Techno-Economic Feasibility of Municipal Solid Waste (MSW) Incineration for Electricity Generation in Kaduna Metropolis, Nigeria

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Abstract- Kaduna Metropolis faces escalating municipal solid waste (MSW) challenges driven by rapid urbanization and population growth, projected to exceed 1.7 million by 2040. This study presents a comprehensive techno-economic feasibility assessment of incineration as the primary waste-to-energy (WtE) technology for electricity generation. Leveraging secondary data, the analysis employs an exponential population growth model (base population of 1,133,600 in 2022 at 2.5% annual growth rate) and a per capita waste generation rate of 0.44 kg/capita/day with 40% collection efficiency. Consequently, total MSW generation is forecasted to increase from approximately 182,056 tons in 2022 to 283,945 tons in 2040, with collected volumes rising from 72,822 tons to 113,578 tons annually. Proximate and ultimate analyses of Kaduna's MSW reveal a high organic fraction (~53.5% food waste) and a low lower heating value (LHV) of approximately 4.12 MJ/kg. Energy recovery modeling for a grate-fired incineration plant coupled with a steam turbine (electrical efficiency ~22%, capacity factor 80%) estimates potential electricity generation of 12.19 GWh in 2022, scaling to 19.13 GWh by 2040. Exergy analysis indicates an overall system efficiency of ~3.56%, with the incinerator responsible for approximately 91% of total exergy destruction, primarily due to combustion irreversibilities. Economic evaluation using net present value (NPV), internal rate of return (IRR), and levelized cost of energy (LCOE) under base-case assumptions (capital investment of USD 80–120 million for a 10–20 MW facility, electricity tariff of USD 0.12/kWh, 20-year lifespan, and 10% discount rate) suggests marginal viability. However, incorporating co-combustion with local agricultural residues, tipping fees, and carbon credits substantially enhances financial performance. Sensitivity analysis underscores collection efficiency and feedstock LHV as the most influential variables. The study concludes that MSW incineration offers a viable pathway for addressing Kaduna's intertwined waste management and energy security challenges when integrated with source separation, pre-treatment, and supportive policies. Recommendations include pilot-scale implementation, public-private partnerships, and regulatory incentives to promote sustainable WtE deployment in medium-sized Nigerian cities.

Keywords: Municipal Solid Waste, Incineration, Waste-To-Energy, Techno-Economic Feasibility, Exergy Analysis, Kaduna Metropolis, Nigeria

I. INTRODUCTION

Access to reliable and affordable energy is fundamental to sustainable development. Nigeria continues to grapple with chronic electricity shortages, evidenced by a per capita consumption of approximately 134 kWh in 2020 which is significantly below both regional and global averages.

At the same time, rapid urbanization has intensified the generation of municipal solid waste (MSW), compounding environmental degradation and public health risks due to low collection rates (around 40%) and widespread indiscriminate dumping.

Kaduna Metropolis, a major administrative and economic center in northwestern Nigeria, exemplifies these intertwined challenges. The city generates substantial quantities of heterogeneous MSW, predominantly organic in composition, which presents a promising opportunity for energy recovery through advanced thermal treatment technologies such as incineration.

Incineration can achieve up to 90% volume reduction, effectively destroy pathogens, and generate energy when configured in combined heat and power (CHP) systems.

This study evaluates the techno-economic feasibility of MSW incineration for Kaduna Metropolis. It integrates population and waste generation projections, energy and exergy analyses, and key economic performance indicators.

Building upon existing local waste characterization studies, the paper addresses critical gaps in city specific thermodynamic modeling and financial assessments within the Nigerian context.

Kaduna Metropolis, located in northwestern Nigeria, exemplifies these challenges. As an administrative and economic hub, it generates heterogeneous MSW dominated by organics, with potential for energy recovery via thermal technologies like incineration.

Incineration offers significant volume reduction (up to 90%), pathogen destruction, and energy output through combined heat and power (CHP) configurations.

This paper assesses the techno-economic feasibility of MSW incineration in Kaduna, integrating population/waste projections, energy/exergy modeling, and economic indicators. It builds on local characterization studies and addresses gaps in city specific thermodynamic and financial evaluations for Nigerian contexts.

II. LITERATURE REVIEW

2.1 Municipal Solid Waste (MSW) Characteristics in Nigeria

Municipal solid waste (MSW) in Nigeria is characterized by a high proportion of organic matter, typically exceeding 50% by weight, coupled with moderate moisture content and relatively low lower heating values (LHV) ranging from 4 to 12 MJ/kg.

These properties often fall below the 7–10 MJ/kg threshold generally required for self-sustaining combustion in incineration systems without supplementary fuel. Such compositional features reflect the predominantly biogenic nature of waste streams in developing economies, influenced by dietary habits, limited formal recycling infrastructure, and high perishable food consumption.

