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STATE-LEVEL ASSESSMENT OF THE WASTE-TO-ENERGY POTENTIAL (VIA INCINERATION) OF MUNICIPAL SOLID WASTES IN NIGERIA

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Abstract

The quest for reliable and adequate power supply in Nigeria has brought about a surge of interest in renewable energy generation, particularly from wind, solar, hydro and biomass resources including municipal solid waste. Waste-derived energy raises unique interest because of the magnitude of benefits to environmental protection and socio-economic advancement. The successful operation of Waste-to Energy (WtE) facilities in Nigeria requires continuous supply of solid waste and enabling environment amongst other factors. This study conducted a state-level assessment of the WtE potential of municipal solid waste (MSW) in Nigeria. Our findings show that the electricity generation potential for the different states in Nigeria varied from 31 – 205 MW, depending on state's waste generation capacity. The country's annual electricity generation potential from MSW was estimated to be 26744 GWh/year, with 89% of the states having sufficient generation capacity at minimum regulatory electricity generation requirement of 50 MW. But, based on current realities such as poor collection efficiencies, Nigeria's exploitable WtE capacity from MSW was below 3800 GWh/year, with all the states having less than 50 MW capacity. On-site power generation such as dedicated power station for industrial estates and corporate users can be a feasible form of distributing energy generated from WtE facilities. The outcomes of this study are important in informing the siting of WtE facilities in Nigeria and for enabling policy framework.

Keywords: Renewable Energy, Solid Waste Master Plan, Waste Energy Recovery, Sustainable Policy Development, Incineration, Biomass

1. INTRODUCTION

Energy plays an important role in meeting the needs of residential, industrial, transport, agricultural and other sectors in an economy. Sub-Sahara Africa (SSA)'s economic growth projected at 4.2% GDP (1) qualifies the sub-region as the new frontier of growth. However, this growth could be impeded by electricity shortages (2). The power generation capacity in the entire SSA compares to Spain's 68 GW, and the average price of power in SSA is high compared to international standards (3). Demand for energy is greater than supply in SSA and this is compounded by rapid population growth and increase in the urban population density. There is low kilowatt-hour (kWh) electric power consumption in SSA. For example, the electric power consumption in Nigeria in 2012 was reported as 156 kWh per capita (4). This value is comparably low to the electric power consumption in other developing countries such as Malaysia, South Africa and Venezuela, which consumed 4114, 4405 and 3413 kWh per capita respectively. The increasing energy demand, insufficient supply of electricity, and quest for reliable and adequate power supply in Nigeria have therefore necessitated a surge of interest in alternative energy sources, particularly from solid waste.

Municipal Solid Waste (MSW) is of unique interest because of the benefits to environmental protection and socio-economic advancement. These resources are readily available in Nigeria, however, illegally dumped in open spaces and poorly managed with enormous environmental consequences. MSW, also referred to as trash or garbage, is a mix of everyday items from local residences, businesses, commercial properties and public institutions including schools and hospitals (5). It consists of degradable materials such as cardboard, paper, food scraps, newspapers, and other combustible elements. MSW also contains non-biomass derived materials such as plastics, glass, metals, appliances and batteries. Hence, the averted dump of such materials in the environment and subsequent use for heat and/or electricity, is considered renewable and the process of recovering energy from waste is referred to as Waste-to-Energy (WtE).

Waste-to-Energy includes processes such as incineration, gasification, pyrolysis that thermally treat solid waste and directly recover energy in the form of electricity and/or heat. It also includes bio-chemical processes such as landfill gas recovery, anaerobic digestion that converts the chemical energy in solid waste to yield products of high energy value e.g. methane. Thermal treatment methods with energy recovery options are widely preferred because of the possibilities to substantially reduce the quantities of waste, opportunities to recover minerals and chemicals and destroy contaminants (6), potential of directly converting the waste to an energy source, which reduces the time of treatment, as well as the potential to treat toxic materials and control emissions from point source. Their use is expected to improve the quality of life as it can minimise the adverse dumping of waste, consequently preventing environmental pollution and land degradation; minimise fossil fuel consumption and greenhouse gas emissions, offset methane that could be released from open landfills, prevent adverse health impacts from exposed burning of waste, and prevent the spread of infectious diseases via parasitic agents (7-9).

Waste-to-Energy can play a significant role in the changing energy climate in Nigeria, particularly as a renewable energy resource, as this is increasingly becoming important. By the year 2025, renewable energy is expected to account for 10% of the total energy demand projection and particularly for remote and off-grid power generation (10). As part of the strategic objectives of the National Renewable Energy and Energy Efficiency Policy (NREEEP), a legislative framework that aims at increasing the power generation capacities and the share of renewable energy sources in Nigeria, pilot projects of biomass energy conversion systems are proposed for development (11). These include the waste-to-energy plant that is proposed for Ikorodu Industrial Estate and surrounding areas in Lagos State and the 12 MW gasification facility in Imo State (12). Since Nigeria is a signatory to the Paris Agreement on Climate Change mitigation in 2015, these projects are intended to contribute to clean development mechanisms (CDMs) for the reduction of indoor and outdoor pollution, and to mitigate the effect of greenhouse gas emissions on climate change. The sustainability of such projects however, requires sufficient quantity and quality of solid waste, the right choice and scale of energy conversion technology, minimum investment risk and optimum financial returns, and a supportive legal framework. The power industry in Nigeria is replete with low planning tendencies, improper estimations and insufficient capacities such as the installation of industrial gas turbine power plants across the country without proper planning of fuel delivery (13). There is also the challenge of transmission and distribution of generated electricity to the end-consumer with cost recovery. As such, there are on-going discussions on how biomass power plants can connect to the transmission networks of the national grid and the potential for a minimum generation requirement for large power plants to ensure and improve grid stability. Communities with multiple biomass power plants under competing conditions for MSW would require a certainty of continuous supply of waste resources across seasons, space and time; hence, the need to assess the WtE potential at state-level and across Nigeria.

Certain studies have carried out a community-level assessment of the WtE potential that could be derived from MSW for selected states in Nigeria including Lagos (14), Bauchi (15), Ogun (16) and Taraba (17). McIlveen-Wright et al. (18) quantified the waste tonnage and components of a typical landfill site in Lagos State. They calculated the electricity potential using fuel's caloric value, moisture content and inert content. The authors further analysed the economic feasibility of a 50 MW Energy from waste coal power plant, assuming a tipping fee of £50/tonne of waste and supported by other environmental and waste management options such as recycling and composting. Udoakah and Akpan (19) estimated the electric potential from MSW using a proposed incineration plant in Southern Nigeria. Furthermore, Amoo et al. (20) carried out a techno-economic assessment for seven states in Nigeria under different energy technologies along with estimation of the electrical power and thermal energy potential generated per kg of MSW. Despite the previous work on WtE in Nigeria, none of them have conducted a holistic assessment of the WtE capacity in the entire country, considering factors such as waste quality, quantities and energy conversion technologies. There is no information in the literature whether there are sufficient waste quantities across the country to inform the siting of future WtE facilities, especially under minimum electricity generation requirement.

This study therefore presents a state-level assessment of the WtE potential in Nigeria. The outcomes are compared to the exploitable WtE for the different states at various MSW generation rates and collection efficiencies, and considering a minimum electricity generation requirement of 50-100 MW for connecting to the national grid. The overall exploitable WtE of the country are presented in broad scales for different waste conversion technologies using net plant efficiencies, MSW generation rates and waste collection efficiencies. Sensitivity analysis was conducted using various waste quantities and fuel composition to highlight the influence of these parameters on net plant efficiency. The study concludes by proposing ways to enhance the deployment of WtE facilities in Nigeria, as this can inform the development of appropriate policy framework.

2. METHODS

The study exploited the MSW generation capacities of the 36 states in Nigeria and the Federal Capital Territory (FCT), according to population size. The average population size as reported by the National Population Commission for all the states in Nigeria and the FCT (21) was adjusted for the period of 2007-2013 using the population growth rate factors in Table 1 and assuming the same growth rate factor for year 2014-2015, as year 2013. The growth rate factors were calculated from the World Development Indicators (22) for birth and death rates using Eqn. 1. These were expressed as percentage per year and used to determine the state and country's mean population at study year 2015.

Table 1: Growth Rate Factors and Adjusted Population Size/Year

Growth Rate Factor, GRF (%/year) = [(birth rate– death rate), crude (per 1,000 people)]/1000 (Eqn. 1)

Mean Population (μ) = μ_0 (1 + GRF) (Eqn. 2)

A state level assessment of the exploitable WtE in Nigeria was carried out at different MSW generation capacities rates of 0.30-0.80 kg/cap/day and waste collection efficiencies of 30-80%, assuming incineration as the preferred thermal treatment technology for the MSW.

2.1. Model description

The waste conversion and energy recovery processes were simulated in Aspen Plus® environment, as depicted in Figure 1 using a non-stoichiometric thermodynamic equilibrium model that minimises the Gibbs free energy in the system.

Figure 1: Schematic flow diagram of the waste conversion and energy recovery processes of the MSW

The main processes include the combustion of the MSW in a conventional incinerator, exhaust gas clean up, heat recovery via a heat recovery steam generator (HRSG) and electricity generation with a steam turbine. Figure 1 models the introduction of the moist MSW into a DRIER that is coupled to a flash separator (DRY-FLASH) to remove the moisture from the biomass stream. The MSW was defined as a non-conventional stream using proximate and ultimate compositions as well as the lower heating value (LHV) of the fuel. The exit fuel (dry MSW) was introduced into a yield-based reactor (DECOMPSR) where the fuel is broken down to its elemental constituents. The heat produced from the decomposed fuel and the elemental constituents of the dry fuel were introduced into a RGIBBS reactor (PRI-COMB). This reactor minimizes the Gibbs free energy at defined temperature and pressure under constraints of elemental balance, without requirements for reactor design and reaction stoichiometry, that is typically a balance between the amounts of reactants and products. Air stream was introduced into the PRI-COMB block at standard temperature and pressure to maintain combustion and this was defined in Aspen Plus® as a conventional mixed stream.

The combustion gas products that exit the PRI-COMB were separated into solids and gas streams using a SSPLIT block (SEPARATR). The heat from the gas stream was recovered through the HRSG block that is connected to a steam boiler. The steam generated from the boiler flowed to the steam turbine where work was produced while the residual heat in the exhaust gas was removed via heat exchange in the block (CONDNSR). The cooling water required for heat exchange from the hot flue gases and to produce steam was supplied by a PUMP block. The air supply rate and cooling water flow rate were calculated using calculator and design spec blocks. A steady state simulation was achieved, assuming ideal gas behaviour for all gases including air (21 vol. % oxygen and 79 vol. % nitrogen). The boiler, steam and overall efficiencies, and the exploitable WtE were derived using Eqn. 3-6. This Exploitable WtE is all denoted as MW, that is MWh per hour of operating the plant, except otherwise stated.

$$\eta_{Boiler} = Q_{Boiler} / HHV_{Biomass} \text{ x Fuel Burn Rate} \quad \text{Eqn. 3}$$

$$\eta_{themal} = W_{Turbine} - W_{Pump} / Q_{Boiler} \quad \text{Eqn. 4}$$

$$\eta_{overall} = \eta_{themal} \text{ x } \eta_{Boiler} \quad \text{Eqn. 5}$$

$$\text{Exploitable WtE (MW)} = (W_{Turbine} - W_{Pump}).\ \eta_{wce} \quad \text{Eqn. 6}$$

where η_{Boiler} - efficiency of the boiler (%); Q_{Boiler} - heat recovered from the flue gas (MJ/s); $HHV_{Biomass}$ - higher heating value of the biomass (MJ/kg); $W_{Turbine}$ - work output of the turbine (MW); W_{Pump} - work done by the pump (MW); $\eta_{overall}$ - overall thermal efficiency (%); η_{themal} - thermal efficiency of the heat recovery section (%); η_{wce}- waste collection efficiency (%).

The input parameters as listed in Aspen Plus® environment are listed in Table 2 while the ultimate and proximate compositions of the MSW as inputted in the model are listed in Table 3.

Table 2: Input Parameters in Aspen Plus® for the Base-case Scenario

Table 3: The ultimate and proximate compositions of a typical MSW in Nigeria (Amber et al. 2012)

The average amount of waste generated at the state level was deduced from the average MSW generation capacities and the adjusted population size using Eqn. 7.

Tonnage/day = [state mean population x average MSW generation rate (kg/cap/day)]/1000 Eqn. 7

The analysis considered waste treatment rate of 50 tonnes per hour, equivalent to 1200 tonnes per day and obtained net plant efficiency of 26%, a value that is within the range of 17-27% (20-21). This analysis presents a point estimate performance of the WtE facility based on the defined boundaries in this study. Other energy conversion technologies are considered using varying net plant efficiencies in the range of 17-67%. To account for fuel variabilities, sensitivity analysis was conducted with wastes of varying composition and quantities and the results are presented in Section 3.3.

