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Renewable municipal solid waste pathways for energy generation and sustainable development in the Nigerian context

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Abstract

The continued concerns over energy prices, increase in population, and climate change issues have led towards a need for alternative and new energy sources. Municipal solid waste (MSW) is generally accepted as a renewable energy resource. This research study presents a techno-economic assessment potential to utilize the energy obtainable from MSW for the generation of electrical power. The assessment was carried out for energy generation by thermochemical (incineration or combustion) and biochemical (landfilling and anaerobic digestion) processes and based on the available data from seven selected municipalities. Due to the broad scope of this topic, life cycle impact of waste management, social acceptance, policy aspects, and emission reduction or fossil fuel offset are not considered and are not part of the assessment. Results presented in tabular form indicate, for example, that the price of steam generated by a fluidized steam generator is in the range of US$0.018/kWh$_t$ (Lagos) to US$0.044/kWh (Nsukka) and compares favorably with the typical cost of steam at US$0.015/kWh. Electrical power generation using a combined heat and power plant provides electricity at a cost that is in the range of US$0.017/kWh$_e$ (Lagos) to US$0.040/kWh$_e$ (Nsukka) and also compares well with the typical cost of electricity in Nigeria at US$0.14/kWh$_e$ (as of 2012).

Keywords: Municipal solid waste; Combustion; Energy; Electricity; Environment; Economics; Nigeria

Background

Nations are today faced with an overwhelming social problem of processing and disposal of municipal solid waste (MSW). With increasing population growth, rapid urbanization, rising levels of affluence, and resource scarcity, waste-to-energy (WTE) is reestablishing itself as an attractive technology option to promote low carbon growth among other renewable energy technologies. WTE is a proven process that provides electricity and steam generation in a sustainable way.

Nigeria is the most populated nation in Africa. With a 2011 population estimate of 162.4 million, growing annually at an estimated rate of 3% [1] and generating 0.55 to 0.58 kg of municipal solid waste per person per day [2], Nigeria can be said to be equally experiencing significant waste-related environmental problems. These problems can be said to have begun in the period when Nigeria gained independence, became rapidly urbanized, and thus generated more solid waste than nature can absorb or that Nigeria can efficiently dispose. MSW is produced daily all over the world, and it is a renewable energy resource with the potential to produce energy via WTE plants while also reducing the volume of waste. WTE can address the twin issues of land use and pollution from landfills and the well-established environmental perils of fossil fuels known as greenhouse gas emissions (GHG). Figure 1 shows the map of Nigeria showing Abuja, the capital.

Rapid urbanization, oil spills, and loss of arable land have created several environmental problems in Nigeria [3]. Among these environmental problems are sheet and gully erosion, coastal and marine erosion and land subsidence, flooding, drought and desertification, oil pollution, urban decay and squatter settlements, industrial pollution and waste, municipal solid waste, biodegradable petrochemical products, concrete jungles or cities, loss of fauna and flora, and climatic change [4].

MSW can be regarded as ‘useless’, unwanted, and discarded materials that resulted from society's normal or

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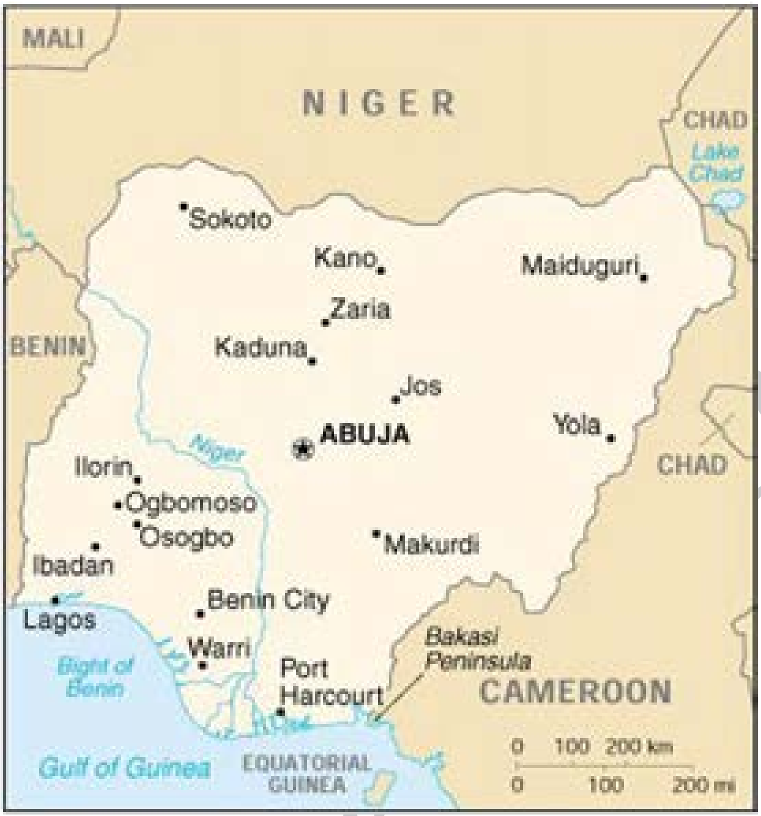

Figure 1 Map of Nigeria.

routine daily activities and, in general, may be in solid, liquid, or gaseous form [5]. It is often accompanied by commercial waste, whether solid or semisolid. It also comes in the form of food wastes, paper, cardboard, plastics, textiles, leather, wood, glass, and other household items. In most industrialized nations, from the time wastes are generated, they go through a solid waste chain, consisting of waste handling and separation; storage and processing at source; collection, separation, processing, and transformation of solid wastes; transfer and transport; energy generation; and disposal. This is however not the case in Nigeria or most developing countries. In many parts of the developing world, solid waste disposal is done through dumping and burning without control [6]. These practices pollute land, water, and air. Although these practices are illegal and their consequences recognized and felt in Nigeria, they persist in both urban and rural areas because of weak law enforcement regimen and limited public sector financial resources. A sustainable solution to this gigantic problem, which affects every populace, is through more efficient solid waste management. The generation of energy from MSW (though largely dependent on MSW composition) has the propensity to reduce greenhouse gas emissions, to generate renewable energy, and to provide energy diversity while also ensuring safe, hygienic, and reliable disposal practices.

The volume of waste generated in the world today is enormous. This volume of waste generated is to some degree due to inefficiencies (e.g., in usage, sorting, and processing) and, in principle, might be reduced [7]. As of 2011, the world generated an estimated two billion tons of MSW, and this number is expected to grow much higher [8]. MSW is a renewable form of energy that includes both commercial and residential wastes generated in municipalities. The US Environmental Pollution Agency (USEPA) goes further to classify MSW as a source of clean energy. From a sustainable development perspective, the focus is on reduction of waste, followed by recycling, both of which are advantageous in terms of reducing greenhouse gas emissions. Several analysis done using the USEPA models show that WTE avoids 36 million tons of greenhouse gases yearly [9]. However, not all wastes are recyclable, and as such, an energy recovery method becomes essential.

The interest in the practical applications of WTE dates back to several decades. WTE is hardly a new or novel idea. What is however new is the confluence of factors that have increased the attractiveness of WTE. These factors include rising oil prices, urban air pollution, energy supply security, reduction in foreign oil imports, carbon dioxide (CO_2) emissions, and climate change. These considerations are not confined to a single nation or part of the world and thus render the concept of WTE as abundantly and equitably available to humanity. Energy recovery through WTE can be defined as a waste treatment process that allows for the generation of energy in the form of electricity or heat from wastes that would have otherwise been disposed off in landfills [7-13]. It involves the use of modern combustion technologies for the recovery of energy from a mix of MSW. Today, more than 800 thermal WTE plants currently operate in nearly 40 countries around the globe [14]. WTE systems will treat at least 261 million tons of waste annually by 2022, with a total estimated output of 283 TWh of electricity and heat generation, which increased from 221 TWh in 2010. Under a more optimistic scenario, WTE will potentially treat 396 million tons of MSW a year, producing 429 TWh of power [14]. The global market for thermal and biological WTE technologies will reach about US$6.2 billion in 2012 and grow to about US$29.2 billion by 2022, according to forecasts by Cleantech market intelligence [14], while under an optimistic scenario, market value could reach US$80.6 billion by 2022. WTE facilities are integrated into broader waste management practices and policies with the goal of reducing the use of landfills. Although combustion technologies continue to lead the market, advanced thermal treatment technology deployments such as pyrolysis are expected to pick up as diminishing landfill capacity improves WTE economics. The utilization of biological technologies is also expected to increase worldwide.

