Incineration Plant Integration for Waste Management; a case of Nairobi City, Kenya

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Abstract. Population of the Nairobi city stands at approximately 5.119 million, with each individual generating about 0.65 kgs of garbage per day. It is approximated that the production will be 3,990 tons every day by the year 2030. This has led to the need for waste management programs and policies to handle the growing challenge. The Nairobi City County Solid Waste Management Bill of 2015 outlines procedures for collection and disposal of wastes, but there have been challenges in effective collection and treatment of these wastes. Also, with the growth in population in the city, there is a need to look for new energy ventures to handle the growing load. This work therefore proposes the adoption of biogas plant for energy generation through incineration of wastes collected within the city. Analysis showed that 3327.35 ton/day of wastes can produce approximately 11 KWh of energy that can be fed to the national grid or used to lit up the city.

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1 Introduction

The continual influx of individuals from rural areas to Nairobi city has been on a rapid increase overwhelming the city's ability to deliver necessary social services. According to UN-habitat, the capital is approximated to produce approximately 3207 tonnes of solid waste a day[1]. In Dandora, the main dumpsite in Nairobi City, over 2000 tonnes of waste are poured in daily from the capital[2] These wastes include domestic, industrial, hospital, and agricultural waste. Poorly managed waste has been the biggest pollutant for air, water, and soil which has caused significant health and environmental issues. This situation is mainly attributed to the lack of efficient municipal waste management as little segregation goes on, and there are hardly any incentives for people to sort or recycle their waste.
Waste management is one of the services affecting most cities as the policies put in place to govern waste collection are either not being implemented or have poor implementation plans. In urban cities, common methods employed for municipal solid waste (MSW) disposal are compositing, landfilling, recycling, and incineration (or waste to energy (WTE)). WTE has an advantage in that it ensures a considerable reduction of between 60% to 80% of the original weight in addition to power generation [1][3].
Previous studies [1]–[3]on municipal solid waste studies in Nairobi have reported mainly on solid waste production and composition i.e., the quantities and percent composition. However, there is a lack of data on the physical and chemical characteristics of solid wastes. This paper looks into the composition of waste in Nairobi city to determine whether an incineration plant can be constructed to convert waste to energy and help in power provision to the Grid as well as maintaining a clean environment for the habitants of the city.
The organization of the rest of the paper is as follows.
Section 2 discusses various waste management techniques. Section 3 looks at the feasibility while section 4 sizes the waste plant. Section 5 and 6 looks at financial analysis and environmental implications respectively, while section 7 concludes the work.

2 Waste management

Typical household wastes consist of a range of materials that vary in composition. This is dependent on; the community and its consumer's incomes and lifestyle, degree of industrialization, institutionalism and commercialism. Other effects include seasons in the year and number of inhabitants in the household also affect the amount and composition of wastes. Generally, modern societies produce garbage which consists of both organic and inorganic wastes. Organic wastes comprise of things like food, wood, and garden wastes, paper, plastics, textiles, rubber, leather and other materials. Inorganic material comprises mainly of glass and metals [5].
A variety of waste management practices have been studied and developed[4]. Some of them were adopted as key solutions in waste management as seen below:

[redacted]Landfills

Landfills have long been utilized as a key garbage disposal strategy, however new data indicates that the number of landfills is declining [5]. New legislation governing safe garbage disposal, as well as the adoption of novel linear systems to reduce the risk of groundwater contamination from leachate infiltration and migration, have resulted in a significant increase in landfill disposal costs. Furthermore, public opposition to landfills is growing, fuelled in part by recollections of prior uncontrolled dumping techniques and the unintended consequences of unregulated vectors, contaminated groundwater, unrestrained odours, and subsequent decreased property values.[5]

[redacted]Waste minimization

Not every waste can be gotten rid of. Waste reduction is used to cut back on or lessen the production of such wastes. Waste in the industrial sector can be decreased by recycling resources, switching to less

dangerous substitutes, or changing design and manufacturing-related elements. Waste minimization is majorly used in lessening the consumption of natural resources and the toxicity of wastes[4].
Waste reduction measures are popular in manufacturing applications. This is so that less material is used, which not only conserves resources but also saves a lot on manufacturing-related expenses. The use of materials is reduced by improvements in efficient packing, while the usage of fuel and resulting emissions are reduced by improvements in distribution efficiency[5].
Engineered building materials are frequently created with specific beneficial qualities that, when accounted for in overall structural design, can significantly lower the overall mass and weight of material required for a given project. This eliminates the requirement for additional material and the waste associated with component manufacture.