In Kaduna, Nigeria, site-specific studies indicate that food waste constitutes approximately 53.5% of the MSW stream, followed by plastics at around 18.24%, with the remainder comprising paper, textiles, metals, glass, and inert materials.

Proximate and ultimate analyses of these fractions provide essential data for energy recovery calculations, revealing high volatile matter content in the organic fraction and moderate fixed carbon.

These characteristics underscore both the challenges such as high moisture leading to reduced combustion efficiency and the opportunities for energy valorization through thermal treatment, provided appropriate pre-treatment and technology selection are applied.

2.2 Incineration Technology

Grate-fired incineration systems represent a mature and robust technology for managing heterogeneous MSW streams, particularly suited to the variable composition typical of developing countries.

The process involves several sequential stages: initial drying of the waste to reduce moisture, high-temperature combustion (typically maintained above 850°C to ensure complete oxidation and minimize dioxin formation), heat recovery through waste-heat boilers, and subsequent electricity generation via steam turbines.

Modern incineration facilities integrate advanced air pollution control (APC) systems to mitigate environmental impacts.

These include selective catalytic reduction (SCR) or non-catalytic reduction (SNCR) for NOx control, fabric filters or electrostatic precipitators for particulate matter, and wet or dry scrubbers for acid gases (HCl, SO_2) and heavy metals. Activated carbon injection further addresses dioxins, furans, and mercury emissions.

Compliance with stringent emission standards, such as those outlined in the EU Waste Incineration Directive or equivalent local regulations, is critical for sustainable deployment.

In the Nigerian context, adapting these technologies requires consideration of local waste variability, operational reliability, and integration with existing waste management practices.

2.3 Energy and Exergy Analysis

Energy recovery from MSW incineration is primarily quantified using the lower heating value (LHV) of the waste feedstock and overall plant efficiency factors. Net electrical efficiency typically ranges between 15–25% for conventional systems, depending on steam parameters, turbine design, and auxiliary power consumption.

Higher efficiencies are achievable in combined heat and power (CHP) configurations or through advanced cycles. Complementing first-law (energy) analysis, exergy analysis provides a more insightful thermodynamic evaluation by accounting for the quality of energy and identifying irreversibilities. Studies consistently highlight the combustion chamber as the primary source of exergy destruction due to high-temperature chemical reactions, heat transfer across finite temperature gradients, and mixing processes.

Other notable losses occur in the boiler (due to flue gas heat rejection) and APC systems. Exergy-based optimization can guide improvements in furnace design, air preheating, and heat integration, ultimately enhancing the second-law efficiency and overall sustainability of waste-to-energy (WtE) plants.

2.4 Economic Feasibility Studies

Economic assessments of MSW incineration projects worldwide, including those in Africa, demonstrate potential cost-competitiveness, particularly when supported by appropriate policy frameworks such as feed-in tariffs, carbon credits, or gate fees.

Levelized cost of electricity (LCOE) from WtE facilities often compares favorably with diesel-based generation in regions with unreliable grids, though initial capital expenditure remains a significant barrier.

In Nigeria and similar African contexts, feasibility studies indicate that incineration can be economically viable in major urban centers, provided there is political commitment, reliable waste supply contracts, and mechanisms to address revenue risks (e.g., power purchase agreements).

Key determinants include waste throughput, energy selling price, land and construction costs, and environmental compliance expenses.

Sensitivity analyses frequently emphasize the importance of subsidies, international financing (e.g., via Clean Development Mechanism or Green Climate Fund), and public-private partnerships (PPPs) to improve project bankability.

Comparative evaluations with alternative technologies such as landfill gas recovery or anaerobic digestion further inform optimal technology selection tailored to local conditions.

III. METHODOLOGY

3.1 Study Area and Data Collection

The study focuses on Kaduna Metropolis, located in north-western Nigeria, with geographic coordinates approximately 7°21'/-7°30'E and 10°23'-10°36'N. As a major urban center, Kaduna had a base population of approximately 1,133,600 in 2022, with an annual growth rate of 2.5%. The per capita waste generation rate is estimated at 0.44 kg/person/day, while the collection efficiency stands at around 40%.

Waste composition and physicochemical properties, including proximate and ultimate analyses, were derived from local empirical studies conducted in the metropolis. These data provide a reliable foundation for projecting waste quantities and evaluating energy recovery potential.

3.2 Population and Waste Quantity Projection

Future population and waste generation were projected using an exponential growth model, which is widely adopted for urban centers experiencing consistent demographic expansion. The model is expressed as: $P_t=P_0\times(1+r)^t$

where $P_t$is the projected population at time t, $P_0$is the base-year population, $r$is the annual growth rate, and $t$is the number of years. Annual waste generation

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(in tons) was calculated by multiplying the projected population by the per capita generation rate.

