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Prospective Life Cycle Costing of Electricity Generation from Municipal Solid Waste in Nigeria

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Abstract: Waste management and electricity supply have always been among the main challenges faced by developing countries. So far, the use of waste to energy (WtE) is one strategy that could simultaneously address these two challenges. However, the use of such technologies requires detailed studies to ensure their sustainability. In this paper, the potential of WtE in two cities in Nigeria (Abuja and Lagos) using anaerobic digestion (AD), incineration, gasification and landfill gas to energy (LFGTE), is presented with the aim of evaluating their economic viability using life cycle costing (LCC) as an analytical tool. This economic feasibility analysis includes LCC, levelised cost of electricity (LCOE), net present value (NPV), internal rate of return (IRR) and payback period. A sensitivity analysis was conducted to investigate the influence of several parameters on the economic viability of the selected technologies for the two cities. The economic assessment revealed that all the WtE systems were feasible and viable in both cities except for LFGTE in Abuja where the NPV was negative (−USD 105.42/t), and the IRR was 4.17%. Overall, incineration for both cities proved to be the most favourable economic option based on its positive LCC (Lagos USD 214.1/t Abuja USD 232.76/t), lowest LCOE (Lagos USD 0.046/t Abuja USD 0.062/t), lowest payback period (Lagos 1.6 years Abuja 2.2 years) and the highest IRR (Lagos 62.8% Abuja 45.3%). The results of the sensitivity analysis also indicated that variation in parameters such as the capital cost and discount rate have significant effects on the LCC. This paper provides information for potential investors and policy makers to enhance optimal investment in WtE technologies in Nigeria.

Keywords: waste management; electricity supply; waste to energy

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1. Introduction

A rapid increase in population along with economic growth constitute the major reasons for the present increase in the generation of municipal solid waste (MSW) globally [1]. This has made waste management a complex issue worldwide especially with a 70% increase in global waste generation expected by 2050 if the current situation persists [2]. Consequently, this will have a negative impact on sustainable living, local environment, and human health if the global waste generated is not managed properly [3]. The same applies to the electricity sector where global demand has increased by more than 4% annually between 1990 and 2015 [4]. This is expected to increase continuously due to economic development, electrification, and climate change [4]. Thus, inadequate supply of electricity could also have a significant impact on the economic and social development of any nation. Effective management, usage, and conversion of MSW to useful energy could serve as a potential means of providing a sustainable solution that can bridge the gap between electricity supply and waste management [5].

This has brought about the development and use of waste to energy (WtE) approaches which involves the thermal or biological extraction of usable energy stored in MSW to produce heat or electricity or both (combined heat and power) [6]. Some typical WtE systems are landfill gas to energy technology (LFGTE), incineration, gasification, pyrolysis and anaerobic digestion (AD) [7]. Some of these WtE processes (incineration) can reduce the volume of MSW significantly by approximately 50–90% [8]. In addition, MSW has a net energy potential of about 0.13–0.38 tonnes of oil equivalent (toe) per tonne which can be extracted using WtE [9]. Thus, WtE systems offer the potential to treat some 261–396 million tonnes of global waste annually along with a total estimated output of 283–429 TWh of power [10]. Currently, more than 800 WtE plants are operated in nearly 40 countries treating approximately 11% of MSW generated worldwide and generating up to 283 TWh of power [6].

According to the National Bureau of Statistics [11], Nigeria with an estimated population of 193,392,517 in 2016 generates an average of 42 million tonnes of waste annually, representing a waste generation rate of between 0.65 and 0.95 kg/capita/day [12]. The current waste management infrastructure in the country is unable to handle the rate of waste generation [5]. In addition, there is a huge gap between the electricity generation and demand in Nigeria resulting in electricity deficit [5]. A reflection of this is seen in the country's 2019 electricity consumption per capita, which was 145 kWh [13], a figure which is low compared to most countries in the world, such as the USA (12,083 kWh), Germany (7204 kWh), UK (4740 kWh), China (4039 kWh), Ghana (403 kWh) and South Africa (4363 kWh) [14].

Hence, the adoption of WtE projects for electricity generation in Nigeria could be a promising sustainable strategy to overcome the dual problem of inadequate waste management and inadequate power supply [5]. -This may also be beneficial especially for developing countries that depend on expensive imported fuel and thus could generate a significant economic advantage. However, WtE projects require a large initial investment and have high operating cost due to a long service life [15]. Various studies have reported WtE as environmentally safe, but its level of economic sustainability remains debated due to cost [16]. As a result, assessment tools and approaches are needed, e.g., the life cycle assessment (LCA) methodology, to support decision-making policies in the field of waste management [17]. LCA 'traditionally' focusses on the environmental impacts and benefits of systems such as WtE [18,19]. However, the economic and social performance are also vital considerations for sustainable waste management [20–22]. Hence, there are tools such as life cycle costing (LCC) and social life cycle costing (sLCA) that look at those other aspects of the triple bottom line and along with LCA which looks at environment impact these collectively form what is known as life cycle sustainability assessment (LCSA).

LCC is a life-cycle approach that enables comparative cost assessments to be made over a specified period, considering all relevant economic factors, both in terms of initial costs and future operational costs [23]. The aim of LCC is to assess costs across the entire life cycle of a process, service, or fixed asset system, including the stages of decision making, construction, operation, and end-of-life, based on satisfying reliability requirements [24]. The introduction of LCC for waste management strategies such as WtE could provide excellent guidance for planning the construction and operation scheme for such projects [25]. However, the application of LCC to assess MSW management is not yet very common in the literature although LCC studies of different types of MSW management systems have shown that it is a powerful tool to provide a systematic economic analysis [26].

For instance, Dong et al. [27] applied LCC to make economic comparisons of three existing MSW treatment technologies in Hangzhou, China: (1) landfill, (2) landfill with biogas conversion to electricity, (3) fluidized bed incineration with energy recovery. The results revealed that landfill with biogas conversion to electricity performed the best among the three scenarios with net LCC of 16.57 Yuan per tonne of MSW compared to 34.78 Yuan per tonne for incineration and 45.87 Yuan per tonne for landfill. Slorach et al. [28] in another study involving LCC analysis of four food waste treatment options in the UK using in-vessel composting, moving-grate incineration with energy recovery, anaerobic digestion, and landfill with energy recovery showed that incineration had the highest LCC among all the scenarios while generating the most revenue. Incineration was found to be the most economical option with a net LCC of EUR 71 per tonne while landfill was the costliest option with a net LCC of EUR 123 per tonne due to high gate fees.

In the case of Nigeria, LCC has rarely been used for the economic assessment of waste management systems particularly that of WtE. Ayodele et al. [29] conducted an economic assessment of electricity generation using biogas from AD and LFGTE processing of the organic fraction of MSW for the city of Ibadan in Oyo State, South-West Nigeria. The study showed that both technologies had a total LCC of USD 871/MWh and USD 997/MWh, respectively. From the results presented, it was evident that AD was a better technology to invest in than LFGTE in Ibadan. However, this study was limited to only one city and considered just two WtE technologies. Given that the results of LCC analysis could vary significantly depending on context as well as the very limited studies done on such waste management approaches in Nigeria (and elsewhere), there is a need to address this gap by analysing the LCC of WtE for Nigeria. Thus, the aim of this study is to assess and compare different prospective WtE systems for two key Nigerian cities (Lagos and Abuja) using a LCC analysis approach. The objective was to identify which of the WtE options was most sustainable from an economic perspective and to see if there were differences between the two cities. The cities differ in terms of their size, geography, history, and socio-economic status of the population, and these could have impacts on waste collection and disposal processes. This research is intended to support decision-making for optimal, sustainable investment in WtE in Nigeria as well as to complement similar LCA and social LCA evaluations [18,30] in a comprehensive approach. In this study, four WtE waste options (Incineration, AD, Gasification and LFGTE) were selected and analysed based on their large-scale commercial usage.