3. RESULTS & DISCUSSION

3.1. State-level Assessment of Electricity Generation Potential from MSW in Nigeria

Nigeria is classified as a low-income country with average MSW generation rate of 0.49-0.56 kg MSW/cap/day (23-25). The country is however projected to produce about 100,000 tonnes of MSW/day at urban waste generation rate of 0.80 kg MSW/cap/day (23) by 2025. As such, Table 4 shows that the electricity generation potential per hour of operating the WtE incineration facilities in different states in Nigeria can vary from 31 - 205 MW at 0.53 kg/cap/day. At projected MSW generation rate of 0.80 kg/cap/day, the electricity generation potential for the individual states can vary from 47 - 312 MW. These results sum up the country's electricity generation potential to be 26744 GWh/year (0.53 kg/cap/day) and 40753 GWh/year (0.80 kg/cap/day), corresponding to 0.78 MWh/tonne of MSW. World Bank (26) reported that 0.68 MWh of electricity can be recovered per tonne of incinerated waste. Amber et al. (27) estimated a WtE potential of 0.70 MWh/tonne MSW and Amoo et al. (20) reported a range of 0.75 - 1.59 MWh/tonne MSW for electricity generated via incineration and for the entire waste generated. Thus, the values reported in Table 4 agree with those reported in literature. However, it is unknown if the quantity of waste available is sufficient to power large WtE facilities that can connect to the national grid under a minimum regulatory electricity generation requirement. Assuming a minimum generation requirement of 50 MW is imposed, the results in Table 4 show that 33 states have sufficient generation capacity to connect to the grid at 0.53 kg/cap/day; but only 7 states can meet a higher minimum generation requirement of 100 MW. At projected waste generation rate (0.80 kg/cap/day), all the states, except the FCT, will meet the 50 MW requirement while 26 states can satisfy 100 MW minimum generation requirement. The states with the highest electricity generation potential are Kano, Lagos and Kaduna while Nasarawa, Bayelsa and FCT had the lowest potential.

Table 4: Electricity Generation Potential at MSW generation rate of 0.53 and 0.80 kg/cap/day

The MSW generation rates used in Table 4 are based on a nationwide average. However, generation capacities vary within and between countries, regions and cities, and between urban and rural communities. In Ogwueleka (28), MSW generation rates varied between 0.44 and 0.66 kg/cap/day in urban cities. Nnaji (29) showed that MSW generation rate can vary widely within and between states from 0.13 to 0.71 kg/cap/day. Some of the low waste generating states, according to Nnaji (29), include Oyo, Borno, Delta, Kaduna, and Kano State with values of 0.13, 0.25, 0.29, 0.30, and 0.31 kg/cap/day respectively, and such capacities are typical of rural communities. Rivers, Lagos and Ogun states generated high amount of waste with average waste generation capacities of 0.60, 0.63 and 0.66 kg/cap/day respectively, (29). These high waste generation states are within the estimated range of 0.6 - 1.0 kg/cap/day for low-income countries. The report on Oyo state was conflicting as it was regarded as both high- and low- waste generating state (29). The differences in waste generation capacities for different states are attributed to seasonal variations and economic activities including urbanisation and industrialisation that triggers the consumption of more goods and services, as well as socio-cultural factors. Urban communities are known to generate high amount of waste with non-organic fractions, while rural communities produce a high amount of organic waste, but a relative small quantity of inorganic waste (27). Hence, the use of a nationwide average of MSW generation rate for estimating the WtE potential in Nigeria is an ideal, which may be impracticable under current waste management realities.

The results also assume that all the waste generated at households and commercial properties reaches the MSW treatment facilities; however, there are several limiting factors hindering the successful transportation of waste in Nigeria. Some of the known factors include poor road conditions, waste management practices, vehicle maintenance, transportation networks and infrastructures (30-31). Open dumping of solid wastes in illegal sites and scavenging, an informal activity that involves the picking of waste streams for valuable items and for economic reasons are also well mentioned as frequent practices (28; 32). Studies by Ogwueleka (33) and Emelumadu et al. (34) have indicated that the collection efficiency in Nigeria is poor, at best 60% efficiency for established waste management agencies. Anestina et al. (35) reported a collection efficiency between 14% and 88% by private partnership operators for various frequency rates. Hoornweg et al. (23) estimated the collection efficiency of MSW in Nigeria to be about 41%. Thus, the reported tonnage of waste in landfills is only a fraction of the waste generated.

Additionally, there are indications that the average MSW generation per capita largely reported in literature are not true estimates. Nnaji (29) showed that there is a high disparity in the data reported for the average MSW generation rate, even for the same city and state in Nigeria. Two instances of under- and over-estimation of the average MSW generation rate were cited in Bauchi and Kano State. Lawal and Garba (15) predicted a value of 0.31 kg/cap/day in Bauchi state, while Audu et al. (36) predicted a value of 0.86 kg/cap/day for the same state. Bichi et al. (25) estimated a value of 0.30 kg/cap/day for Kano state while Oumarou (37) stated 0.81 kg/cap/day for the same city. There was no distinct correlation between the rate of generation of MSW and factors common among the cities evaluated. The disparities were attributed to scope and methodological differences, poor sampling and test designs, and low quality of data sources due to the use of semi-structured interviews and questionnaire to waste management agency workers and informal waste collectors with little or no data validation and quality checks. Thus, the true measure of waste generation capacities for different cities, states and for the country's overall is yet unknown. A point estimate of the WtE potential based on the reported waste generation capacities in literature or an underlying assumption that all the waste generated at household, and commercial levels reaches the landfill does not provide a realistic data set for the exploitable energy potential in Nigeria, which limits the use of these studies for practical scenarios. To this end, a state-level assessment of the exploitable electricity generation potential in Nigeria was carried out at varying MSW generation capacities (0.30-0.80 kg/cap/day) and collection efficiencies (30-80%), retaining incineration as the preferred choice of thermal treatment. The word 'exploitable' was used because the deductions were based on waste that was collected and utilised, not just the amount that is generated.

3.2. State-level Assessment of Exploitable Electricity Generation Potential

Figure 2 provides the contour plot of the exploitable electricity generation potential for each state in Nigeria, as a function of average waste collection efficiency (WCE) and generation rates. At MSW generation rate of 0.30 kg/cap/day and WCE of 30-50%, all the states had electricity generation potential of less than 50 MW and at 60-80% WCE, only two of the states (Kano and Lagos) had up to 50 MW. At high MSW generation rate of 0.80 kg/cap/day, 2-15 states had up to 50 MW at WCE of 30-50% but more than 26 states had 50 MW at WCE of 60-80%. Thus, the country's exploitable electricity generation potential from MSW is estimated to vary between 3768 - 26082 GWh/year, assuming a plant capacity factor of 80%. This means that MSW generation rate of $\geq$0.60 kg/cap/day and WCE $\geq$70% would be required for at least half of the states to own a WtE facility that can connect to the national grid. These results show that there is a wide variation in the exploitable electricity generation potential from MSW across the different states in Nigeria and from those presented in Section 3.1. There is therefore the need for proper feasibility assessment of waste generation rates within and between states before siting a WtE facility, because if a WtE facility is sited in a location without easy access to MSW, the facility may run at suboptimal capacity and this could have severe economic consequences. The contour plot in Figure 2 provides a broad range of exploitable WtE scales that can inform siting of WtE facilities for the different states. The plot can be used for identifying the minimum operating WCE that is required to achieve an intended WtE capacity. This can be applied after in-depth pre-feasibility study of the waste generation rates across seasons.

Figure 2: The annual exploitable WtE in Nigeria for different energy conversion technologies, WCE (30-80%) and MSW generation rates (0.30-0.80 kg/cap/day)

The energy recovered from MSW can be a major contribution to electricity supply in Nigeria. According to the Nigerian Electricity Supply Industry (38), the installed electricity generation from gas and hydro-electric power plants in Nigeria was 12522 MW in 2015, but the available capacity was 7141 MW due to maintenance and repair constraints. Insufficient gas and water supply, reduced transmission capacities and demand imbalances reduced the available capacity further to 3879 MW in 2015. Based on a report by the Nigerian Energy Support Programme (NESP, 2014), electricity demand was estimated as 8664 - 12800 MW in 2014, but predictions by various authors and projected growth rates suggest the increase in electricity demand to 28261 - 88698 MW by 2020. To meet current and projected energy demands, the Energy Commission of Nigeria expect the contributions from renewable energy sources to be 14970 MW (Solar), 47 MW, 12132 MW (large-hydro), 1660 MW (small-hydro) and 65 MW (dedicated biomass crops) with an indicative annual electricity consumption of 99590 GWh in 2025. The projected energy inputs from conventional energy sources for the same period are estimated as 120513 MW (gas), 14011 MW (coal) and 7199 MW (nuclear). Thus, comparing the exploitable electricity generation potential in Figure 2 to the electricity generation capacities and supply in Nigeria, it can be deduced that potential energy recovery from MSW via incineration amounts to 11 - 77% of the current operational capacity, and 6 - 42% of the available electricity generation capacity of the electricity supply industry. Considering exploitable electricity generation potential at MSW of 0.80 kg/cap/day at WCE of 30-80%, projected WtE potential can provide up to 10% of the projected renewable energy supply, 0.7 - 1.7% of the total projected energy supply in 2025, and meet 9.8 - 26.2% of the indicative energy consumption in 2025.

The cumulative energy potential from large-, small-, and micro- hydropower plants in Nigeria is estimated at 12220 MW (39), and 1900 MW of large hydropower is currently being exploited. More recently, Akuru et al. (40) estimated that the exploitable energy from hydropower stations will be 36000 GWh/year, which is one-third fraction of the value reported by Mohammed et al. (39). Seasonal variations, high investment costs, flooding, dam collapse and drought are listed as some of the drawbacks of hydropower in Nigeria (41). For solar energy, the country is well located just below the equator; hence solar energy is well distributed across the country. The energy potential is said to vary from 4 $kWh/m^2/day$ in the southern states to 6.5 $kWh/m^2/day$ in the northern states (NESP, 2014), but large-scale generation is yet to be implemented. Regarding wind energy, the energy potential in Nigeria is estimated at 50046 MWh/year at medium generation capacity of 5 $MW/km^{2,}$ 25 m height and 30% capacity factor across 22 selected states (42), although Mohammed et al. (39) reported a higher range of 120-790 MW at mean wind speed of 1.6-4.4 m/s and height of 10-25 m. Brimmo et al. (43) reported higher wind speeds of up to 7.8 m/s in Kano and Katsina states in Northern Nigeria. The estimated energy potentials are however not indicative of large-scale national projects. The contributions from 10 major agricultural crop residues is estimated to be 1958 PJ/year (44), with no further indication on their energy conversion. As such, the energy from MSW can be a significant contribution to Nigeria's energy supply.

A comparison of the results in this study with other African countries as provided by Scarlat et al. (45) shows that Nigeria ranks with South Africa and Egypt as one of the countries with the highest WtE potential based on waste generation rates. The total energy potential for African countries was estimated as 1125 PJ/year (incineration) and 182 PJ/year (landfill) in 2012 and projected to be 2199 PJ/year (incineration) and 530 PJ/year (landfill) in 2025. Nigeria was estimated to have a WtE potential of 157 PJ/year at 30% electricity conversion efficiency, corresponding to 43611 GWh in 2012. This value can account for ~14% of Africa's WtE potential and is similar to those reported in this study. Based on the waste collected, the total energy potential for Africa was deduced as 612 PJ/year (incineration) and 323 PJ/year (landfill) in Scarlat et al. (45), implying an average WCE of 54.5% for Africa. The WtE potential for Nigeria was estimated as 65 PJ/year, corresponding to 18055 GWh/year, based on MSW generation rate of 0.53 kg/cap/day and 40% WCE. This low WtE potential ranks Nigeria with Sudan, Congo and Cameroon, values that are within the range reported in this study. Further comparison with other countries is not straightforward, due to differences in macroeconomic variables. For instance, Ouda et al. (46) investigated WtE potential for three main cities in Saudi Arabia and stated that the electricity potential via incineration was 671 MW at MSW recovery rate of 1.4 kg/cap/day. In Malaysia, an upper middle income country with an average MSW rate of 0.80 kg/cap/day, it was estimated that 2400 GWh of electricity could have been produced from waste in 2014, if appropriate technology were employed, and this is projected to increase to 2650 GWh by 2020 (47). Islam (48) showed that in Dhaka and Chittagong cities of Bangladesh, an estimated amount of 1444 and 1394 GWh of electricity can be produced via incineration by 2050, due to increase in waste generation trend. There is however no clear basis for comparison, due to varying population, level of industrialisation and socio-economic activities.

