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Economic Viability of Waste-to-Energy: Pathways for Sustainable Power Generation in Jalingo, Taraba State, Nigeria

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Abstract

This study evaluates the technical and economic viability of waste-to-energy (WtE) technologies for sustainable electricity generation in Jalingo metropolis, Taraba State, Nigeria. Two WtE pathways were assessed: (i) thermal conversion through incineration with power generation, and (ii) landfill gas (LFG) capture with reciprocating engines. Locally reported municipal solid waste (MSW) data and performance-cost ranges from literature were applied to estimate electricity potential, installed capacity, levelized cost of electricity (LCOE), net present value (NPV), and internal rate of return (IRR). The waste composition was dominated by plastics (29.67–34.67%) and agricultural residues (28–29%), followed by paper/cardboard (9.88–11.93%), textiles (4.04–9.20%), and food waste (5.66–6%). Metals (0.42–1.11%) and glass (0.90–1.30%) constituted the smallest fractions. Moisture content ranged from 25.40% at Mile Six dumpsite to 28.98% at Pantinapu; volatile matter peaked at 38.84% at Mile Six. Heat values between 6.32 and 6.68 MJ/kg confirmed the technical feasibility of incineration-based energy recovery. Electricity generation potential was estimated at 39,417.74 kWh/day from incineration and 1,644,106.24 MWh/year (≈4.5 million kWh/day) from LFG, capable of supplying approximately 17,127 and 1,957 households respectively, based on average household consumption of 840 kWh/year. Economic analysis revealed positive NPVs ($1.20–1.45 million) and IRRs of 18–79% at a tariff of N250/kWh (US $0.15), demonstrating profitability. Environmental assessment indicated that methane combustion for electricity reduced carbon dioxide emissions by about 88.18% compared to uncontrolled waste disposal. The findings highlight that municipal solid waste in Jalingo possesses sufficient energy content to support WtE initiatives. Both incineration and LFG capture not only offer substantial electricity generation potential but also present economically viable and environmentally sustainable alternatives to current waste management practices.

Keywords: *Incineration, landfill gas, LCOE, techno-economic, waste-to-energy.*

1.0 Introduction

Waste accumulation is a global issue intensified by population growth and rising incomes [1]. Municipal solid waste (MSW) which includes household, industrial, and commercial debris, poses severe challenges in developing countries where municipal resources for waste management are often scarce [2-3]. Nigeria exemplifies these problems, with urban areas facing clogged drains and littered streets. In almost every city in the country, the poor state of solid waste management is evident in the number of drainages clogged by waste and streets littered with waste [4].

Energy recovery from MSW, or waste-to-energy (WtE), is an established concept dating back to the 19th century. WtE technologies generally rely on thermochemical processes such as incineration, pyrolysis, and gasification or biochemical methods like anaerobic digestion. [5]. These processes recover energy from waste either by direct combustion of wastes or by processing wastes into combustible fuels. Among these, incineration remains the most efficient and cost-effective for unsegregated MSW, which is common in developing regions [6].

Prior studies have evaluated WtE potential in various regions, including Pakistani and Nigerian cities, often highlighting incineration as a suitable technology. There is quite a large body of work that has been undertaken on waste to energy both locally and internationally [7]. In the Pakistani city of Hyderabad, a study was intending to estimate the potential for power generation from MSW [8]. The study was necessitated due to the shortage in electricity supply in the states and the country at large. Samples were collected following the ASTM standard. The study was able to determine the estimated power generation potential of the city's MSW to be 1,512 kWh per tonne of MSW. The authors' concluded that the MSW generated in Hyderabad city is suitable for electricity generation. They recommended mass-burn as the most appropriate WTE technology for the city.

