(g)} \longrightarrow 2Ca(NO_3)_{2(s)} + 2H_2O_{\,(l)}$

4.7. Restricting and Limiting Conditions

The lack of up-to-date data on municipal solid waste generated in the city regarding the amount generated daily and waste streams was the main limiting factor in our project. Secondly, the time required to conceptualize the proposal, collect data and make the actual design was a limiting factor due to the complex nature of the plant design.

5. Results

5.1 Technical data obtained

Tables 3 and 4 explains the waste fractions and the projected waste generation from 2009 to 2019 taking population into perspective.

Table 3: Technical Data Obtained (Kokalj, & Samec, 2019).

Waste fractions	**2009**	**2010**
Organic waste	1671	2160.3
Paper	574.5	484.7
Plastic	528.6	377.4
Glass	65.66	51.9
Metal	65.66	24.2
Others	374.3	363.5
Total Waste	**3283 tons**	**3462 tons**

From table 3, it is noted that the total municipal solid waste for 2010 was 3,462 tons. However some elements like metal and glass may be of no value in combustion for steam generation and can be removed (Nordi et al, 2017).
There is a significant increase in the total amount of municipal solid waste produced and this could be attributed to population growth and an increase in affluence. The amount of plastic and paper waste is seen to have decreased and

this is due to efforts in recycling and reusing the materials. The ban on plastic bags by NEMA will see a further decline in the amount of plastic wastes.

Table 4: Projection of Solid Waste Generation (Khamala, & Aganda, 2013)

Projected population		
Year	Logistic Population (millions)	Total MSW (tons/day)
2009	3.5633	3283
2010	3.7046	3462
2011	3.8475	3644
2012	3.9918	3829
2013	4.1372	4016
2014	4.2833	4206
2015	4.4299	4398
2016	4.5766	4592
2017	4.7231	4788
2018	4.8692	4986
2019	5.0145	5186
2020	5.1588	5386

The table 4 above shows a projection of solid waste generation from the years 2009 to 2020 based on a research by JICA. The projection shows that by the year 2020, Nairobi will about 5,386 tons of municipal solid waste per day. This is significant growth of about 64% between 2009 and 2020, and hence any planning should capture this growth projections. The trend is shown in figure 5 below.

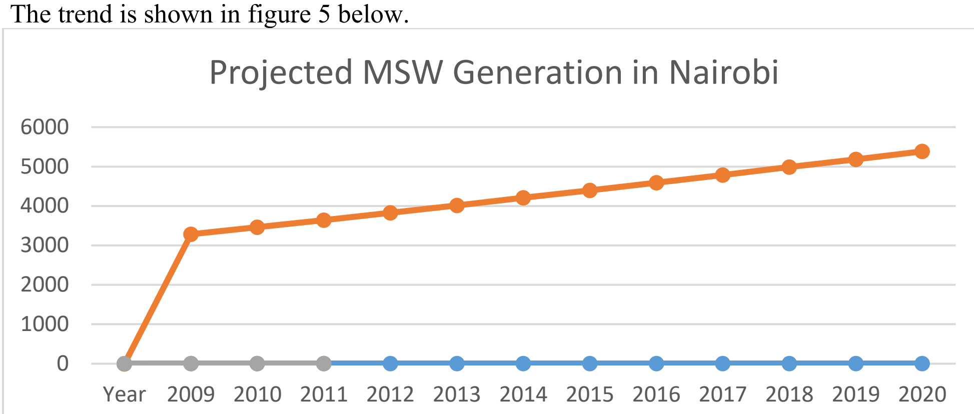

Figure 5: Projected MSW generation in Nairobi (JICA, 2010)

Figure 5 above demonstrates the projected growth trajectory of total solid waste management in the city of Nairobi up to the year 2020. It shows a steady growth projection hence the need for proper capacity planning.