3.2.1. Choice of Waste Conversion Technology

There are proven conventional combustion systems, as well as new and emerging technologies that could be used for treating MSW thermally with options for energy recovery. The conventional systems include grate-fired incineration, fluidized bed incineration, modular two-stage incineration and batch waste combustion systems (49-50). The grate-fired incineration requires minimal pre-processing of waste and allows the treatment of waste *en masse*, thus referred as mass burn facilities. Typical grate-fired incineration involves the discharge of waste directly from the consumer into a pit or bunker at the waste site, subsequent transfer of waste via an overhead crane into a feed hopper and then a final transfer to a moving grate, where combustion process is initiated (51). Reactions include the initial reduction of moisture, degassing, primary oxidation of readily combustible elements under limited oxygen conditions and subsequent combustion of fixed carbon, to yield product gas (mainly composed of carbon dioxide), heat and inert ash. Energy could be recovered as heat or electricity and efficiencies of such systems are in the range of 14-27% (electricity), and up to 60% (heat plus electricity), while their capacities range from 40 - 400 MT per year, depending on fuel characteristics (26). The fluidized systems are similar to mass burn incineration; however, requires pre-processing such as sorting, shredding, and separation of materials. Thus, homogenous fuel is required to be fed into the combustor chamber, a bed of inert material on a grate with inflow of oxidant. The batch waste incinerator processes smaller amount of waste, at most 3 tonnes per batch and are not typically used for energy recovery, except retrofitted for this purpose. The advance thermal treatment facilities include pyrolysis and gasification technologies. These systems are less proven on a commercial scale, less adaptable to heterogeneous and fluctuating waste streams and employs more complex processes and controls than the incineration systems (53-54).

This study has demonstrated the use of mass burn incineration as the most applicable WtE facility for the waste management landscape in Nigeria, as it requires minimal waste pre-treatment requirement such as waste prevention, re-use, recycling and composting. It is also a proven technology and allows the combustion of the MSW (as received basis) at temperatures above 800^{o}C and under excess air conditions and can be operated with or without heat recovery (26); hence enabling a modular operation for countries with less maintenance capabilities. They are also preferred in countries with large quantities of waste as it ensures the reduction of 75-90% of the MSW (55). The disadvantage of this technology; however, includes low overall efficiency compared to recent technologies such as pyrolysis, gasification with plant efficiency >40% for electricity generation and combined heat and power (CHP) plant that can ensure 66-78% efficiency (56). Because of the high temperatures reached in incinerating plants which is >800^{o}C, dioxins and other toxic emissions can be produced (57); hence, flue gas treatment is a major requirement to ensure environmental standards. The ash that is also produced requires a safe form of disposal in landfills so it does not ensure 100% conversion of the fuel. More so, if waste segregation becomes properly established in the country, the use of alternative technologies such as anaerobic digestion could replace incineration, since waste composition in developing countries is largely organic (58). The most striking disadvantage, particularly for developing countries is the high cost of maintenance, repair, and technical expertise required for this technology. These disadvantages are however not out of place when compared to other recent technologies such as gasification, pyrolysis and various modifications that are complex designs and requires high level of technical operation and the use of homogenised, pre-treated form of waste such as shredding, drying to an acceptable limit and thorough mixing of the MSW. More so, the deployment of CHP plant will require the establishment of heat utilising industries. Thus, mass burn incineration is proposed for early development of WtE facilities in Nigeria, particularly for states with low WCE and recycling priorities. This recommendation does not undermine the importance and prospects of modern technologies.

The exploitable electricity generation potential for various energy conversion technologies are presented in Figure 3 as contour plots as a function of MSW generation rates and WCE. This is to highlight the opportunities with modern technologies such as gasification, pyrolysis and CHP, that have higher net plant efficiencies, > 40%. While the annual exploitable WtE of the country was within the range of 3769 - 26082 GWh/year for incineration based technologies (net plant efficiencies of 26%), Figure 3 shows that these values can range from 6378 - 44138 GWh/year, at net plant efficiency of 44% and 9422 - 65204 GWh/ year at net plant efficiency of 65%. This range of values corresponds to WCE of 30-80% and MSW generation rates of 0.30-0.80 kg/cap/day.

Figure 3: The exploitable WtE in Nigeria for technologies with net plant efficiency of 17-67% at varying WCE (30-80%) and MSW generation rates (0.30-0.80 kg/cap/day)

The contour plots in Figure 3 can be used for ascertaining the minimum operating WCE that is required nationally to obtain a given band of exploitable WtE and for technologies with net plant efficiency (NPE) of 17-67%. These plots indicate the limit at which increasing WCE does not correspond to an increasing power output for WtE facilities. For instance, at MSW generation rate of <0.40 kg/cap/day, WtE facilities cannot generate more than 20000 GWh/year of electricity using plants with NPE of 40% or less, even if WCE is increased to 80%. At MSW generation rate of <0.5 kg/cap/day, modern WtE facilities can be employed to generate more than 20000 GWh/year provided minimum NPE of ~33% is met at WCE of 80%. At 0.60 kg/cap/day, 50% WCE can be maintained with a technology such as gasification, otherwise, plants with higher NPEs must be employed at low WCEs (<50%). Assuming a dedicated CHP is in use with 65% NPE, the exploitable WtE can exceed 20000 GWh/year using the following options: 0.30 kg/cap/day at 63% WCE, 0.40 kg/cap/day at 50% WCE, 0.50 kg/cap/day at 40% WCE, 0.60 kg/cap/day at WCE of 32%. Figure 3 therefore provides a view of exploitable WtE scales for various waste conversion technologies with net plant efficiencies of 17-67%, and WCE of 30 - 80% and highlights the minimum requirements that are needed to achieve a target WtE potential. These results emphasise the need for national feasibility studies and strategic siting of WtE facilities in Nigeria. It is clearly shown in this study that Lagos and Kano have sufficient capacities, even at poor WCE of 30% and waste generation rates of 0.30 kg/cap/day, which position the states for early development of WtE facilities in Nigeria. Other states will require to improve their waste collection efficiency, explore highly efficient waste conversion technologies, merge supplies from surrounding cities or consider multiple forms of renewable energy sources for large scale power generation. At current low waste collection efficiency in Nigeria, which is not clearly measured for individual states, a minimum regulatory electricity generation requirement of up to 50MW can hinder the development of WtE projects. On-site power generation such as dedicated power station for industrial estates and corporate users can be a feasible form of distributing energy generated from WtE facilities.

We therefore propose the following recommendations to maximise the Nigeria's waste-to-energy potential. Firstly, considering the disconnect between policy-makers and stakeholders in solid waste management, there is need for adequate reference and structure for the deployment of WtE projects in Nigeria. We recommend appropriate legal, policy, regulatory, and institutional framework to promote newer and more sustainable energy recovery options from wastes. Secondly, there are opportunities to be explored between the formal and informal sectors within and between the states via strategic partnership to promote a sustainable waste management system and to secure sufficient quantities of waste. Waste management policies that incorporate waste pickers and scavengers can create jobs, reduce environmental damage caused by growing use of disposable goods, and reduce fiscal costs of landfill operations (62). There could be inherent challenges in the cooperation and future competition between MSW firms and waste pickers in the states studied. Evidence from a waste management operator, WestAfricaENRG, which recently acquired the largest landfills in Lagos, indicated some initial operational difficulties and lack of cooperation from scavengers. The informal waste pickers can be organised in cooperative societies and engage directly with government and private sector. The partnership between the key stakeholders will help to organise integration of scavengers and waste pickers in a positive way into the formal sector, and enhance the recycling, recovery and transfer process of waste. This approach is beneficial as it helps the waste pickers can earn higher incomes (63), increase contribution to energy recovery and increase firms' profits by excluding the agent's role in the transfer process (64). Studies in Jordan have alluded to the fact that scavengers have an important role in the informal MSW sector, and are willing to involve municipals, private companies and NGOs to cooperate in strategic planning for MSW (64). Thirdly, Public-Private Partnership (PPP) is suggested to create an enabling environment for service delivery within and between states. Public-Private Partnership is employed in several countries across all levels of the waste chain (65-66). Unlike public dominated waste management systems, PPP can attract investment from the private sector which reduces the operational and construction costs (67-68). The establishment of PPPs will however require defined clear boundaries of operation and roles to prevent institutional borderline problems, overlap of duties and to eliminate voids. Fourthly, lack of quality nation-wide data is a major hindrance to reliable projections. We recommend a nation-wide assessment and open access database and repository of waste composition, characteristics, generation rates, collection, disposal and transportation route and distances across seasons, with independent data quality checks and validation for reliable environmental, cost, socioeconomic life cycle assessments and projections. Collaboration between universities, industry and government for capacity building, collaborative research and knowledge exchange initiatives will be helpful in developing a solid waste masterplan based on reliable feasibility studies. Lastly, due to the perceived concerns on emissions from WtE facilities, there will be need for stringent emission standards and safe disposal of the incineration residues under independent audit and monitoring to ensure environmental protection and assure residents of their safety. Information on the WtE facilities should be open to the public and operators should engage with relevant stakeholders through public hearings and public education on the use of these technologies, so as to prevent adverse environmental campaigns. Optimised road networks, transportation routes, and local appropriate equipment and tools, as well as effective training of waste management workers, public education will be needed to improve collection efficiency nation-wide and to reduce environmental impacts. Further work is required to examine the environmental and economic implications of waste-to-energy projects in Nigeria, particularly from a life cycle perspective to highlight the opportunities from averted waste dump and challenges presented by energy recovery from MSW. This study has considered mass burn incineration for early development of WtE facilities in Nigeria, but not considered the impact of competing technologies on fuel availability or increased technology advancement on plant operation; this will be necessary in the future.

3.3. Sensitivity Analysis

The analysis in section 3.1-3.2 have considered the treatment of 1200 tonnes of MSW/day, and fuel with fixed composition and calorific value, but MSW may vary in composition across seasons, over time and for different locations. Igoni et al. (59) reported a range of 0.8–7.0 wt.% as received basis (arb) for the ash content in MSW obtained from urban cities in Nigeria. Eboh et al. (60) showed that these values can vary as much as 0.04–39.82 wt.% on the dry basis (db). A range of moisture content of 7.8 - 65.2 wt.% arb is cited for MSW from developing countries in Igoni et al. (59) and Mohee et al. (61). All these varying qualities in fuel composition can impact the fuel's calorific value and reduced or increased quantities of waste can affect net plant efficiency. Thus, to establish the influence of varying waste quantities and qualities on plant performance, sensitivity analysis was conducted with fuels of varying waste quantities, moisture levels and organic matter-to-ash content.

Figure 4: Radar chart of the sensitivity analysis: a) waste quantities (tonnes/day), b) moisture content (wt.% as received basis), c) volatile matter-to-ash ratio

Figure 4a shows that a decrease in waste quantity by 5-10 tonnes/hour, corresponding to 960-1080 tonnes/day in this study can increase net plant efficiency by 1.5-1.7% while a similar increase in waste quantity, corresponding to 1320-1440 tonnes/day can cause a 4-7% reduction in the net efficiency of the WtE facility. The decline in net plant efficiency at increased fuel quantities is attributed to poor conversion rate with respect to fuel input rate. Typically, WtE facilities are designed with capacity limits and operational constraints to preserve the life of engine components and quality of steam recovered. As such, there is a limit to the amount of fuel that can be consumed and consequently, the amount of waste that can be treated for a given configuration to achieve the limits imposed e.g. exhaust gas temperature.

Figure 4b shows that the removal of moisture from MSW can increase net plant efficiency. At 0 wt.% arb, the NPE improved by 33% with respect to the baseline fuel scenario, and at 20 wt.% arb, the NPE improved by 22%. The results imply that a 10% reduction in the moisture content of the MSW can improve net plant efficiency of the WtE facility by 4-7%. High moisture levels in waste streams is limiting for energy recovery because the energy that could be derived from the fuel is significantly reduced, which might only be sufficient for part-drying the incoming waste streams. This is particularly important for mass burn incineration, where there is no pre-treatment of the waste.

Figure 4c shows that the changes in net efficiency of the WtE facility varied from 1-4% due to varying ratio of organic matter-to-ash content. A change in composition that reduces the organic matter-to-ash ratio of the MSW to 4:1, indicated as volatile matter (80 wt.% db) and ash content (20 wt.% db) in this study, will cause a reduction in NPE by 4%, while an increase in this ratio to 19:1, corresponding to volatile matter content of 95 wt.% db and ash content of 5 wt.% db, can bring about an increase of 3% in NPE. These changes are caused by the effect of fuel composition on fuel calorific value. Figure 5 shows that moisture can significantly reduce the energy content of fuel. Here, the LHV of the MSW is 27.18 MJ/kg at moisture levels of 0 wt.% arb, but 6.68 MJ/kg at moisture levels of 50 wt.% arb. At ash content of 21 wt.% db, the LHV of the MSW is 6.09 MJ/kg and 7.14 MJ/kg at ash content of 3 wt.% db. It is therefore crucial that the waste targeted for waste-to-energy is in sufficient, not excess quantities and of good combustible quality. To minimise loss in plant performance and ascertain the sustainability of WtE facilities, World Bank (26) recommends that waste supply should not be less than 50,000 tonnes annually, equivalent to 137 tonnes/day and waste variations should not be more than 20% at any given time for incineration. The same report recommends that the average fuel lower calorific value should be at least 6 MJ/kg. The composition using a tenner diagram is suggested to contain less than moisture 50%, ash content less than 60% and carbon content that is above 25%.