2. Materials and Methods

2.1. Lagos and Abuja

It is reasonable to assume that urban context, such as geography, historical development, governance, and social-economic status of the population, could potentially generate differences in LCC results for WtE systems. Thus, for the research reported here it was deemed necessary to undertake the LCC in more than one city in Nigeria and in cities that provided different contexts. The two cities chosen were Lagos, and Abuja (Figure 1) and both share the same challenges associated with increases in population growth such as increases in the amount of MSW generated and issues associated with an inadequate electricity supply.

Lagos is a metropolitan city that forms part of Lagos State, south-western Nigeria and serves as the country's commercial capital with an estimated population of almost 20 million making it the most populous city in the country [31]. The city covers an area of 3577 km^2 and sits on the coast of Nigeria some 140 km south of Ibadan, the city that provided the basis for the WtE studies of Ayodele et al. [29]. Lagos has an average population growth rate of almost 4% per year and a density of about 5032 people/km^2. Lagos has been identified as one of the most rapidly growing metropolitan areas in the world [32]. The city was once the capital city of the country but in 1991 the capital became Abuja. As Lagos is an old city, its streets tend to be narrow and winding, and indeed the city now spans a number of islands near to the coast all of which are connected by bridges. Lagos generates waste at 0.72 kg/person/day which equates to approximately 15,000 tonnes of waste daily [33]. This led to the state government establishing the Lagos State Waste Management Authority (LAWMA) which performs a supervisory role and is charged with implementation, advocacy, monitoring, and enforcement of waste management policies [34]. The disposal of solid waste takes place at four official sites in Lagos (Figure 1); Olusosun, Solous I, Solous II and Abule- Egba, with ages ranging between 5 and 25 years and a combined capacity of 63.67 hectares with the Olushosun dumpsite being the largest of the sites covering about 42 hectares [34]. The main dumpsites in Lagos are almost reaching their maximum capacity and are all surrounded by dense urban development.

Abuja is the Federal Capital City (FCC) of Nigeria and sits at the geographical centre of the country within the Federal Capital Territory (FCT). Unlike Lagos and Oyo States, The FCT is not a state and does not have an elected governor or assembly. Instead, the FCT is run by the Federal Capital Territory Administration, with a minister appointed by the Federal Government. Abuja has a land area of 8000 km^2 and a population of 1,406,239 in 2012 [31]. Being located in the centre of the country, the spread of Abuja is not restricted by geographical features such as the sea and unlike Lagos, Abuja is a newer and planned city with relatively wide and straight roads and zones demarcated for residential, government and commercial purposes. In 2014, the amount of waste generated monthly in Abuja was estimated to be approximately 30,000 tonnes and this equates to an average per capita generation of MSW of about 0.66 kg/person daily [35]. The dumpsites that serve Abuja are on outskirts of the city (Figure 1).

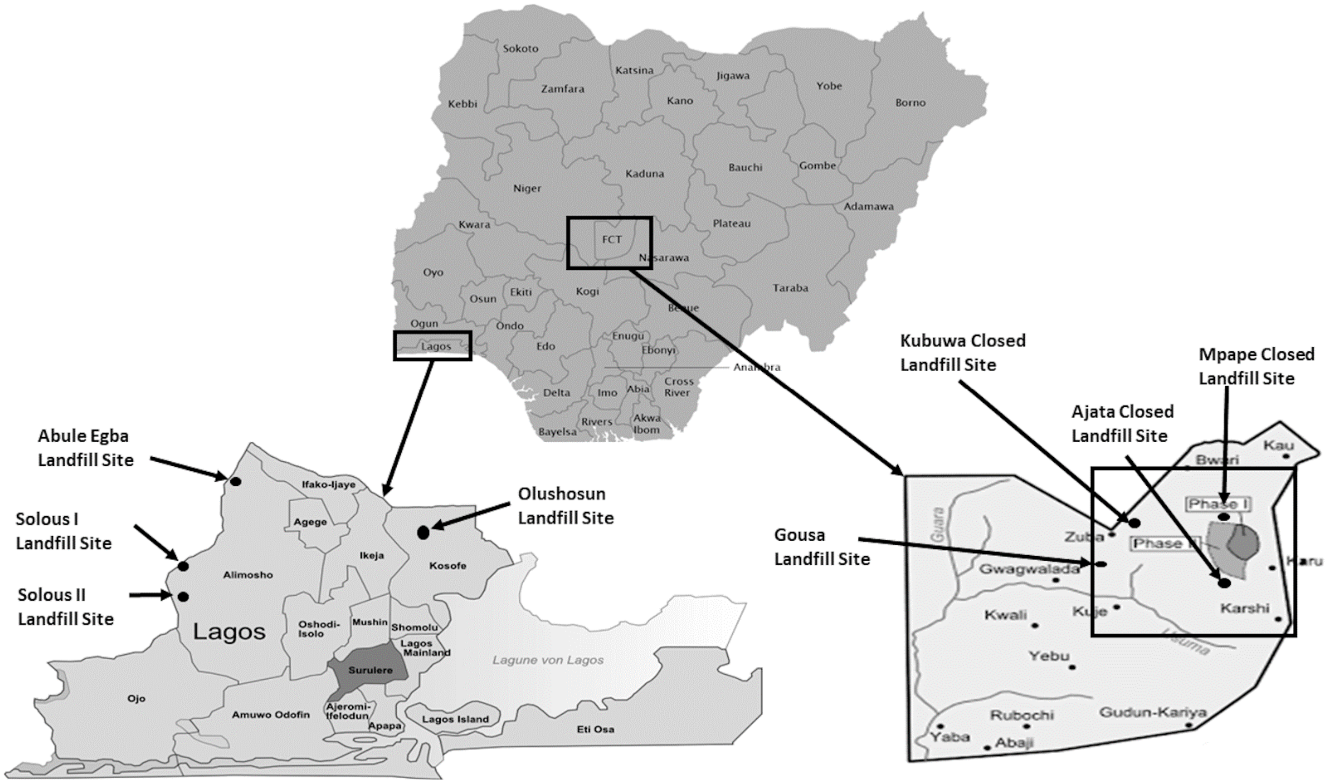

Figure 1. Map of the Lagos and Abuja metropolitan areas indicating their major landfill sites [36–38].

As with many cities in Nigeria, there is a need for both Lagos and Abuja to effectively and efficiently manage the MSW generated [39]. Both cities through their respective agencies—the Lagos State Waste Management Authority (LAWMA) and the Abuja Environmental Protection Board (AEPB)—have taken various steps to address these issues by the adoption of their own Private Sector Participation (PSP) programmes. In the case of Lagos, the collection of waste from public areas is undertaken by government authorities while residential and commercial wastes are collected by private companies [33]. For Abuja, districts are allotted to various individual companies for waste collection and transportation [40]. In terms of inadequate electricity supply, households and companies in both cities have attempted to bridge the gap between the electricity demand and current supply by using petrol/diesel generators as an alternative electricity supply. These generate environmental hazards in terms of particulate matter and toxic gases, but they are also expensive to run and maintain. With both cities sharing similar challenges of addressing issues of waste and energy, the use of WtE could provide a sustainable solution.

2.2. LCC

LCC is a standardized approach under the International Standards Organisation (ISO) ISO 14040 and 14044. It follows four methodological steps (i) Goal and Scope, (ii) Inventory Analysis, (iii) Impact Assessment, and (iv) Interpretation.

