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Design of Waste-to-Electricity Model: Estimating the Potential of Electricity Recovery in Nigerian Geopolitical Zones

Projekt modelu przetwarzania odpadów na energię elektryczną: Szacowanie potencjału odzysku energii elektrycznej w nigeryjskich strefach geopolitycznych

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Keywords: *Waste-to-Electricity*

Abstract
As Nigeria faces rapid urbanization and population growth, effective waste management becomes increasingly critical. The current inadequate practices lead to waste accumulation, harming public health and urban aesthetics, while insufficient electricity supply hampers sustainable living. Waste-to-Electricity (WtE) presents a dual solution to these issues.
In the master's thesis, that formed the basis for this article, a MATLAB App Designer-based model to forecast electricity generation from municipal solid waste in Nigerian geopolitical zones from 2024 to 2034 was introduced. The model uses socio-demographic and economic factors, projecting a 44% increase in annual waste generation from 66 million tons in 2024 to 95 million tons by 2034. With an average waste calorific value of 9.6 MJ/kg, the North-west and South-west zones are expected to lead in electricity generation due to their large populations. If 80% of waste is incinerated by 2034, electricity generation could reach 5800MW, meeting up to 15% of Nigeria's 2030 power demand target, with potential to supply 50% with high-efficiency plants. The study advocates for improved waste management practices, government investment in incineration plants, and alignment with UN SDG 11 for sustainable cities. The adaptable model provides a valuable tool for global decision-makers to anticipate WtE outcomes and support sustainable development (in line with the propagation of UN SD Goal 11).

Słowa kluczowe: *Energia elektryczna z odpadów*

Streszczenie
Ponieważ Nigeria stoi w obliczu szybkiej urbanizacji i wzrostu liczby ludności, skuteczne zarządzanie odpadami staje się coraz bardziej istotne. Obecne nieodpowiednie praktyki prowadzą do gromadzenia się odpadów, szkodząc zdrowiu publicznemu i estetyce miejskiej, podczas gdy niewystarczające dostawy energii elektrycznej utrudniają zrównoważone życie. Technologia Waste-to-Electricity (WtE) stanowi podwójne rozwiązanie tych problemów.
W pracy magisterskiej, która stała się podstawą niniejszego artykułu, wprowadzono model oparty na aplikacji MATLAB App Designer do prognozowania wytwarzania energii elektrycznej z odpadów komunalnych w nigeryjskich strefach geopolitycznych w latach 2024-2034. Model wykorzystuje czynniki społeczno-demograficzne i ekonomiczne, przewidując 44% wzrost rocznej produkcji odpadów z 66 milionów ton w 2024 r. do 95 milionów ton do 2034 r. Przy średniej wartości opałowej odpadów wynoszącej 9,6 MJ/kg, oczekuje się, że strefy północno-zachodnia i południowo-zachodnia będą liderem w produkcji energii elektrycznej, ze względu na ich dużą populację. Jeśli 80% odpadów zostanie spalonych do 2034 r., produkcja energii elektrycznej może osiągnąć 5800 MW, zaspokajając do 15% docelowego zapotrzebowania Nigerii na energię w 2030 r.,z potencjałem do dostarczenia 50% dzięki wysokowydajnym elektrowniom. Badanie opowiada się za ulepszonymi praktykami gospodarowania odpadami, inwestycjami rządowymi w spalarnie i dostosowaniem do 11 celu zrównoważonego rozwoju ONZ dla zrównoważonych miast. Adaptowalny model stanowi cenne narzędzie dla globalnych decydentów do przewidywania wyników WtE i wspierania zrównoważonego rozwoju (zgodnie z propagowaniem 11 celu zrównoważonego rozwoju ONZ).

INTRODUCTION

Nigeria is often referred to as the most populous country in Africa with a growing population of over 200 million (equivalent to about 2.64% of the World population) (Worldometers, 2022). Despite this huge record of population growth, 70% of the urban cities in the country have been reportedly influenced by poor management of municipal waste, resulting majorly from the growing population, urbanization, and industrialization (Pona *et al.,* 2022).

It has been recorded that the waste generation rate in Nigeria is estimated at 0.65-0.95 kg/capita/day which gives an average of 42 million tons of wastes generated annually by Nigerians. This is outrageously more than half of 62 million tons of waste generated in sub-Sahara Africa annually, and yet, the study forecasts that the amount rises to 107 million tons by 2050. This has led to increased urban waste generation leading to environmental health hazards, underground water pollution, and affected air and aesthetic qualities.

