E3S Web of Conferences 729, 08003 (2026) https://doi.org/10.1051/e3sconf/202672908003
SPETM 2026

Bridging Nigeria's energy deficit through waste-to-energy: evidence, pathways and policy imperatives

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Abstract. Nigeria faces persistent electricity shortages and increasing municipal solid waste generation, both of which negatively affect economic productivity, environmental sustainability, and urban livelihood. This study evaluates the feasibility of deploying waste-to-energy (WtE) systems as an integrated solution to simultaneously address energy deficits and waste management challenges in Nigeria. A documentary-based assessment was conducted using peer-reviewed literature, national policy documents, and industry reports published between 2015 and 2026. The study applied a multi-criteria readiness framework to classify Nigerian states into high, medium, and low-readiness deployment tiers based on waste generation volume, collection efficiency, and energy recovery potential. Findings reveal different readiness levels, the highest demonstrating recoverable energy potential exceeding 50 MW. A second tier of states shows moderate feasibility but depends on improvements in waste logistics, feedstock consistency, and infrastructure efficiency. Lower-tier states remain constrained by poor waste collection systems, weak infrastructure, and policy limitations. The study further highlights that successful WtE implementation requires integrated system design, emissions control, regulatory stability, and stakeholder coordination. It recommends a phased "flagship-first" deployment strategy through public-private partnerships, complemented by an "organics-first" approach that integrates anaerobic digestion and the informal waste sector for sustainable recovery.

Keywords: Nigeria, waste-to-energy, municipal solid waste, collection efficiency, incineration, anaerobic digestion, policy, grid reliability

1 Introduction

Nigeria's inadequate electricity supply has driven widespread dependence on self-generation through generators, which are costly, inefficient, and environmentally unsustainable. Simultaneously, rapid urbanization, population growth, and industrial expansion have intensified MSW generation, placing increasing pressure on already inadequate waste collection and disposal systems. These conditions highlight the need for integrated solutions that jointly address energy insecurity and waste management.

Waste-to-energy (WtE) systems have gained global attention as viable technologies for converting municipal waste into electricity, heat, and fuel while reducing reliance on landfills and greenhouse gas emissions. Unlike conventional waste disposal methods, WtE provides a dual function of waste treatment and energy recovery. However, its performance depends strongly on waste composition, feedstock consistency, collection efficiency, infrastructure readiness, and emissions control, which must be treated as core engineering and operational parameters rather than secondary municipal concerns [1].

In the context of rising fossil fuel costs, climate variability, and global energy security concerns, WtE is increasingly relevant as a dispatchable, locally available energy source that can complement intermittent renewables such as solar and wind [2].

WtE technologies broadly include thermal pathways such as incineration, pyrolysis, and gasification, as well as biological pathways such as anaerobic digesti\on (AD) and landfill gas recovery [3]. Thermal systems are best suited for high-calorific, non-recyclable waste fractions, while biological systems are more appropriate for organic-rich waste streams. Recent literature emphasizes integrated WtE configurations that combine multiple technologies to improve energy efficiency and reduce emissions. Among these, anaerobic digestion is relevant in developing economies due to the high organic content of municipal waste.

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Despite these advantages, WtE deployment in developing countries remains constrained by technical, financial, institutional, and environmental challenges [11]. Key barriers include inefficient waste logistics, high moisture content, low calorific value, feedstock variability, weak infrastructure, high capital costs, financing constraints, emissions concerns, regulatory uncertainty, and low public acceptance.

In Nigeria, although interest in WtE has increased through policy discussions and pilot initiatives, implementation remains limited due to fragmented waste systems, weak coordination, inconsistent waste data, and inadequate infrastructure readiness [12–13].

2 Research gaps in waste-to-energy studies

Despite growing research on WtE systems in Nigeria, several critical gaps remain. Most studies focus on national-level feasibility, with limited state or city-level deployment analysis, restricting practical planning and prioritization. Existing research typically assesses incineration, anaerobic digestion, gasification, and landfill gas systems independently, with limited attention to integrated or hybrid configurations suitable for Nigeria's waste profile. Electricity generation, waste management, environmental sustainability, and policy frameworks are often treated separately, rather than as an integrated planning system aligned with circular economy objectives. There is also limited practical direction on deployment sequencing, technology prioritization, and scalable implementation strategies under real infrastructure, financial, and regulatory constraints. Furthermore, significant differences in waste generation, collection efficiency, urbanization, infrastructure capacity, and institutional strength across Nigerian states are not adequately reflected in existing models. Collectively, these gaps demonstrate the need for an integrated, location-specific, and implementation-oriented WtE framework for Nigeria.