2.2.1. Goal and Scope Definition and Functional Unit

The goal of this LCC study was to assess and compare the economic impacts of implementing WtE in the two major cities in Nigeria mentioned above using four different WtE technologies.

The Functional Unit of the system in this study is:

"*The processing* via *WtE technologies of 1 tonne of the suitable MSW processed*".

2.2.2. Inventory Analysis

The field work for this study was conducted in Lagos and Abuja for a period of three months. A detailed survey was conducted during this period by the first author involving a series of interviews with officials of the waste management authorities of both cities and direct observations. MSW generation and disposal data for both cities from 2000 to 2018 were collected from the relevant authorities. An extensive literature review was also performed to compare the composition and characteristics of MSW of both cities complemented with the use of technical reports and national database from the National Population Commission (NPC) on the current population and growth rate in both Lagos and Abuja. From this a projection of the future population and MSW generation in both cities over a period of 20 years (2022–2042) was made. Data on costs for the WtE systems were obtained from relevant literature as there were no site-specific data available for Nigeria. Data on the electricity tariff were obtained from the Nigerian Electricity Regulatory Commission (NERC).

2.2.3. Population and MSW Growth and Electricity Generation Potential

The modelling of the population projections, MSW generation along with the electricity generation potential for the WtE different technologies and their economic assessment were made to determine the economic impacts of these options (see Supplementary Materials for detailed calculations). The total waste collected each year between 2022 and 2042 (20 years) was estimated using projected population changes in each city over that period.

It was assumed that the waste/capita for each city was constant over the 20 years and based on the figure for 2019. While this assumption of a constant waste/capita over 20 years can be critiqued, it does allow for a straightforward comparison of the economic performance of the WtE technologies. Therefore, the total MSW generated for each city and year was estimated by multiplying the projected population by the waste generated/capita. The relevant Equations (1) and (2) for this calculation are as follows:

$$Wg = \frac{P(t) \times Wgr \times 365}{1000} \tag{1}$$

where Wg is the projected total waste generation in tonnes/year, Wgr is waste generation rate in kg/capita/day (assumed to be a constant for each city over the 20 years) and $P(t)$ is the estimated population projection over a specified period which can be evaluated using:

$$P(t) = P_0\ (1 + r)^n \tag{2}$$

where P_0 is the current population in 2022 and r is the population growth rate for the respective cities.

It should be considered that not all the wastes generated will be collected and taken to the sorting and WtE facilities. Some fractions of waste generated are deposited in unauthorized places.

Hence, the quantity of waste collected can be evaluated using:

$$Wc = Wg \times D_f \tag{3}$$

From Equation (3), Wc is the amount of MSW collected and D_f is the fraction of the waste collected (assumed to be 0.4).

According to Ogunjuyigbe et al. [41], different WtE technologies require different waste compositions. Therefore, the amount from the waste composition (W_f) that could be used for each WtE technologies can be estimated as:

$$W_f = W_c \times f \tag{4}$$

where f is the fraction of the waste composition that goes into a specific WtE facility.

The values of the parameters used to estimate the waste generation potential for both cities are presented in Table 1.

Table 1. Parameters for evaluating the waste generation potential of Lagos and Abuja.

City	P_0	r (%)	*Wgr* (kg/Capita/Day)	D_f (%)	Lifetime (years)
Lagos	15,387,639 [a]	3.2 [a]	0.72 [b]	40	20
Abuja	3,464,000 [a]	5.67 [a]	0.66 [c]	40	20

a: [42]; b: [43]; c: [35].

For the electricity generation potential, different WtE systems require different methods of extracting useful energy for electricity generation (see detailed calculations in Supplementary Materials). For AD, the amount of biogas (m^3/ton) from the feedstock fed into the digester should be evaluated to determine the electricity generating potential. The theoretical potential quantity of biogas from the substrate is estimated using Buswell's equation [44–47]. The equation is based on stoichiometry of the degradation by considering the elemental composition of the waste material and is given as:

$$\mathrm{C_nH_aO_bN_c} + (n - 0.25a - 0.5b + 0.75c)\ \mathrm{H_2O} \rightarrow (0.5n - 0.125a + 0.25b + 0.375c)\ \mathrm{CO_2} + (0.5n + 0.125a - 0.25b - 0.375c)\ \mathrm{CH_4} + \mathrm{cNH_3} \tag{5}$$

where n, a, b, and c, are constants whose values can be determined by using the normalised mole ratio proposed by [48]. This was obtained as follows:

$$Mole\ Ratio = \frac{K|C, H, ON|}{M|C, H, ON|} \tag{6}$$

where, K is the elemental composition (carbon (C), hydrogen (H), oxygen (O) and nitrogen (N)) obtained from the ultimate analysis of the organic fraction of the waste, M is the molar mass of the respective elements as shown in Table 2.

Table 2. Molar Mass of relevant elements [29].

Element	*C*	*H*	*O*	*N*
Molar mass (M) (g)	12.01	1.01	16	14.01

The mass of methane (kg), M_{CH4} required for anaerobic digestion technology can be determined using

$$M_{CH4} = \frac{16 \times A}{(M_{c \times n}) + (M_H \times a) + (M_O \times b) + M_N} \times 100 \tag{7}$$

where $A = 0.5n + 0.125a - 0.25b - 0.375c$ which represents the stochiometric ratio of CH_4 in the Buswell Equation. Hence, the volume of the methane can be calculated as:

$$V_{CH4} = \frac{M_{CH4}}{\rho_{CH4}} \tag{8}$$

ρ_{CH4} = Density of Methane (0.717) kg/m^3 [5].

According to Ayodele et al. [29], Ogunjuyigbe et al. [41], the actual amount of methane production is less than the amount of theoretical methane as such it is calculated as 85% of the theoretical amount as given below in Equation (9):

$$V_{\text{CH4}\ AD\ (Actual)} = 0.85 \times V_{CH4AD} \tag{9}$$

Hence, the amount of possible electrical energy (kWh/t) that can be generated from a generator powered by biogas can be evaluated using Equation (10) below:

$$E_P(AD) = \frac{V_{CH4\ AD(Actual)} \times LHV_{(Methane)} \times 0.85 \times \eta}{3.6} \tag{10}$$

where $LHV_{(Methane)}$ is the lower heating value for methane (37.2 MJ/m^3), η is the conversion efficiency (0.26), capacity factor (0.85) and conversion factor from MJ to kWh (3.6), respectively [49].

The electricity generated from LFGTE depends on the methane content of the landfill gas generated, which is also dependent on the methane generation potential of the waste landfilled. In this study, the amount of landfill gas generated from the proposed landfill sites in the selected areas was calculated using the IPCC methodology, which is based upon a mass balance approach as indicated in Equation (11). Hence, the methane generation in kg/tonne of MSW from a typical landfill can be estimated as:

$$\text{CH}_4\ (\text{kg/tonne of MSW}) = W_F \times MCF \times DOC \times DOC_F \times F \times \left(\frac{16}{12} - R\right) \times (1 - OX) \tag{11}$$

For this present study, the default values for some of the empirical constants in this equation are used except for the decomposable organic carbon (*DOC*) which was calculated using Equation (12). The following assumptions, based on the IPCC Tier I method [50], were made regarding the variables in Equation (11):

- A methane correction factor (*MCF*) of 0.6 was employed as the landfills in Lagos and Abuja were considered to be unmanaged.
- The fraction of degradable organic carbon dissimilated (DOC_F) was taken to be 0.77.
- The oxidation factor (*OX*) was assumed to be zero.
- The fraction of MSW disposed at landfill (MSWF) was taken to be 100%.
- The fraction by volume of CH_4 in landfill gas (*F*) was assumed to be 50%.
- Recovered methane (*R*) was assumed to be zero.