In Ilorin, the capital of Kwara State, one of the 36 states in Nigeria, a study was conducted to characterize the dry season MSW generated in the city and determine the amount of energy that can be generated from it [9]. The researcher found that the MSW disposed of at the Eyenkorin dumpsite of Ilorin metropolis has an estimated heating value of 19 MJ/kg and that the dumpsite has the potential to generate 18MW of electrical energy.

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Jalingo, the capital of Taraba State in the north-eastern part of Nigeria which is an urban area, is not an exception to the twin problems of poor solid waste management (SWM) and the shortage of electricity supply that is common to most cities in developing economies. The SWM technique practiced in the city involves the collection and transportation of wastes from communal dumpsites by the Waste Management Unit of the state's Ministry of Urban and Rural Development to open dumpsites a few kilometres away from the city center. The disposed waste is managed by occasionally burning it or just allowing it to decompose, this pollutes the environment and also constitutes a health hazard to the inhabitants of the immediate surrounding communities and the society at large. This kind of SWM technique which is very popular in Nigeria [10], and in other developing countries has been found to lead to increased environmental contamination and risks to public health [11]. However, if properly managed, the MSW which is seen as a nuisance can be utilized in the generation of electricity which can greatly augment the amount of electricity allocated to the city from the national grid while also tackling environmental pollution and health risks posed by the current SWM techniques being practiced. For these reasons, a number of research works have been undertaken in the city. Study was conducted in a section of the city with the aim of determining the suitability of energy recovery from the MSW generated by households [12]. Using ASTM method, the researchers were able to determine that the household waste in the study location had a moisture content of 61.33% and therefore concluded that it was unfit for energy generation. In the same city, another group of researchers undertook a quite similar study with the aim of estimating the potential for energy generation from MSW [13-16]. Despite these researches in Jalingo, quantitative assessments of recoverable electricity and financial feasibility have been lacking, forming the basis for this investigation. This study aims to quantify the energy recoverable from Jalingo's MSW and assess the economic viability of incineration as the preferred WtE approach based on local waste characteristics and economic conditions. Incineration was chosen as the preferred technology because it has been proven to be the best technology for the type of waste generated in Jalingo.

2.0 Methodology

2.1 Study Area

Jalingo, the capital city of Taraba State, Nigeria, lies between latitudes 8°89'28.5" N and longitudes 11°37'71.5" E, at an elevation of roughly 260-290 meters. Characterized by a Sudan savannah climate, it experiences a dry season lasting November to March and a rainy season from April to October. Solid waste management in Jalingo remains undeveloped, involving unsegregated waste collection from residential points, transfer stations, and final deposition on open dumpsites on the city's outskirts, primarily at Mile Six and Pantinapu. The state's Ministry of Urban and Rural Development oversees waste collection, law enforcement, and facility maintenance at these sites.

2.2 Data Collection

Secondary data on waste management practices, dump site sizes, and waste quantities were sourced from the state ministry's waste management unit. Geographic coordinates of the dumpsites were obtained via Google Maps. Waste samples for compositional analysis were collected during three different months in 2024 (January, April, August) to capture seasonal changes. Waste characterization followed ASTM D5231 standards, with categorized samples stored for laboratory analysis.

2.3 Technical Analysis

Proximate analyses followed ASTM methods to determine moisture content, volatile matter, ash content, and fixed carbon percentages [17]. Moisture was evaluated by weighing samples before and after drying at 105°C. Volatile matter was measured by combusting dried samples at 950°C in a muffle furnace, while ash content was determined after heating at 750°C. Fixed carbon was calculated by difference. The lower heating value (LHV) of the waste was estimated from these proximate results using a standard formula. Potential power generation from incineration was estimated using the calculated LHV, daily waste tonnage, and assumed conversion efficiencies. The moisture content was then calculated thus:

$$\%\ of\ Moisture\ content\ \%W_C = \left[\frac{W1 - W2}{W1}\right] \times 100\% \quad (1)$$