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3 Research innovation and study contributions

To address these limitations, this study develops an integrated, implementation-oriented framework for evaluating the feasibility of WtE in Nigeria. The novelty lies in a structured multi-criteria readiness assessment model based on three key indicators: waste generation volume, collection efficiency, and energy recovery potential. Unlike broad national assessments, this framework enables systematic classification of Nigerian states into high-, medium-, and low-readiness tiers, allowing precise identification of locations where WtE systems are technically viable, economically feasible, and operationally sustainable.

The study further introduces a phased "flagship-first" deployment strategy, prioritizing high-readiness urban centers for initial pilot implementation before scaling to lower-readiness regions. This reduces investment risk, improves operational learning, and enhances scalability under existing infrastructure and financing constraints. In addition, an "organics-first" pathway is proposed, prioritizing anaerobic digestion for biodegradable waste while reserving thermal WtE technologies for non-recyclable residuals. This aligns with the waste hierarchy, circular economy principles, and Nigeria's National Policy on Solid Waste Management (2020). The integration of the informal waste sector into collection and feedstock systems further strengthens socio-economic inclusiveness and system resilience.

The key contributions of this study are:
(i) development of a multi-criteria WtE readiness assessment framework tailored to Nigeria; (ii) identification and prioritization of states suitable for scalable WtE deployment based on technical and infrastructural indicators; (iii) formulation of a practical deployment roadmap integrating anaerobic digestion, phased implementation, PPP models, and circular resource recovery strategies.

By integrating technical, environmental, infrastructural, and policy dimensions into a unified framework, this study advances the discourse on decentralized energy systems and sustainable waste management in developing economies. It ultimately provides a scalable and context-specific pathway to improve electricity access, reduce dependence on landfills, strengthen municipal waste recovery systems, and support Nigeria's transition toward a circular economy.

4 System model

4.1 Research design

This study adopts a qualitative-analytical research design supported by secondary data analysis. The approach is appropriate for evaluating the feasibility of waste-to-energy (WtE) in data-constrained environments, where primary field measurements are limited. The methodology integrates documentary analysis with a structured multi-criteria decision framework to assess WtE deployment readiness across Nigerian states.

The analysis focuses on identifying socio-economic, technical, and infrastructural conditions that influence WtE implementation, with an emphasis on waste generation dynamics, collection efficiency, and energy recovery potential.

Secondary data were obtained from peer-reviewed journal articles, government policy documents, technical reports, and reputable international energy and waste databases. The study period covers 2015–2026 to capture recent developments in WtE technologies, policy evolution, and waste management practices in developing economies.

To ensure data reliability and scientific validity, the following criteria were applied:

Inclusion criteria:

- Peer-reviewed journal articles (2015–2026)
- Empirical, modeling, or case-study-based WtE research
- Studies relevant to developing countries, particularly Sub-Saharan Africa
- Official government or institutional energy and waste management reports

Exclusion criteria:

- Non-peer-reviewed sources (blogs, opinion articles, informal reports)
- Non-technical or unverified computational tools
- Studies lacking methodological or empirical rigor

4.2 Analytical framework for WtE assessment

A multi-criteria readiness assessment framework was developed to evaluate the potential for WtE deployment across Nigerian states. The framework integrates three vital indicators:

- Waste generation volume (tons/year)
- Waste collection efficiency (WCE)
- Energy recovery potential (based on waste composition and calorific value)

Each state was evaluated using a normalized scoring approach on a 0–1 scale, with weighted indicators to classify WtE deployment readiness into three categories: high, medium, and low.

This approach enables a comparative assessment of states based on both waste availability and system-efficiency constraints.

Table1. Comparative table of municipal waste generation across selected Nigerian states (figures are indicative planning estimates) [17].