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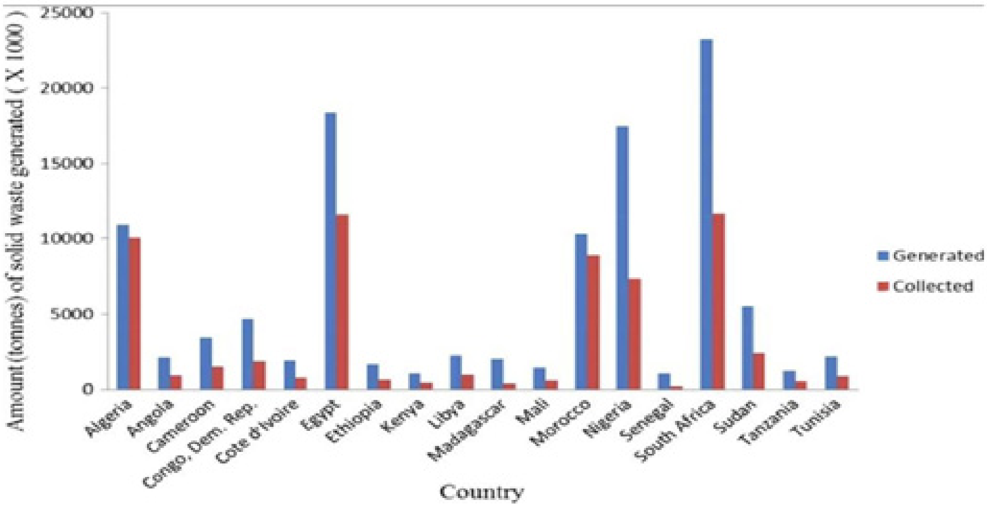

Fig.1. Trends of Waste Generation and Collection in African Countries (Babayemi et al., 2021)

Rys.1. Trendy w wytwarzaniu i zbiórce odpadów w krajach afrykańskich (Babayemi i in., 2021)

Most of these wastes are generated by households and largely by industries like petroleum, pharmaceutical, agricultural farms, plastics, and textiles. Despite the intensifying waste generation trends in Nigeria, only few fractions of these generated wastes are usually collected.

Babayemi *et al.,* (2021) reported that, out of the African countries with highest rate of waste generation, only Nigeria collected less than 50% of the total solid waste generated in the country in 2021 (with approximately 40% collected).

Currently, the fate of the remaining uncollected 60% of municipal waste is of serious environmental concern, both in terms of losing secondary resources and in terms of potential environmental contamination.

Additionally, energy crisis in Nigeria has been persistent for quite a long time. Nigeria's power demand is 40,000MW, however the current is 12,522MW from mainly Gas, hydro, and coal respectively, of which only 40% of generated power is utilized, which leaves most of the population in Nigeria without power (OANDO, 2021).

It is reported that only about 53% of the Nigerian population has access to grid electricity. Nigeria has one of the lowest rates of grid-based electricity generation capacity per capita in the world (Adewuyi & Emmanuel, 2020). The young population is growing at a rate of 2.5% per annum and is forecast to reach about 392 million people in 2050, becoming the world's fourth most populous country. Based on the country's GDP and global trends, electricity consumption is expected to grow to about 91,000 MWh by 2040 (CIA World Fact Book, 2022).

As a result of this, researchers are currently searching for alternative energy sources to help deliver energy-saving and environmental-protection provisions for development. One such strategic approach is to use MSW (Municipal Solid Waste) to generate energy (in the form of electricity); this is referred to as waste-to-energy (WtE) technology.

The adoption of WtE can potentially serve as a sustainable platform for simultaneous waste management and energy provision by providing an alternative pathway to the trends of extreme poor waste management in Nigeria, whilst also contributing to meeting the energy demand through renewable sources.

Hence, in sequel to the quest for reliable and adequate power supply in Nigeria, and efficient municipal waste management techniques, this research attempts to make a forecast on the quantity of waste generation in Nigeria's six geopolitical zones for the next decade and highlight the potentials of the generated waste in contributing to the nation's energy mix.

Case Study: Geopolitical Zones in Nigeria: Background, Demography and Levels of Industrialization

Geopolitical zones are basically divisions of the country, created to bring people together and provide ease of governing. These zones are composed of states that share certain cultural, historical, and environmental characteristics (Samuel, 2023).