It is imperative for every nation to find environmentally benign methods related to sound management of MSW for sustainable development. The energy potential of MSW is contained in materials that are either biogenic or anthropogenic in origin [15]. Biogenic materials are those that include paper, food, and yard wastes and are considered to be renewable. Anthropogenic materials, on the other hand, are those that include plastics which are derived from fossil fuels and are not sustainable. Several methods exist to analytically determine the biogenic and anthropogenic fractions of energy-generating components of MSW. Unlike some other renewable energy resources such as tidal, solar, and wind, MSW is always available. Benefits of WTE include waste volume reduction, sanitation and detoxification, stabilization, and energy recovery. The technologies that exist to produce energy from wastes are anaerobic digestion, combustion, gasification, and landfill gas to energy.

WTE has been well proven in Europe, where energy and solid waste policies have evolved from the Kyoto protocol [16] GHG reduction goals, to include renewable energy (RE) and decreased waste emissions from landfills [16]. This has been invariably good in advancing the state of technology for waste management and conversion to energy such that it is an integral component of solid waste management in Europe. About 18 European Union countries engage in thermally treating 58 million tons of wastes in WTE plants to produce energy annually [17]. As such, RE aspects of solid waste management policies work well together with waste reduction policies.

Waste management practices in Nigeria

Waste management practices then and now

The collection and disposal of solid waste in Nigeria were controllable and not a problem before the country's independence in 1960. Before the 1960s, the population was low and not concentrated in urban areas, and people lived in traditional ways [18]. Previous studies described the major cities of Nigeria, such as Ibadan, Calabar, and Port Harcourt, as clean and beautiful. However, when the country gained independence from the colonial masters and oil was subsequently discovered, migration from rural areas to urban areas increased as a result of people wanting to live more comfortably. Nigeria began importing many varieties of foods and luxury goods with consequent increase in solid wastes. Plastics and polythene produced negligible waste in 1971. Today, they make up a large part of the refuse. Empty beverage cans are found littered in every corner of the road. In fact, consumption patterns have dramatically changed since the 1960s and 1970s. For example, according to Paris-based magazine *Jeane Afrique*, Nigerians consumed 593,000 bottles of champagne in 2010, 50% more than the richer rival nation of South Africa - possibly due to the population effect with Nigeria being at least three times larger in population than South Africa.

Solid waste is now a troubling problem to both the government and the public [18]. As with many other nations, solid waste generation in Nigeria is a function of the population, its industrialization level, socioeconomic status, and dominant commercial activities [18]. Some of the factors, which influence the generation and stockpiling of solid waste, are the lack of modern waste disposal technology; the lack of facility to separate the waste at source; the effectiveness of existing solid waste management policy and its enforcement, environmental education, and awareness; and the income status. The indiscriminate dumping of secondhand electronic gadgets has also contributed to the waste disposal problem [18]. Waste storage and collection are the responsibility of state environmental agencies, private companies, or both. The wastes collected are dumped together, that is, unsegregated, indicating a lack of awareness of their nature and compatibility with one another. The populace also burns their refuse in open dump sites, e.g., documents, rags, and tires, often without sanitary or environmental control. This attracts scavengers at the dumps where they gather plastic cans and bottles, glass, and other recyclables mainly for sale to other secondhand goods markets. More than 50% of the people's wastes are highly decaying food surpluses, and more than 15% are plastic wastes. Wastes are generally recycled by the informal sector while scavengers scan for usable items, as described earlier [19].

The solid waste problem is acutely felt in Lagos State because it is the most populated city and among the most industrialized in sub-Saharan Africa. In 1995 alone, it produced approximately four million tons of solid wastes. The long history of the waste problem in Lagos goes back to the transfer of waste management from the local governments to the state. Policies kept on changing, leading to management lag. The wastes are generally not treated but moved to landfill sites where they are openly burned. The two incineration plants in Lagos are capable of treating wastes with less than 20% water, but they have never been used as the state's wastes contain 30% to 40% water. Lagos is currently undertaking efforts to generate revenue from waste management [20,21].

A brief on waste management policies in Nigeria

Intervention by the Federal Ministry of Environment has been in the form of a revised policy on environment in 1999 and the National Agenda 21 published also in 1999 [19]. These measures complemented existing guidelines and standards for environmental pollution, the waste management regulation of 1991, the Environmental Impact Assessment Decree number 86 of 1992, and an environmental edit of 1997. However, as earlier mentioned, nature's way of absorbing waste and human efforts combined have been surpassed by the enormity of the problem and its impact on the environment. Every material or product goes through a long cycle, consisting of activities, which produce greenhouse gas emissions. These are through energy consumption, methane emissions, and carbon storage. The current state of waste management in Nigeria is clearly a picture of neglect and failure in the enforcement of solid waste management policies. The effects of this neglect include unnecessarily lost resources, increased adverse impact on biological processes, disruption of infrastructure, greater risks of flooding and distribution of vermin and pests, and the deterioration of air quality.

Waste-to-energy technologies and opportunities for Nigeria

Technologies for WTE production have been rapidly evolving and changing communities and countries [20] yielding dual benefits from effective solid waste management practices. Not only will WTE deliver useful energy that is needed in many countries, but it will also aid to dispose of MSW effectively and safely. A community or country's solid waste management goals and objectives, the environmental impact, and production and consumption patterns will help determine if WTE production technology is appropriate for that community or country [20]. For example, with current government interest and the necessary investment, over the coming years, Lagos State is expected to generate revenue from better waste management, which would be beneficial to remote and rural areas of the state overall [21].

The main categories of waste to energy technologies are (1) physical technologies which process waste to produce fuel (i.e., refuse-derived fuel or solid-recovered fuel), (2) thermal technologies which can produce heat, fuel oil, or syngas from both organic and inorganic wastes, and (3) biological technologies whereby bacterial fermentation is used to digest organic wastes to produce useful fuel. These can be further elaborated as gasification (pyrolysis - thermal and plasma-arc types), anaerobic digestion, and combustion. Gasification of waste involves thermochemical conversion reactions, which will induce gases under high temperature and low concentration of pure oxygen or air. Methane is produced and can be applied to run an internal combustion engine to generate electricity. Gasification can reduce waste by 70% to 80% while preserving the land area.

Anaerobic digestion is a biochemical conversion process, which produces fuel for energy through an enclosure called a *digester*. It is currently used in both developed and developing countries to treat both wet and dry biomass resources and to convert MSW and other wastes and residues. It has been successfully used to generate electricity for rural and remote areas of developing countries.

Combustion or incineration consists of burning the whole mass of waste in an incinerator. Incineration of MSW can drastically reduce the volume of MSW by up to 80% to 90%. The process releases gaseous pollutants such that a pollution control system needs to be set up along with it. This technology operates at 800°C to 1,000°C. It is also important to note that it is however not as popular as gasification.

Since WTE would be a relatively new concept in Nigeria, the populace would need effective public awareness and sensitization programs and campaigns. The government, for its part, must establish partnership with the organized private sector entities for the needed investments [20-24]. With the exception of recent progress on waste issues in Lagos State, issues related to sound MSW management such as recycling programs, waste reduction, and waste disposal have not been adequately addressed in Nigeria. Investigation of the potential contribution of such underutilized fuels like MSW to the energy mix in a sustainable way while minimizing GHG emissions currently produced from landfilling, open dumps, and open burning of solid wastes is a worthwhile undertaking in a developing country like Nigeria.

Methods

Materials and methodology for the estimation of the potential

We begin this work by estimating the calorific value in MSW for selected municipalities in Nigeria based on available data from the literature. The calorific value is derived from the MSW weight distribution (wt.% for as-received MSW on a wet basis) that was obtained from [25-31]. The MSW was categorized as food waste or vegetables as well as putrescibles, paper, plastics, metals, textile or rubber, and inert or miscellaneous. The calorific values in the MSW collected for Lagos, Port Harcourt, Abuja, Ibadan, Kano, Makurdi, and Nsukka are estimated from their respective MSW data. We consider three ways of handling MSW which have been mentioned earlier. Solid waste is not recycled or composted and is hence disposed to the MSW collection system. It is assumed that plastics, metals, and glass will be recycled with a high degree of success and will not be introduced into a landfill, an incinerator, or an anaerobic digester. From the known moisture and ash content, the dry percentage weight (wt.%) for each category of the MSW was determined.