The DOC was estimated using Equation (12):

$$DOC = (0.4 \times \text{A}) + (0.17 \times \text{B}) + (0.15 \times \text{C}) + (0.3 \times \text{D}) \tag{12}$$

From Equation (12), A, B, C and D represent the fraction of paper and textile waste, garden waste, food waste and wood waste, respectively, in the MSW. However, given that there are no garden and wood waste in the MSW, the values of B and D were assumed to be zero for this study. From there, the volume of methane can be obtained using Equation (8) above. Hence, electricity generated from LFGTE, $E_{P(LFGTE)}$ can be calculated as:

$$E_{P(LFGTE)} = \frac{V_{CH4\ (LFGTE)} \times LHV_{(Methane)} \times \lambda \times 0.85 \times \eta}{3.6} \tag{13}$$

where $V_{CH4(LFGTE)}$ is the volume of the methane in the landfill gas, λ represents the collection efficiency which is assumed to be 0.75 [51], the value 0.85 is the capacity factor while η is the electrical conversion efficiency for internal combustion engine which is given as 0.33 [52].

In the case of incineration technology, the combustible portion of the MSW is burnt, thereby producing a large amount of heat which is used to raise steam in a boiler that drives a turbine connected to a generator. Thus, the amount of electrical energy that can be generated from the useful heat produced in the turbine can be calculated as:

$$E_{P(INC)} = \frac{M_{INC} \times LCV_{(Waste,INC)} \times \eta_{INC}}{3.6} \tag{14}$$

where M_{INC}, $LCV_{(Waste,INC)}$, η_{INC} and 3.6 are average annual mass of waste, lower calorific value for the waste incinerated (MJ/kg), conversion efficiency and conversion factor from MJ to kWh, respectively. For η_{INC}, the value is given as 0.2 [53] while $LCV_{(Waste,INC)}$ is calculated using Equation (15) given below (see Supplementary Materials for the detailed calculation):

$$LCV_{(Waste,INC)} = \frac{40\ (a+b+c+d) + 90e - 46W}{238.86} \tag{15}$$

From Equation (15), a, b, c, d, and e represent the percentage by mass of paper, textile, wood, food waste while W represents the moisture content [54].

For Gasification, all the fraction of the MSW is gasified except for the metals and glass which are assumed to be taken for recycling. Equation (16) provides the expressions required to calculate the amount of electricity from gasification, $E_{P(GAS)}$:

$$E_{P(GAS)} = \frac{M_{GAS} \times R_f \times LHV_{(Waste,GAS)} \times \eta_{GAS}}{3.6} \tag{16}$$

where M_{GAS} is the amount of MSW to be processed (tonnes), R_f is the percentage of rejection after the mechanical treatment which is taken as 72.5% [55], $LHV_{(Waste,GAS)}$ is the lower heating value of waste of the MSW (MJ/kg) and η_{GAS} is the efficiency of the process is 23% [56].

2.2.4. Economic Evaluation of WtE Systems

In terms of the economic feasibility and sustainability of the WtE scenarios, these were determined using life cycle and economic metrics such as overall life cycle cost (LCC), net present value (NPV), internal rate of return (IRR), levelised cost of energy (LCOE), and payback period (PBP). Details of the calculations are provided in the Supplementary Materials and summaries are provided here.

The LCC, is a key financial life cycle indicator for an investment project. It consists of the total cost of owning and operating a project over its lifetime [57]. LCC is the sum of investment cost and operation and maintenance costs calculated using the following equation:

$$LCC = C_{inv(\mathrm{i})} + \textstyle\sum_{n=1}^{N} \frac{C_{o\&m(i)}}{(1+dr)} \tag{17}$$

where $C_{inv\,(\mathrm{i})}$, $C_{o\&m(i)}$ and d_r represent initial investment cost, operations and maintenance cost and discount rate, respectively.

The difference between the cash inflow and cash outflow for each year for each WtE system is its annual net cash flow represented by Equation (18):

$$CF_n = Rev_n - \left(C_{inv_n} + C_{o\&m_n}\right) \tag{18}$$

where CF_n is the Net Cash Flow (USD), Rev_n is the revenue generated (USD) while C_{inv_n} and $C_{o\&m_n}$ are the capital and operating and maintenance costs, respectively.

In this study, the revenue generated, Rev from the respective WtE technologies is the electricity sale calculated as shown in Equation (19):

$$Rev = E_P \times F_d \tag{19}$$

From Equation (19), F_d refers to the sale price for the electricity in Nigeria at USD 0.1868/kWh [58] and E_P is Total Electrical Energy from each of the technologies (kWh).

NPV is the difference between all costs incurred and the revenue earned by the system over its lifetime. For any system to be considered as economically viable, the value of the NPV must be positive [59]. NPV was obtained from Equation (20):

$$NPV = \sum_{n=0}^{N} \frac{CF_n}{(1+d_r)^n} = F_o + \frac{CF_1}{(1+d_r)^1} + \frac{CF_2}{(1+d_r)^2} + \ldots\ldots\ldots + \frac{CF_N}{(1+d_r)^N} \tag{20}$$

With CF_n representing the Net Cash Flow Rate (USD) while d_r and n are the discount rate (%) which was taken as 10% after [29] and the project life time in years (20 years), respectively.

The *IRR* is the discount rate that makes the *NPV* equal to zero [60]. It cannot be estimated analytically but rather can be approximated iteratively as the highest discount rate at which the project still breaks even:

$$IRR - The\ value\ of\ d_r\ such\ that\ NPV = \sum_{n=0}^{N} \frac{CF_n}{(1+d_r)^n} = 0 \tag{21}$$

The WtE system will be economically attractive only if the *NPV* is greater than zero and the *IRR* is at the highest value possible.

The LCOE refers to the minimum cost at which electricity is generated for a system when it breaks even [41]. From the calculation of the *LCOE* in USD/kWh, the lowest selling price of the electricity produced is determined [61]. It can be determined for each of the technologies using Equation (22):

$$LCOE = \frac{LCC}{E_p} \tag{22}$$

where *LCC* (USD) is the life cycle cost of the project, d_r is the discount rate, n is the economic lifetime of the project.

PBP is the time (in years) at which the project cost breaks even which is the time after which the revenue (income) has paid back the initial investment costs. This is the maximum period (years) after which there begins to be return on investment [62], and it was determined using a simple payback period formulation shown as Equation (23):

$$PBP = \frac{C_{inv}}{Rev - C_{o\&m}} \tag{23}$$

where C_{inv}, $C_{o\&m}$ and Rev represent the initial investment cost, operations and maintenance cost and the revenue generated from the respective WtE technology.

2.2.5. Cost Structure for WtE Systems

For AD, the investment cost $C_{inv(AD)}$ and operating and maintenance costs ($C_{O\&M_{(AD)}}$) used according to Hadidi and Omer [60], were determined as shown in Equations (24) and (25) (see Supplementary Materials for detailed calculations):

$$C_{inv(AD)} = C_{P_{(AD)}} \times P_{sAD} \tag{24}$$

$$C_{O\&M_{(AD)}} = 0.03C_{inv(AD)} + 0.005\ E_{P_{(AD)}} \tag{25}$$

From Equations (24) and (25), $C_{P_{(AD)}}$ is the plant specific cost of AD plants and its value is taken as USD4339 /kW [52], $0.03C_{inv(AD)}$ is the fixed operating and maintenance costs (USD) which is expressed as 3% of capital cost while 0.005 $E_{P_{(AD)}}$ refers to the variable operating and maintenance costs (USD) which is related to the plant output and P_{sAD} is kW plant capacity [60].