Hence, this section summarizes the number of geopolitical zones in Nigeria, the states they include and the typical activities that take place in each zone (Samuel, 2023):

1) North Central (Middle Belt) Region of Nigeria

The North Central region of Nigeria, commonly known as the Middle Belt, encompasses seven states: Plateau, Niger, Nasarawa, Kwara, Kogi, Abuja (the Federal Capital Territory), and Benue. Each state is unique in its characteristics:

- **Niger State:** The largest in area, featuring diverse landscapes from the Niger River Valley to rolling hills, with cities like Minna, Suleja, and Bida.
- **Nasarawa State:** Known for its rich historical significance and rural agricultural land, it hosts small-scale industries in mining, textile manufacturing, and quarrying, along with various tourist attractions.
- **Kwara State:** An industrial hub established during military rule, producing automobiles, pharmaceuticals, and textiles, and rich in natural resources like gold, iron ore, and coal.
- **Kogi State:** Strategically located in central Nigeria, rich in coal, limestone, and tar sands, and home to small-scale industries in agro-processing and food production.
- **Abuja (FCT):** The nation's capital, seventh in population size, housing key administrative buildings and cultural institutions, with the Central Area and Three Arms Zone being significant landmarks.
- **Benue State:** Known as the "food basket of Nigeria" for its prolific agricultural production, characterized by its hilly and valley-dominated topography and being one of the most populous states.

The Middle Belt Zone collectively hosts approximately 33 million people, representing 15% of Nigeria's total population. Abuja, the nation's capital, is the largest city in this region.

2) North-East Region of Nigeria

The North-East region of Nigeria, comprising six states—Taraba, Adamawa, Borno, Gombe, Yobe, and Bauchi—features a diverse landscape from the Sahara Desert to lush tropical vegetation and wooded savannahs. This area is rich in biodiversity, home to species such as the endangered African Wild Dog, various antelope species, and a wide array of birds, including migratory and birds of prey.

With a population of approximately 30 million, representing 13% of Nigeria's total population, Bauchi and Maiduguri are the most densely populated cities in the region.

Economically, the North-East boasts a diversified agricultural base, producing crops like cotton and peanuts, supported by favourable soil and climate conditions. It also has a thriving mining sector, extracting valuable resources such as gold, iron ore, columbite-tantalite, lead-zinc ore, limestone, and coal.

Fig.2. Map of Geopolitical Zones in Nigeria (Samuel, 2023)

Rys. 2. Mapa stref geopolitycznych w Nigerii (Samuel, 2023)

Overall, North-East Nigeria is a region of natural beauty and significant business potential, offering a mix of ecological richness and economic opportunities.

3) North-West Region of Nigeria

The North-West region of Nigeria consists of seven states: Kaduna, Kano, Katsina, Jigawa, Zamfara, Sokoto, and Kebbi. It is home to over 50 million people, with some of Nigeria's most densely populated urban centers, including Kano and Kaduna.

The region's economy is primarily driven by large-scale farming and livestock rearing, which sustain local food supplies and support other Nigerian regions and international markets. Small-scale trading also plays a vital role in the livelihoods of many residents.

Overall, the North-West geopolitical zone is of significant importance to Nigeria, contributing substantially to the nation's economy through its robust agricultural and trading activities.

4) South-East Region of Nigeria

The South-East geopolitical zone of Nigeria comprises five states: Abia, Anambra, Ebonyi, Enugu, and Imo. With a population exceeding 25 million, it is one of the most densely inhabited regions, accounting for about 12% of Nigeria's total population.

Predominantly Igbo-speaking, the South-East is celebrated for its rich cultural heritage and traditional music. Key attractions include the National Museum in Enugu and the Imo Safari Park. Urban centers such as Aba, Awka, and Owerri highlight the region's vibrancy.

The South-East is also known for its colourful traditional festivals, like the New Yam Festival and the Igbo Ukwu Festival, which contribute to its cultural richness. Overall, the South-East stands out for its unique cultural heritage and vibrant traditions, making it a distinguished region within Nigeria and globally.

5) South-South Region of Nigeria

The South-South geopolitical zone in Nigeria consists of six states: Akwa Ibom, Bayelsa, Cross River, Delta, Edo, and Rivers. Renowned for its vast oil reserves, this region holds approximately 40% of Nigeria's proven oil resources, making it a cornerstone of the nation's oil industry. Despite its wealth in natural resources, the South-South faces challenges with infrastructure and electricity supply.