State	Estimated Population (Millions)	Waste Generation Rate (kg/person/day)	Estimated Waste (tons/day)	Ranking
Lagos	20 – 22	0.65 – 0.75	13,000 – 16,500	1st
Kano	15 – 16	0.50 – 0.65	7,500 – 10,400	2nd
Rivers	7 – 8	0.60 – 0.70	4,200 – 5,600	3rd
FCT (Abuja)	4 – 5	0.70 – 0.80	2,800 – 4,000	4th
Oyo	7 – 8	0.50 – 0.60	3,500 – 4,800	5th
Kaduna	9 – 10	0.45 – 0.60	4,000 – 5,500	6th
Ogun	7 – 8	0.55 – 0.65	3,800 – 5,200	7th
Delta	5 – 6	0.55 – 0.65	2,800 – 3,900	8th
Anambra	5 – 6	0.50 – 0.60	2,500 – 3,600	9th
Plateau	4 – 5	0.45 – 0.55	1,800 – 2,700	10th

According to Table 1:

- Lagos is the highest waste generator due to its very high population density, industrialization, and commercial activities. Kano ranks second, driven mainly by large population size and expanding urban settlements.
- States with strong urban centers (e.g., Rivers, FCT) show higher per capita waste rates, even if their populations are smaller.

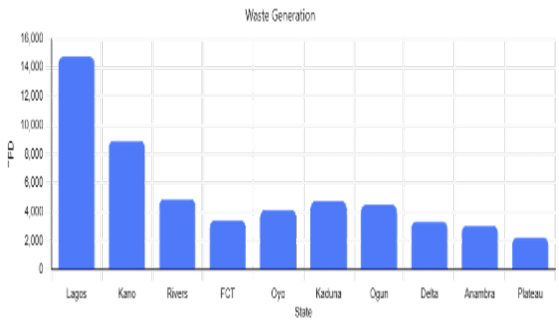

Fig. 1. Estimated municipal waste generation across selected Nigerian states.

Fig 1 represents Estimated municipal waste generation across selected Nigerian states. Lagos stands significantly above all states due to its very high population and intense economic activity. Kano follows as the second-largest contributor. Other states generate notably less waste, though urban centers (Rivers, FCT, Kaduna) still show relatively high values.

The energy potential of municipal solid waste was estimated using established engineering conversion factors derived from literature. WtE facilities typically generate approximately 500–600 kWh per ton of waste, with an average operational benchmark of 550 kWh/ton adopted in this study. For general planning purposes, this corresponds to an energy yield of approximately 0.5-0.7 kWh/kg of waste.

The technical energy output was estimated based on assumptions about annual waste generation and conversion efficiency. The exploitable energy output was further adjusted using system performance factors, defined as:

$$X_0 = T_0 \times WCE \times AF \quad (1)$$

where:
X_0 = Exploitable Output
T_0 = Technical Output
AF = Availability Factor
WCE = Waste Collection Efficiency
AF = 0.85 (assumed average operational uptime for WtE facilities)

This formulation accounts for both collection system losses and plant operational reliability [13].

States were classified into three deployment readiness tiers based on combined energy potential and waste system performance:

High readiness: WCE ≥ 70% and energy potential ≥ 50 MW

Medium readiness: WCE 50–70% and energy potential between 15–50 MW

Low readiness: WCE < 50% or energy potential < 15 MW

This classification provides a decision-support tool for identifying priority regions for phased WtE deployment and infrastructure planning

5 Results and findings

5.1 WtE technical and exploitable potential

The assessment of waste-to-energy (WtE) potential across Nigerian states reveals a clear divergence between theoretical technical capacity and the energy output that can be practically exploited. Table 1 summarizes the relationship between technical scale, waste system efficiency, and near-term deployment readiness.

The results indicate that WtE feasibility is primarily constrained by waste collection efficiency (WCE) and waste composition characteristics rather than absolute waste availability. States with high WCE and favorable waste characteristics demonstrate significantly higher exploitable energy outputs, while most states experience substantial losses between theoretical and usable potential due to system inefficiencies.

Table 2. Technical vs Exploitable WtE Potential and Readiness Classification

State / Tier	Indicative Technical Scale	Exploitable Output Drivers
Lagos	≥ 50 MW class	High WCE, favorable LHV, manageable moisture
Kano	≥ 50 MW class	High WCE, relatively stable waste streams
Next Tier (Kaduna, Oyo, Rivers, FCT)	15–50 MW	Moderate WCE (up to ~70%), variable composition
Other States	< 15–50 MW threshold (< 50 MW overall)	Low WCE dominates system performance

According to Table 2, the high-readiness category comprises Lagos and Kano, both exceeding the 50 MW exploitable threshold. These states exhibit:

- High waste generation density
- Relatively stronger waste logistics systems
- Improved collection efficiency compared to national averages
- More stable waste composition profiles

These conditions make them suitable for initial WtE deployment under a flagship model, particularly using combined heat and power (CHP)-ready systems and integrated municipal-energy frameworks.