For Mile six January: From equation (1),
where;
W_c = is moisture content; W_1=is wet weight of solid waste sample before drying; W_2 = is dry weight of the solid waste sample after drying in the oven.
January Sample calculation using the waste from Mile 6 dump site;
Wet weight of solid waste sample before drying W_1 = 0.50 kg
Dry weight of the solid waste sample after drying in the oven W_2 = 0.344 kg

$$\%W_c = \frac{0.50-0.344}{0.50} \times 100\% = 31.20\%$$

where;
W1 = Weight of the solid waste sample before placing it in the oven.
W2 = Weight of the solid waste sample after drying in the oven.
The volatile matter content of the sample was determined by placing 5g of the dried MSW sample in a muffle furnace for 7 minutes at 950°C following ASTM 3175 standard. After complete combustion, it was then cooled in a desiccator and weighed on the digital weighing balance to determine the dry weight of the residual ash. The Volatile matter content was then estimated thus:

$$\%\text{Volatile matter} = \left[\frac{\text{Dry sample weight} - \text{Ash weight}}{\text{Dry sample weight}}\right] \times 100\% \quad (2)$$

Sample calculation using data for Mile 6 dump site; January.
Dried sample weight = 0.344 kg; Ash weight = 0.2181 kg

$$\%\text{ Volatile matter content} = V = \frac{0.344-0.2181}{0.344} \times 100\% = 36.63\%$$

The ash content of the MSW samples was determined by heating the samples in an oven at 750°C according to ASTM 3174 method, the residue remaining which is the ash content was then weighed.
The fixed carbon content of the MSW samples was then estimated thus:
Fixed Carbon is typically calculated by difference, using the following formula:

Fixed Carbon (%weight): = 100 – Weight (%moisture content + %Volatile matter + %Ash) (3)

The calorific value or lower heating value (LHV) of MSW is the most important parameter for determining its suitability for energy generation [18]. Using a proximate analysis based model equation (4) [19], the LHV of the MSW generated in Jalingo was determined.

$$LHV = 45V - 6W \quad (4)$$

$LHV_M = 45 \times 38.8433 - 6 \times 25.40 = 1747.9485 - 152.4 = 1595.5485$kcal/kg
1595.5485kcal/kg = 1595.5485×4.184kJ/kg = 6,675.775KJ/kg (conversion from kcal/kg to kJ/kg)
$LHV_P = 45 \times 37.45 - 6 \times 28.98 = 1685.25 - 173.88 = 1511.37$kcal/kg
1511.37kcal/kg = 1511.37kcal/k×4.184 kJ/kg = 6,323.5721kJ/kg (conversion from kcal/kg to kJ/kg)
Where LHV: lower calorific value (kcal/kg); V: physically combustible component content (%), W: moisture content (%)
The power that can be generated from the incineration of the MSW disposed of in dumpsites in Jalingo was estimated using the following Equation (5)

$$E_{MSW} = LHV \times W_1 \times \frac{1000}{3600} \times \eta \quad (5)$$

Potential power generation (kW) $= 6675.775 \times \frac{53.90}{24} \times \frac{1000}{3600} \times 0.22 = 916.226$kW.

Therefore, potential electricity generation per day (kWh/day) = 916.22×24 = 21,989.28kWh/day
Where: E_{MSW} = Energy recovery potential (kwh/day)
LHV = Lower heating values of the solid waste (kcal/kg)
W_t = daily waste disposal (tonnes/day)
η = conversion efficient which ranges between 22-28% (IEA, 2007)
3600 = Conversion factor from kcal to kW.