Figure 5: Influence of fuel composition on Lower Heating Value of MSW a) moisture content (wt.% arb), b) volatile matter-to-ash

4. Conclusions

This study conducted a state-level assessment the available WtE potential in Nigeria at various MSW generation rates, collection efficiencies and energy conversion technologies. The study showed that the electricity generation energy potential for the different states in Nigeria can vary from 31 - 205 MW at waste generation capacity of 0.53 kg/cap/day, assuming incineration with energy recovery as the preferred choice of thermal treatment. This sums up the country's annual electricity generation potential from MSW to be 26744 GWh/year, and could be as low as 3768 GWh/year at poor waste generation capacity of 0.30 kg/cap/day and collection efficiency of 30%. To this end, we showed that a MSW generation rate of ≥0.60 kg/cap/day and WCE ≥70% would be required for at least half of the states to own a WtE facility that can connect to the national grid, under a minimum electricity generation requirement of 50 MW. The wide variations in the exploitable electricity generation potential across the different states in Nigeria therefore shows the need for proper feasibility assessment of waste generation rates within and between states before siting a WtE facility, to ensure economic viability. The WtE maps in this study can inform the siting of WtE facilities in Nigeria as it shows the minimum operating WCE for an intended WtE capacity and for various energy technologies using net plant efficiencies. This is of high importance for the current waste management practices in Nigeria, where there is little information on the true measures of waste generation capacities for different states, and the whole country. Waste quantities and qualities can play a significant role in plant's energy recovery; hence sensitivity analysis showed their impact on net plant efficiency. The successful establishment and operation of WtE facilities for MSW in Nigeria will require enabling policies and regulations, as well as supportive legal and institutional framework. At low waste collection efficiency, minimum regulatory generation requirement can hinder development of WtE projects due to insufficient waste capacities across the states.

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STATE-LEVEL ASSESSMENT OF THE WASTE-TO-ENERGY POTENTIAL (VIA INCINERATION) OF MUNICIPAL SOLID WASTES IN NIGERIA

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Abstract

The quest for reliable and adequate power supply in Nigeria has brought about a surge of interest in renewable energy generation, particularly from wind, solar, hydro and biomass resources including municipal solid waste. Waste-derived energy raises unique interest because of the magnitude of benefits to environmental protection and socio-economic advancement. The successful operation of Waste-to Energy (WtE) facilities in Nigeria requires continuous supply of solid waste and enabling environment amongst other factors. This study conducted a state-level assessment of the WtE potential of municipal solid waste (MSW) in Nigeria. Our findings show that the electricity generation potential for the different states in Nigeria varied from 31 – 205 MW, depending on state's waste generation capacity. The country's annual electricity generation potential from MSW was estimated to be 26744 GWh/year, with 89% of the states having sufficient generation capacity at minimum regulatory electricity generation requirement of 50 MW. But, based on current realities such as poor collection efficiencies, Nigeria's exploitable WtE capacity from MSW was below 3800 GWh/year, with all the states having less than 50 MW capacity. On-site power generation such as dedicated power station for industrial estates and corporate users can be a feasible form of distributing energy generated from WtE facilities. The outcomes of this study are important in informing the siting of WtE facilities in Nigeria and for enabling policy framework.

Keywords: Renewable Energy, Solid Waste Master Plan, Waste Energy Recovery, Sustainable Policy Development, Incineration, Biomass

1. INTRODUCTION

Energy plays an important role in meeting the needs of residential, industrial, transport, agricultural and other sectors in an economy. Sub-Sahara Africa (SSA)'s economic growth projected at 4.2% GDP (1) qualifies the sub-region as the new frontier of growth. However, this growth could be impeded by electricity shortages (2). The power generation capacity in the entire SSA compares to Spain's 68 GW, and the average price of power in SSA is high compared to international standards (3). Demand for energy is greater than supply in SSA and this is compounded by rapid population growth and increase in the urban population density. There is low kilowatt-hour (kWh) electric power consumption in SSA. For example, the electric power consumption in Nigeria in 2012 was reported as 156 kWh per capita (4). This value is comparably low to the electric power consumption in other developing countries such as Malaysia, South Africa and Venezuela, which consumed 4114, 4405 and 3413 kWh per capita respectively. The increasing energy demand, insufficient supply of electricity, and quest for reliable and adequate power supply in Nigeria have therefore necessitated a surge of interest in alternative energy sources, particularly from solid waste.

Municipal Solid Waste (MSW) is of unique interest because of the benefits to environmental protection and socio-economic advancement. These resources are readily available in Nigeria, however, illegally dumped in open spaces and poorly managed with enormous environmental consequences. MSW, also referred to as trash or garbage, is a mix of everyday items from local residences, businesses, commercial properties and public institutions including schools and hospitals (5). It consists of degradable materials such as cardboard, paper, food scraps, newspapers, and other combustible elements. MSW also contains non-biomass derived materials such as plastics, glass, metals, appliances and batteries. Hence, the averted dump of such materials in the environment and subsequent use for heat and/or electricity, is considered renewable and the process of recovering energy from waste is referred to as Waste-to-Energy (WtE).

Waste-to-Energy includes processes such as incineration, gasification, pyrolysis that thermally treat solid waste and directly recover energy in the form of electricity and/or heat. It also includes bio-chemical processes such as landfill gas recovery, anaerobic digestion that converts the chemical energy in solid waste to yield products of high energy value e.g. methane. Thermal treatment methods with energy recovery options are widely preferred because of the possibilities to substantially reduce the quantities of waste, opportunities to recover minerals and chemicals and destroy contaminants (6), potential of directly converting the waste to an energy source, which reduces the time of treatment, as well as the potential to treat toxic materials and control emissions from point source. Their use is expected to improve the quality of life as it can minimise the adverse dumping of waste, consequently preventing environmental pollution and land degradation; minimise fossil fuel consumption and greenhouse gas emissions, offset methane that could be released from open landfills, prevent adverse health impacts from exposed burning of waste, and prevent the spread of infectious diseases via parasitic agents (7-9).

Waste-to-Energy can play a significant role in the changing energy climate in Nigeria, particularly as a renewable energy resource, as this is increasingly becoming important. By the year 2025, renewable energy is expected to account for 10% of the total energy demand projection and particularly for remote and off-grid power generation (10). As part of the strategic objectives of the National Renewable Energy and Energy Efficiency Policy (NREEEP), a legislative framework that aims at increasing the power generation capacities and the share of renewable energy sources in Nigeria, pilot projects of biomass energy conversion systems are proposed for development (11). These include the waste-to-energy plant that is proposed for Ikorodu Industrial Estate and surrounding areas in Lagos State and the 12 MW gasification facility in Imo State (12). Since Nigeria is a signatory to the Paris Agreement on Climate Change mitigation in 2015, these projects are intended to contribute to clean development mechanisms (CDMs) for the reduction of indoor and outdoor pollution, and to mitigate the effect of greenhouse gas emissions on climate change. The sustainability of such projects however, requires sufficient quantity and quality of solid waste, the right choice and scale of energy conversion technology, minimum investment risk and optimum financial returns, and a supportive legal framework. The power industry in Nigeria is replete with low planning tendencies, improper estimations and insufficient capacities such as the installation of industrial gas turbine power plants across the country without proper planning of fuel delivery (13). There is also the challenge of transmission and distribution of generated electricity to the end-consumer with cost recovery. As such, there are on-going discussions on how biomass power plants can connect to the transmission networks of the national grid and the potential for a minimum generation requirement for large power plants to ensure and improve grid stability. Communities with multiple biomass power plants under competing conditions for MSW would require a certainty of continuous supply of waste resources across seasons, space and time; hence, the need to assess the WtE potential at state-level and across Nigeria.

Certain studies have carried out a community-level assessment of the WtE potential that could be derived from MSW for selected states in Nigeria including Lagos (14), Bauchi (15), Ogun (16) and Taraba (17). McIlveen-Wright et al. (18) quantified the waste tonnage and components of a typical landfill site in Lagos State. They calculated the electricity potential using fuel's caloric value, moisture content and inert content. The authors further analysed the economic feasibility of a 50 MW Energy from waste coal power plant, assuming a tipping fee of £50/tonne of waste and supported by other environmental and waste management options such as recycling and composting. Udoakah and Akpan (19) estimated the electric potential from MSW using a proposed incineration plant in Southern Nigeria. Furthermore, Amoo et al. (20) carried out a techno-economic assessment for seven states in Nigeria under different energy technologies along with estimation of the electrical power and thermal energy potential generated per kg of MSW. Despite the previous work on WtE in Nigeria, none of them have conducted a holistic assessment of the WtE capacity in the entire country, considering factors such as waste quality, quantities and energy conversion technologies. There is no information in the literature whether there are sufficient waste quantities across the country to inform the siting of future WtE facilities, especially under minimum electricity generation requirement.

This study therefore presents a state-level assessment of the WtE potential in Nigeria. The outcomes are compared to the exploitable WtE for the different states at various MSW generation rates and collection efficiencies, and considering a minimum electricity generation requirement of 50-100 MW for connecting to the national grid. The overall exploitable WtE of the country are presented in broad scales for different waste conversion technologies using net plant efficiencies, MSW generation rates and waste collection efficiencies. Sensitivity analysis was conducted using various waste quantities and fuel composition to highlight the influence of these parameters on net plant efficiency. The study concludes by proposing ways to enhance the deployment of WtE facilities in Nigeria, as this can inform the development of appropriate policy framework.

2. METHODS

The study exploited the MSW generation capacities of the 36 states in Nigeria and the Federal Capital Territory (FCT), according to population size. The average population size as reported by the National Population Commission for all the states in Nigeria and the FCT (21) was adjusted for the period of 2007-2013 using the population growth rate factors in Table 1 and assuming the same growth rate factor for year 2014-2015, as year 2013. The growth rate factors were calculated from the World Development Indicators (22) for birth and death rates using Eqn. 1. These were expressed as percentage per year and used to determine the state and country's mean population at study year 2015.

Table 1: Growth Rate Factors and Adjusted Population Size/Year

Growth Rate Factor, GRF (%/year) = [(birth rate– death rate), crude (per 1,000 people)]/1000 (Eqn. 1)

Mean Population (μ) = μ_0 (1 + GRF) (Eqn. 2)

A state level assessment of the exploitable WtE in Nigeria was carried out at different MSW generation capacities rates of 0.30-0.80 kg/cap/day and waste collection efficiencies of 30-80%, assuming incineration as the preferred thermal treatment technology for the MSW.

2.1. Model description

The waste conversion and energy recovery processes were simulated in Aspen Plus® environment, as depicted in Figure 1 using a non-stoichiometric thermodynamic equilibrium model that minimises the Gibbs free energy in the system.

Figure 1: Schematic flow diagram of the waste conversion and energy recovery processes of the MSW

The main processes include the combustion of the MSW in a conventional incinerator, exhaust gas clean up, heat recovery via a heat recovery steam generator (HRSG) and electricity generation with a steam turbine. Figure 1 models the introduction of the moist MSW into a DRIER that is coupled to a flash separator (DRY-FLASH) to remove the moisture from the biomass stream. The MSW was defined as a non-conventional stream using proximate and ultimate compositions as well as the lower heating value (LHV) of the fuel. The exit fuel (dry MSW) was introduced into a yield-based reactor (DECOMPSR) where the fuel is broken down to its elemental constituents. The heat produced from the decomposed fuel and the elemental constituents of the dry fuel were introduced into a RGIBBS reactor (PRI-COMB). This reactor minimizes the Gibbs free energy at defined temperature and pressure under constraints of elemental balance, without requirements for reactor design and reaction stoichiometry, that is typically a balance between the amounts of reactants and products. Air stream was introduced into the PRI-COMB block at standard temperature and pressure to maintain combustion and this was defined in Aspen Plus® as a conventional mixed stream.