[redacted] Recycling and Reuse

Recycling is the recovery of useful materials from waste streams such as glass, paper, plastics, wood, and metals so that they can be used in the manufacture of new products. The amount of raw materials needed for similar applications decreases with increased recycling of materials. Recycling decreases the need to mine natural resources for raw materials while also enabling the recovery and use of waste products as valuable resource materials. Recycling wastes directly protects natural resources, reduces energy consumption and greenhouse gas emissions associated with the extraction of virgin materials and their subsequent manufacture into finished goods, and decreases the incineration or landfilling of previously used materials. Additionally, recycling has the ability to stimulate growth and establish job markets, among other economic advantages [3][5].
Paper, plastics, glass, aluminum, steel, and wood are examples of commonly recycled materials. Furthermore, many construction materials, such as concrete, asphalt materials, brickwork, and reinforcing steel, can be reused. "Green" plant-based wastes are frequently recovered and used right away as mulch or fertilizer[5]. Various by products are also recovered by many businesses, and they may refine and "re-generate" solvents for future use.
Incineration
Waste degradation not only produces useful solid end-products (such as compost), degradation by-products can also be used as a beneficial energy source. As discussed above, anaerobic digestion of waste can generate biogas, which can be captured and incorporated into electricity generation. Alternatively, waste can be directly incinerated to produce energy. Incineration consists of waste combustion at very high temperatures to produce electrical energy[5], [6]. The by-product of incineration is ash, which requires proper characterization prior to disposal, or in some cases, beneficial re-use.
While public perception of incineration can be negative, this is often based reactions to older, less efficient technologies. New incinerators are cleaner, more flexible and efficient, and are an excellent means to convert waste to energy while reducing the volume of waste. Incineration can also offset fossil fuel use and reduce greenhouse gas (GHG) emissions [6]. It is widely used in developed countries due to landfill space limitations. It is estimated that about 130 million tons of waste are annually combusted in more than 600 plants in 35 countries.[7] Further, incineration is often used to effectively mitigate hazardous wastes such as chlorinated hydrocarbons, oils, solvents, medical wastes, and pesticides.
Despite all these advantages, incineration is often viewed negatively because of the resulting air emissions, the creation of daughter chemical compounds, and production of ash, which is commonly toxic. Currently, many 'next generation" systems are being researched and developed, and the USEPA is developing new regulations to carefully monitor incinerator air emissions under the Clean Air Act[8].

3 Feasibility

The rise in energy consumption due to industrialization and the improvement of living standards is inevitable. There is need to consider other renewable sources of energy as they are environmentally friendly. Many countries' investment is on befoul technologies for energy production. Biogas plants are one of the most viable renewable energy technologies. Its economic efficiency however depends on the investment costs, cost of operating the biogas plant and optimum methane production. Its profitability also rests on its use directly for either cooking or conversion to electricity. Also, a number of studies have

proved that use of biogas plants is effective for the management of organic wastes in an environmentally friendly and cost-effective manner [8].
In developing countries, specifically in the Sub-Saharan African countries, promotion and development of this technology has suffered a setback. Some of the set backs are attributed to the following[4]:

i. Failure of Government to support the technology through a focussed energy policy.
ii. Lack of information regarding the economic viability.
iii. Poor design and construction of the digesters.
iv. Wrong operation.
v. Lack of maintenance by the users.

Operators have identified operation and maintenance, and after sale service as the major causes derailing a speedy adoption of the technology in most developing countries[4]. However, biogas production processes have the advantage of low energy requirement for operation, low initial investment costs and low sludge production when compared to the conventional aerobic processes.