5.2. Plant Performance Analysis and Calculations

Figure 6 shows the main elements of the Rankine cycle power plant cycle

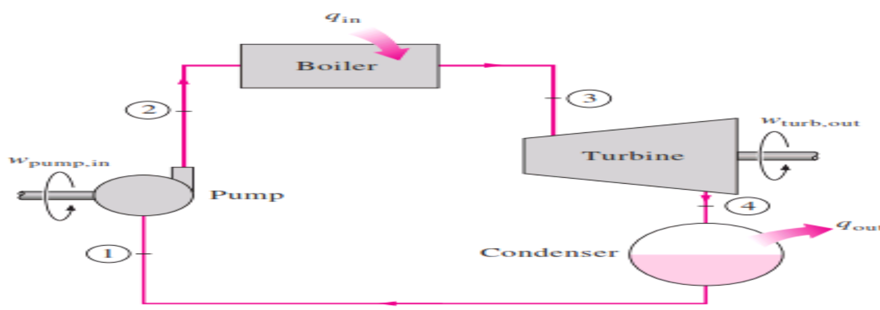

Figure 1: Flow analysis in the Rankine Cycle for the Power plant (Kabeyi, 2020).

From figure 6, the main processes in the power plant correspond to the Rankine vapour power cycle which consists of the following four processes;
Process 1-2 – Isentropic compression in a pump
Process 2-3 – Constant pressure heat addition in a boiler
Process 3-4 – Isentropic expansion in a turbine
Process 4-1 – Constant pressure heat rejection in a condenser

5.3. Combustion analysis

The stoichiometric combustion equations are:

$C + (O_2 + \frac{79}{21} N_2) \rightarrow CO_2 + \frac{79}{21} N_2$

$H + \frac{1}{2} (O_2 + \frac{79}{21} N_2) \rightarrow H_2O + \frac{79}{42} N_2$

$S + (O_2 + \frac{79}{21} N_2) \rightarrow SO_2 + \frac{79}{21} N_2$

Expressions for complete combustion using excess air:

$H + (1+\emptyset)(O_2 + 3.76N_2) \rightarrow 0.5H_2O + (1+\emptyset)(3.76 N_2) + (0.75+\emptyset) O_2$

$C + (1+\emptyset)(O_2 + 3.76CO_2) \rightarrow CO_2 + (1+\emptyset)(3.76N_2) + \emptyset O_2$

$S + (1+\emptyset)(O_2 + 3.76N_2) \rightarrow SO_2 + (1+\emptyset)(3.76N_2) + \emptyset O_2$

Mass balance can be expressed as:

$m_{in} = m_{out}$

Where: m_{in} – mass of reactants
m_{out} –mass of products

$m_{air} + m_{fuel} = m_{ash} + m_{fluegas} + m_{mst}$

$m_{air} = (m_{ash} + m_{fluegas} + m_{mst}) - m_{fuel}$

Stoichiometric air amount can be calculated as follows:

$m_{air,stoich}$= O_2 of air required by one kg of fuel/23.3% of O_2 in air, where air assumed to contain 23.3% of mass

$$m_{air,steo} = \frac{m_{O,H}X_H - m_{O,O}X_O + m_{O,S}X_S + m_{O,C}X_C}{0.233}$$

Where: $m_{O,H}$, $m_{O,O}$, $m_{O,S}$, $m_{O,C}$ are the masses of O_2 in hydrogen, oxygen, sulphur and carbon respectively.
X – Percentage amount of an element contained in a chemical composition.

Theoretical combustion analysis of MSW yields:

$C + O_2 \rightarrow CO_2$

$H_2 + 0.5O_2 \rightarrow H_2O$

$S + O_2 \rightarrow SO_2$

$$m_{air,steo} = \frac{\frac{16.00}{2.016}X_H - \frac{32.00}{32.00}X_O + \frac{32.00}{32.06}X_S + \frac{32.00}{12.01}X_C}{0.233}$$
$$= 34.3348X_H - 4.2918X_O + 4.2918X_S + 11.4449X_C$$

With excess air ratio,

$n = (1 + \emptyset)$

Where n –excess air ratio

$$\emptyset = \frac{\text{Actual}\frac{A}{F}\text{ratio} - \text{Stoichiometric}\frac{A}{F}\text{ratio}}{\text{Stoichiometric}\frac{A}{F}\text{ratio}}$$