Calorific value by thermochemical conversion or direct combustion

The calorific value has been determined using a universal correlation for the process where MSW is incinerated. Two processes - using grate furnace and fluidized furnace steam generators - were considered to convert chemical energy to thermal energy (steam). Conventional Rankine cycle and combined heat and power (CHP) plant were considered to convert chemical energy to electrical energy. The thermal energy (steam generation) or electrical energy generated was calculated using assumed conversion efficiencies for the processes. In the first instance, calorific value was determined for the following categories: vegetables and putrescible or food waste, paper, textiles, and plastics. Glass and metals with zero or negligible free carbon content were not included in the calculation of the calorific value. It is also assumed that these materials will eventually be recycled and will not enter the MSW stream meant for recovering its calorific value through some process. The inputs that are necessary to determine the calorific value, that is, the high heating value (HHV; in MJ/kg dry MSW), are the mass of MSW collected, weight percentage on a dry and ash-free basis, ash content from a proximate analysis, and the ultimate analysis.

Two correlations were used, both of which depend on the knowledge of ash content determined by a proximate analysis and the elemental compositions of carbon, hydrogen, nitrogen, oxygen, sulfur, phosphorous, and chlorine obtained from an ultimate analysis. The unified correlations used were presented by Channiwala and Parikh [32] and has been found to estimate the calorific value (HHV) of a variety of MSW with acceptable accuracy. Another correlation by Grabosky and Bain, used for comparison, has been found to have 1.5% accuracy in the predicted calorific value for biomass [32]. The MSW collected in most cities is predominated by biomass contribution. The calculated HHV was then converted to low heating value (LHV in MJ/kg dry MSW) using Equation 1:

$$\text{LHV (MJ/kg)} = \text{HHV (MJ/kg)} - (9 \times \%\text{H} + \%\text{H}_2\text{O}) \times 2.44\ \text{MJ/kg}, \tag{1}$$

where %H and $\%H_2O$ are the weight percentages of atomic hydrogen and water, respectively. HHV and LHV per unit mass were converted to calorific value potential per month using the following equation:

$$\text{LHV or HHV (MJ/month)} = \text{LHV or HHV (MJ/kg dry mass)} \times \text{dry mass (kg/month)}. \tag{2}$$

Landfill methane generation

The second scenario that was considered is where the organic wastes (food and yard waste, wood, and textiles) [25-31] are sent to (a landfill) and undergo a biodegradation process. In order to calculate methane generation potential (L_O) from the landfill, decomposable organic carbon (%DOC) on a dry mass basis was determined for the categories of MSW mentioned earlier. Furthermore, the calculation assumes that only putrescible and other organic wastes are discarded in the landfill. The net quantity of the methane generation potential from the landfill (combusted in an internal combustion engine) may be lower due to some of the methane not collected (i.e., flared or emitted as GHG). The %DOC was calculated as follows:

$$\%\text{DOC} = (\%\text{C}_{\text{textile}} \times \%\text{W}_{\text{textile}}) + (\%\text{C}_{\text{gardenwaste}} \times \%\text{W}_{\text{gardenwaste}}) + (\%\text{C}_{\text{foodwaste}} \times \%\text{W}_{\text{foodwaste}}) + (\%\text{C}_{\text{wood}} \times \%\text{W}_{\text{wood}}), \tag{3}$$

where %C is the carbon percentage on a dry mass basis obtained from an ultimate analysis of the specific category of MSW. The calculated %DOC is converted to a fraction and is used in the equation below. The quantity %W is the weight percent of the category of MSW that is considered. Mass of methane potentially generated in a month (M_{methane} (Gg/month)) is calculated as follows [30]:

$$\text{M}_{\text{methane}}(\text{Gg/month}) = \text{MSW}_T \times \text{MSW}_F \times \text{MCF} \times \text{DOC} \times \text{DOCF} \times F \times \left(\frac{16}{12} - R\right) \times 1 - O_x, \tag{4}$$

where MSW_T is the total MSW generated and collected (Gg/month), MSW_F is the fraction of MSW that is collected and disposed in the landfill (taken to be 0.74), MCF is the methane correction factor (taken to be 0.4 for a shallow unmanaged landfill), DOC_F is the fraction of DOC converted to landfill gas by decomposition, F is the fraction of methane (by volume) in the landfill gas, set at a default value of 0.5, and R is the amount of methane recovered and is set to zero. This enables the calculation of the maximum methane generation potential, i.e., the amount that will be potentially emitted as GHG, O_x is the oxidation factor, taken as zero, which implies that the biodegradation takes place strictly anaerobically, and the ratio (16:12) is the mass ratio of 1 g mol methane for each gram mole of carbon. The value of DOC_F was determined as follows:

$$\text{DOC}_F = (0.014 \times T(^\circ\text{C})) + 0.28 \quad (5)$$

An average temperature T of 28°C was assumed for the municipalities considered. It should be pointed out that this calculation determines the methane generation potential only. The fraction out of the generated total that is not recovered is what is lost to the atmosphere as a GHG emission. The calculated mass of methane potentially generated (M_methane) per month can be converted to methane generation potential, L_O:

$$L_o(\text{m}^3/\text{Gg MSW}) = \frac{(M_\text{methane}(\text{kg}))/0.717(\text{kg/m}^3)}{\text{MSW}_T(\text{Gg/month})} \quad (6)$$

or reported as gravimetric ratio ($\text{Gg}_\text{methane}/\text{Gg}_\text{MSW}$).

These calculations do not determine the time dependence of methane generation potential and the effect on the methane generation potential as more MSW is added to an operating landfill over its lifetime. However, the calculated L_O has been used to determine the methane generated over the lifetime of a landfill and is presented in the next section that discusses the economics of energy generation using the landfill methane that is generated.

Economic analysis of landfill methane generation

It is assumed that the organic part of the MSW will be sorted and that 74% of MSW_F collected will be discarded in the landfill [33]. We consider a situation where the landfill already exists or existing ones will be improved and that they are shallow and poorly managed with a MCF of 0.4. The electrical energy generated by combustion of methane was calculated using a LHV of methane of 37.2 MJ/Nm^3.

The economic analysis assumes the following: (1) The landfill will be operational in 2013. (2) The landfill will collect MSW at the same level as mentioned for 30 years at the end of which it will be shut down; after the shutdown, the landfill will no longer accept any MSW. (3) However, the landfill will continue to produce methane. The landfill will be monitored, and with the inherent methane collected for the next 30 years, (4) only 50% (by volume) of the methane that is produced is captured by the recovery system. Remainder is emitted and constitutes a greenhouse gas emission, (5) the capital investment is assumed to be financed for 30 years at the rate of 9%, (6) the operating costs are not financed, (7) methane will be combusted in an internal combustion engine that is coupled to an electric generator with a thermal efficiency of 0.33 [34] and (8) the plant is operational for 7,488 h/year, and (9) tipping fees collected from the municipality or other revenue streams are not considered. In this sense, the costs calculated below for the cost of electricity is the minimum pricing at which electricity can be sold to the consumer or to the grid; (10) for the direct gas use scenario, the monetary value for greenhouse gas offset is set at US$0 per tonne of carbon equivalent. In other words, no credit is allowed for the offset of greenhouse gas emissions. Capital investment and operating costs only include investment on the landfill and gas handling. The costs associated with the internal combustion engine plant are excluded, and (11) ‘direct gas’ is assumed to be purified and compressed to 344,737.5 Pa (or 50 psi) and piped to a customer 8 km (or five miles) away [35] for direct use. The costs calculated are for a gas that is predominantly methane. The capital investment includes the investment made in developing/improving the landfill and in establishing the ICE power plant. The purpose of the economic analysis is to determine the specific unit price of electrical energy obtainable from methane combustion in an ICE-driven power generation plant.

LandGEM a software developed by the USEPA [36,37] was used to determine the amount of methane generated from 2013 till 2073, for a period of 60 years. The program requires the following for an input and proceeds as described in the Equation 7: (1) amount of MSW added to the landfill each year (M_i), (2) values for maximum methane generation potential L_O (in m^3/Mg MSW) were used from Table 1, (3) fraction of methane in the landfill gas 50%, with the other 50% being predominantly CO_2, (4) a MCF value of 0.4, and (5) reaction rate constant (k) of 0.05/year. This can be represented as

$$V_{\text{CH}_4}(\text{m}^3/\text{year}) = \sum_{i=1}^{n}\sum_{j=0.1}^{1} kL_o\left(\frac{M_i}{10}\right)e^{-kt_{ij}}. \quad (7)$$

V_{CH4} is the volume of methane generated (m^3/year) in the year of calculation, i is a 1-year time increment, n is year of calculation, that is, initial year of waste acceptance. The value of n changes from 0 to 30 based on the assumption that the landfill is operational for 30 years, k

Table 1 Methane generation potential in selected municipalities and the corresponding degradable organic carbon

Location	%DOC	L_O (m^3/Mg MSW)
Lagos	32.36	63.09
Port Harcourt	17.84	22.29
Abuja	26.26	48.56
Ibadan	32.24	59.62
Kano	23.75	35.62
Makurdi	25.32	41.14
Nsukka	27.32	50.54

is the reaction rate constant, j is a 0.1-year time increment, L_o is the potential methane generation capacity (m^3/Mg), M_i is the mass of waste accepted in the ith year (Mg), and t_{ij} is the age of jth section of waste mass M_i accepted in the ith year.