The combustion gas products that exit the PRI-COMB were separated into solids and gas streams using a SSPLIT block (SEPARATR). The heat from the gas stream was recovered through the HRSG block that is connected to a steam boiler. The steam generated from the boiler flowed to the steam turbine where work was produced while the residual heat in the exhaust gas was removed via heat exchange in the block (CONDNSR). The cooling water required for heat exchange from the hot flue gases and to produce steam was supplied by a PUMP block. The air supply rate and cooling water flow rate were calculated using calculator and design spec blocks. A steady state simulation was achieved, assuming ideal gas behaviour for all gases including air (21 vol. % oxygen and 79 vol. % nitrogen). The boiler, steam and overall efficiencies, and the exploitable WtE were derived using Eqn. 3-6. This Exploitable WtE is all denoted as MW, that is MWh per hour of operating the plant, except otherwise stated.

$$\eta_{Boiler} = {Q_{Boiler}} \big/ {HHV_{Biomass} \text{ x Fuel Burn Rate}} \qquad \text{Eqn. 3}$$

$$\eta_{themal} = {W_{Turbine} - W_{Pump}} \Big/ {Q_{Boiler}} \qquad \text{Eqn. 4}$$

$$\eta_{overall} = \eta_{themal} \text{ x } \eta_{Boiler} \qquad \text{Eqn. 5}$$

$$\text{Exploitable WtE (MW)} = (W_{Turbine} - W_{Pump}).\ \eta_{wce} \qquad \text{Eqn. 6}$$

where η_{Boiler} - efficiency of the boiler (%); Q_{Boiler} - heat recovered from the flue gas (MJ/s); $HHV_{Biomass}$ - higher heating value of the biomass (MJ/kg); $W_{Turbine}$ - work output of the turbine (MW); W_{Pump} - work done by the pump (MW); $\eta_{overall}$ - overall thermal efficiency (%); η_{themal} - thermal efficiency of the heat recovery section (%); η_{wce}- waste collection efficiency (%).

The input parameters as listed in Aspen Plus® environment are listed in Table 2 while the ultimate and proximate compositions of the MSW as inputted in the model are listed in Table 3.

Table 2: Input Parameters in Aspen Plus® for the Base-case Scenario

Table 3: The ultimate and proximate compositions of a typical MSW in Nigeria (Amber et al. 2012)

The average amount of waste generated at the state level was deduced from the average MSW generation capacities and the adjusted population size using Eqn. 7.

Tonnage/day = [state mean population x average MSW generation rate (kg/cap/day)]/1000 Eqn. 7

The analysis considered waste treatment rate of 50 tonnes per hour, equivalent to 1200 tonnes per day and obtained net plant efficiency of 26%, a value that is within the range of 17-27% (20-21). This analysis presents a point estimate performance of the WtE facility based on the defined boundaries in this study. Other energy conversion technologies are considered using varying net plant efficiencies in the range of 17-67%. To account for fuel variabilities, sensitivity analysis was conducted with wastes of varying composition and quantities and the results are presented in Section 3.3.

3. RESULTS & DISCUSSION

3.1. State-level Assessment of Electricity Generation Potential from MSW in Nigeria

Nigeria is classified as a low-income country with average MSW generation rate of 0.49-0.56 kg MSW/cap/day (23-25). The country is however projected to produce about 100,000 tonnes of MSW/day at urban waste generation rate of 0.80 kg MSW/cap/day (23) by 2025. As such, Table 4 shows that the electricity generation potential per hour of operating the WtE incineration facilities in different states in Nigeria can vary from 31 - 205 MW at 0.53 kg/cap/day. At projected MSW generation rate of 0.80 kg/cap/day, the electricity generation potential for the individual states can vary from 47 - 312 MW. These results sum up the country's electricity generation potential to be 26744 GWh/year (0.53 kg/cap/day) and 40753 GWh/year (0.80 kg/cap/day), corresponding to 0.78 MWh/tonne of MSW. World Bank (26) reported that 0.68 MWh of electricity can be recovered per tonne of incinerated waste. Amber et al. (27) estimated a WtE potential of 0.70 MWh/tonne MSW and Amoo et al. (20) reported a range of 0.75 - 1.59 MWh/tonne MSW for electricity generated via incineration and for the entire waste generated. Thus, the values reported in Table 4 agree with those reported in literature. However, it is unknown if the quantity of waste available is sufficient to power large WtE facilities that can connect to the national grid under a minimum regulatory electricity generation requirement. Assuming a minimum generation requirement of 50 MW is imposed, the results in Table 4 show that 33 states have sufficient generation capacity to connect to the grid at 0.53 kg/cap/day; but only 7 states can meet a higher minimum generation requirement of 100 MW. At projected waste generation rate (0.80 kg/cap/day), all the states, except the FCT, will meet the 50 MW requirement while 26 states can satisfy 100 MW minimum generation requirement. The states with the highest electricity generation potential are Kano, Lagos and Kaduna while Nasarawa, Bayelsa and FCT had the lowest potential.

Table 4: Electricity Generation Potential at MSW generation rate of 0.53 and 0.80 kg/cap/day

The MSW generation rates used in Table 4 are based on a nationwide average. However, generation capacities vary within and between countries, regions and cities, and between urban and rural communities. In Ogwueleka (28), MSW generation rates varied between 0.44 and 0.66 kg/cap/day in urban cities. Nnaji (29) showed that MSW generation rate can vary widely within and between states from 0.13 to 0.71 kg/cap/day. Some of the low waste generating states, according to Nnaji (29), include Oyo, Borno, Delta, Kaduna, and Kano State with values of 0.13, 0.25, 0.29, 0.30, and 0.31 kg/cap/day respectively, and such capacities are typical of rural communities. Rivers, Lagos and Ogun states generated high amount of waste with average waste generation capacities of 0.60, 0.63 and 0.66 kg/cap/day respectively, (29). These high waste generation states are within the estimated range of 0.6 - 1.0 kg/cap/day for low-income countries. The report on Oyo state was conflicting as it was regarded as both high- and low- waste generating state (29). The differences in waste generation capacities for different states are attributed to seasonal variations and economic activities including urbanisation and industrialisation that triggers the consumption of more goods and services, as well as socio-cultural factors. Urban communities are known to generate high amount of waste with non-organic fractions, while rural communities produce a high amount of organic waste, but a relative small quantity of inorganic waste (27). Hence, the use of a nationwide average of MSW generation rate for estimating the WtE potential in Nigeria is an ideal, which may be impracticable under current waste management realities.

The results also assume that all the waste generated at households and commercial properties reaches the MSW treatment facilities; however, there are several limiting factors hindering the successful transportation of waste in Nigeria. Some of the known factors include poor road conditions, waste management practices, vehicle maintenance, transportation networks and infrastructures (30-31). Open dumping of solid wastes in illegal sites and scavenging, an informal activity that involves the picking of waste streams for valuable items and for economic reasons are also well mentioned as frequent practices (28; 32). Studies by Ogwueleka (33) and Emelumadu et al. (34) have indicated that the collection efficiency in Nigeria is poor, at best 60% efficiency for established waste management agencies. Anestina et al. (35) reported a collection efficiency between 14% and 88% by private partnership operators for various frequency rates. Hoornweg et al. (23) estimated the collection efficiency of MSW in Nigeria to be about 41%. Thus, the reported tonnage of waste in landfills is only a fraction of the waste generated.

Additionally, there are indications that the average MSW generation per capita largely reported in literature are not true estimates. Nnaji (29) showed that there is a high disparity in the data reported for the average MSW generation rate, even for the same city and state in Nigeria. Two instances of under- and over-estimation of the average MSW generation rate were cited in Bauchi and Kano State. Lawal and Garba (15) predicted a value of 0.31 kg/cap/day in Bauchi state, while Audu et al. (36) predicted a value of 0.86 kg/cap/day for the same state. Bichi et al. (25) estimated a value of 0.30 kg/cap/day for Kano state while Oumarou (37) stated 0.81 kg/cap/day for the same city. There was no distinct correlation between the rate of generation of MSW and factors common among the cities evaluated. The disparities were attributed to scope and methodological differences, poor sampling and test designs, and low quality of data sources due to the use of semi-structured interviews and questionnaire to waste management agency workers and informal waste collectors with little or no data validation and quality checks. Thus, the true measure of waste generation capacities for different cities, states and for the country's overall is yet unknown. A point estimate of the WtE potential based on the reported waste generation capacities in literature or an underlying assumption that all the waste generated at household, and commercial levels reaches the landfill does not provide a realistic data set for the exploitable energy potential in Nigeria, which limits the use of these studies for practical scenarios. To this end, a state-level assessment of the exploitable electricity generation potential in Nigeria was carried out at varying MSW generation capacities (0.30-0.80 kg/cap/day) and collection efficiencies (30-80%), retaining incineration as the preferred choice of thermal treatment. The word 'exploitable' was used because the deductions were based on waste that was collected and utilised, not just the amount that is generated.

3.2. State-level Assessment of Exploitable Electricity Generation Potential

Figure 2 provides the contour plot of the exploitable electricity generation potential for each state in Nigeria, as a function of average waste collection efficiency (WCE) and generation rates. At MSW generation rate of 0.30 kg/cap/day and WCE of 30-50%, all the states had electricity generation potential of less than 50 MW and at 60-80% WCE, only two of the states (Kano and Lagos) had up to 50 MW. At high MSW generation rate of 0.80 kg/cap/day, 2-15 states had up to 50 MW at WCE of 30-50% but more than 26 states had 50 MW at WCE of 60-80%. Thus, the country's exploitable electricity generation potential from MSW is estimated to vary between 3768 - 26082 GWh/year, assuming a plant capacity factor of 80%. This means that MSW generation rate of $\geq$0.60 kg/cap/day and WCE $\geq$70% would be required for at least half of the states to own a WtE facility that can connect to the national grid. These results show that there is a wide variation in the exploitable electricity generation potential from MSW across the different states in Nigeria and from those presented in Section 3.1. There is therefore the need for proper feasibility assessment of waste generation rates within and between states before siting a WtE facility, because if a WtE facility is sited in a location without easy access to MSW, the facility may run at suboptimal capacity and this could have severe economic consequences. The contour plot in Figure 2 provides a broad range of exploitable WtE scales that can inform siting of WtE facilities for the different states. The plot can be used for identifying the minimum operating WCE that is required to achieve an intended WtE capacity. This can be applied after in-depth pre-feasibility study of the waste generation rates across seasons.

Figure 2: The annual exploitable WtE in Nigeria for different energy conversion technologies, WCE (30-80%) and MSW generation rates (0.30-0.80 kg/cap/day)

The energy recovered from MSW can be a major contribution to electricity supply in Nigeria. According to the Nigerian Electricity Supply Industry (38), the installed electricity generation from gas and hydro-electric power plants in Nigeria was 12522 MW in 2015, but the available capacity was 7141 MW due to maintenance and repair constraints. Insufficient gas and water supply, reduced transmission capacities and demand imbalances reduced the available capacity further to 3879 MW in 2015. Based on a report by the Nigerian Energy Support Programme (NESP, 2014), electricity demand was estimated as 8664 - 12800 MW in 2014, but predictions by various authors and projected growth rates suggest the increase in electricity demand to 28261 - 88698 MW by 2020. To meet current and projected energy demands, the Energy Commission of Nigeria expect the contributions from renewable energy sources to be 14970 MW (Solar), 47 MW, 12132 MW (large-hydro), 1660 MW (small-hydro) and 65 MW (dedicated biomass crops) with an indicative annual electricity consumption of 99590 GWh in 2025. The projected energy inputs from conventional energy sources for the same period are estimated as 120513 MW (gas), 14011 MW (coal) and 7199 MW (nuclear). Thus, comparing the exploitable electricity generation potential in Figure 2 to the electricity generation capacities and supply in Nigeria, it can be deduced that potential energy recovery from MSW via incineration amounts to 11 - 77% of the current operational capacity, and 6 - 42% of the available electricity generation capacity of the electricity supply industry. Considering exploitable electricity generation potential at MSW of 0.80 kg/cap/day at WCE of 30-80%, projected WtE potential can provide up to 10% of the projected renewable energy supply, 0.7 - 1.7% of the total projected energy supply in 2025, and meet 9.8 - 26.2% of the indicative energy consumption in 2025.

The cumulative energy potential from large-, small-, and micro- hydropower plants in Nigeria is estimated at 12220 MW (39), and 1900 MW of large hydropower is currently being exploited. More recently, Akuru et al. (40) estimated that the exploitable energy from hydropower stations will be 36000 GWh/year, which is one-third fraction of the value reported by Mohammed et al. (39). Seasonal variations, high investment costs, flooding, dam collapse and drought are listed as some of the drawbacks of hydropower in Nigeria (41). For solar energy, the country is well located just below the equator; hence solar energy is well distributed across the country. The energy potential is said to vary from 4 $kWh/m^2/day$ in the southern states to 6.5 $kWh/m^2/day$ in the northern states (NESP, 2014), but large-scale generation is yet to be implemented. Regarding wind energy, the energy potential in Nigeria is estimated at 50046 MWh/year at medium generation capacity of 5 MW/km^2, 25 m height and 30% capacity factor across 22 selected states (42), although Mohammed et al. (39) reported a higher range of 120-790 MW at mean wind speed of 1.6-4.4 m/s and height of 10-25 m. Brimmo et al. (43) reported higher wind speeds of up to 7.8 m/s in Kano and Katsina states in Northern Nigeria. The estimated energy potentials are however not indicative of large-scale national projects. The contributions from 10 major agricultural crop residues is estimated to be 1958 PJ/year (44), with no further indication on their energy conversion. As such, the energy from MSW can be a significant contribution to Nigeria's energy supply.