For air supply in excess of 80%, it is suggested to optimize the combustion of solid refuse in the mass burning systems.
$m_{air} = (34.3348X_H - 4.2918X_O + 4.2918X_S + 11.4449X_C)(1 + \emptyset)$
$m_{fluegas} = (34.3348X_H - 4.2918X_O + 4.2918X_S + 11.4449X_C) + (1 - X_{ash} + X_{mst})$
When there is excess air:
$m_{fluegas} = (34.3348X_H - 4.2918X_O + 4.2918X_S + 11.4449X_C)(1 + \emptyset) + (1 - X_{ash} + X_{mst})$
The calculation of the mass of air above can be solved by using the elemental analysis of waste given in the table below.

Table 5: Elemental Analysis of Waste (Khamala, & Aganda, 2013)

Element	C	H	O	S	N	Moisture	Ash
Percentage	47.025	5.175	29.700	0.09	1.620	10.000	6.390

Table 5 shows the elemental analysis of the municipal solid waste which can be used to develop combustion equations for determine the stoichiometric air fuel ratio for the municipal solid waste. The main elements are carbon, hydrogen, Sulphur and Nitrogen as combustible elements.

$C + O_2 \rightarrow CO_2$
$12.01kgC + 32.00kgO_2 \rightarrow 44.01CO_2$
Oxygen $= \frac{32.00}{12.01} \times 0.47025 = 1.253\ kg/kgMSW$
Carbon dioxide$= \frac{44.01}{12.01} \times 0.47025 = 1.723 kg/kgMSW$
$H_2 + 0.5O_2 \rightarrow H_2O$
$2.01kgH_2 + 16.00kgO_2 \rightarrow 18.01kgH_2O$
Oxygen$= \frac{16.00}{2.01} \times 0.05175 = 0.412 kg/kgMSW$
Steam produced$= \frac{18.01}{2.01} \times 0.05175 = 0.464 kg/kgMSW$
$S + O_2 \rightarrow SO_2$
$32.06kgS + 32.00kgO_2 \rightarrow 64.06kgSO_2$
Oxygen$= \frac{32.00}{32.06} \times 0.0009 = 0.000898 kg/kgMSW$
Sulphur dioxide$= \frac{64.06}{32.06} \times 0.0009 = 0.001798 kg/kgMSW$

Table 6: Oxygen required per kilogram of MSW (authors' calculation)

Constituent	Mass fraction	Oxygen required (Kg/Kg MSW)
Hydrogen (H)	0.05175	0.412
Oxygen (O)	0.2970	-0.2970
Sulphur (S)	0.0009	0.000898
Carbon (C)	0.47025	1.253
Nitrogen (N)	0.01620	
Moisture	0.1000	
Ash	0.0639	
Total	1	1.3689

From table 6, it is established that the stoichiometric air fuel ratio for the MSW is 1.3689 kg of air per kilogram of MSW. This is air that is just enough for complete combustion of 1 kg of municipal solid waste.

$$\emptyset = \frac{\text{Actual}\,\frac{A}{F}\text{ratio} - \text{Stoichiometric}\,\frac{A}{F}\text{ratio}}{\text{Stoichiometric}\,\frac{A}{F}\text{ratio}}$$

Oxygen required per kilogram of MSW= 1.3689kg
Air required per kilogram of MSW $= \frac{1.3689}{0.233} = 5.875$
Stoichiometric $\frac{A}{F}$ratio = 5.875:1
Actual $\frac{A}{F}$ratio, $m_{air} = 5.875 + \left(\frac{80}{100} \times 5.875\right) = 10.575$
$\emptyset = \frac{10.575 - 5.875}{5.875} = 0.8$
n = 1+0.8=1.8