2.4 Economic Analysis

The study distinguished two main cost categories: capital and operating expenses. These cost was obtained from established literature adjusted for freight and customs duties. The capital cost was set at about $15.23 per tonne of waste processed, including a 5% surcharge for logistics, with operating costs at $1.5 per tonne. The incineration plant was assumed to operate at 90% capacity considering maintenance downtime. Revenues were projected solely from electricity sales, using prevailing Nigerian electricity tariffs. Financial feasibility was assessed through Net Present Value (NPV) and Internal Rate of Return (IRR), while payback periods were also calculated. Established formulas were used for these calculations, assessing the profitability and return on investment over a ten-year horizon [20-21].

$$\text{NPV} = \sum_{n=1}^{N} \left(\frac{B-C}{(1+r)^n}\right) \quad (6)$$

where;
B is the benefit, C is the cost, r is the discount rate; n is the period and N is the total periods.
NPV is a useful tool to determine whether a project or investment will result in net profit or lose. A positive NPV result in profit while a negative NPV result in a loss.

$$IRR = \sum_{n-1}^{N} \left(\frac{B}{(1+r^n)}\right) = \sum_{n-1}^{N} \left(\frac{c}{(1+r)^n}\right) \quad (7)$$

The payback period (PBP) is expressed as the amount of time to recover the total investment:
Software for calculating NPV and IRR of projects or investments had been developed, which include programs in Excel spread sheet, Ret screen, US EPA project advisor etc.

3.0 Results and Discussion

3.1 Technical Analysis

Quantities and compositions of MSW disposed of at dumpsites in Jalingo: Data from the Ministry showed a steady increase in waste accepted at the two main dumpsites over recent years, with daily averages of approximately 54 and 45 tonnes at Mile Six and Pantinapu respectively in 2024 [22]. Plastics dominated the waste stream by weight (around 30–35%), followed by agricultural/garden waste (28–29%), with smaller proportions of paper, textiles, food waste, metals, and glass. The waste composition aligns with local socioeconomic and climatic conditions. The estimated average daily, monthly, and annual quantities of wastes disposed of in these two sites and the average composition of the MSW at each site are presented in Tables 1 and 2 respectively.

Table 1. Quantities of waste disposed of at dumpsites

	Dumpsites waste generation (tonnes)	
Year	**Mile six**	**Pantinapu**
2022	18,945.80	15,707.80
2023	19,840.90	16,033.80
2024	20,233.80	17,642.90
Sum	59,020.50	49,384.50
Annul average	19,673.50	16,461.50
Monthly average	1,639.46	1,371.79
Daily average	53.90	45.10

Source: Ministry of Rural and Urban Development Taraba State, (2024)

Table 2. Composition of solid waste

Category	**% Weight Composition**	
	Mile six	**Pantinapu**
Agricultural/Garden waste	28.00	29.00
Earth/Garbage	13.33	14.87
Food waste	5.67	6.00
Glass	1.30	0.90
Metals	1.11	0.43
Paper/Cardboards	11.88	9.93
Plastics	34.67	29.67
Textiles	4.04	9.20

Records obtained from the waste management unit of the state's Ministry of Rural and Urban Development show that the data obtained is in steady increase of the quantities of wastes accepted at the dumpsites from their inception till date, it can be deduced that this increase is due to the steady rise in the population of the city. By the end of the year 2024, the yearly average waste acceptance for Mile six and Pantinapu were found to be 19,673.50

tonnes, and 16,461.50tonnes respectively. While the total amount of waste accepted into each of the sites for the period of their existence is59, 020.50 tonnes and 49,384.50 tonnes, respectively.

In all the sites, it was found that plastics had the highest composition by weight, this is not unsurprising given the high usage of plastics in the day-to-day lives of the people in Jalingo and by extension, Nigeria, and this is corroborated by studies done in other city by other researchers [23]. The next category of waste that was found to be prominent in the MSW generated in Jalingo after plastics is agricultural waste. Given that Jalingo lies in the semi-arid zone of Nigeria, it is expected to be characterized by wet weather and occasional sand storms, therefore, its MSW composition having high agricultural waste content can be considered normal. For food waste, the values obtained are low compared to studies undertaken in other parts of the world, particularly countries with more developed economies. Researchers have postulated that the quantity of food waste in MSW is usually a reflection of the economy of that location [24], therefore, it is normal that the food waste in Jalingo ranges between just 5.66-6.00%.