Economically, the region is dominated by oil production and its ancillary industries, though a growing agricultural sector is contributing to its economic diversification. Geographically, it is divided into the Niger Delta to the east and the coastal region to the west, featuring major rivers like the Niger and Benue. These rivers are vital for sustenance, water resources, transportation, and fuel for local communities. The geographical and economic attributes of the South-South underscore its significant role within Nigeria.

6) South-West Region of Nigeria

The South-West geopolitical zone of Nigeria includes six states: Lagos, Ogun, Ondo, Ekiti, Osun, and Oyo. Lagos, the most populous state in Nigeria, is renowned for its vibrant energy and vast economic opportunities. Ogun is known for its strong industrial sector, housing numerous factories and production facilities.

Ekiti, east of Ogun, is celebrated for its fertile agricultural lands producing diverse crops like corn and cassava. Ondo boasts tourist attractions such as Igbokoda Beach and Idanre Hill, drawing visitors year-round. Osun, rich in history, features ancient relics and the sacred Osogbo Grove. Oyo, located in the Northwest, is famous for its annual Egungun festivals, celebrated by Yoruba communities.

With bustling urban centres, historical sites, and a rich cultural heritage, the South-West zone is one of Nigeria's most densely populated regions. Its vibrant industries and cultural landmarks significantly contribute to the nation's economy.

METHODOLOGY

Summary of Waste Generation and Energy Content Estimation

1) Estimation of Waste Generation

Estimating waste generation involves various methodologies, recognizing the impact of socio-demographic, economic, geographic, and waste-related factors. Ordonez-Ponce (2004) developed a simplified equation to estimate annual waste generation:

$$G_{Ti} = G_{Ri} \times 10^{-3} \times P_i \times 365 \; ... \; ... \; (1)$$

Where, G_{Ti} is the total waste generation in year *i*, (ton/annum)
G_{Ri} is the per capita rate of waste generation in year *i*, (kg/person/day)
P_i is the population of the country/place in year *i*.

Forecasting future waste generation introduces complexities due to uncertainties. Researchers employ mathematical models to project waste generation, incorporating future population and per capita generation rates (Atta *at al.*, 2016). The European Commission (2003) provides the following equations:

$$P_i = P_o\,(1 + r)^n \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots (2)$$

Where, P_o is the population figure for the base year,
$\boldsymbol{P_i}$ is the population figure for year *i*,
$\boldsymbol{r}$ is the annual population growth rate, and
$\boldsymbol{n}$ is the number of years between the base year and the year *i*.

For the base year 2021, the annual growth rate (*r*) is determined to be 2.58% (Worldometers, 2021), with official population data for each geopolitical zone sourced from the National Population Commission (NPC, 2021). Thus, 2021 serves as the base year for this study.

Similarly, per capita waste generation rate is estimated:

$$G_{Ri} = G_{Ro}\,(1 + r)^n \ldots \ldots \ldots \ldots \ldots (3)$$

Where, G_{Ro} is the per capita generation rate at the base year (kg/person/day),
$\boldsymbol{G_{Ri}}$ is the per capita generation rate for year i,
$\boldsymbol{r}$ is the GDP growth rate, 1.2% (i.e., GDP per capita growth rate), and
$\boldsymbol{n}$ is the number of years between the base year and the year *i*.

Using data from Abila & Kantola (2021) and the National Population Commission (NBS, 2021), Table.1 shows population waste generation rates for Nigerian geopolitical zones in 2021:

Geopolitical Zone	Population (Million)	Rate of waste generation (kg/person/day)
NORTH-WEST	55.5	0.79
SOUTH-WEST	43.4	0.75
NORTH-CENTRAL	33.2	0.73
SOUTH-SOUTH	32.7	0.65
NORTH-EAST	29.8	0.71
SOUTH-EAST	24.9	0.70

2) Estimation of Energy Content from Generated Waste

To estimate the energy potential of waste, current waste-to-energy (WtE) plants exhibit efficiencies of 14% - 28%. Attah *et al.* (2016) introduced the Khan Equation to estimate the energy content (LCV) of waste:

$$E = 0{,}051[F + 3{,}6(CP)] + 0{,}352(PLR) \ldots (4)$$

Where, *E* is the energy content of the waste in MJ/kg.
F is the fraction of Food/garbage in the waste (%)
CP is the fraction of Cardboard and Paper in the waste (%)
PLR is the fraction of Plastics/Rubber in the waste (%).