3.1 Incineration plants

Incineration is the process of burning waste materials at high temperature as a way of disposal, a process known as thermal treatment. Some of the safest materials to burn are organic material and vegetation due to the lack of manmade chemicals and elements within these materials hence only small amounts of carbon are produced. Materials commonly used in waste incineration plants are Municipal solid wastes. These wastes are usually safe to incinerate.

3.2 Future Challenge

Currently, about 80% of the world's energy supply is derived from fossil fuels. Biogas energy supply is based at about 10 - 15% of the energy supply. On average, in industrialized countries, biomass contributes 9-13% of the total energy supply; due to its low population and intense energy usage for cooking and heating during the winter periods. Developing countries have a higher proportion due to their population hence more production of organic wastes. In Sub – Sahara Africa, biomass supplies 70 – 90% of the total energy demand [9].
Currently, biomass plays a smaller, but steadily growing role. Energy recovery from biogas by anaerobic digestion has been a welcome by-product of sewage sludge treatment for a number of decades. Incineration plants emit some harmful gases and have some ash residue that requires disposal. Further research on the technology used in these plants is required to ensure almost all toxic gases are collected and that the disposition of the ash residue is made safer.

4 Sizing of the plant

Waste to energy plants burn municipal solid wastes (MSW), often called garbage or trash, to produce steam in a boiler, and the steam is used to power an electric generator turbine. MSW is usually a mixture of energy rich materials such as paper, plastics, yard waste, and products made from wood. Research shows that for every 100pounds of MSW, about 85 pounds can be burned as fuel to generate electricity. The waste to energy plants reduces 2000 pounds of garbage to ash that weighs between 300pounds and 600pounds, ad they reduce the volume of waste of about 87%.

4.1 Working Principle

The most common waste to energy is the mass-burn system shown in Figure 1. In this system, unprocessed MSW is burned in a large incinerator with a boiler and a generator to produce electricity.
In this process, waste material is received in an enclosed receiving area, where it is thoroughly mixed in preparation for combustion. The mixed wastes enter the combustion chamber on a timed moving grate, which turns it over repeatedly to keep it exposed and burning. Fine air bone particulates are removed in the filter baghouse. The acidic combustion gases are neutralised with an injection of lime or sodium hydroxide. The unburned remains of combustion are passed by magnets and eddy current separators to

remove both ferrous (steel and iron) and other metals, such as copper, brass, nickel, and aluminium for recycling.

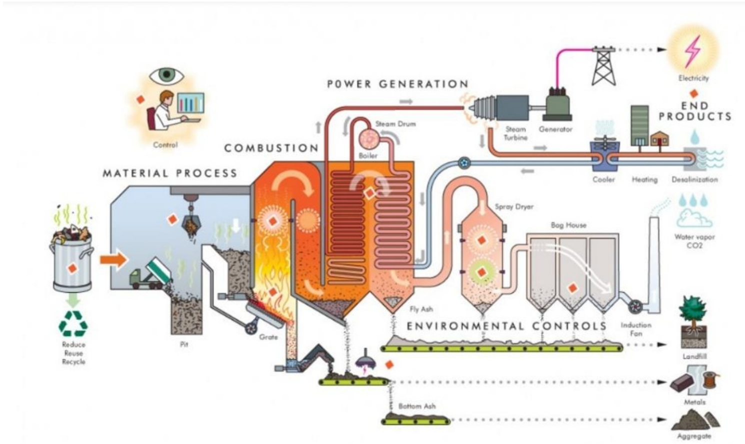


Fig. 1: Biogas Incineration Plant

4.2 Estimation of Wastes Produced

Waste generation rates are dependent on several factors. The most basic factor is population which is the number of people generating waste in the area in question. A highly populated area has a high rate of waste generation. Waste generation is also dependent on other factors like socio-economic development, degree of industrialization and climate. Equation 1 is used to calculate waste generated (W) (ton) per day

$$W = \frac{(P_{op})(I_g)}{1000} \qquad (1)$$

where, P_{op} is the population size and I_g is per capita waste generation index (kg/person day).
In Nairobi region, Kenya, the population size as of 2022 was approximately 5.119 million and the per capita waste generation index is 0.65kg/person/day. Hence, the amount of waste produced can be estimated as shown in equation (2) below.