States in the medium category, including Kaduna, Oyo, Rivers, and the Federal Capital Territory (FCT), demonstrate a moderate WtE potential of 15–50 MW. However, exploitable output is strongly dependent on system improvements, particularly:

- Waste collection efficiency improvements (up to ~70%)
- Source segregation of organic and recyclable fractions
- Improved logistics and transfer station efficiency
- Infrastructure modernization for waste handling

These states are technically viable but require supportive policy, PPP-driven logistics systems, and phased infrastructure development before large-scale deployment.

Most remaining states fall within the low-readiness category, with exploitable potential below 15 MW. In these regions:

- Waste collection systems are fragmented or inconsistent
- Low urban waste density limits economies of scale
- High moisture and poor segregation reduce calorific value
- Institutional capacity for WtE operations remains weak

Under current conditions, centralized WtE systems are not economically viable. However, decentralized biological systems, particularly small-scale anaerobic digestion, remain technically feasible for localized organic waste streams.

6 Informal waste sectors in system performance

A crucial finding from the analysis is that WtE performance in Nigeria is strongly influenced by the informal waste sector, which plays a major role in material recovery and waste stream organization.

Waste pickers, aggregators, and small recyclers contribute significantly to pre-processing activities, particularly around dumpsites and transfer stations. Evidence suggests that their integration improves recycling rates, reduces municipal collection costs, and enhances system efficiency, while exclusion can lead to social conflict and reduced system performance.

In the Nigerian context, particularly in Lagos, past waste reforms demonstrate that excluding the informal sector undermines waste stream stability. Therefore, effective WtE deployment must incorporate structured integration mechanisms such as:

- cooperative-based organization models
- micro-franchising for collection services
- licensed participation in material recovery facilities (MRFs)
- formal recognition in pre-sorting operations

This integration improves feedstock quality for both anaerobic digestion and thermal systems while strengthening social acceptance and operational resilience.

The results support a staged implementation pathway aligned with readiness tiers:

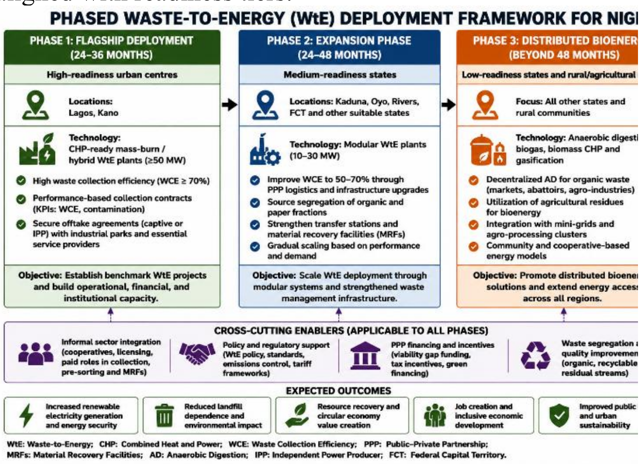

Fig. 2. Phased waste-to-energy (WtE) deployment framework.

Figure 2 presents a phased waste-to-energy (WtE) deployment framework for Nigeria, structured into three implementation stages. Phase 1 prioritizes flagship projects in high-readiness urban centers (Lagos and Kano), focusing on large-scale CHP-ready systems supported by strong waste collection efficiency and secured energy offtake agreements. Phase 2 expands deployment to medium-readiness states through modular 10–30 MW facilities, improved logistics, and enhanced source segregation supported by public–private partnerships (PPPs). Phase 3 extends decentralized bioenergy solutions to low-readiness and rural areas using anaerobic digestion, biomass, and mini-grid integration.

The framework is supported by cross-cutting enablers, including informal-sector integration, policy and regulatory support, PPP financing mechanisms, and waste-segregation systems. Overall, the model illustrates a structured transition from centralized high-capacity systems to decentralized circular bioenergy solutions, ensuring scalability, inclusiveness, and sustainability.