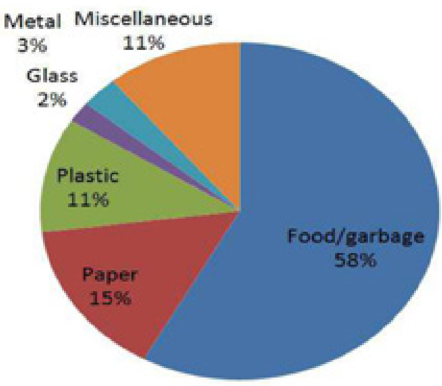

Fig.3. Average Estimate of Waste Composition for Middle-income Countries (Typical of Nigeria (Attah et al., 2016; Chukwuebuka et al., 2022)

Rys. 3. Średnie oszacowanie składu odpadów dla krajów o średnim dochodzie (typowe dla Nigerii (Attah i in., 2016; Chukwuebuka i in., 2022)

The Khan Equation is suitable where garden and textile wastes are minimal. Chukwuebuka *et al.* (2022) found these components constituted less than 2% of Nigerian waste, making the equation reliable for 2021-2034 forecasts.

Hence, by applying Equation 4 to the Nigerian waste profile, the average calorific value of the waste mix is found to be about **9.6 MJ/kg** which is approximately **9600 MJ/ton**.

The recoverable energy from waste (Mtoe/annum) is determined as follows:

$$Recoverable\ Energy\ from\ waste\ \left(\frac{Mtoe}{annum}\right) = \frac{Overall\ quantity\ of\ waste\ \left(10^6\,\frac{ton}{annum}\right) \times 9600\,\frac{MJ}{ton}}{41870 \cdot 10^6\,\frac{MJ}{Mtoe}}$$

The electricity generation potential (MW) from recoverable energy is:

$$MW\ of\ electricity = \left(\frac{Recovery\ energy\ from\ waste\ \left(\frac{Mtoe}{annum}\right) \times 11630000\,\frac{MWh}{Mtoe}}{8760\,\frac{h}{annum}}\right) \times Incinerator\ eff. \times Collection\ eff.$$

For practical purposes, a consistent 25% net electrical efficiency and 80% collection efficiency are assumed throughout the study period, in line with Nigeria's WtE master plan by OANDO (2021).

This set of equations is represented in MATLAB GUI to simulate the waste-to-electricity conversion process. Steps include system identification, mathematical formulation, model development, simulation and analysis, model validation, and sensitivity analysis (MathWorks, 2023).

This approach provides a robust framework for forecasting and optimizing Nigeria's waste-to-electricity potential, contributing significantly to sustainable energy solutions.

Results and analysis

This section presents a comprehensive forecast analysis of waste generation across Nigeria's six geopolitical zones for the next decade. It also explores the potential of this waste to significantly enhance the nation's energy portfolio, assuming the implementation of Waste-to-Electricity (WtE) technology by 2024.

Waste Generation Forecast

The chart above clearly indicates a substantial 44% increase in waste generation across all six geopolitical zones over the next decade (66 million tons to about 95 million tons). Each zone shows an approximate growth rate of 45% from 2024 to 2034, suggesting consistent trends in population growth, urbanization, and economic activities. The North-West zone is expected to remain the highest waste generator, followed by the South-West zone, reflecting their roles as major population and economic centres.

This projected increase in waste generation underscores the pressing need for effective waste management strategies and infrastructure development. The potential implementation of Waste-to-Electricity (WtE) technology by 2024 could significantly mitigate the environmental impact and contribute to Nigeria’s energy portfolio. This technological advancement could transform waste into a valuable resource, promoting sustainability and supporting the nation's energy needs.

Electricity Recovery Potential from the Generated Waste

The chart illustrates a significant growth in the electricity generation potential from waste across all six geopolitical zones over the decade.