The investment cost for a LFGTE according to Cudjoe et al. [63], can be estimated as the sum of the following costs as indicated in Equation (26)

$$C_{inv(LFGTE)} = Cv + C_w + C_{kout} + C_{eng} + C_{ICE} \tag{26}$$

where Cv, C_w, C_{kout}, C_{eng} and C_{ICE} are the installed capital cost of vertical gas extraction wells, cost of installing wellheads and pipes gathering, cost of installing knockout, blower and flare, cost of engineering, permitting and surveying system and cost of installation of reciprocating internal combustion engine respectively. These are calculated using Equations (27)–(31):

$$C_v = [z(ft) - 10(ft)] \times \text{USD}85 \times W \tag{27}$$

$$C_w = \text{USD}17{,}000 \times W \tag{28}$$

$$C_{kout} = v^{0.6} \times \text{USD}4600 \tag{29}$$

$$C_{eng} = \text{USD}700 \times W \tag{30}$$

$$C_{ICE} = (\text{USD}1300 \times P_{s\,(LFGTE)}) + \text{USD}1{,}100{,}000 \tag{31}$$

where z, v, W and $P_{s\,(LFGTE)}$ represent the depth of the well which is 65 ft according to [64] and Ayodele et al. [29], the methane flow rate (m^3/year), the number of wells dug at the landfill site which is 50 and kW-rated capacity of the proposed internal combustion engine (ICE), respectively.

In terms of the operation and maintenance of cost of the LFGTE system $C_{o\&m\ (LFGTE)}$, it can be obtained as shown in Equation (32):

$$C_{o\&m(LFGTE)} = C_{o\&m(LF)} + C_{o\&m(ICE)} \tag{32}$$

where $C_{o\&m(LF)}$ and $C_{o\&m(ICE)}$ are operating and maintenance cost of the land fill site and operating and maintenance cost of the internal combustion engine [63]. The two operations and maintenance costs can be calculated as shown in Equations (33) and (34), respectively:

$$C_{o\&m(ICE)} = \text{USD}0.025 \times E_{P(LFGTE)} \tag{33}$$

$$C_{o\&m(LF)} = \text{USD}2600 \times W + \text{USD}5100 \tag{34}$$

$E_{P(LFGTE)}$ = Annual energy (kWh) produced by the Internal Combustion Engine.

For Incineration, the model for the investment cost $C_{inv(INC)}$ and the operating and maintenance costs $C_{o\&m(INC)}$ was developed according to Alzate-Arias et al. [65] using Equations (35) and (36):

$$C_{inv(INC)} = \text{USD}16{,}587 \times (P_{S(INC)})^{0.82} \tag{35}$$

$$C_{o\&m(INC)} = 0.04 \times (C_{inv(INC)}) \tag{36}$$

where $P_{S(INC)}$ refers to the kW-capacity of the incineration plant.

The economic model developed in this paper for a gasification WtE plant considers that a Bubbling Fluidized Bed (BFB) gasification will be used as the conversion technology. The reason for this choice is that this type of gasifier, when compared with other gasifier types, has a higher performance, produces syngas with higher energy content and can process a wider range of wastes [52]. As such the capital cost for a WtE plant using BFB gasification technology is 3925 USD/KW [66]. The fixed O&M cost used for this research assumes it as 4% of the total capital cost [66]. The variable O&M cost for a BFB gasification technology is USD 0.004/kWh [52].

Given this, the investment cost $C_{inv(GAS)}$ as well as the operating and maintenance costs $C_{o\&m(GAS)}$ for gasification technology according to Mabalane et al. [67] can be determined as shown in Equations (37) and (38):

$$C_{inv(GAS)} = \text{USD}3925/\text{kW} \times P_{s(GAS)} \tag{37}$$

$$C_{o\&m(GAS)} = F_{O\&M\ (GAS)} + V_{O\&M\ (GAS)} \tag{38}$$

where $P_{s(GAS)}$ is the kW capacity of the gasification plant while $F_{O\&M\ (GAS)}$ and $V_{O\&M\ (GAS)}$ are fixed and variable operating and maintenance costs for gasification (USD) calculated as shown in Equations (39) and (40):

$$F_{O\&M(GAS)} = 0.04 \times C_{inv(GAS)} \tag{39}$$

$$V_{O\&M(GAS)} = \text{USD}0.004/\text{kWh} \times E_{p\ (GAS)} \tag{40}$$

For the size or kW capacity for all the WtE systems P_S, this can be calculated by dividing the total energy generated (E_p) in kWh by the plant life for year in hours (8760 h) as shown in Equation (41):

$$P_S = \frac{E_p}{8760} \tag{41}$$

2.2.6. Interpretation

The interpretation of the results of the LCC and economic performance of the WtE systems includes identification of the main drivers of economic cost, the benefit derived from net revenues, consideration of limitations in the study, and sensitivity analysis. Sensitivity analysis was conducted to measure the effect of variations of the discount rate, capital and O&M costs, and the collection rate and energy generating efficiencies on the LCC results. These parameters were altered individually to determine their impact on the analysis outcomes.

3. Results

Figure 2 illustrates the amount of waste generation projected for a 20-year period (spanning 2022 to 2042) in Lagos and Abuja, respectively. The projected results in Figure 2 suggest that Lagos has approximately four times higher MSW generation than Abuja over the 20-year period (4,043,872 tonnes/year to 7,592,614 tonnes/year compared with 834,478 tonnes/year to 2,514,484 tonnes/year, respectively.

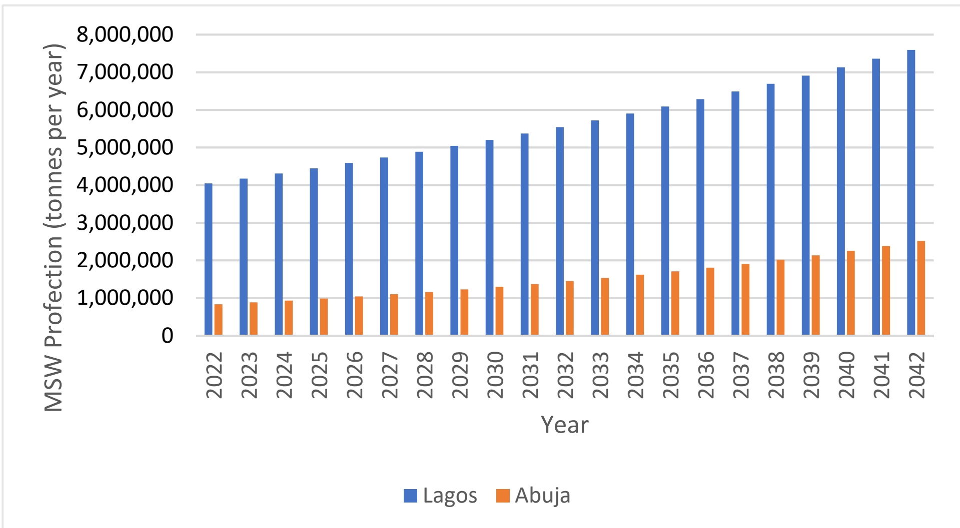

Figure 2. The projected results of MSW generation (tonnes/year) for metropolitan Lagos and Abuja from 2022 to 2042.