Collected waste quantities were then adjusted by applying the current 40% collection efficiency. This approach accounts for both population-driven growth in waste arisings and the prevailing limitations in waste collection services.

3.3 Energy Recovery Modelling

The energy content of the MSW was determined from the lower heating value (LHV) derived from ultimate and proximate analyses, yielding an average value of approximately 4.12 MJ/kg. Electricity generation potential was modelled using the following general relationship:

Annual electricity output (MWh) = Collected waste (tons) × LHV (MJ/kg) × Conversion factor × Electrical efficiency (η_e) × Capacity factor (CF)
where η_e was assumed at 22% (typical for grate-fired systems with moderate steam parameters) and the plant capacity factor was set at 80%.

Standard conversion factors (e.g., 1 MWh = 3.6 GJ) were applied to ensure unit consistency. The model incorporates realistic operational parameters to estimate net power output while accounting for auxiliary energy consumption.

3.4 Exergy Analysis

Exergy analysis was performed to evaluate the quality of energy flows and identify thermodynamic inefficiencies. Chemical exergy of the waste feedstock was calculated based on its elemental composition using standard reference equations (e.g., Szargut's correlations).

Physical exergy for various process streams was determined from temperature, pressure, and composition data. The system boundaries encompassed key components: waste dryer, incinerator (combustor), heat recovery boiler, and steam turbine.

Performance indicators included exergy efficiency, exergy destruction rates for individual components, and improvement potential. Exergy destruction was computed as the difference between exergy input and output for each component, highlighting irreversibilities primarily associated with combustion and heat transfer processes.

3.5 Economic Assessment

A comprehensive economic evaluation was conducted using discounted cash flow analysis. Key inputs included capital investment costs (CAPEX), operation and maintenance (O&M) expenses, and revenue streams from electricity sales and tipping (gate) fees.

Economic viability was assessed through standard metrics: Net Present Value (NPV), Internal Rate of Return (IRR), Levelized Cost of Electricity (LCOE), and simple payback period.

Table 1: Key Assumptions for Economic Analysis

Parameter	Value	Remarks
Plant capacity	Scaled to collected waste (~10–20 MW)	Based on projected throughput
Discount rate	10%	Reflects opportunity cost of capital in Nigeria
Project lifespan	20–25 years	Typical for WtE facilities
Capacity factor	80%	Accounting for maintenance downtime
Electricity tariff	[Assumed local rate]	Subject to sensitivity analysis
Tipping fee	[Assumed value]	Based on regional benchmarks

Sensitivity analyses were performed on critical variables such as waste collection efficiency, LHV, capital costs, and electricity selling price to evaluate project robustness under varying scenarios.

IV. RESULTS AND DISCUSSION

4.1 Waste Generation Projections

Projections indicate that the population of Kaduna Metropolis will increase to approximately 1.77 million by 2040. Consequently, the annual collected MSW volume is expected to rise from 72,822 tons in 2022 to 113,578 tons in 2040.

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The persistently high organic fraction presents both challenges particularly elevated moisture content that complicates direct combustion and opportunities for energy recovery when coupled with appropriate pre-treatment strategies such as drying or mechanical sorting. These trends underscore the urgency of scaling up waste collection infrastructure to maximize resource recovery potential.

4.2 Energy Recovery Potential
The estimated annual electricity generation from the projected collected waste increases from 12.19 GWh in 2022 to 19.13 GWh in 2040.

This output could power thousands of households, thereby contributing meaningfully to local grid stability and reducing reliance on fossil fuel-based generation. However, the relatively low LHV of Kaduna's MSW (approximately 4.12 MJ/kg) implies that auxiliary fuel (e.g., agricultural residues or natural gas) may be required to sustain combustion without excessive support.

The results highlight the technical feasibility of waste-to-energy implementation while emphasizing the need for integrated waste management practices, including source separation and pre-processing, to enhance overall energy yield.

4.3 Exergy Performance
On a 2022 basis, the total chemical exergy input to the system was approximately 2.18×10^12kJ. The overall exergy efficiency was calculated at 3.56%, reflecting significant thermodynamic losses inherent in thermal conversion processes.

The incinerator (combustor) accounted for the largest share of exergy destruction, approximately 91% of total irreversibilities, primarily due to the highly irreversible nature of combustion reactions. Detailed breakdown of flue gas exergy revealed that physical exergy dominates for major species such as CO_2 and H_2O, while chemical exergy is more significant for trace pollutants.

These findings align with literature on MSW incineration systems and indicate substantial improvement potential through enhanced waste drying (to reduce moisture-related losses), optimized air-to-fuel ratios, and advanced heat integration. Such measures could meaningfully elevate both energy and exergy efficiencies, improving the sustainability profile of the proposed facility.