3.2 Proximate Analysis, Calorific Value, and Potential Power Generation Capacity

Moisture content ranged between 25% and 29%, and volatile matter was near 38–39%. Ash content was roughly 22%, while fixed carbon levels were between 11% and 13%. These results indicate that the waste is suitable for incineration-based energy recovery, with LHV values ranging from approximately 6,320 to 6,680 kJ/kg, surpassing the 6 MJ/kg threshold needed for thermochemical energy extraction.

Table 4. Proximate analysis of solid waste samples

Items	**Months (2024)**	
	Mile six	**Pantinapu**
Moisture content (%weight)	25.40	28.98
Volatile content (%weight)	38.84	37.45
Ash content (%weight)	22.51	22.23
Fixed carbon content (%weight)	13.24	11.34

As can be seen from the data presented in Table 4, the results of the proximate analyses for the two sites are close with the widest standard deviation being 2.02. This is because the composition of the MSW for the two sites are quite similar and this similarity in the composition is because of the following obvious reasons as regards the population that generates these wastes that are disposed of at the dumpsites: same climate; similar socio-economic characteristics; similar spending habit and similar culture.

It has been found that when the moisture content of MSW is less than 45%, its volatile matter content is around 40% and the fixed carbon content is less than 15%, it is suitable for energy recovery via incineration [25]. This means that the result of the proximate analysis conducted shows that the MSW disposed of in the dumpsites in Jalingo are suitable for energy recovery using incineration.

The calorific values (lower heating value) of the solid waste disposed of in each of the two dumpsites in Jalingo are presented in Table 5.

Table 5: Electricity and power generation potentials of the solid waste (2024)

S/N	**Dumpsite**	**LHV (kJ/kg)**	**Potential Electricity generation (kWh/day)**	**Potential Electricity generation (kWh/tonne)**	**Potential power generation (kW)**
1	Mile six	6,675.775	21,989.28	407.9644	916.226
2	Pantinapu	6,323.572	17,428.4615	3864404	726.1839
Total			39,417.7415	794.4045	1642.4099

Estimations showed that incinerating the collected waste could generate about 21,990 kWh/day at Mile Six and 17,430 kWh/day at Pantinapu, aggregating to around 39,420 kWh/day. Annually, this corresponds to over 32 million kWh. Using regional consumption rates, this electricity could supply power to roughly 15,000 households in total. Using the average household size of Jalingo to be 7 persons, and the annual per capita electricity consumption of the region to be 840 kWh, it can be estimated that the potential amount of electricity that can be recovered from the two sites by thermochemical means can power 9,554 and 7,573 households respectively in an ideal case assuming no losses occur.

3.3 Economic Analysis

The Net Present Value (NPV) and Internal Rate of Return (IRR) for the generation of electricity by incineration of MSW for ten years were estimated and the results obtained are presented in Table 6.

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Table 6. Economic parameters for electricity generation via incineration

	Mile six	Pantinapu	Total
Potential annual electricity (kWh)	8,031,453.518	6,365,649.275	14,397,102.79
Average Annual MSW Disposed (Tonnes)	19,673.50	16,461.50	1,665,823.50
Annual Emission from Open Dumping (tCO_2e)	9,365.406	6,578.0736	15,943.4796
Emission from incineration (tCO_2e)	3,389.941	1,494.836	4,884.777
CO_2e savings from incineration/tonne of waste (tCO_2e)	00	00	20,828.2566
Revenue from Sale at N250 ($ 0.15)	1,062,263.979	954,847.3913	2,017,111.37
Revenue from CDM ($ 40)/tCO_2	00	00	00
Total Revenue	1,204,718.028	954,847.3913	2,159,565.419
Capital Cost ($ 15.225/tonne of MSW)	299,529.0375	250,626.3375	550,155.375
Operational Cost ($ 1.5/tonne of MSW)	29,510.25	24,692.25	54,202.50
Total Cost for First Year (Capital + Operational)	329,039.2875	275,318.5875	604,357.875
Net revenue for each year (Revenue-operational cost)	1,175,207.7778	930,155.1413	2,105,362.919
Net Present Value ($)	1,204,226.17	1,453,930.86	
Payback period (Years)	7.3932	7.3932	0.5981
Levelized Cost of Electricity ($/kWh)	0.05160	0.05143	
Internal Rate of Return (IRR)	19.87%	18.60%	