This gave a 20-year average of 5,642,419 tonnes/year for Lagos and 1,530,677 tonnes/year for Abuja. In both cities, the amount of waste produced is projected to rise in parallel with the annual projected population growth of Lagos (3.2%) and Abuja (5.67%) [11]. Despite Abuja having a higher population growth rate than Lagos, the former has a smaller population along with a lower per capita waste generation rate (0.66 kg/capita/day vs. 0.72 kg/capita/day, respectively). The WtE electricity generation potential for both cities is shown in Table 3. AD had the highest electricity generation potential for both Lagos (683 kWh/t of processed suitable waste) and Abuja (667 kWh/t of processed suitable waste), due to the high percentage of food waste in their waste streams. This was followed by gasification and incineration (where the differences between Lagos and Abuja were due to the calorific value of the waste) while LFGTE had the lowest electricity generation potential for both cities. This can be attributed to the fact that only 50% of the methane in the landfill gas is assumed to be captured for electricity generation while the rest is lost to the atmosphere as a fugitive air emission.

Table 3. Electricity Generated from WtE systems for Lagos and Abuja.

Electricity Generated (kWh/t of Processed Suitable MSW)	Lagos	Abuja
AD	683	667
Incineration	549	441
Gasification	626	639
LFGTE	171	135

When comparing the two cities, Lagos had a higher electricity generation potential than Abuja for all the WtE technologies except for gasification where Abuja had a marginally higher value. This difference is likely due to minor differences in waste composition.

For the economic assessment, this study uses the results of the five economic metrics (LCC, LCOE, NPV, IRR and PBP) to estimate the economic sustainability and viability of the technologies for both cities and the results are presented in Table 4 for Lagos and Abuja, respectively, with shading used to illustrate cells in each row having the highest/lowest values of the indicators.

Table 4. The Economic Performance of four WtE Systems for the processed waste in Abuja and Lagos projected over a 20-year period (spanning 2022 to 2042).

Economic Indicators	AD	Incineration	Gasification	LFGTE
LCC (USD/t)	456.4 (A)	232.76 (A)	419.58 (A)	323.71 (A)
	467.35 (L)	214.1 (L)	411.04 (L)	240.53 (L)
LCOE (USD/kWh)	0.08 (A)	0.062 (A)	0.077 (A)	0.28 (A)
	0.0803 (L)	0.046 (L)	0.077 (L)	0.16 (L)
NPV (USD/t)	617.6 (A)	475.56 (A)	610.65 (A)	−105.42 (A)
	632.42 (L)	665.42 (L)	598.23 (L)	35.75 (L)
IRR (%)	33.6 (A)	45.31 (A)	36.73 (A)	4.17 (A)
	33.6 (L)	62.84 (L)	36.73 (L)	12.55 (L)
PBP (Years)	2.97 (A)	2.21 (A)	2.72 (A)	13.39 (A)
	2.97 (L)	1.59 (L)	2.72 (L)	7.22 (L)
	Lowest			Highest

[A = Abuja, L = Lagos. Box fill indicates ranking of impact: Dark Grey = Highest-Impact, Light Grey = Lowest impact].

It can be observed from Table 4 that Incineration had the lowest LCC value for both cities (Lagos USD 214/t and Abuja USD 232/t). AD had the highest LCC with values of USD 467/t and USD 456/t, respectively, for Lagos and Abuja. LFGTE had the highest LCOE for Lagos (USD 0.16/kWh) and Abuja (USD 0.28/kWh), respectively, thus making this WtE system unfavourable from an economic perspective. However, incineration had the lowest LCOE for both cities (Lagos USD 0.046/kWh and Abuja USD 0.062/kWh).

In comparison with the electricity tariff of USD 0.1868/kWh set by [58], all the WtE systems in both cities, except for LFGTE, offer electricity generation cost with a beneficial margin to the tariff without accounting for the other revenue streams. In terms of the NPV, the results obtained were all positive for the four WtE technologies in Lagos indicating that they are economically feasible. However, in Abuja, this applied to only three of the WtE systems, as LFGTE had a negative NPV and was considered not economically feasible for the city. This could have been due to the future revenue generated not being worth more than the initial investment cost. Incineration and AD had the highest NPV for Lagos (USD 665/t) and Abuja (USD 617/t), respectively, while LFGTE was marginal for Lagos (USD35/t) and negative for Abuja (−USD 105/t).

For the IRR, Table 4 reveal that all WtE technologies are viable for the two cities as they all have positive IRR higher than the 10% discount rate except for LFGTE in Abuja where the IRR was 4%. This is an indication that investing in this technology for Abuja would be financially unprofitable. Incineration has the highest IRR for both cities (Lagos approximately 63% and Abuja approximately 45%) followed by gasification at 37% for both cities followed by AD with an IRR of 34%. LFGTE had lowest IRR both Lagos and Abuja, respectively, even though the technology in the former had an IRR (13%) that made it financially profitable. Incineration had lowest PBP for Lagos (1.59 years) and Abuja (2.2 years). This was followed by gasification with both cities having a PBP of 2.7 years. LFGTE had the highest PBP for both cities (Lagos: 7.2 years; Abuja: 13.4 years).

Overall, the results indicate incineration to be the most economically sustainable technology with the highest IRR and lowest LCOE, LCC and PBP. When comparing the two cities this technology proved to be more sustainable economically in Lagos than in Abuja. LFGTE, on the other hand, proved to be the least favourable option in both cities having the lowest NPV and IRR as well as the highest LCOE and PBP. It however proved to be more sustainable in Lagos than in Abuja. Additionally, Lagos had a higher electricity generation potential than Abuja for all the WtE systems except for gasification. The city also showed a better economic performance for all the WtE systems than Abuja in terms of the economic indicators considered (LCC, LCOE, NPV, IRR and PBP).

Sensitivity Analysis

Any LCC-based analysis is clearly dependent on assumptions made for the systems being explored. Thus, it is important to apply sensitivity analysis in order to provide insights on the influence of variables such as capital cost, O&M cost, discount rate, collection rate and energy generation efficiency on economic viability of all the WtE technologies, and the results of these are presented in this section. This was achieved using a 10% increase and decrease in the assumed values of the variables.

The capital and operating/management (O&M) costs are very difficult to predict as they depend on several factors [68–70]. The results of the sensitivity analysis on capital costs for Lagos and Abuja (Figures 3 and 4, respectively) indicate that a 10% increase in capital cost leads to 8–10% increment in the LCC, LCOE and PBP; suggesting they are very sensitive to the capital cost. The NPV was also very sensitive to a 10% change in the capital cost particularly for LFGTE in both cities with NPV results affected by approximately 25–55% (see Supplementary Materials). A similar trend was obtained for a change of 10% in O&M cost (Figures 5 and 6) although the parameters for the scenarios were found to be less sensitive to the change in O&M than capital costs.

The discount rate is a crucial factor for the economic viability of WtE projects, and a sensitivity analysis is required to determine its variation [71]. In this study, the LCC analysis was based on a 10% discount rate. The LCC of all sensitivity scenarios changes substantially once the discount rate is varied, with a higher discount rate favouring options with low costs as shown in Figures 7 and 8. For instance, a 10% increase in discount rate will reduce the LCOE, LCC and NPV for the four WtE scenarios but had no effect on the IRR and PBP for both Lagos and Abuja. For example, in the case of incineration, a 10% increase in discount rate lowers the LCOE, LCC and NPV by 4.4, 1.7 and 8.00%, respectively, for Lagos while 10% decrease raises the LCOE, LCC and NPV by 5.5, 1.95 and 8.9%, the same trend was seen in Abuja for all the WtE systems (See Supplementary Materials). There were, however, no changes in the IRR and PBP.