Anaerobic digestion of MSW

The anaerobic digestion (AD) process has been around for a long time and has found varied success [38]. There is a renewed effort to improve this process and recognize its full potential to handle the biodegradable organic matter (yard, kitchen, and agricultural waste) and combustible organic fraction (paper, wood) in a municipal solid waste. There is a variety of anaerobic digestion processes, but the general reaction block diagram of the process consists of the following:

1. Waste sorting (to separate plastics, glass, and metals) and shredding
2. Feeding system and retention in an anaerobic bioreactor in the presence of microorganisms that promote acidogenesis and methanogenesis [39]. (This reaction occurs under well-controlled temperature, pH, elemental ratio, and feed dilution with water.)
3. Biogas removal from bioreactor and purification (removing carbon dioxide and ammonia from the product methane stream)
4. Methane gas handling for the distribution or feeding system into a single- or dual-fuel engine plant

The degradation of organic matter in a municipal solid waste in an anaerobic-controlled environment of a digester serves as a responsible way to handle municipal solid waste [38]. In order to calculate the methane generation potential, the elemental compositions of C, H, N, and O that are available from an ultimate analysis of various organic fractions of an MSW were used as suggested by Parkin and Owen [40]. The authors suggest that for an organic compound with the composition $C_nH_aO_bN_c$, the amount of methane generated by anaerobic digestion, where water is used as a reactant, proceeds as per the reaction:

$$\begin{aligned}&\mathrm{C}_n\mathrm{H}_a\mathrm{O}_b\mathrm{N}_c\\&\quad+\left[n-\frac{a}{4}-\frac{b}{2}+3\frac{c}{4}\right]\mathrm{H_2O}\left[\frac{n}{2}-\frac{a}{8}+\frac{b}{4}+3\frac{c}{8}\right]\mathrm{CO_2}\left[\frac{n}{2}+\frac{a}{8}-\frac{b}{4}-3\frac{c}{8}\right]\mathrm{CH_4}\\&\quad+c\mathrm{NH_3}.\end{aligned} \tag{8}$$

Anaerobic digestion tends to be a preferred method, over landfilling, for handling the organic content of municipal solid waste. The organic content consists of vegetative matter, food waste, and agricultural wastes. The advantage of anaerobic digestion over landfilling is its high decomposition potential and production of biogas, which is predominantly methane and compost as a final product [40]. The methane generation potential is calculated using the mass fraction (on a dry mass MSW basis) of elemental C, H, O, and N obtained from the ultimate analysis for each of the following categories indicated by index I: vegetables and putrescibles, paper, and textiles. The mass fraction is converted to gram moles of the elements n_C, n_H, n_O, and n_N from which the maximum potential for methane generation is calculated as

$$\frac{\left(n_{\mathrm{CH_4}}\right)_i}{\mathrm{kg\ MSW}}=\left(\frac{n_C}{2}+\frac{n_H}{2}+\frac{n_O}{2}+\frac{n_N}{2}\right)_i. \tag{9}$$

The total number of moles of methane generated is the sum of the number of moles of methane generated from each of the categories of waste that is considered and represented as

$$n_{\mathrm{CH_4}}(\mathrm{g\,moles\ CH_4/kg\ MSW})=\sum_i\left(n_{\mathrm{CH_4}}\right)_i. \tag{10}$$

Equation 10 is then converted to the actual mass or volume of the methane generated for a given dry mass or as-received mass of municipal solid waste.

Economic analysis of methane generation in an AD process

Among the several AD processes, the Valorga process is the one that is widely used and, as of May 2010, had a combined installed methane production capacity of 263 million cubic meters [39]. Hence, the economic analysis was based on the Valorga design. Typical biogas generation capacity for this plant is in the range of 80 to 160 Nm^3/Mg MSW and typical methane fraction in the biogas is 0.6. *While performing the economic analysis, an average methane production of 72 m^3/Mg MSW was used*. This number is much lower than the calculated potential presented in Table 2.

The economic analysis assumes the following:

- Methane constitutes about 60% (by volume) of the biogas produced.

Table 2 Calculated methane production potential (m^3/Mg MSW) via an AD process for various locations in Nigeria

Location	MSW generated (Mg/month)	VGF (wet basis) (Mg/month)	Calculated potential (m^3 CH_4/Mg MSW)
Lagos	3.71×10^5	3.04×10^5	296
Port Harcourt	1.81×10^5	9.07×10^4	168
Abuja	2.78×10^4	1.94×10^4	257
Ibadan	1.35×10^5	1.16×10^5	313
Kano	1.57×10^5	9.41×10^4	231
Makurdi	2.42×10^4	1.62×10^4	247
Nsukka	1.19×10^4	8.68×10^3	266

VGF: Vegetables, Garden and Fruit waste.

- An average biogas production of 120 Nm^3/Mg MSW and specifically an average methane production of 72 m^3/Mg MSW. Using a calorific value for methane of 37.2 MJ/Nm^3, this translates to a specific energy of 707 MJ/Mg MSW.
- Methane will be combusted in an internal combustion engine that is coupled to an electric generator with a thermal efficiency (η_e) of 0.26. This efficiency is lower than the value of 0.33 assumed for a methane landfill plant as the AD process uses some of the gas and electricity produced for its operation.
- The capital investment is assumed to be financed for 20 years at the rate of 9%.
- The operating costs are not financed.
- The plant is operational for 7,488 h/year or for 24 h/day for 26 days/month.
- Tipping fees collected from the municipality or other revenue streams are not considered. In this sense the costs calculated below for the cost of electricity or the cost of methane is the minimum pricing at which electricity or gas can be sold to the consumer.

The capital costs were then estimated using a power law based on capacity ratios as given below:

$$\text{AD plant}/C_{\text{cpl}} = C_{\text{cpl}_{\text{reference}}}\left(\frac{M_{\text{MSW}}\,(\text{tonnes/year})}{\text{Capacity}_{\text{reference}}}\right)^{0.6}, \tag{11}$$

$$\text{ICE power plant}/C_{\text{cpp}} = C_{\text{cpp}_{\text{reference}}}\left(\frac{\text{Nominal power generation capacity}}{\text{Power generation capacity}_{\text{reference}}}\right)^{0.6} \tag{12}$$

The reference ICE power plant was identified for cost comparison based on the nominal power generation capacity expected for the AD plants being considered. The capital costs and operating costs for the reference AD and the power plant are given in Table 3. The nominal generation capacity was carried out as shown in Equation 13:

$$\text{Plant capacity}\,(\text{W},\ \text{MW}_e) = \frac{120\ \left(\text{Nm}^3\ \text{biogas/Mg MSW}\right) \times M_{\text{MSW}}(\text{Mg/month}) \times Q_{\text{CH}_4}(\text{MJ/m}^3) \times \eta e \times 0.6\ \text{Nm}^3\ \text{methane/Nm}^3\ \text{biogas}}{26\ \text{days/month} \times 24\ \text{h/day} \times 3,600\ \text{s/h}} \tag{13}$$

where Q_{CH4} is the calorific value of methane and taken to be 37.2 MJ/m^3 and η_e is the thermal-to-electrical efficiency of methane gas-powered ICE plant and taken to be 0.26.

The typical capital cost (US\$/kW_e) ranges from US \$1,100 to US\$1,300 for a co-firing biogas power plant to US\$3,000 to US\$4,000 for a gasification and CHP plant. The reference capital costs used here (US\$1,200/kW_e) compares to the capital cost of a co-firing plant.