The results demonstrate that:

- WtE feasibility in Nigeria is system-constrained rather than resource-constrained
- Waste collection efficiency is the primary determinant of energy recovery potential
- Only a small number of states meet conditions for near-term large-scale deployment
- Medium and low tiers require infrastructure and logistics transformation before viability
- Informal-sector integration is essential for feedstock stability and system performance
- A phased, tier-based deployment strategy is the most practical pathway for implementation

7 Policy implications: creating an enabling environment

Effective WtE deployment in Nigeria requires a supportive regulatory, institutional, and financial framework. The Electricity Act 2023 provides a strong foundation for decentralized electricity generation, state-level electricity market development, and the integration of renewable energy [6-7]. This creates opportunities for sub-national WtE procurement, captive power arrangements, and localized energy recovery systems.

Similarly, the National Policy on Solid Waste Management (2020) supports integrated solid waste management, recycling, waste recovery, and energy generation from non-recyclable residual waste streams [8]. Aligning WtE deployment with this waste hierarchy improves environmental legitimacy and reduces conflicts between energy recovery and recycling objectives.

To strengthen implementation, policy support should prioritize:

- Improved waste collection efficiency and segregation systems
- Public–private partnership (PPP) financing models
- Feedstock quality monitoring and contamination control
- Grid reliability and power offtake assurance
- Integration of informal waste workers through cooperative and semi-formal collection systems
- Environmental compliance and emission regulation

8 Practical implications

8.1. High-Readiness Urban Centers

The analysis confirms that Lagos and Kano are currently the most suitable locations for near-term grid-relevant WtE deployment due to high waste throughput, relatively stronger collection systems, and favorable scale thresholds [5]. These cities can serve as flagship locations for demonstrating technical viability, financial bankability, and institutional readiness.

8.2. Feedstock Quality and Moisture Constraints

Waste moisture content remains a major technical limitation because it reduces lower heating value (LHV), lowers combustion efficiency, and increases operational instability in thermal WtE plants. Addressing this challenge requires practical measures such as:

- Covered waste storage systems
- Waste blending to stabilize LHV
- Pre-drying where economically feasible
- Improved segregation of wet and dry fractions
- Strict feedstock loading control

These interventions improve plant stability and enhance exploitable energy recovery.

8.3. Scalable Phased Deployment

The results support a phased deployment strategy in which large urban facilities are implemented first, followed by modular WtE systems and decentralized bioenergy pathways in medium and low-readiness states. This reduces capital exposure while allowing progressive infrastructure development.

9 Study limitations

This study is primarily based on secondary datasets on waste generation, waste composition, and infrastructure readiness. As a result, some state-level estimates may be influenced by outdated or uncertain municipal data. Future studies should integrate localized waste characterization surveys and real-time collection performance assessments to improve model precision.

In addition, this work did not fully quantify detailed techno-economic indicators such as the internal rate of return, lifecycle cost analysis, willingness to pay, or social acceptance metrics. These factors remain important for implementation feasibility and should be explored in future research.

Other practical limitations include:

- Weak municipal governance structures
- Inconsistent feedstock supply
- Poor revenue assurance mechanisms
- Limited financing sustainability
- Informal-sector resistance or exclusion risks
- Land acquisition constraints
- Public opposition to thermal facilities
- Electricity distribution instability

10 Conclusion

Waste-to-energy (WtE) offers a viable pathway to address Nigeria's dual challenges of municipal waste management and energy deficits. However, sustainable deployment depends on realistic planning that accounts for waste collection efficiency, feedstock quality, moisture content, and regional infrastructure disparities. The findings show that Lagos and Kano possess the strongest near-term readiness for flagship WtE deployment due to their higher waste throughput and relatively stronger collection systems. In these locations, CHP-ready thermal or hybrid WtE systems may offer practical large-scale recovery opportunities when supported by robust public-private partnerships (PPPs), secured power offtake arrangements, and efficient waste logistics. For medium-readiness states, modular WtE plants and improved segregation systems provide a scalable pathway for gradual expansion. In lower-readiness and agricultural regions, decentralized bioenergy solutions, particularly anaerobic digestion, biomass conversion, and agricultural residue utilization, offer more technically suitable alternatives.

Overall, this study demonstrates that Nigeria's most feasible WtE future is not a single centralized model, but a hybrid, phased, and organics-led deployment strategy that integrates infrastructure readiness, circular economy principles, and localized energy recovery. Such an approach can enhance renewable energy generation, reduce reliance on landfills, improve environmental sustainability, and strengthen inclusive economic development.

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