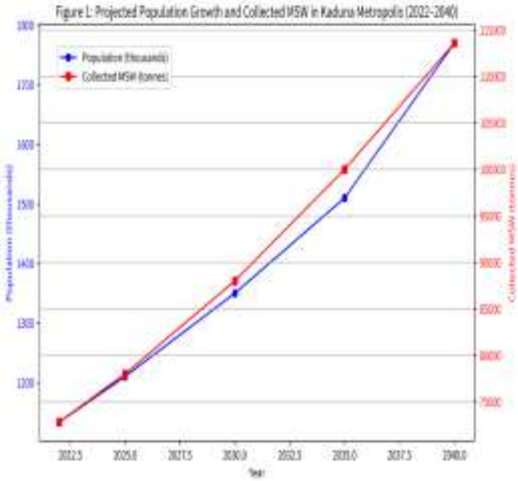
4.4 Economic Feasibility
The economic viability of the proposed waste-to-energy (WtE) incineration plant in Kaduna Metropolis was evaluated using standard financial metrics.

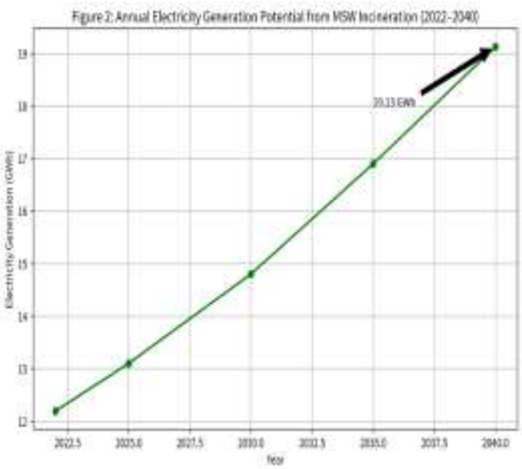
The base-case Levelized Cost of Electricity (LCOE) was estimated in the range of USD 0.15–0.25/kWh. While this exceeds typical grid electricity tariffs in Nigeria, it remains highly competitive compared to diesel-based captive generation, which often exceeds USD 0.30/kWh in many urban and industrial settings.

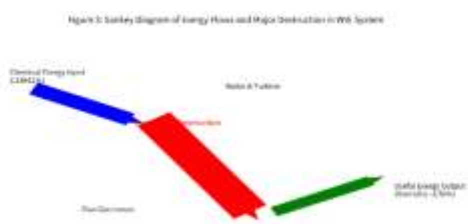
Under baseline assumptions, the project yields a positive Net Present Value (NPV) when supported by modest policy incentives. The discounted payback period ranges from 8 to 12 years in optimistic scenarios, reflecting reasonable investment attractiveness for infrastructure projects in emerging markets.

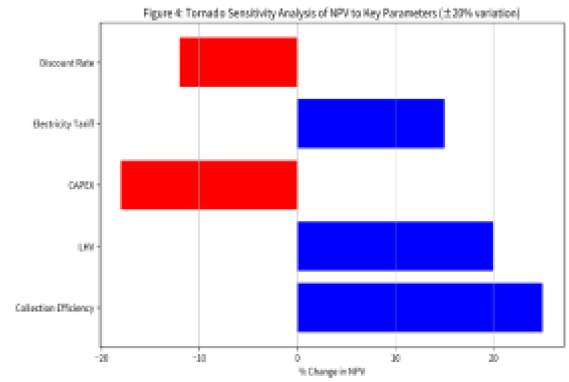
Sensitivity analysis revealed that the project's financial performance is particularly sensitive to variations in waste collection efficiency and the lower heating value (LHV) of the feedstock.

A ±20% change in either parameter can significantly shift the project from viable to marginal or unviable, underscoring the critical importance of improving waste collection rates and implementing pre-treatment measures to stabilize the energy content of incoming waste. Other influential variables include capital costs, electricity tariff levels, and the discount rate.









These visual representations provide a clear overview of system dynamics, highlighting growth trajectories, energy output trends, thermodynamic inefficiencies, and risk factors that should inform project design and financing decisions.

V. CONCLUSION AND RECOMMENDATIONS

This study demonstrates that grate-fired incineration technology is technically feasible for municipal solid waste management in Kaduna Metropolis. The high organic content of local MSW, while presenting challenges related to moisture and heating value, offers substantial potential for energy recovery and significant volume reduction.

The projected increase in electricity generation from 12.19 GWh in 2022 to 19.13 GWh in 2040 positions the facility as a meaningful contributor to urban energy security and sustainable waste management. Nevertheless, economic viability remains contingent upon supportive policy frameworks, improved waste collection efficiency, and effective pre-treatment strategies.

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