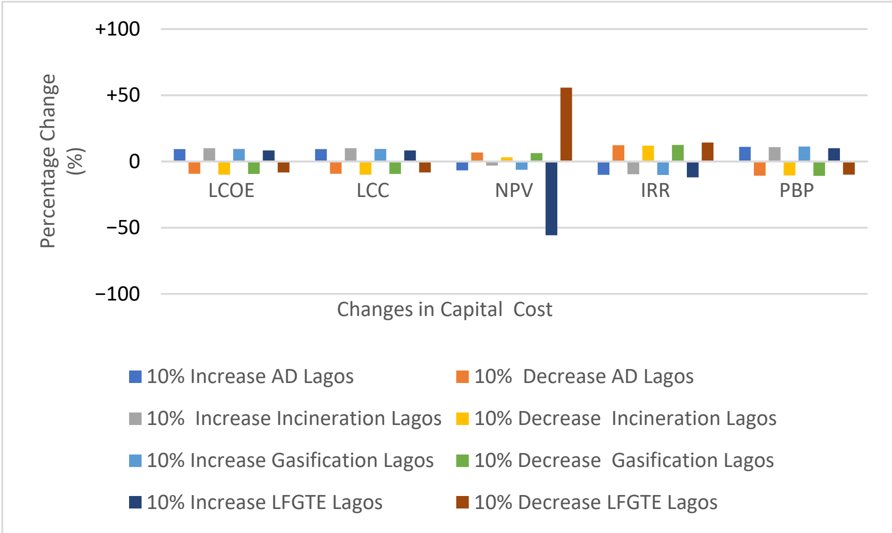

Figure 3. Sensitivity Analysis: Changes in Capital Cost for WtE Systems in Lagos.

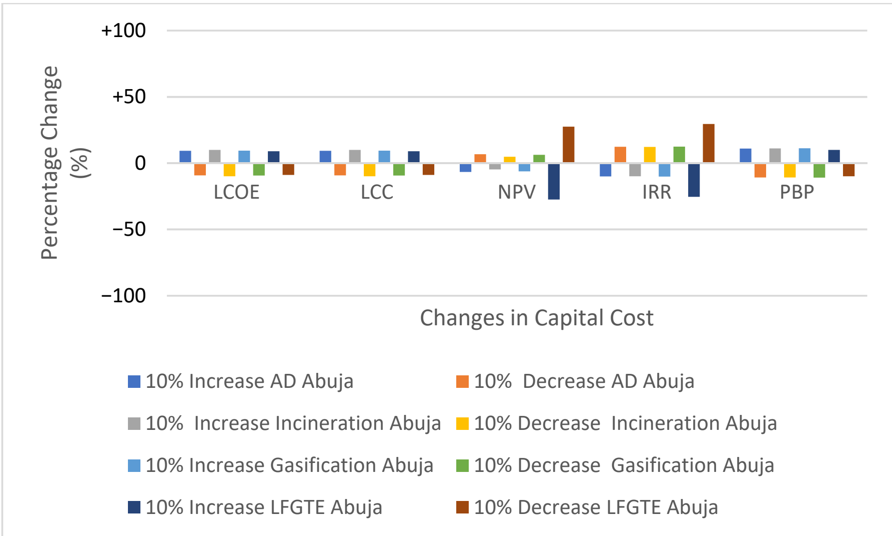

Figure 4. Sensitivity Analysis: Changes in Capital Cost for WtE Systems in Abuja.

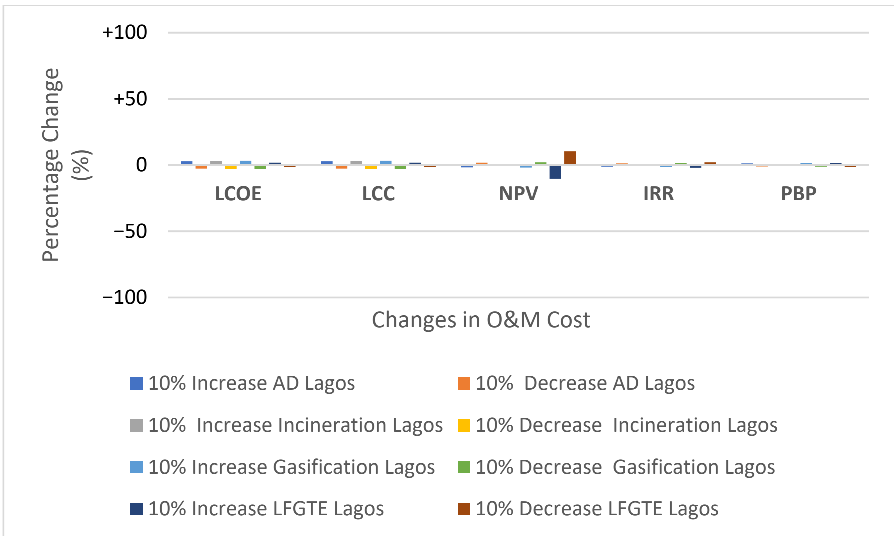

Figure 5. Sensitivity Analysis: Changes in O&M Cost for WtE Systems in Lagos.

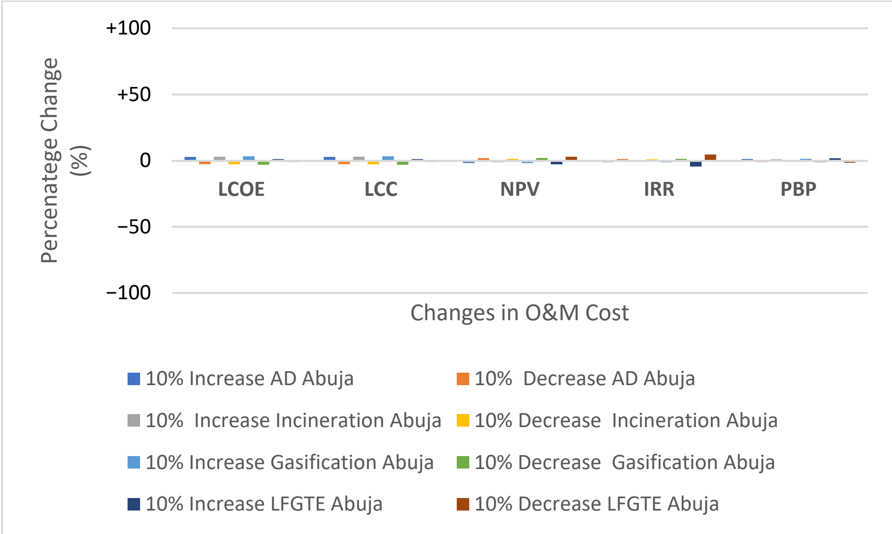

Figure 6. Sensitivity Analysis: Changes in O&M Cost for WtE Systems in Abuja.