A comparison of the results in this study with other African countries as provided by Scarlat et al. (45) shows that Nigeria ranks with South Africa and Egypt as one of the countries with the highest WtE potential based on waste generation rates. The total energy potential for African countries was estimated as 1125 PJ/year (incineration) and 182 PJ/year (landfill) in 2012 and projected to be 2199 PJ/year (incineration) and 530 PJ/year (landfill) in 2025. Nigeria was estimated to have a WtE potential of 157 PJ/year at 30% electricity conversion efficiency, corresponding to 43611 GWh in 2012. This value can account for ~14% of Africa's WtE potential and is similar to those reported in this study. Based on the waste collected, the total energy potential for Africa was deduced as 612 PJ/year (incineration) and 323 PJ/year (landfill) in Scarlat et al. (45), implying an average WCE of 54.5% for Africa. The WtE potential for Nigeria was estimated as 65 PJ/year, corresponding to 18055 GWh/year, based on MSW generation rate of 0.53 kg/cap/day and 40% WCE. This low WtE potential ranks Nigeria with Sudan, Congo and Cameroon, values that are within the range reported in this study. Further comparison with other countries is not straightforward, due to differences in macroeconomic variables. For instance, Ouda et al. (46) investigated WtE potential for three main cities in Saudi Arabia and stated that the electricity potential via incineration was 671 MW at MSW recovery rate of 1.4 kg/cap/day. In Malaysia, an upper middle income country with an average MSW rate of 0.80 kg/cap/day, it was estimated that 2400 GWh of electricity could have been produced from waste in 2014, if appropriate technology were employed, and this is projected to increase to 2650 GWh by 2020 (47). Islam (48) showed that in Dhaka and Chittagong cities of Bangladesh, an estimated amount of 1444 and 1394 GWh of electricity can be produced via incineration by 2050, due to increase in waste generation trend. There is however no clear basis for comparison, due to varying population, level of industrialisation and socio-economic activities.

3.2.1. Choice of Waste Conversion Technology

There are proven conventional combustion systems, as well as new and emerging technologies that could be used for treating MSW thermally with options for energy recovery. The conventional systems include grate-fired incineration, fluidized bed incineration, modular two-stage incineration and batch waste combustion systems (49-50). The grate-fired incineration requires minimal pre-processing of waste and allows the treatment of waste *en masse*, thus referred as mass burn facilities. Typical grate-fired incineration involves the discharge of waste directly from the consumer into a pit or bunker at the waste site, subsequent transfer of waste via an overhead crane into a feed hopper and then a final transfer to a moving grate, where combustion process is initiated (51). Reactions include the initial reduction of moisture, degassing, primary oxidation of readily combustible elements under limited oxygen conditions and subsequent combustion of fixed carbon, to yield product gas (mainly composed of carbon dioxide), heat and inert ash. Energy could be recovered as heat or electricity and efficiencies of such systems are in the range of 14-27% (electricity), and up to 60% (heat plus electricity), while their capacities range from 40 - 400 MT per year, depending on fuel characteristics (26). The fluidized systems are similar to mass burn incineration; however, requires pre-processing such as sorting, shredding, and separation of materials. Thus, homogenous fuel is required to be fed into the combustor chamber, a bed of inert material on a grate with inflow of oxidant. The batch waste incinerator processes smaller amount of waste, at most 3 tonnes per batch and are not typically used for energy recovery, except retrofitted for this purpose. The advance thermal treatment facilities include pyrolysis and gasification technologies. These systems are less proven on a commercial scale, less adaptable to heterogeneous and fluctuating waste streams and employs more complex processes and controls than the incineration systems (53-54).

This study has demonstrated the use of mass burn incineration as the most applicable WtE facility for the waste management landscape in Nigeria, as it requires minimal waste pre-treatment requirement such as waste prevention, re-use, recycling and composting. It is also a proven technology and allows the combustion of the MSW (as received basis) at temperatures above 800^{o}C and under excess air conditions and can be operated with or without heat recovery (26); hence enabling a modular operation for countries with less maintenance capabilities. They are also preferred in countries with large quantities of waste as it ensures the reduction of 75-90% of the MSW (55). The disadvantage of this technology; however, includes low overall efficiency compared to recent technologies such as pyrolysis, gasification with plant efficiency >40% for electricity generation and combined heat and power (CHP) plant that can ensure 66-78% efficiency (56). Because of the high temperatures reached in incinerating plants which is $>800^{o}$C, dioxins and other toxic emissions can be produced (57); hence, flue gas treatment is a major requirement to ensure environmental standards. The ash that is also produced requires a safe form of disposal in landfills so it does not ensure 100% conversion of the fuel. More so, if waste segregation becomes properly established in the country, the use of alternative technologies such as anaerobic digestion could replace incineration, since waste composition in developing countries is largely organic (58). The most striking disadvantage, particularly for developing countries is the high cost of maintenance, repair, and technical expertise required for this technology. These disadvantages are however not out of place when compared to other recent technologies such as gasification, pyrolysis and various modifications that are complex designs and requires high level of technical operation and the use of homogenised, pre-treated form of waste such as shredding, drying to an acceptable limit and thorough mixing of the MSW. More so, the deployment of CHP plant will require the establishment of heat utilising industries. Thus, mass burn incineration is proposed for early development of WtE facilities in Nigeria, particularly for states with low WCE and recycling priorities. This recommendation does not undermine the importance and prospects of modern technologies.

The exploitable electricity generation potential for various energy conversion technologies are presented in Figure 3 as contour plots as a function of MSW generation rates and WCE. This is to highlight the opportunities with modern technologies such as gasification, pyrolysis and CHP, that have higher net plant efficiencies, > 40%. While the annual exploitable WtE of the country was within the range of 3769 - 26082 GWh/year for incineration based technologies (net plant efficiencies of 26%), Figure 3 shows that these values can range from 6378 - 44138 GWh/year, at net plant efficiency of 44% and 9422 - 65204 GWh/ year at net plant efficiency of 65%. This range of values corresponds to WCE of 30-80% and MSW generation rates of 0.30-0.80 kg/cap/day.

Figure 3: The exploitable WtE in Nigeria for technologies with net plant efficiency of 17-67% at varying WCE (30-80%) and MSW generation rates (0.30-0.80 kg/cap/day)

The contour plots in Figure 3 can be used for ascertaining the minimum operating WCE that is required nationally to obtain a given band of exploitable WtE and for technologies with net plant efficiency (NPE) of 17-67%. These plots indicate the limit at which increasing WCE does not correspond to an increasing power output for WtE facilities. For instance, at MSW generation rate of <0.40 kg/cap/day, WtE facilities cannot generate more than 20000 GWh/year of electricity using plants with NPE of 40% or less, even if WCE is increased to 80%. At MSW generation rate of <0.5 kg/cap/day, modern WtE facilities can be employed to generate more than 20000 GWh/year provided minimum NPE of ~33% is met at WCE of 80%. At 0.60 kg/cap/day, 50% WCE can be maintained with a technology such as gasification, otherwise, plants with higher NPEs must be employed at low WCEs (<50%). Assuming a dedicated CHP is in use with 65% NPE, the exploitable WtE can exceed 20000 GWh/year using the following options: 0.30 kg/cap/day at 63% WCE, 0.40 kg/cap/day at 50% WCE, 0.50 kg/cap/day at 40% WCE, 0.60 kg/cap/day at WCE of 32%. Figure 3 therefore provides a view of exploitable WtE scales for various waste conversion technologies with net plant efficiencies of 17-67%, and WCE of 30 - 80% and highlights the minimum requirements that are needed to achieve a target WtE potential. These results emphasise the need for national feasibility studies and strategic siting of WtE facilities in Nigeria. It is clearly shown in this study that Lagos and Kano have sufficient capacities, even at poor WCE of 30% and waste generation rates of 0.30 kg/cap/day, which position the states for early development of WtE facilities in Nigeria. Other states will require to improve their waste collection efficiency, explore highly efficient waste conversion technologies, merge supplies from surrounding cities or consider multiple forms of renewable energy sources for large scale power generation. At current low waste collection efficiency in Nigeria, which is not clearly measured for individual states, a minimum regulatory electricity generation requirement of up to 50MW can hinder the development of WtE projects. On-site power generation such as dedicated power station for industrial estates and corporate users can be a feasible form of distributing energy generated from WtE facilities.

We therefore propose the following recommendations to maximise the Nigeria's waste-to-energy potential. Firstly, considering the disconnect between policy-makers and stakeholders in solid waste management, there is need for adequate reference and structure for the deployment of WtE projects in Nigeria. We recommend appropriate legal, policy, regulatory, and institutional framework to promote newer and more sustainable energy recovery options from wastes. Secondly, there are opportunities to be explored between the formal and informal sectors within and between the states via strategic partnership to promote a sustainable waste management system and to secure sufficient quantities of waste. Waste management policies that incorporate waste pickers and scavengers can create jobs, reduce environmental damage caused by growing use of disposable goods, and reduce fiscal costs of landfill operations (62). There could be inherent challenges in the cooperation and future competition between MSW firms and waste pickers in the states studied. Evidence from a waste management operator, WestAfricaENRG, which recently acquired the largest landfills in Lagos, indicated some initial operational difficulties and lack of cooperation from scavengers. The informal waste pickers can be organised in cooperative societies and engage directly with government and private sector. The partnership between the key stakeholders will help to organise integration of scavengers and waste pickers in a positive way into the formal sector, and enhance the recycling, recovery and transfer process of waste. This approach is beneficial as it helps the waste pickers can earn higher incomes (63), increase contribution to energy recovery and increase firms' profits by excluding the agent's role in the transfer process (64). Studies in Jordan have alluded to the fact that scavengers have an important role in the informal MSW sector, and are willing to involve municipals, private companies and NGOs to cooperate in strategic planning for MSW (64). Thirdly, Public-Private Partnership (PPP) is suggested to create an enabling environment for service delivery within and between states. Public-Private Partnership is employed in several countries across all levels of the waste chain (65-66). Unlike public dominated waste management systems, PPP can attract investment from the private sector which reduces the operational and construction costs (67-68). The establishment of PPPs will however require defined clear boundaries of operation and roles to prevent institutional borderline problems, overlap of duties and to eliminate voids. Fourthly, lack of quality nation-wide data is a major hindrance to reliable projections. We recommend a nation-wide assessment and open access database and repository of waste composition, characteristics, generation rates, collection, disposal and transportation route and distances across seasons, with independent data quality checks and validation for reliable environmental, cost, socioeconomic life cycle assessments and projections. Collaboration between universities, industry and government for capacity building, collaborative research and knowledge exchange initiatives will be helpful in developing a solid waste masterplan based on reliable feasibility studies. Lastly, due to the perceived concerns on emissions from WtE facilities, there will be need for stringent emission standards and safe disposal of the incineration residues under independent audit and monitoring to ensure environmental protection and assure residents of their safety. Information on the WtE facilities should be open to the public and operators should engage with relevant stakeholders through public hearings and public education on the use of these technologies, so as to prevent adverse environmental campaigns. Optimised road networks, transportation routes, and local appropriate equipment and tools, as well as effective training of waste management workers, public education will be needed to improve collection efficiency nation-wide and to reduce environmental impacts. Further work is required to examine the environmental and economic implications of waste-to-energy projects in Nigeria, particularly from a life cycle perspective to highlight the opportunities from averted waste dump and challenges presented by energy recovery from MSW. This study has considered mass burn incineration for early development of WtE facilities in Nigeria, but not considered the impact of competing technologies on fuel availability or increased technology advancement on plant operation; this will be necessary in the future.

3.3. Sensitivity Analysis

The analysis in section 3.1-3.2 have considered the treatment of 1200 tonnes of MSW/day, and fuel with fixed composition and calorific value, but MSW may vary in composition across seasons, over time and for different locations. Igoni et al. (59) reported a range of 0.8–7.0 wt.% as received basis (arb) for the ash content in MSW obtained from urban cities in Nigeria. Eboh et al. (60) showed that these values can vary as much as 0.04–39.82 wt.% on the dry basis (db). A range of moisture content of 7.8 - 65.2 wt.% arb is cited for MSW from developing countries in Igoni et al. (59) and Mohee et al. (61). All these varying qualities in fuel composition can impact the fuel's calorific value and reduced or increased quantities of waste can affect net plant efficiency. Thus, to establish the influence of varying waste quantities and qualities on plant performance, sensitivity analysis was conducted with fuels of varying waste quantities, moisture levels and organic matter-to-ash content.