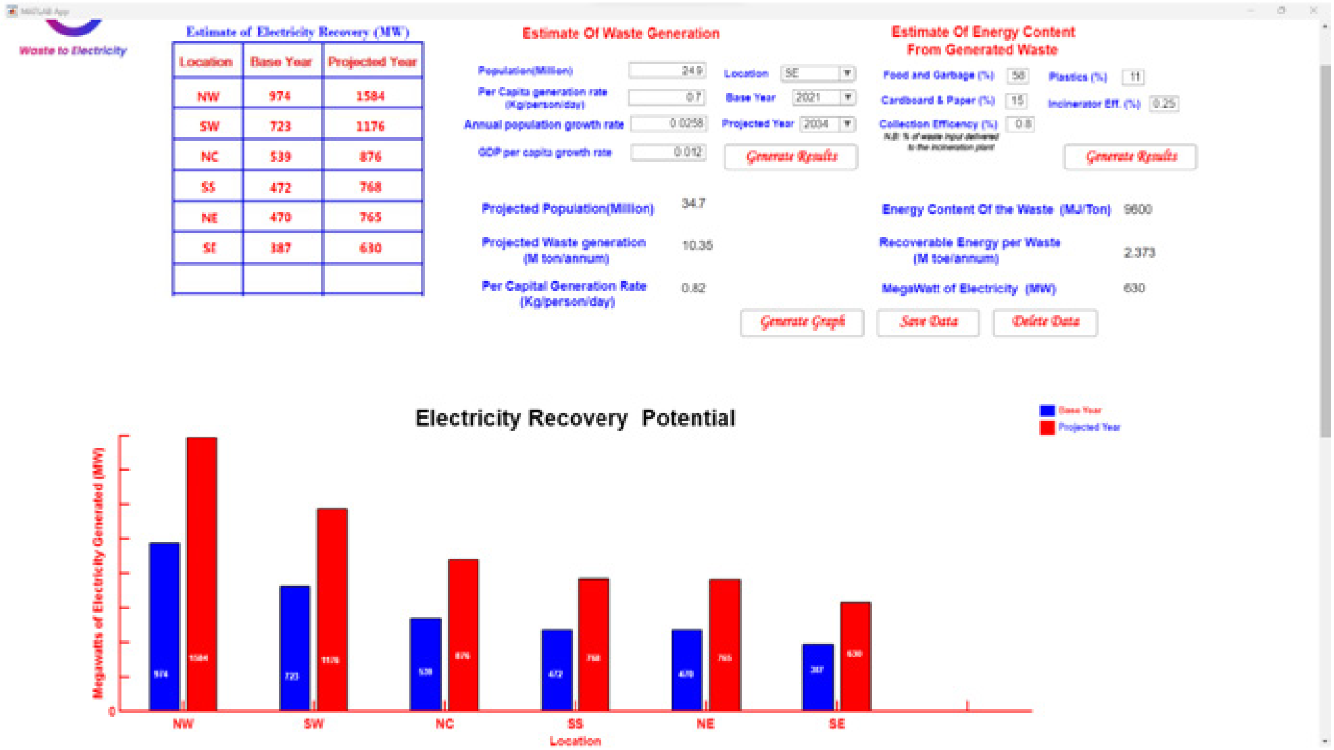

Fig.4. Design View of the Waste-to-Electricity Model

Rys.4. Widok projektu modelu przetwarzania odpadów na energię elektryczną

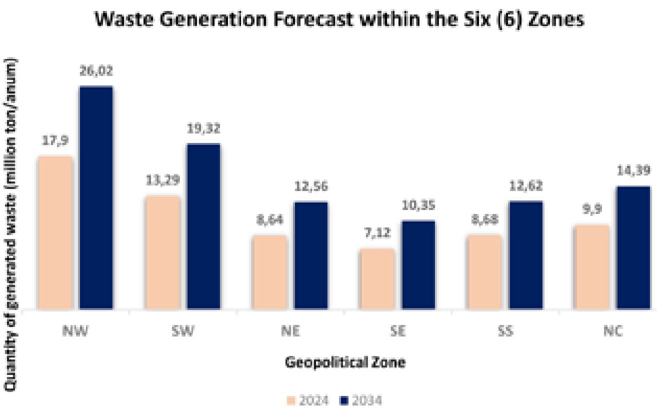

Fig. 5. Waste Volume Forecast in the Nigerian Geopolitical Zones

Rys. 5. Prognoza ilości odpadów w nigeryjskich strefach geopolitycznych

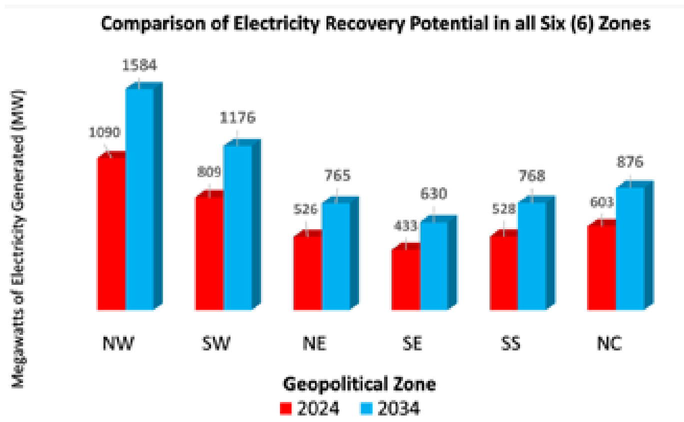

Fig.6. Comparison of WtE Potential in the Nigerian Geopolitical Zones

Rys. 6. Porównanie potencjału WtE w nigeryjskich strefach geopolitycznych

Each zone demonstrates a uniform increase of approximately 45%, underscoring the substantial potential of waste-to-energy (WtE) technology in augmenting Nigeria's energy portfolio.