The unit cost of electricity is calculated as follows:

$$C_{5/\text{kWh}_e} = \frac{\left[\left(\text{CO}_{\text{AD}} + \text{CC}_{\text{pp}}\right) - \text{PMT}\left(\frac{9.9\%}{12},\ 30\ \times\ 12, \text{CC}_{\text{AD}} + \text{CC}_{\text{PP}}\right)\right]}{E(\text{kWh}_e/\text{year})}, \tag{14}$$

where CO_{AD} and CC_{pp} are respectively the annual operating cost for the AD and power plant. CC_{AD} and CC_{pp} are the respective capital cost for the AD and power plant. E is the electrical energy generated per year using the methane separated from the biogas and is calculated using Equation 15:

$$E_{\text{kWh}_e/\text{year}} = \frac{M_{\text{MSW}}(\text{Mg/year}) \times 120\ \text{m}^3\ \text{biogas/Mg MSW} \times 0.6\ \text{m}^3\ \text{CH}_4/\text{m}^3\ \text{biogas} \times 37.2\ \text{MJ/m}^3\ \text{CH}_4 \times \eta_e}{3.6\ \text{MJ/kWh}_e}, \tag{15}$$

where η_e (0.26) is the thermal-to-electrical energy efficiency. The unit cost of gas is calculated as

$$C_{5/\text{m}^3\,\text{CH}_4} = \frac{\left[\text{CO}_{\text{AD}} - \text{PMT}\left(\frac{9\%}{12},\ 20\ \times\ 12,\ \text{CC}_{\text{AD}}\right)\right]}{V(\text{m}^3\ \text{CH}_4/\text{year})} \tag{16}$$

$$V\left(\text{m}^3\ \text{CH}_4/\text{year}\right) = M_{\text{MSW}}(\text{Mg/year}) \times 120\ \text{m}^3\ \text{biogas/Mg MSW} \times 0.6\ \text{m}^3\ \text{CH}_4/\text{m}^3\ \text{biogas}. \tag{17}$$

Table 3 Plant capacity, capital, and annual operating costs for reference AD and ICE power plants

Cost		Value
Reference AD plant (Valorga at Tillburg)	Capacity capital cost $\left(C_{\mathrm{cpl}_{\mathrm{reference}}}\right)$	52,000 VGF tonnes/year
		US$17,500,000
	Annual operating cost	US$800,000/year (labor)
		US$ 800,000/year (supply/maintenance)
Reference ICE power plant (generating capacity 5 MW$_e$)	Capital cost $\left(C_{\mathrm{cpp}_{\mathrm{reference}}}\right)$	US$6,000,000
	Operating cost	US$657,000

Incineration and combined heat and power

The 'fuel' or waste can be incinerated in a grate furnace or a fluidized furnace. Detailed engineering analysis is required to determine which furnace design is the optimal choice. The calorific value of the fuel is converted to electrical energy or thermal energy or both in a CHP plant. The reference plant used is shown in Table 4. The electrical (E_e) or thermal energy (E_{th}) generated by each of the energy conversion mechanisms was derived from the calorific value as follows:

$$E_{\mathrm{th}}\,or\,E_e(\mathrm{MJ/Mg\,MSW}) = \eta(\mathrm{LHV}(\mathrm{MJ/Mg\,MSW})), \tag{18}$$

where $\eta = E_e/\mathrm{LHV}$ for a thermal power plant and also $\eta = E_{\mathrm{th}}/\mathrm{LHV}$ for a steam generation boiler (E_{th} is ≥ the enthalpy change between the liquid water and steam at a specified temperature and pressure).

For a CHP plant, two efficiencies may be defined - electrical efficiency and thermal efficiency. Also relevant to determining the total energy generation is the steam-to-power ratio. For the CHP process, the total energy generated ($E_{\mathrm{th}} + E_e$) per megagram MSW is presented below. The preliminary calculations assume the use of four different options:

- Grate furnace boiler/steam generator – Thermal efficiency = 0.4.
- Fluidized bed steam generator – Thermal efficiency = 0.85.
- Rankine cycle-based thermal power plant with fluidized bed furnace – Overall efficiency = 0.35.
- The CHP plant electrical efficiency is taken as 0.27, and thermal efficiency is taken as 0.64, while for the overall efficiency, we use 0.88 with a power to heat ratio of 0.42 [41].

Economic analysis of MSW incineration

The economic analysis of MSW incineration proceeds in two different ways:

1. Given the selling price of energy (heat or electrical power), what does it cost (capital investment C_{cp} and operating costs C_{o}) the company to generate energy at that cost? In this case, the energy sold is revenue. This approach assumes that electrical energy is sold at US$35/MWh and thermal energy (steam) is sold at US$15/MWh.
2. Given the costs of capital investment and operating costs, what should be the price of energy to the consumer, i.e., determine the unit cost estimate?

Baseline capital costs and operating costs

Baseline costs were determined from an article by the ASME committee [42]. This article evaluates the cost of incinerating wastes with or without polymer polyvinylchloride and across incineration plants that are categorized as small (200 metric tons (MT)/day), medium (800 MT/day), and large (2250 MT/day). The small- and medium-sized plants had two incinerator lines each, while the large plant had three incinerator lines. The plants are equipped with air pollution control devices (APCD) and continuous emission monitoring systems (CEM) and use dry lime injectors, fabric filters, and/or spray drying for air pollution control. The small plants were designed to produce steam, while the medium- and large-sized plants generate electricity. The capital investment costs and operating costs for the reference plants were averaged for each size classification, and the average costs were used in the calculations. The capital cost includes the cost of the incinerator plant and cost of APCD and CEM facilities. The plant is assumed to operate for 7,488 h/year. The annual operating cost includes both direct and indirect operating costs. The amount of MSW collected per month was compared to the plant size in the baseline that was the closest. The actual fixed capital cost (C_{cp}) for the plants were estimated by applying the power factor formula to the plant capacity ratio as shown [43]:

$$C_{\mathrm{cp}} = C_{\mathrm{cp\ reference}}\left(\frac{(M_{\mathrm{MSW}}(\mathrm{tonnes/year}))_{\mathrm{actual}}}{(M_{\mathrm{MSW}}(\mathrm{tonnes/year}))_{\mathrm{reference}}}\right)^{0.7}, \tag{19}$$

where M_{MSW} is the mass of MSW collected annually and $C_{\mathrm{cp\ reference}}$ is the known capital investment for the reference plant. The operating cost was assumed

Table 4 Parameters of the reference MSW incineration plant (capacity, capital investment, and operating costs)

Reference plant size (tonnes/day)	Capital investment ($Ccp_{reference}$) (US$)	Annual operating cost (reference) (US$)	Operating cost/capital investment
62,500	21.3 million	6.76 million	0.32
703,000	212.7 million	41.4 million	0.19

to be the same fraction of the capital cost for both the reference plant and the actual plant. The reference capital investment and operating costs were assumed to be the same for a plant of a given MSW handling capacity for a thermal power plant, a fluidized or grate boiler steam generator, and a CHP plant. It was assumed that the cost of capital included the yearly repayment of the borrowed capital investment and the interest on the borrowing (at 9% per annum for 30 years). The PMT function in Microsoft Excel was used to calculate the yearly payments (US$/year) on the borrowed capital. The PMT function returns a number with a negative sign implying that it is a cost for the plant operator or company. If the funds to meet the operating costs are not borrowed, then there is no cost involved in acquiring the operating capital. When the generated heat (E_{th} in MWh/year) and electric power (E_e in MWh/year) are sold at US$15/MWh and US$35/MWh, respectively, the net annual cost factor (C_F in US$/Mg MSW) may be calculated as

$$C_F = \frac{C_O - \mathrm{PMT}\left(\frac{9\%}{12},\ 30\times 12,\ C_{\mathrm{cp}}\right) - \left[\left(E_{\mathrm{th}}\times \mathrm{US15/MWh}\right) + \left(E_e \times \mathrm{US35/MWh}\right)\right]}{\mathrm{Mg\ MSW.}} \tag{20}$$

It should be noted that the tipping fee collected by the incinerator facility is not included in the revenue stream. Hence, the cost factor is positive in most instances, except for a CHP plant in Lagos. A positive cost factor implies that the expense exceeds the revenue. The positive cost factor thus indicates the additional revenue that must be generated through tipping fee and subsidies that must be secured. Alternately, one may determine the specific unit price of energy (C in US$/kWh) as shown in Equation 21:

$$C(\mathrm{US/kWh}) = \frac{\left(C_O - \mathrm{PMT}\left(\frac{9\%}{12},\ 30\times 12,\ C_{\mathrm{cp}}\right)\right)}{M_{\mathrm{MSW}}(\mathrm{Mg/year})\times E(\mathrm{kWh/Mg})}, \tag{21}$$

where E is the annual energy generation per metric ton MSW. The specific energy costs are in US$/kWh$_e$ for a thermal plant and in US$/kWh$_{\mathrm{th}}$ for fluidized and grate furnace plants. The CHP plant generates both steam and electricity, with a power-to-heat ratio of 0.42, and the specific energy cost is the average of both thermal and electrical energies.