Table 7: Economic parameters for electricity generation via LFG recovery (2024)

	MILE SIX	PANTINAPU	TOTAL
Average Potential Annual Electricity (kWh)	988,602.95	655,503.29	1,644,452.24
Annual Emission from Open Dumping (tCO2e)	9,410.102	6,167.397	15,577.499
Emission from Incineration of LFG (tCO2e)	1,226.415	861.421	2,087.846
CO2e Savings from Incineration/tonne of waste (tCO2e)	8,183.687	5,305.976	13,489.663
Revenue from Sale at N250 ($ 0.15)	141,583.0442	100,735.0134	242,318.0576
Revenue from CDM ($ 40)/tCO2	327,347.48	212,239.04	539,586.52
Total revenue ($)	468,930.5242	312,974.0534	796,543.23
Capital Cost ($ 0.2885/kWh)	272,311.3882	193,747.0091	466,058.3973
Operational Cost ($ 0.0604/kWh)	57,010.77244	40,562.63206	97,573.4045
Net revenue for each year (Revenue-operational cost)	1,032,753.729	930,155.1413	1,962,908.87
Net Present Value ($)	2,879,488.57	1,862,442.96	
Payback Period (Years)	2.325	2.326	4.651
Levelized Cost of Electricity ($/kWh)	0.0796	0.0796	0.1592
Internal Rate of Return (IRR)	67.74%	79.64%	

Economic indicators from a ten-year project evaluation revealed positive NPV (between $1.2 and $1.45 million) and IRR values around 18% to 20%, supporting the financial accuracy of the proposed WtE plant. Capital costs were estimated around $300,000 for the larger site, complemented by operational costs near $30,000 annually. The levelized cost of electricity (LCOE) was calculated near $0.05 per kWh, which is lower than current tariffs, indicating competitiveness. Payback periods were approximately 7.4 years. Additionally, environmental benefits were noted, methane combustion from landfill gas reduces greenhouse gas emissions significantly compared to open dumping. Since the NPV for all two sites is positive, and their respective IRR for 10 years are 19.87% and 18.60% then it can be said that the economics of recovery of energy from the wastes disposed of in dumpsites in Jalingo looks good.

4.0 Conclusion

Techno-economic analysis of energy recovery from municipal solid waste in Jalingo metropolis was undertaken in this research, incineration was chosen as the preferred WTE technology based on the composition and qualities of the MSW generated in the city. At the end of this study, the following tentative conclusions were reached based on technical and economic facts unraveled, also, these findings are novel in respect to energy recovery from the MSW generated in the study location, Jalingo.

i. The quantity and composition of MSW are key to determining if the MSW generated in any particular location is suitable for energy recovery. The study found that the quantity and composition of MSW disposed of at dumpsites in Jalingo are suitable for energy generation.

ii. Even though other researchers had determined that the MSW generated in Jalingo is suitable for energy recovery, none had quantified the energy that can be recovered, this research fills that void and has found that on an annual basis, and about 14,397,102.79kWh of electricity can be recovered from the waste disposed of in the city's dumpsites.

iii. None of the studies undertaken in the city has been able to state the most suitable waste to energy technology for the city, this research fills that void as it found out from an economic perspective and based on the composition of the waste generated in the city that incineration of MSW is the viable WTE technology for Jalingo.

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