Figure 4: Radar chart of the sensitivity analysis: a) waste quantities (tonnes/day), b) moisture content (wt.% as received basis), c) volatile matter-to-ash ratio

Figure 4a shows that a decrease in waste quantity by 5-10 tonnes/hour, corresponding to 960-1080 tonnes/day in this study can increase net plant efficiency by 1.5-1.7% while a similar increase in waste quantity, corresponding to 1320-1440 tonnes/day can cause a 4-7% reduction in the net efficiency of the WtE facility. The decline in net plant efficiency at increased fuel quantities is attributed to poor conversion rate with respect to fuel input rate. Typically, WtE facilities are designed with capacity limits and operational constraints to preserve the life of engine components and quality of steam recovered. As such, there is a limit to the amount of fuel that can be consumed and consequently, the amount of waste that can be treated for a given configuration to achieve the limits imposed e.g. exhaust gas temperature.

Figure 4b shows that the removal of moisture from MSW can increase net plant efficiency. At 0 wt.% arb, the NPE improved by 33% with respect to the baseline fuel scenario, and at 20 wt.% arb, the NPE improved by 22%. The results imply that a 10% reduction in the moisture content of the MSW can improve net plant efficiency of the WtE facility by 4-7%. High moisture levels in waste streams is limiting for energy recovery because the energy that could be derived from the fuel is significantly reduced, which might only be sufficient for part-drying the incoming waste streams. This is particularly important for mass burn incineration, where there is no pre-treatment of the waste.

Figure 4c shows that the changes in net efficiency of the WtE facility varied from 1-4% due to varying ratio of organic matter-to-ash content. A change in composition that reduces the organic matter-to-ash ratio of the MSW to 4:1, indicated as volatile matter (80 wt.% db) and ash content (20 wt.% db) in this study, will cause a reduction in NPE by 4%, while an increase in this ratio to 19:1, corresponding to volatile matter content of 95 wt.% db and ash content of 5 wt.% db, can bring about an increase of 3% in NPE. These changes are caused by the effect of fuel composition on fuel calorific value. Figure 5 shows that moisture can significantly reduce the energy content of fuel. Here, the LHV of the MSW is 27.18 MJ/kg at moisture levels of 0 wt.% arb, but 6.68 MJ/kg at moisture levels of 50 wt.% arb. At ash content of 21 wt.% db, the LHV of the MSW is 6.09 MJ/kg and 7.14 MJ/kg at ash content of 3 wt.% db. It is therefore crucial that the waste targeted for waste-to-energy is in sufficient, not excess quantities and of good combustible quality. To minimise loss in plant performance and ascertain the sustainability of WtE facilities, World Bank (26) recommends that waste supply should not be less than 50,000 tonnes annually, equivalent to 137 tonnes/day and waste variations should not be more than 20% at any given time for incineration. The same report recommends that the average fuel lower calorific value should be at least 6 MJ/kg. The composition using a tenner diagram is suggested to contain less than moisture 50%, ash content less than 60% and carbon content that is above 25%.

Figure 5: Influence of fuel composition on Lower Heating Value of MSW a) moisture content (wt.% arb), b) volatile matter-to-ash

4. Conclusions

This study conducted a state-level assessment the available WtE potential in Nigeria at various MSW generation rates, collection efficiencies and energy conversion technologies. The study showed that the electricity generation energy potential for the different states in Nigeria can vary from 31 - 205 MW at waste generation capacity of 0.53 kg/cap/day, assuming incineration with energy recovery as the preferred choice of thermal treatment. This sums up the country's annual electricity generation potential from MSW to be 26744 GWh/year, and could be as low as 3768 GWh/year at poor waste generation capacity of 0.30 kg/cap/day and collection efficiency of 30%. To this end, we showed that a MSW generation rate of ≥0.60 kg/cap/day and WCE ≥70% would be required for at least half of the states to own a WtE facility that can connect to the national grid, under a minimum electricity generation requirement of 50 MW. The wide variations in the exploitable electricity generation potential across the different states in Nigeria therefore shows the need for proper feasibility assessment of waste generation rates within and between states before siting a WtE facility, to ensure economic viability. The WtE maps in this study can inform the siting of WtE facilities in Nigeria as it shows the minimum operating WCE for an intended WtE capacity and for various energy technologies using net plant efficiencies. This is of high importance for the current waste management practices in Nigeria, where there is little information on the true measures of waste generation capacities for different states, and the whole country. Waste quantities and qualities can play a significant role in plant's energy recovery; hence sensitivity analysis showed their impact on net plant efficiency. The successful establishment and operation of WtE facilities for MSW in Nigeria will require enabling policies and regulations, as well as supportive legal and institutional framework. At low waste collection efficiency, minimum regulatory generation requirement can hinder development of WtE projects due to insufficient waste capacities across the states.

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Figure

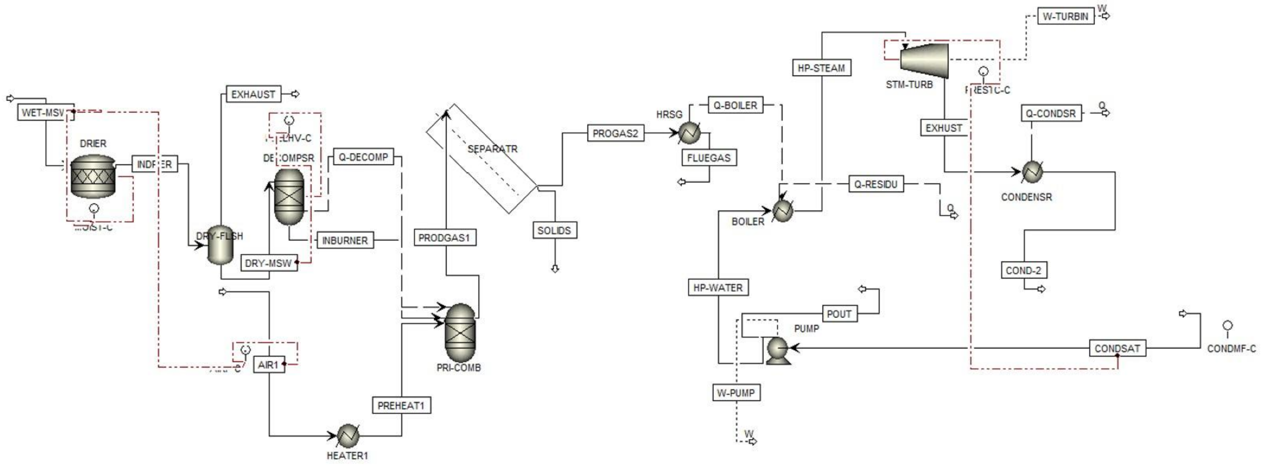

Figure 1: The schematic flow diagram of the waste conversion and energy recovery processes of the MSW

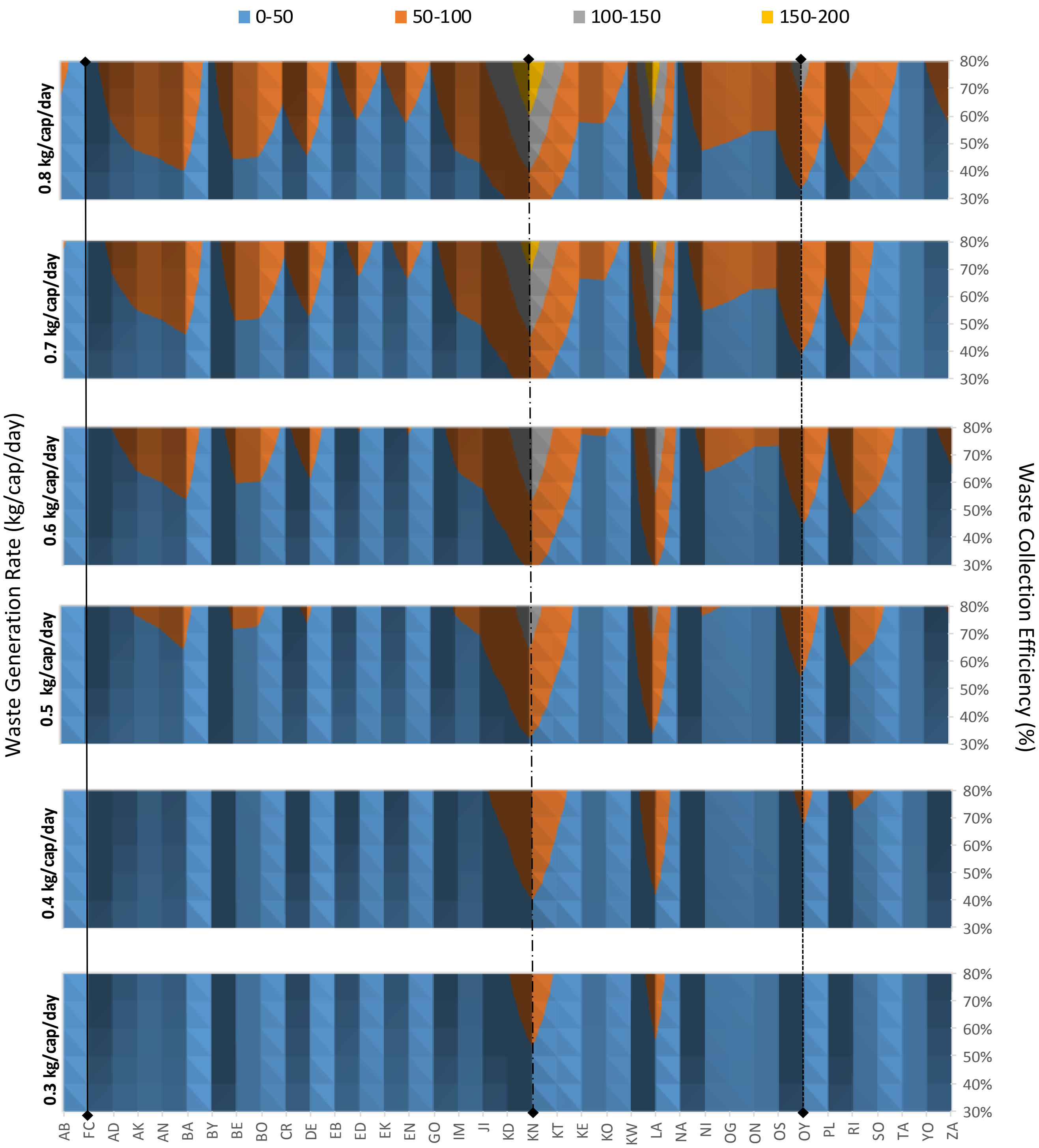

Figure 2: Exploitable Waste-to-Energy (MW) for different states in Nigeria and as a function of Waste Collection Efficiency (30-80%) and MSW generation rate (0.3-0.8 kg/cap/day)

AB-Abia; FCT-Federal Capital Territory, AD-Adamawa, AK-Akwa Ibom, AN-Anambra, BA-Bauchi, BY-Bayelsa, BE-Benue, Bo-Borno, CR-Cross River, DE-Delta, EB-Ebonyi, ED-Edo, EK-Ekiti, EN-Enugu, GO-Gombe, IM-Imo, KD-Kaduna, KN-Kano, KT-Katsina, KE-Kebbi, LA-Lagos, KO-Kobe, KW-Kwara, MA-Maiduguru, NI-Niger, OG-Ogun, ON-Ondo, OS-Osun, OY-Oyo, PL-Plateau, RI-River, SO-Sokoto, TA-Taraba, YO-Yobe, ZA-Zamfara