Excess air 180%

$$m_{air,steo} = 34.3348X_H - 4.2918X_O + 4.2918X_S + 11.4449X_C$$
$$= 34.3348(0.05175) - 4.2918(0.297) + 4.2918(0.0009) + 11.4449(0.47025)$$
$$= 5.88799kg$$
$$m_{fluegas} = (34.3348X_H - 4.2918X_O + 4.2918X_S + 11.4449X_C) + (1 - X_{ash} + X_{mst})$$
$$= \big(34.3348(0.05175) - 4.2918(0.297) + 4.2918(0.0009) + 11.4449(0.47025)\big) + (1 - 0.0639 + 1) = 7.82409kg$$

With excess air;

$$m_{air} = (34.3348X_H - 4.2918X_O + 4.2918X_S + 11.4449X_C)(1 + \emptyset)$$
$$= \big((34.3348 \times 0.05175) - (4.2918 \times 0.297) + (4.2918 \times 0.0009) + (11.4449 \times 0.47025)\big)(1.8) = 10.5984kg$$
$$m_{fluegas} = (34.3348X_H - 4.2918X_O + 4.2918X_S + 11.4449X_C)(1 + \emptyset) + (1 - X_{ash} + X_{mst})$$
$$=\big(34.3348(0.05175) - 4.2918(0.297) + 4.2918(0.0009) + 11.4449(0.47025)\big)(1.8) + (1 - 0.0639 + 1) = 12.5344\text{kg}$$

5.4. Calculation of the Calorific value of MSW

$$H_{low,overall} = \frac{M_1}{100} \times H_{low,1} + \frac{M_2}{100} \times H_{low,2} + \frac{M_3}{100} \times H_{low,3}$$

$$H_{low,overall} = \frac{14}{100} \times 16 + \frac{10.9}{100} \times 35 + \frac{62.4}{100} \times 4 + \frac{10.5}{100} \times 11$$

$C_V = 9,706\text{KJ/Kg}$

5.5. Heat generated in Combustion Chamber

The following calculation shows the amount of heat generated in the combustion chamber

$Q=\dot{m}_{msw} \times Cv$

$\dot{m}_{msw}$ =3000tons/day = 125tons/hour

CV=9.706MJ/kg

∴Q=3000000kg×9.706×10^6J/kg×0.2=5823.6GJ/day

1MJ/s=1MW

5823.6GJ=?

No. of seconds per day = 60×60×24=86400seconds

$\frac{5823.6\times10^9}{86400}=67.40278\times10^6$J/s = 67.40278MW

4.2.3Boiler Calculations

The desired boiler efficiency, η=80%

The heat generated in the combustion chamber is the heat in for the boiler.

Q_{in}=67.40278MW

$\eta = \frac{Qout}{Qin}$

$Q_{out} = \eta \times Q_{in}$

Q_{out}=0.8×67.40278=53.9222MW

$\dot{m}_s = \frac{Qout}{(h2-h1)}$

$\dot{m}_s = \frac{53.9222\times10^6}{(3148\times10^3 - 546\times10^3)}$=20.72337kg/s

Equivalent Evaporation (EE) = $\frac{\text{heat required to generate steam for one unity of fuel}}{\text{standard unit of evaporation(2257)}}$

$EE = \frac{m(h_2-h_1)}{2257} = \frac{0.5968(3418-546)}{2257}$ =0.7594

Table 7: Calculations for heat recovery steam results (authors' calculations)

Heat rejected by the flue gases	53.9222MW
Economizer	7.8092MW
Evaporator	23.11765MW

Super heater	1.969542MW

From table 7, it is deduced that most of the heat recovery from flue gases to water/steam takes place in the evaporator of the steam generator, followed by the economizer and super heater.

Table 8: Net power output at the generator terminal of the steam turbine (authors' calculations)

Isentropic steam turbine power output	11.7853MW
Actual steam turbine power output	10.6068MW
Pump work	379.0061KW

From table 8, the turbine efficiency can be 90% being the ratio of actual work to isentropic work

5.6. Energy balance and thermal efficiency

Energy addition (Q_1) = 53.9222MW
Energy rejection (Q_2) =50.944MW

Thermal efficiency (η) $=\frac{(h_4-h_5)-(h_2-h_1)}{(h_4-h_2)}$

$=\frac{11785.3-379.0061}{53.9222}$

= 21.15%

Table 8 below is a summary of the steam and water conditions in the plant.