- **North-West Zone**: Leading in both 2024 and 2034, with projections of 1090 MW and 1584 MW, respectively. This highlights the substantial waste generation in this zone and its potential for energy recovery.
- **South-West Zone**: Following closely, with electricity generation potential rising from 809 MW in 2024 to 1176 MW in 2034. This is indicative of its dense population and economic activities, particularly in Lagos.
- **Other Zones**: The North-East, South-East, South-South, and North-Central zones all show significant potential increases, reflecting regional waste generation trends and potential for energy recovery.

This analysis highlights the importance of implementing WtE technology across Nigeria. The uniform 45% percentage increase across all zones suggest a consistent growth pattern in waste generation and corresponding energy recovery potential. By 2034, the total electricity generation potential from waste is projected to increase by approximately 36.3%, from 4989 MW in 2024 to 6799 MW in 2034. This substantial growth underscores the critical role of WtE technology in addressing waste management challenges and enhancing the nation's energy security.

Conclusion & recommendations

Conclusion

This study presents a comprehensive forecast analysis of electricity recovery potential from waste generated in Nigeria's geopolitical zones. Key findings include:

1. **Dual-purpose Solution**: Waste-to-Energy (WtE) is highlighted as an environmentally preferable solution, addressing both waste management and electricity generation challenges in Nigeria.
2. **Waste Generation Increase**: Annual waste generation in Nigeria is predicted to increase from 66 million tons in 2024 to approximately 95 million tons by 2034, representing a 44% increase over the decade.

3. **Calorific Value of Waste**: The average calorific value of Nigeria's waste mix is about 9.6 MJ/kg, roughly one-third the heating value of coal, indicating its significant potential for energy recovery.
4. **Regional Electricity Generation**: The North-West and South-West zones are projected to generate the highest electricity from waste by 2034, driven by their large populations. All six zones are expected to see about a 45% increase in electricity potential by 2034.
5. **Electricity Potential**: If 80% of generated waste is incinerated in modern WtE facilities, Nigeria could produce around 4000 MW of electricity in 2024, increasing to about 5800 MW by 2034.
6. **Contribution to Power Demand**: Even with a low operating efficiency of 25%, recovered electricity from waste could meet up to 15% of Nigeria's targeted 40,000 MW power demand by 2030. Enhanced efficiency could potentially contribute over 30% to the nation's electricity needs.
7. **Model Accuracy**: The forecasting model integrates demographic and socio-economic data, providing a user-friendly, accurate tool for predicting annual WtE generation outcomes. It represents a significant advancement in anticipating waste-to-electricity results while incorporating key contextual factors.

In conclusion, the implementation of WtE technology in Nigeria holds substantial promise for improving waste management and significantly contributing to the country's electricity supply. This initiative could play a crucial role in addressing Nigeria's energy needs and environmental challenges.

Recommendations

To enhance Nigeria's waste management system and leverage waste incineration for supplementing electricity demand, the following recommendations are provided based on an evaluation of existing environmental laws, agencies, and regulatory authorities:

1. **Engagement of Waste Sources**: Households, industries, and institutions should actively participate in primary waste management. This includes adhering to waste management rules, regulations, and ensuring timely payment of waste collection dues.
2. **Strengthening Municipal Waste Management**: Municipal Waste Management Agencies should improve waste collection, transportation, and disposal techniques. They should also promote awareness and training programs, utilizing diverse knowledge-sharing methods for staff.
3. **Utilization of Heat Energy**: Heat energy from waste incineration should be strategically directed and sold to hotels, hospitals, agro-food industries, and similar sectors for purposes such as water heating, food processing, and sterilization.
4. **Monitoring and Motivation**: Municipal authorities and regulatory agencies should establish monitoring programs that encourage material reuse, recovery, and recycling. These programs should include motivational factors to foster public adoption of these practices.
5. **Government Investment**: Governments should fund the installation and maintenance of waste incineration plants across Nigeria's geopo-