$$W = \frac{5{,}119{,}000 \times 0.65}{1000} = 3327.35 ton/day \qquad (2)$$

Table 1 and figure 2 indicates the approximations for each type of waste in tons/day:

Table 1: Type of waste in tons/day

Waste	% concentration	Ton/day
Organic Material	58%	1929.86
Metals	3%	99.8205
Textile and others	8%	266.1880
Plastics	12%	399.2820
Paper	17%	565.6495
Glass	2%	66.5470

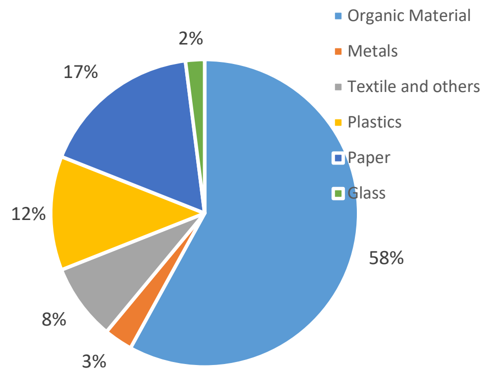


Figure 2: Distribution of type of waste in tons/day

4.3 Estimation of Energy Outputs

The basis for the generation of energy through incineration is the use of the calorific value of the waste by taking advantage of the amount of energy per unit of mass or unit of volume of matter that can be released when a chemical oxidation reaction occurs. Since the analysis will evaluate only moving grate incineration processes, our estimation of energy considered the heat-generating values according to three main categories: organic waste, plastic waste and paper waste. Electric energy produced (E) in MWh/year can be calculate as follows:

$$LCV_i = (LCV)(W_i)(k_1) \quad (3)$$

$$LCV_{total} = \sum_{i=1}^{m} LCV_i \quad (4)$$

$$P = (LCV_{total})(\eta)(W)(k_2) \quad (5)$$

$$E = \frac{(P)(C_f)(8760)}{1000} \quad (6)$$

where

- LCV = Lower calorific value kcal/kg
- LCV_i = Calorific value contained in each RSU fraction in kJ/kg
- LCV_{Total} = Total calorific value of the residue in kJ/kg
- k_1 = Conversion constant from kcal/kg to kJ/kg (4.184)
- η = Electric recovery considering a thermal replacement achievable
- k_2 = Unit adjustment constant
- P = Electric power in kW
- 8760 = Number of hours per year
- C_f = Capacity factor

For the case of Nairobi county, considering the calorific values of all the material are not available, the power produced in kW is estimated as follows:

$$P = (11MJ/tonne)(0.8)(3327.35tonnes/day)(k_2) \quad (7)$$

$$P = \frac{11MJ}{ton} \times 0.65 \times \frac{3327.35tons}{86400} \times 1$$

$$= \frac{275{,}353.6169 J}{s} = 275.353 kW$$

$$E = \frac{(275.353)(0.90)(8760)}{1000} = 2170.883 MWh/year$$

5 Financial Analysis

5.1 Estimation of Economic Parameters

Table 2 show the parameters that are in considered estimating the economic feasibility of a waste incineration plant based on a moving grate incineration technology.