Landfill gas and ICE power plant scaling: the reference data

In order to estimate the capital cost of a landfill (C_{cpl}) and the relevant operating costs, reference cost information was established based on two USEPA reports [35,44]. The capital cost for establishing a landfill is scaled as per a power law based on the capacity of the landfill over its lifetime (known as *the amount of waste in place* (WIP)). The landfill used as a reference consisted of gas handling and flare systems and has a total WIP of one million metric tons [35]. As per USEPA classification, these landfills range from very large (>15 million metric tons (MMT)) to medium (>5 MMT) in size. The landfill that is used as a reference is located in Munster, IN, USA. The LandGEM program was executed to determine the volume of methane generated per year. Using that information, the average electrical energy produced (in MW) over the 60-year period was calculated. This provided an estimate of the nominal power generation capacity of the plant to be installed onsite. The capital investment cost for the actual plant (C_{cpl} and C_{cpp}) was then scaled based on the power generation capacity as per a power law relation as given Equations 22 and 23.

$$\mathrm{Landfill}/C_{\mathrm{cpl}} = C_{\mathrm{cpl,reference}} \times \left(\frac{M_{\mathrm{MSW}}(\mathrm{tonnes/year}) \times 12\ \mathrm{months/year} \times 30\,\mathrm{years}}{\mathrm{Capacity}_{\mathrm{reference}}}\right)^{0.6}, \tag{22}$$

$$\mathrm{Power\,plant}/C_{\mathrm{cpp}} = C_{\mathrm{ccp,reference}} \times \left(\frac{\mathrm{Nominal\,power\,generation\,capacity}}{\mathrm{Power\,generation\,capacity}_{\mathrm{reference}}}\right)^{0.6}. \tag{23}$$

The annual operating cost for the landfill is scaled as a power of 0.6 based on the mass of MSW handled per year. The annual operating cost of the ICE power plant is assumed to be a fixed percentage (9.9%) of the capital cost of the ICE power plant. This assumption is justified when the estimated costs are presented below. The continuous power generation capacity is determined based on methane generated for a given year. The methane production rate is assumed to be constant and that only 50% of the methane that is generated is captured and utilized (the recovery factor of 0.5 in Equation 24). The plant is assumed to operate for 7,488 h/year.

$$\mathrm{Power\,generation,\ \ year}\,i\,(\mathrm{W}_i, \mathrm{MW}_e) = \frac{V_{\mathrm{CH_4}}(\mathrm{m^3/year}) \times Q_{\mathrm{CH_4}}(\mathrm{MJ/m^3}) \times \eta_e \times 0.5}{7,488\ \mathrm{h/year} \times 360\ \mathrm{s/h}}, \tag{24}$$

$$\mathrm{Nominal\ power\ generation}\,(\mathrm{MW}_e) = \frac{\Sigma_{i=1}^{60} W_i}{60}. \tag{25}$$

The nominal size of the plant is the average of the power generation capacity averaged over the 60 operating years of the plant. The capital cost is determined based on this nominal plant capacity:

$$E_{\text{avg}}\ (\text{GWh}_e/\text{year}) = \left[\left(\frac{\frac{\Sigma_i^{60}(V_{\text{CH}_4})_i(\text{m}^3/\text{year}) \times 0.5 \times Q_{\text{CH}_4}\ (\text{MJ}/\text{m}^3) \times \eta_e}{60}}{1,000\ \text{MJ}/\text{GJ} \times 3,600\ \text{GJ}/\text{GWh}}\right)\right]. \tag{26}$$

The unit-specific cost of electricity generated (C_e) after suitable unit conversions is calculated from Equation 27:

$$\text{Cost}\ (\text{s}/\text{kWh}_e) = \frac{[(C_{\text{ol}} + C_{\text{op}}) - \text{PMT}(\frac{9\%}{12},\ 30 \times 12,\ C_{\text{cpl}} + C_{\text{cpp}})]}{E_{\text{avg}}\ (\text{kWh}_e/\text{year}),} \tag{27}$$

where C_{ol} is the operating cost of the landfill and C_{op} is the operating cost of the power plant. E_{avg} is the average electrical energy generated over a 60-year period. The direct use, the landfill methane, *as a fuel for combustion in household or commercial applications is considered as well*. The capital cost includes the costs associated with the development and operation of the landfill, collecting, flaring, compressing, handling, purification, and piping of the landfill gas. The ICE power plant costs are excluded as there is no power generation on site.

Table 5 gives the pertinent information for the reference landfill capital and operating costs as well as the costs for direct gas plant. The capital cost of the landfill and direct gas plant are scaled as a power of 0.6 of the ratio of the WIP amount, as specified in Equation 13. The annual operating cost for the landfill is scaled as a power of 0.6 based on the mass of MSW handled per year [42]. The landfill that is used as a reference is located in Munster, IN, USA. Equation 7 gives the annual methane production rate which is averaged over 60 years to give $\bar{V}_{\text{CH4}}$. The unit-specific cost of methane recovered (C_{gas}) for use is calculated as

$$C_{\text{gas}}\ (\text{US}/\text{MJ}) = \frac{\left[\left(C_{\text{ol}}+C_{o,\text{gas}}\right)-\text{PMT}\left(\frac{9\%}{12},\ 30\times 12,\ C_{\text{cpl}}+C_{\text{op,gas}}\right)\right]}{\frac{\left[\bar{V}_{\text{CH}_4}\times 0.5\ \left(\text{m}^3/\text{year}\right)\right]}{Q_{\text{CH}_4}\ \left(\text{MJ}/\text{m}^3\right)}} \tag{28}$$

Table 6 gives the capital and operating costs for the reference landfill and ICE power plant.

Waste composition of the selected municipalities and assumptions

The calorific value of the MSW collected in each city was calculated for vegetable and yard waste, paper, and textiles only. It was assumed that plastics, bottles, and metals will be captured by a recycle system and excluded from incineration.

Lagos

The MSW collected in Lagos has significant food waste and putrescible content (68 w/o on an as-received basis). Papers make the next major category. The moisture and ash contents in the MSW are not explicitly known. Hence, typical values were used for the moisture content taken from [45]. The ash content used was obtained [28] as determined for MSW collected in Port Harcourt.

Port Harcourt

The MSW data and the proximate and ultimate analysis data for Port Harcourt are very comprehensive as reported by [28]. Published ash and moisture contents were used to arrive at the ash- and moisture-free elemental ultimate analysis. These values were used in the correlations to arrive at the calorific value for MSW. It is interesting to note that the moisture content is very high in the food waste and wood waste categories at 65.2 and 19.2 w/o. The mass distribution of food waste is low (29.2 w/o); on the other hand, the combined mass

Table 5 Capital and operating cost information for a reference landfill and direct gas plants

Cost		Value
Reference landfill	Capacity (WIP)	1 million MT
	Capital cost $\left(C_{\text{cpl}_{\text{reference}}}\right)$	US$700,000
	Mass MSW received per year	8,000 metric tonnes/year
	Annual operating cost (C_{ol})	US$196,647/year (collection)
		US$765,761/year (sort and dispose)
Reference direct gas plant	Capacity (WIP)	1 million MT
	Capital cost $\left(C_{\text{cpgas}_{\text{reference}}}\right)$	US$1,639,000
	Annual operating cost (C_{ogas})	US$136,000

Table 6 Capital and operating cost information for a reference landfill and ICE power plants

Cost		Value
Reference landfill	Capacity	1 million metric tonnes
	Capital cost $\left(C_{\text{cpl}_{\text{reference}}}\right)$	US$700,000
	Mass MSW received per year	8,000 metric tonnes/year
	Annual operating cost	US$196,647/year (collection)
		US$765,761/year (sort and dispose)
Reference ICE power plants	Generation capacity	5 MW_e
		3 MW_e
		2 MW_e
		1.5 MW_e
		1 MW_e
	Capital cost $\left(C_{\text{cpp}_{\text{reference}}}\right)$	US$6,000,000
		US$3,957,000
		US$2,517,000
		US$1,927,000
		US$1,322,000
	Operating cost	US$657,000
		US$394,000
		US$263,000
		US$197,000
		US$131,000

distribution from plastics, glass, and metal waste is significant at nearly 41 w/o.