SWOT Analysis of WtE Management Policy in Nigeria

This section presents a simplified SWOT analysis matrix for the implementation of WtE technology and effective waste management initiatives in Nigeria:

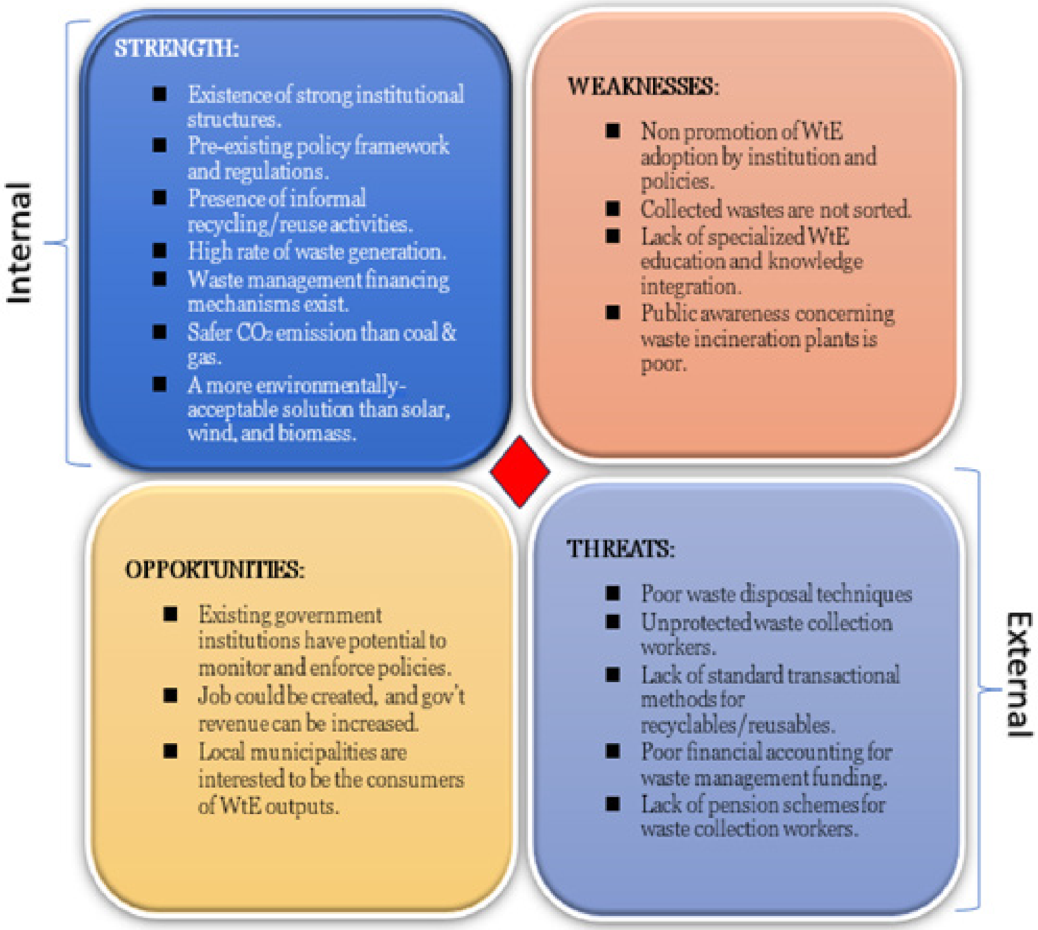

Fig .7. SWOT Matrix of WtE / Waste Management Implementation in Nigeria
Rys. 7. Macierz SWOT wdrażania WtE / Zarządzania Odpadami w Nigerii

SWOT Analysis of the Designed Waste-to-Electricity Model

This section presents a simplified SWOT analysis for the designed waste-to-electricity (WtE) model, focusing on its use across African countries and globally:

Fig. 8. SWOT Matrix for the Designed Waste-to-Electricity Model

Rys.8. Macierz SWOT dla zaprojektowanego modelu przetwarzania odpadów na energię elektryczną

litical zones. Processing non-recyclable waste for energy recovery will address electricity demand and improve waste management, supporting the UN Sustainable Development Goal 11 for sustainable cities and communities.

6. **Model Adaptation**: The developed waste-to-energy model can be adapted for use in other African countries and globally, enhancing waste management and energy recovery efforts worldwide.

Implementing these recommendations will contribute to a more efficient waste management system in Nigeria and help meet the nation's electricity needs while promoting sustainable urban development.

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