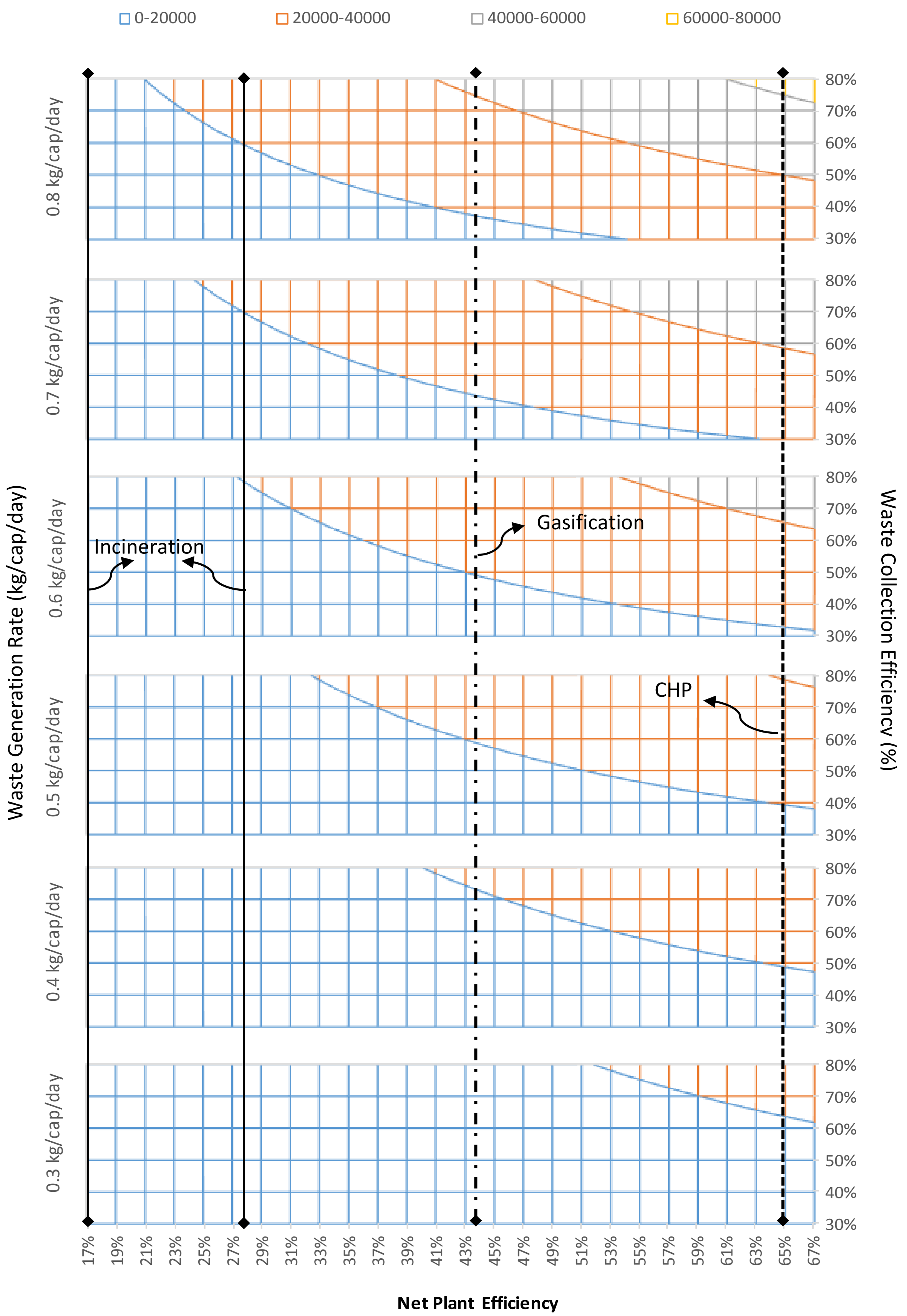

Figure 3: The annual exploitable WtE (MW) in Nigeria for technologies with net plant efficiency of 17-67% at varying WCE (30-80%) and MSW generation rates (0.3-0.8 kg/cap/day)

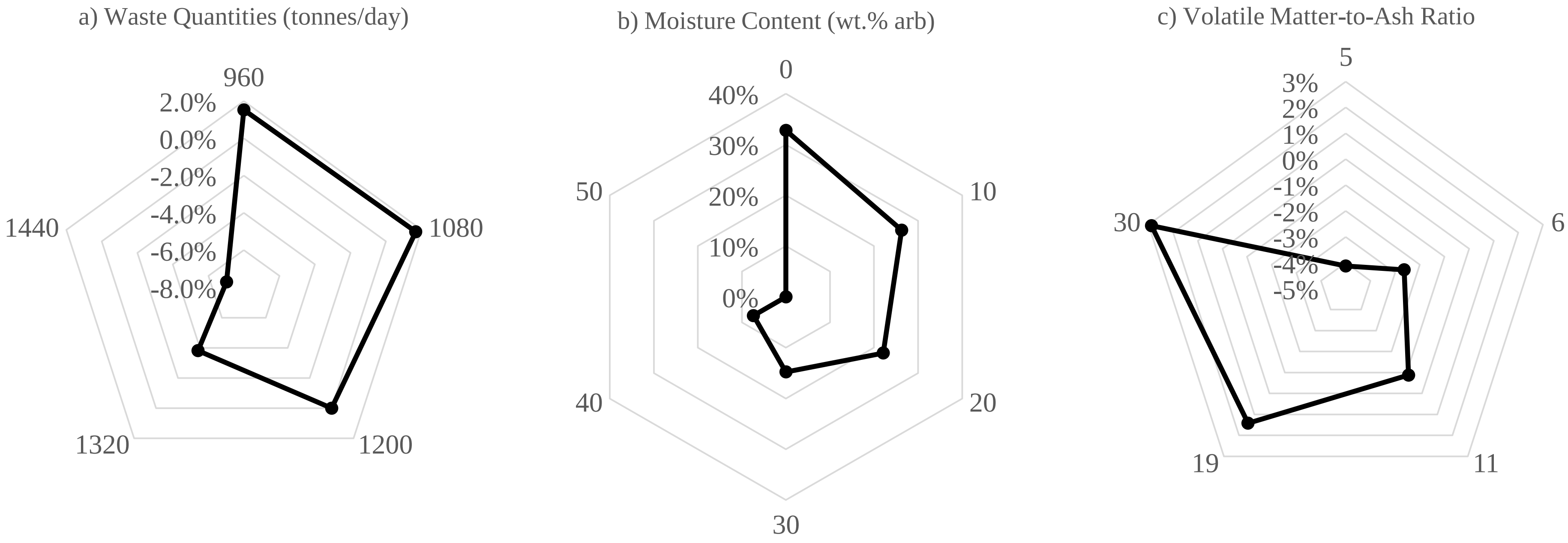

Figure 4: Radar chart of the sensitivity analysis on net plant efficiency: a) waste quantities (tonnes/day) at 50 wt.% moisture as received basis, b) moisture content (wt.% as received basis), c) volatile matter-to-ash at 50 wt.% moisture as received basis

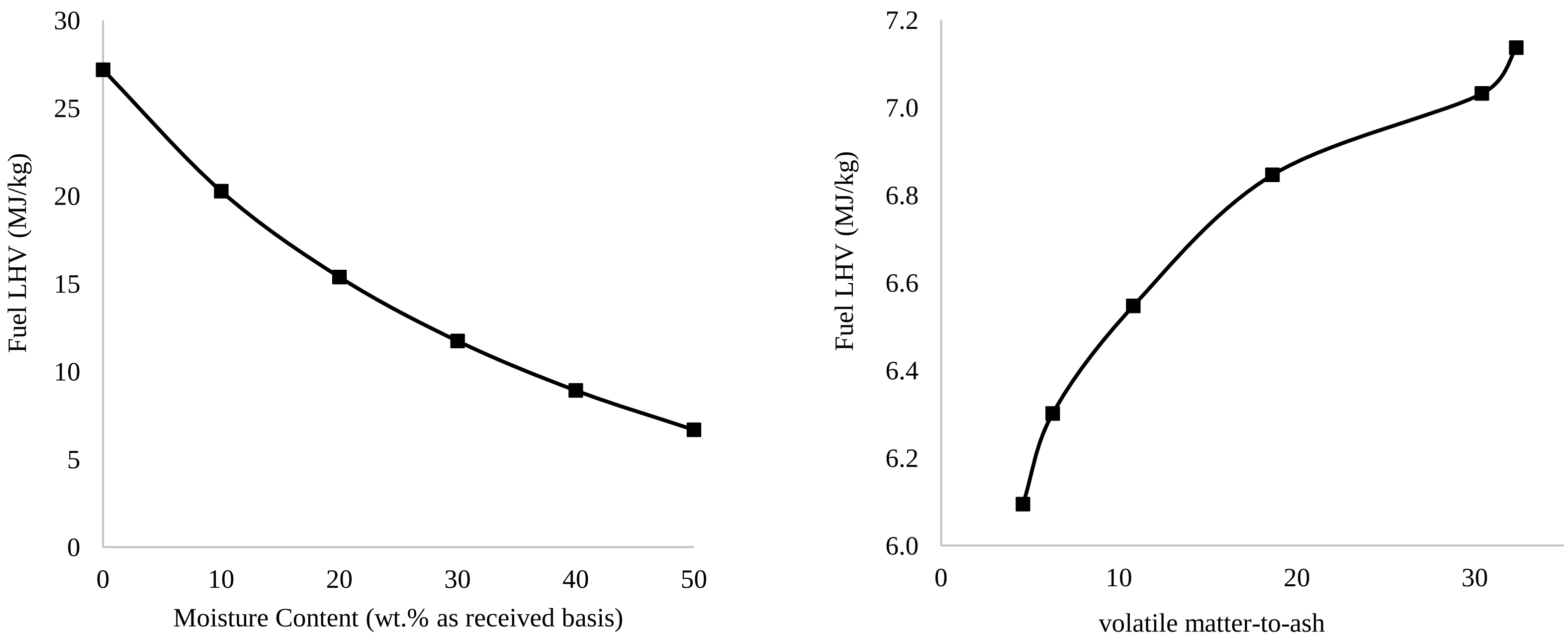

Figure 5: Influence of fuel composition on Lower Heating Value of MSW a) moisture content (wt.% as received basis), b) volatile matter-to-ash at 50 wt.% moisture as received basis

Table

Table 1: Growth Rate Factors and Adjusted Population Size/Year

	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015
Growth Rate Factor (%)	2.68	2.71	2.74	2.77	2.79	2.80	2.81	2.80	2.80	2.80
Total Mean Population (million)	140.0	143.8	147.7	151.8	156.1	160.4	164.9	169.6	174.3	179.2

Table 2: Input Parameters in Aspen Plus® for the Base-case Scenario

ASPEN BLOCK	INPUT PARAMETERS
DECOMPSR	P = 1 Bar; T = 25°C
DRY FLASH	P = 1 Bar; Duty = 0 kW
PRI-COMB	P = 1 Bar
HEATER	P = 1 Bar; T = 25°C
HRSG	Pressure difference = 0 Bar
BOILER	Degree of Supernatant = 0°C; Pressure difference = 0 Bar
PUMP	P = 125 Bar; Pump Efficiency = 90%; Driver Efficiency = 91%;
STM-TURB	Discharge Pressure = 0.19 Bar; Isentropic Efficiency = 88%; Mechanical Efficiency = 98%;
CONDENSR	Degree of Supernatant = 0°C; Pressure difference = 0 Bar

Table 3: The ultimate and proximate compositions of a typical MSW in Nigeria (Amber et al. 2012)

Proximate, wt. % dry wet basis	Moisture Content	Volatile Matter Content	Fixed Carbon	Ash Content		
	49.90	38.28	5.80	5.75		
Ultimate, wt. % dry basis	Carbon	Hydrogen	Nitrogen	Oxygen	Sulphur	Chlorine
	51.30	6.77	1.42	30.12	1.34	0.38
LHV, dry basis (MJ/kg)	17.32					

Table 4: Electricity Generation Potential (MW) at MSW generation rate of 0.53 and 0.8 kg/cap/day

States in Nigeria	0.53 kg/cap/day	0.80 kg/cap/day
Abia (AB)	62	94
Abuja (FCT)	31	47
Adamawa (AD)	69	105
Akwa Ibom (AI)	85	130
Anambra (AN)	91	139
Bauchi (BA)	102	155
Bayelsa (BY)	37	57
Benue (BE)	92	140
Borno (BO)	91	138
Cross River (CR)	63	96
Delta (DT)	89	136
Ebonyi (EB)	47	72
Edo (ED)	70	107
Ekiti (EK)	52	79
Enugu (EN)	71	108
Gombe (GB)	51	78
Imo (IM)	86	131
Jigawa (JG)	95	145
Kaduna (KD)	132	202
Kano (KN)	205	312
Katsina (KS)	126	192
Kebbi (KB)	71	108
Kogi (KG)	71	109
Kwara (KW)	52	79
Lagos (LG)	197	300
Nasarawa (NS)	41	62
Niger (NG)	86	131
Ogun (OG)	81	124
Ondo (ON)	75	114
Osun (OS)	75	114
Oyo (OY)	122	186
Plateau (PT)	69	106
Rivers (RV)	113	172
Sokoto (SO)	81	123
Taraba (TA)	50	76
Yobe (YB)	51	77
Zamfara (ZA)	71	108
Total WtE Potential (MW)	**3053**	**4652**
Annual WtE Potential (GWh/year)	**28527**	**40753**

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Somorin TO, Adesola S, Kolawole A, State-level assessment of the waste-to-energy potential (via incineration) of municipal solid wastes in Nigeria, Journal of Cleaner Production, Vol. 164, 15 October 2017, pp. 804-815

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