Abuja

The MSW distribution in Abuja is dominated by food wastes that contribute 55 w/o. The ash content and ultimate analysis were obtained from a report prepared by the Center for People and Environment prepared for USEPA [46]. This report particularly considered the landfill methane generation potential in Ibadan and Abuja, Nigeria. The moisture content was assumed to be the same as in Lagos [43]. The ash content used was obtained from [28], determined for MSW collected in Port Harcourt.

Ibadan

The MSW distribution in Abuja is dominated by food wastes that contribute 64.9 w/o. The ash content and ultimate analysis were obtained from a report prepared by the Center for People and Environment prepared for USEPA [46]. The moisture content was assumed to be the same as in Lagos [45]. The ash content used was obtained from [28], determined for MSW collected in Port Harcourt. The total mass of the MSW collected per month was not available; hence, representative values published in the literature were used for Ibadan [29].

Kano

MSW collected in Kano has a low contribution from food wastes (38 w/o). Papers contributed as high as 15 w/o, and glass and plastics contributed a combined 22 w/o; these are materials that can potentially be recycled or their usage reduced. The moisture content was assumed to be the same as in Lagos [45]. The ash content used was obtained from [28], determined for MSW collected in Pt. Harcourt.

Makurdi

Makurdi has a significant amount of vegetable waste (52 w/o). The moisture content was assumed to be the same as in Lagos [45]. The ash content used was obtained from [28], determined for MSW collected in Port Harcourt.

Nsukka

Municipal waste collected in Nsukka has a significant amount of vegetable and paper waste. It also contains significant quantity of metals and plastics that can be recycled and not introduced into the MSW stream.

Results and discussion

Landfill methane generation

The methane generation potential was calculated as described earlier. These calculations determine the methane generation potential from the landfill. The results are summarized in Table 1.

The calculated methane generation potential (in m^3 methane/Mg MSW) is lower than the typical range of about 50 to 100 kg methane per tonne MSW (70 to 140 m^3 methane per Mg MSW) for a landfill methane generation estimated by the International Energy Agency (IEA) [47]. The difference could be attributed to the fact that the IEA estimate is based on landfill methane plants operated in developed countries where the degradable carbon content may be higher. Furthermore, the landfill WIP at the end of 30 years for the various cities in Nigeria ranges from approximately 133 million metric tonnes (MMT) for Lagos to 4.3 MMT for Nsukka.

Table 7 gives the summary of the monthly MSW collection and the cost (not the net cost) per tonne of MSW handled. This is the cost incurred at the landfill for collection and sorting operations and does not include the cost associated with electricity generation or direct gas use. The costs of electricity and direct landfill methane are also presented. The daily MSW collection rate ranges from 12,350 to 400 tonnes/day for the selected municipalities. These numbers are derived from the data that was provided. USEPA guidelines for full cost accounting data state that in this range of daily MSW collection rates, the net cost per ton of MSW handled ranges from less than about $36/ton (at 1,500 tons/day) to about $85/ton (at 400 tons/day). The numbers estimated reveal the same

Table 7 Specific cost of electricity and direct landfill methane for the selected municipalities

Location	Waste collection (tonnes/month)	Operating cost of landfill (US$/tonne)	Total CH_4 recovered in 60 years (m^3)	Nominal power (MW_e)	Price of electricity (US$/$KWh_e$)	Price of gas (US$/GJ CH_4)
Lagos	370,556	9.60	2.88×10^9	21.6	0.29	27.60
Port Harcourt	181,450	13.40	3.33×10^8	2.5	1.56	152.00
Abuja	27,795	22.00	1.56×10^8	1.2	1.08	108.00
Ibadan	135,391	14.40	1.86×10^9	13.9	0.25	23.40
Kano	156,676	13.50	5.53×10^8	4.1	0.88	84.60
Makurdi	24,242	28.60	1.06×10^8	0.8	1.47	144.00
Nsukka	12,000	37.90	6.99×10^7	0.5	1.47	145.00

trend but are slightly lower because the cost of capital to establish the landfill is not included. The calculations also assume that the MSW in a place like Lagos goes to a single appropriately sized large landfill. The EPA estimates consider a landfill with 1,500 tonnes/day for the highest daily capacity. The landfill rule was promulgated in the USA as a part of the Clean Air Act of 1996. According to this rule, future landfills, with the size larger than 2.5 MMT and volume greater than 2.5 million m^3, will have to install features that would either collect or flare the landfill gas. The USEPA report has determined the economics of electricity generated from direct gas use of the landfill methane [37]. For landfills that are not subject to the landfill rule and whose range in size is from 50,000 to 11,000,000 MT, the break-even gas price was calculated. For these landfills, electricity generation was not considered feasible. The break-even gas price is the price of gas at which the project results in US$0 NPV (net present value) at the end of the 15-year life of the project. For the landfill project to be viable, the WIP must be greater than or equal to the break-even WIP. The results are summarized in Table 8.

Comparing the estimated price of electricity for Nigerian towns to the USEPA projections, the price of landfill gas electricity for Nigeria is nearly a factor of 5 higher at best. The market price of natural gas is about US$2.74 per one million British thermal units (MMBtu), and the average industrial gas methane price is about US$3.42 per MMBtu. The cost of coal mine gas is also in the same range, about US$2.53 per MMBtu. For a landfill generating electricity to be viable, the break-even WIP is 2.9 MMT and the price of electricity would be US$0.04/$kWh_e$. For a landfill that produces gas for direct use, the price of gas is about US$2.74 per MMBtu (US$2.59/GJ) for a break-even landfill with a WIP of about 1 MMT. Both these projections assume US$0/TCE, i.e., no extra value for the offset of greenhouse gas emission, and do show incremental emission reductions. This renders the cost of landfill direct gas scenario to nearly 17 to 20 times higher for the municipalities considered. A significant reason for the higher estimate for Nigeria is because the calculations assume a minimally managed landfill with gas collection in place but only capturing 50% of the generated methane. This same factor contributes to the higher estimate for the price of gas. In addition, for a given landfill, the capital investments and operating costs appear to be much higher for a direct gas plant versus an ICE power plant. The extra cost comes from the cost of compression that is about 344,737.5 Pa and piping gas to the consumer from the plant. It must be emphasized that this is an estimate that does not take into account any revenue-generating stream such as tipping fee or garbage collection fee.

Table 8 Break-even landfill direct gas price and landfill WIP

Size of landfill WIP (break-even WIP)	Break-even price (US$/GJ CH_4)
50,000 MT	52.00
500,000 MT	6.38
1,000,000 MT	2.04
11,000,000 MT	1.28

Anaerobic digestion

The methane is combusted in an ICE power plant or can be sold as a direct gas at higher pressures transported through a pipe network. The volume of methane generated by anaerobic digestion for each location that was considered is given in Table 2.

It may be noted that the cost of methane generated through anaerobic digestion is much cheaper than landfill methane. The price of the low pressure gas compares very closely with the average cost of natural gas (US$2.59/GJ) as presented in Table 9. When the product gas has to be sold as direct gas to the consumer, it may have to be purified, compressed, and transported through pipes to the consumer. Thus, a factor of 15% has been added to the price of low-pressure product gas to arrive at the price of direct gas. The percentage increase in price is the same as what was estimated to deliver landfill methane for direct gas use. The price of the direct gas obtained through anaerobic digestion is very much competitive with the price of natural gas. In the scenario where methane is generated using an AD process, the methane

Table 9 Specific cost estimate for electricity and gas produced by AD of MSW for various locations in Nigeria

Location	Nominal capacity of power plant (MW_e)	Cost of electricity (US$/$kWh_e$)	Cost of low-pressure gas (US$/GJ CH_4)	Cost of direct gas (US$/GJ CH_4)
Lagos	117	0.0209	0.89	1.27
Port Harcourt	57	0.0239	0.8	1.25
Abuja	9	0.0560	2.28	3.24
Ibadan	43	0.0317	1.37	1.94
Kano	49	0.0268	1.04	1.48
Makurdi	8	0.0584	2.35	3.35
Nsukka	4	0.0792	3.28	4.66

is subsequently combusted in an ICE power plant or is sold as direct gas at higher pressures, transported through a pipe network. The price of methane is competitive with the market price of natural gas at about US$2.74 per MMBtu, and the average industrial methane gas price is about US$3.42 per MMBtu for most of the selected municipalities except perhaps Nsukka. In addition and as an added benefit, the AD process produces compost that has use in agricultural practices.