Table 2: Incineration Parameters

Item	**Characteristic**
Calorific value requirement	More than 1200 kcal/kg (5040 kJ/kg)
Auxiliary fuel	Oil
Application conditions	Higher heat value, plenty of financial resources, state-owned operator
Technical maturity	Long history, mature technology
Operating costs	4% of total capital costs (investment)
Flue gas	3500-4800m^3 per ton of waste
Flying ash	2.5-3% of the waste disposal amount
Leachate treatment	Separate treatment, cannot be sprayed back into the furnace for combustion

The actual investment costs for a waste incineration plant depends on multiple factors as shown below:

$$I = (15797)(P^{0.82}) \qquad (8)$$

Where, I is the investment in US millions and P is the estimated power in kWh/yr. Hence;

$$I = (15797)(275.353^{0.82})$$

$$Investment\ cost = USD\ 1{,}582{,}283.373$$

This investment cost includes costs estimates of equipment and devices, construction costs, land use and other costs, preparation funds, loan interest and risk management. The operation and maintenance costs include estimations of raw materials, plant power consumption, staff salaries, depreciation loss, maintenance charge, environmental expenses (Fly ash handling, bottom ash processing, leachate treatment and environmental monitoring), financial expenses and additional expenditure.

An incinerator has a lifetime of approximately 30years. Assuming his project is financed with a private investor at a discount rate of 10% or less since it is more of a social project than an energy production project, we can calculate the Net present value of investing in the project as show in equation (9).

$$NPV = \sum_{t=0}^{x} \frac{B_t - C_t}{(1+r)^t} - Investment \qquad (9)$$

In Kenya, the cost of 1kWh of electricity can be approximated as 0.170USD/kWh. Hence the revenue from the proposed incineration plant and the operation and maintenance costs can be calculated as;

$$B_t = Energy\ produced\ \times tariff\ costs (10)$$
$$= 2170.883 MWh/yr \times 0.170 USD/kWh \times 1000$$
$$= 369{,}050.11 USD/yr$$

Table 3 : NPV, IRR, and LCOE Estimates

Years	Revenue ($)	O&M COSTS ($)	PROFITS ($)	Present Value ($)	Maintenance ($)	Et	Discount	10.00 %
0			(1,582,283.37)		-	2820290		
1	369,050.11	110,759.84	258,290.27	234,809.34	100,690.76	2563900		
2	369,050.11	110,759.84	258,290.27	213,463.03	91,537.06	2330818.182		
3	369,050.11	110,759.84	258,290.27	194,057.30	83,215.51	2118925.62		
4	369,050.11	110,759.84	258,290.27	176,415.73	75,650.46	1926296.018		
5	369,050.11	110,759.84	258,290.27	160,377.94	68,773.15	1751178.198		
6	369,050.11	110,759.84	258,290.27	145,798.12	62,521.04	1591980.18		
7	369,050.11	110,759.84	258,290.27	132,543.75	56,837.31	1447254.709		
8	369,050.11	110,759.84	258,290.27	120,494.32	51,670.28	1315686.099		
9	369,050.11	110,759.84	258,290.27	109,540.29	46,972.98	1196078.272		
10	369,050.11	110,759.84	258,290.27	99,582.08	42,702.71	1087343.884		
11	369,050.11	110,759.84	258,290.27	90,529.16	38,820.65	988494.4398		
12	369,050.11	110,759.84	258,290.27	82,299.24	35,291.50	898631.3089		
13	369,050.11	110,759.84	258,290.27	74,817.49	32,083.18	816937.5535		
14	369,050.11	110,759.84	258,290.27	68,015.90	29,166.53	742670.5032		
15	369,050.11	110,759.84	258,290.27	61,832.64	26,515.03	675155.0029		
16	369,050.11	110,759.84	258,290.27	56,211.49	24,104.57	613777.2754		
17	369,050.11	110,759.84	258,290.27	51,101.35	21,913.24	557979.3413		
18	369,050.11	110,759.84	258,290.27	46,455.78	19,921.13	507253.9466		
19	369,050.11	110,759.84	258,290.27	42,232.52	18,110.12	461139.9514		
20	369,050.11	110,759.84	258,290.27	38,393.20	16,463.74	419218.1377		
21	369,050.11	110,759.84	258,290.27	34,902.91	14,967.04	381107.3979		
22	369,050.11	110,759.84	258,290.27	31,729.92	13,606.40	346461.2708		
23	369,050.11	110,759.84	258,290.27	28,845.38	12,369.45	314964.7916		
24	369,050.11	110,759.84	258,290.27	26,223.07	11,244.96	286331.6288		
25	369,050.11	110,759.84	258,290.27	23,839.16	10,222.69	260301.4807		