Table 9: Summary of the proposed power plant cycle (authors' calculations)

Parameter	**Value**	**Parameter**	Value
Surface Condenser		**Cooling Tower**	
Cooling water outlet temperature T_{co} (^{0}C)	38	Inlet temperature of the water T_1 (^{0}C)	38
Cooling water inlet temperature T_{ci} (^{0}C)	26	Outlet temperature of the water T_2(^{0}C)	26
Steam inlet temperature T_{si} (^{0}C)	99.6	Dry bulb temperature T_{db} (^{0}C)	30
Steam outlet temperature T_{so} (^{0}C)	29.0	Wet bulb temperature T_{wb} (^{0}C)	22
Mass flow rate of steam $\dot{m}_c$ (Kg/s)	20.7233	Inlet air temperature T_{a1} (^{0}C)	20
Velocity of cooling water per tubes w (m/s)	2.896	Make up water mass flow rate (kg/s)	18.2479Kg/s
Steam Turbine		**Thermal Efficiency**	
Main steam conditions	15bar	Energy addition	53.9222MW
Output (MW)	11.7853	Energy Rejection	50.944MW
Inlet steam temperature	350^{0}C	Efficiency	21.15%

From table 9, it is noted that the proposed MSW mass burn power plant will have steam flow rate of 20.7233 kg/sec at 15 bars at 350^{O}C and turbine power output is about 11.79 MW.

$11.515\times10^3\times19.50$x 24 =224,542.50KSh/dayx24=5,389,008 (USD53, 890)
Allowing a month for annual plant maintenance, and assuming availability of 90% and capacity factor of 0.90 for efficient plants, theoretical overall efficiency is 0.9 x0.9 =0.81.
Anticipated generation is 11.515 kwh x 24 hrs x 325 day x0.81=72, 751,770 kWhrs of electricity annually
Annual sales =224,542.50× 325 days=KSh 5, 5389, 008x 325x 0.81= ksh 1,418,656,356 (US $ 14,186,563.60)/year
The operating/gross income is calculated from the difference between the total product revenue and the grand total of the first year of operation.
=ksh 1,418,656,356-44,900,000
=ksh 1,373,756,356 (USD 1,373,756,356
This amount is meant to take care of other anticipated costs and capital cost of the plant

6.0. CONCLUSION

The city of Nairobi faces significant challenges with its municipal solid waste (MSW) management leading to large wastes remaining uncollected, environmental hazards and lack of space at Dandora dumping cite thereby making MSW a health hazard. The proposed cogeneration plant has the capacity to process 3000 tons of municipal solid waste per day to yield about 12MW of electricity. Consistent processing of solid waste by the plant consumes about 1,008,000 tons per annum, thereby reducing about 34% of the total waste that goes into the Dandora dumpsite. With the streamlining of waste collection services in the city, an extra line could be introduced, processing a total of 6000 tons of waste per day bringing the annual reduction of waste in Dandora to about 64%. The electricity produced from the plant will be connected to the national grid increasing the number of households connected to electricity and avoid generation from fossil fuels thus preserving the environment. Implementation of this project can provide an environmentally friendly and sustainable solution for the disposal of municipal solid waste for the city of Nairobi. It will also generate revenue from electricity sales which will boost the solid waste management system and create extra income for the county government of Nairobi.

7.0. RECOMMENDATIONS

The following recommendations are suggested to enhance electricity generation from municipal waste;

i.) Cities and governments should partner with the private sector to access technology and capital for investment in waste to electricity projects. These id because of lack of own capacity to develop capital projects of this magnitude.
ii.) Cities and municipalities should streamline their MSW systems to ensure that all waste is collected and managed to ensure clean, healthy cities.
iii.) Policy measures should be put in place to encourage cities to invest in commercial waste to electricity projects through attractive feed in tariffs and tax incentives.
iv.) The correct size of the power plant should address current and future generation of municipal solid waste.

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