Incineration or combustion

Table 10 shows the potential for energy generation (E_e in MJ_e) or thermal (E_{th} in MJ_t) by incinerating the *organic part* of the MSW. It is true that at the end of incinerating the MSW or combusting the methane gas, CO_2 will be produced. On the one hand, it is less potent than methane, and it is hoped that local environmental regulations will regulate the CO_2 emissions as well.

The World Bank has determined that for the viability of a WTE project, a minimum LHV of MSW of 6,000 MJ/Mg throughout the season and an annual average of 7,000 MJ/Mg are required [48]. As the calorific value estimates are revealed earlier in Table 3, incineration appears to be *technically* viable in the selected municipalities, except in Port Harcourt. It is clear that the cost factor for incinerating a ton of waste in a grate furnace steam generator is high. In [48], it was also noted that the net cost factor for treating a tonne (Mg) of MSW in an incinerator ranges between US$10 and US$100/Mg with an average cost factor of about US$50/Mg. The cost factor for a CHP-WTE plant is at or below the average cost factor. It may be noted that a fluidized bed steam generator and a thermal power plant have similar cost factors. The specific cost of electrical power generated using CHP compares well with the price of electrical power at US$0.14/$kWh_e$. The price of steam generated using a fluidized steam generator also compares favorably with the average price of steam at about US$0.015/$kWh_t$ as shown in Table 11. The International Energy Agency has reviewed the economic and environmental benefits of a CHP technology based on the installed and projected capacity in G8+5 countries. The report calls for increased adaptation of the CHP technology and projects about 19% reduction in CO_2 emissions in 2030 in comparison with projected emissions from fossil fuel-based power generation without a combined heat cycle [49]. The method and approach presented in this work are very much comparable to that reported in [46] and thus provide credence to the accuracies of the present results.

Implications and recommendations

The effectiveness of the proposed technologies of this study can be described as follows:

1. Propensity to reduce landfill dumping and large amounts of land area designated as dump sites. Such

Table 10 Energy generation potential by incinerating MSW in Nigeria

Location	Calorific value (LHV) (MJ/Mg)	Electrical or thermal energy generated			
		Thermal power plant (MJ_e/Mg MSW)	Fluidized bed steam generator (MJ_t/Mg MSW)	Grate incinerator boiler (MJ_t/Mg MSW)	CHP (MJ/Mg MSW)
Lagos	1.18×10^4	4,141	9,937	4,732	10,766
Port Harcourt	6.76×10^3	2,367	5,680	2,705	6,153
Abuja	1.04×10^4	3,650	8,761	4,172	9,491
Ibadan	1.27×10^4	4,436	10,647	5,070	11,534
Kano	9.49×10^3	3,320	7,968	3,794	8,632
Makurdi	1.00×10^4	3,514	8,433	4,016	9,136
Nsukka	1.08×10^4	3,787	9,088	4,328	9,845

Table 11 Cost factor and specific unit price of energy generated by various processes using MSW as fuel

Location	Thermal plant		Fluidized steam generator		Grate furnace generator		CHP	
	CF	*C*	CF	*C*	CF	*C*	CF	*C*
	US$/Mg	US$/kWh	US$/Mg	US$/kWh	US$/Mg	US$/kWh	US$/Mg	US$/kWh
Lagos	10.4	0.044	9.3	0.018	31.0	0.039	−11.9	0.017
Port Harcourt	39.8	0.095	39.1	0.040	51.5	0.084	27.0	0.037
Abuja	49.9	0.084	48.9	0.035	68.0	0.074	30.0	0.032
Ibadan	25.4	0.056	24.2	0.023	47.4	0.049	1.50	0.021
Kano	33.3	0.071	32.4	0.030	49.8	0.062	15.4	0.027
Makurdi	54.8	0.091	53.8	0.038	72.2	0.080	35.8	0.035
Nsukka	73.0	0.104	72.0	0.044	91.8	0.091	52.6	0.040

lands can be used for other purposes while incineration of waste can produce a much needed energy and reduce the volume of waste by as much as 90%.

2. Propensity to reduce dependence on fossil fuels. The advanced technologies of WTE can produce fuel that does not require mining or drilling for non-renewable fossil fuel resources.
3. Capacity to offset GHG emissions and pollution caused by burning fossil fuels, and
4. Production of clean energy since WTE technologies have significantly advanced as a function of policy measures such as the Kyoto Protocol [16].

Furthermore, the technologies analyzed in this study have been well demonstrated and employed in varying capacities [17]. Electricity generation from MSW is highly feasible in Nigeria considering the population factor and the subsequent large amounts of waste generated which are not effectively managed. Another rationale for exploring underutilized fuels like MSW is for minimizing GHG emissions currently produced by open dumping. WTE is a reasonable and sustainable MSW management strategy in terms of weight and volume reduction coupled with energy recovery, and it is recommended that this should be vigorously explored.

Regulatory and policy measures to promote WTE technologies and market penetration should be established by federal, state, and local governments. Such measures should have clear strategies for implementation and enforcement. Likewise, the weak and almost non-existent financial instruments need to be strengthened and broadened to attract the necessary private sector investments for the adoptions of MSW management via WTE technologies.

Future studies should consider (1) feasibility studies of other municipalities in Nigeria; (2) life cycle assessment of waste disposal options; (3) emissions aspects, carbon offsets, and fossil fuel displaced; and (4) policy and social aspects.

Conclusions

WTE in Nigeria can be developed as an important integrated waste management strategy while simultaneously producing energy, can displace fossil fuels and can reduce pollutant emissions. The operational reliability of WTE systems will be improved over time as more systems are commissioned and operated at a commercial level. WTE should be recognized as part of a future, balanced mix of energy technologies and policies. The location of WTE plants in order to consolidate MSW from various locations to achieve economies of scale will be important. In addition, waste composition is highly unlikely to remain stable, and changes in waste policies and population habits can contribute to waste composition changes which would also affect the performance of WTE plants. Waste having high calorific value will result in more energy recovery. As more societies in the world increasingly adopt the reduce, reuse and recycle strategies, the amount of MSW collected would reduce significantly. While the authors in [50-53] have equally estimated in one capacity or the other the potential for energy generation from other renewable energy sources such as biomass, corn cob, and animal waste for Nigeria, they however did not consider the economics of the potential. Technical and economic assessments of three waste treatment methodologies have been reported in this study. The calorific value and methane generation potential for MSW generated in various towns in Nigeria has been determined. From the estimates of the calorific value and the methane generation potential, the technical feasibility of power generation and/or direct (methane) gas availability has been determined. Within the study, it appears that incineration (particularly a CHP) or anaerobic digestion may be more economical. The costs for power produced by incineration and AD compare very well with what it is in developed countries.

This study has not addressed the emission aspects and carbon offset arguments of the three MSW management approaches considered here. A compelling argument is self-evident if we consider what happens to MSW today in developing countries that are also energy hungry. Currently, MSW is discarded in most developing nations in a landfill. These landfills are undeveloped swath of land that pollutes the environment. Methane and CO_2 are produced in the landfill, often without any means for methane capture and recovery. Given this scenario, the direct benefits of offsetting methane emission are compelling. It is true that at the end of incinerating the MSW or combusting the methane gas, CO_2 will be produced. On the one hand, it is less potent than methane, and it is hoped that local environmental regulations will regulate carbon dioxide emissions as well. Within the stated study limitations, the following were found:

- An incinerator plant based on CHP or a fluidized combustion technology is a viable option for Lagos, Ibadan, and Kano.
- The viability of landfill methane generation may not be excluded, but it requires further analysis, specifically determining the capital cost with better specificity and methane recovery benefits of a landfill with a MCF of 0.7 and a methane recovery greater than 50%. Landfills tend to take up vital land resource, and such lands cannot be put to any other use for years. This may act as a reason against adopting landfill as a MSW management strategy.
- Anaerobic digestion certainly appears to be a promising and viable MSW management strategy for Nigeria. The price of gas or electricity produced is competitive with fuel currently used and electricity generated through other fossil fuel means.
- The economic performance of the different waste management options is sensitive to their capital costs and this would depend on plant scale, suppliers and local area logistics. As such, there are some inevitable and inherent uncertainties in the estimated values.

This work serves as a preliminary assessment aimed at identifying which MSW management option would be technically and economically viable. The benefits of energy recovery from waste fuels are such that any nation's waste management policy should embrace energy recovery irrespective of the individual local strategic preferences.

Abbreviation

ICE: Internal combustion engine.

Competing interests

The author(s) declare that they have no competing interests.

Authors' contributions

OMA conceived the problem and drafted the manuscript. RLF supervised and approved the draft. All authors read and approved the final manuscript.

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