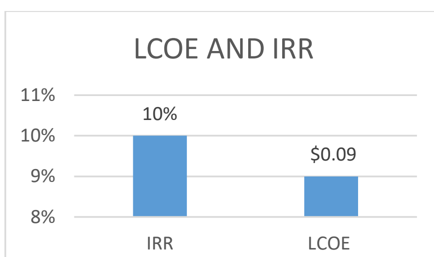
26	369,050.11	110,759.84	258,290.27	21,671.96	9,293.35	236637.7097
27	369,050.11	110,759.84	258,290.27	19,701.78	8,448.50	215125.1907
28	369,050.11	110,759.84	258,290.27	17,910.71	7,680.46	195568.3551
29	369,050.11	110,759.84	258,290.27	16,282.47	6,982.23	177789.4138
30	369,050.11	110,759.84	258,290.27	14,802.24	6,347.49	161626.7398
			Summation	2,434,880.28	1,044,123.54	29406922.6

O&M	$ 110,759.84
ETT	2820290.00
Capital	$ 1,582,283.37
NPV	**$ 852,596.91**
	$ 852,596.91
IRR	10%
LCOE	$ 0.09

$$Operation\ and\ Maintenance\ costs = \frac{7}{100} \times USD\ 1{,}582{,}283.373$$

$$= 110{,}759.8361 USD/yr$$

Hence the net present value (NPV), Internal Rate of Return (IRR) and levelized cost of electricity (LCOE) costs is shown in the table 3 below:



From the table 3, it can be seen that the NPV>0, the IRR is greater than the discount rate and the LCOE is more than the tariff costs. The NPV and the IRR were calculated over an 18year period. The project is still profitable but with a smaller margin. Calculation of the payback period for this project using the simple payback period is as follows:

$$Payback\ period = \frac{Cost\ of\ Investment}{Profits\ per\ year} \qquad (11)$$

$$= \frac{1{,}582{,}383.37}{369{,}051.11} = 4.28 years \approx 5 years$$

6 Environmental Implications

Owing to unsightliness and the threat of groundwater pollution, landfilling of municipal solid waste (MSW) is giving way to incineration in many communities. Environmental contamination from particulate and

gaseous emissions containing heavy metals, polychlorinated dibenzodioxins (PCDD) and polychlorinated dibenzofurans (PCDF), polycyclic aromatics (PCA), acids and other compounds from such incinerators, as well as safe ash disposal, are of great concern[6], [8]–[10], [10].
With the development of efficient air pollution control systems, the focus has now shifted from emission control to the treatment and disposal of fly ash (FA) and air pollution control (APC) residues collected by these systems. The fate of FA and APC residues depends principally on national policies. In most developed countries, treatment and reuse of these residues is possible because of environmental policies and possibly subsidies, while in other countries, these ash residues are buried in landfills. Despite the relatively high concentration of heavy metals, salts, and organic recalcitrant, which may limit utilization possibilities, the best strategy is still treatment followed by utilization as secondary resources. Proper characterization has to be conducted before treatment as the properties of these residues may differ greatly depending on the source of the municipal solid waste (MSW) [10].
In a modern MSW plant, there is the combustion chamber where the waste is burnt for volume reduction, the boiler system to recover energy, and the air pollution control system to reduce emissions. The air pollution control system removes fine particulates (with devices such as the electrostatic precipitator, fabric filter, or cyclone) and regulates harmful gases (with devices such as dry lime scrubbing or wet lime scrubbing[10]).
Depending on the technology being used, some environmental factors are controlled. There is need for more research to be done on disposition of ash produced from this process. There is also need to improve on the efficiency of the system as a whole in order to get more power.

7 Conclusion

An incineration plant is a good investment towards management of waste disposal in Nairobi County. It is more of a social problem than an energy problem hence as an energy investment, it might take a longer payback period. The environmental implications also make the project less viable as compared to landfills hence major research on better ways to handle emissions need to be explored.

8 References

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