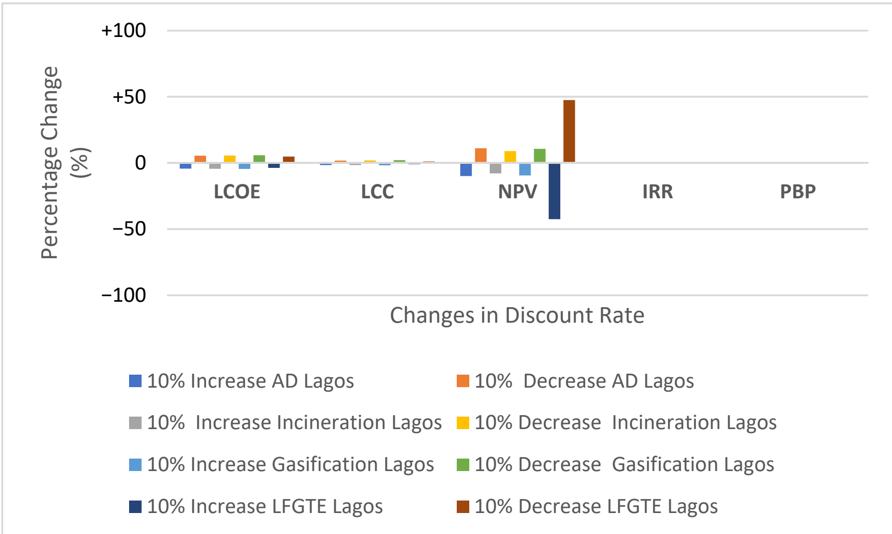

Figure 7. Sensitivity Analysis: Changes in Discount Rate for WtE Systems in Lagos.

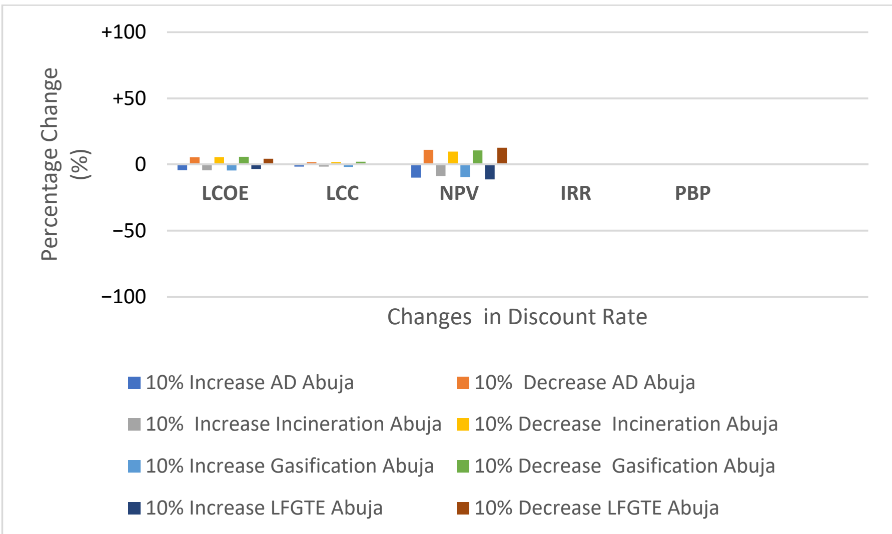

Figure 8. Sensitivity Analysis: Changes in Discount Rate for WtE Systems in Abuja.

In terms of varying the collection rate (Figures 9 and 10), AD and gasification for Lagos and Abuja showed direct changes only in the LCC and NPV, with 10% increase in both parameters when the collection rate was increased by 10% for both cities. However, with incineration and LFGTE, changes were seen in all the parameters with a 10% increase in collection rate resulting in an increase in the LCC, NPV and IRR but decreases in LCOE and PBP for both cities. For the NPV, increases with increased waste collection efficiency suggest that the WtE scenarios would become more economically viable, except for LFGTE in Abuja where even with an improvement in collection rate the technology would not be economically viable.

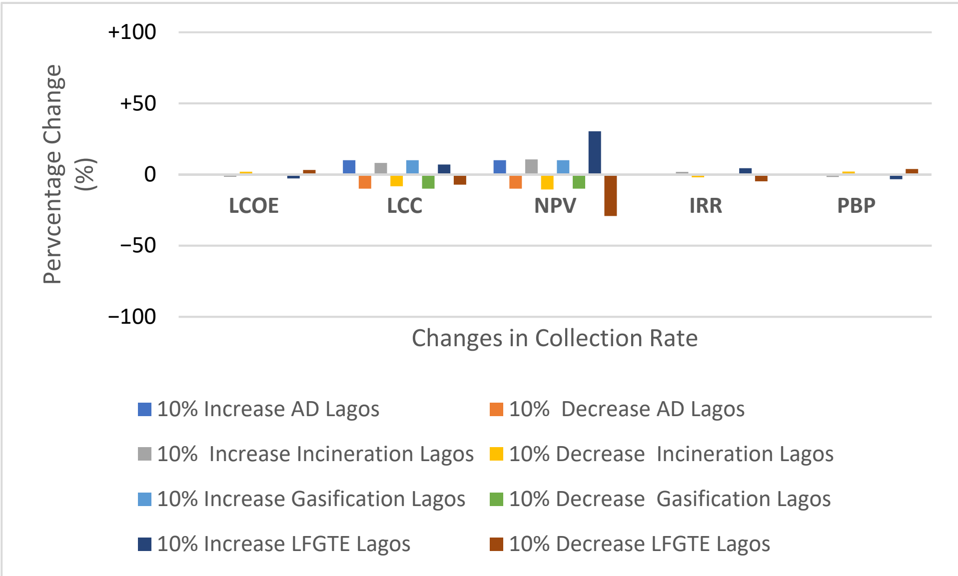

Figure 9. Sensitivity Analysis: Changes in Collection Rate for WtE Systems in Lagos.

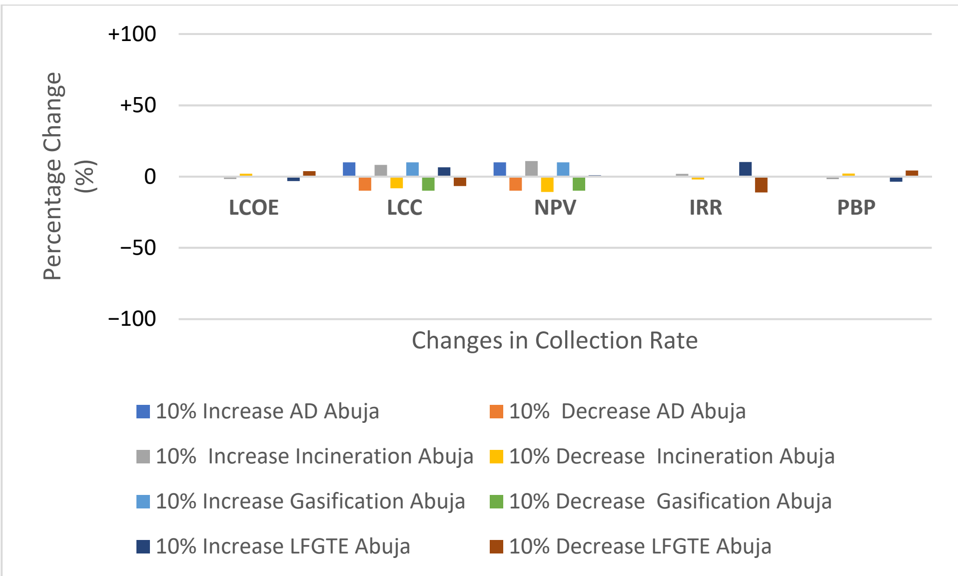

Figure 10. Sensitivity Analysis: Changes in Collection Rate for WtE Systems in Abuja.

For the electricity generation efficiency (Figures 11 and 12), the results of the sensitivity analysis indicated that for AD and gasification in both cities, a 10% increase or decrease in electricity generation efficiency generates a 10% increase or decrease in the LCC and NPV. For incineration, a 10% variation in this parameter results in a 1.7% and 1.8% decrease as well as a 1.91% and 2.04% increase in the LCOE and PBP for Lagos and Abuja, respectively.

This same variation resulted in approximately 8, 11 and 2% increases and decreases in the LCC, NPV and IRR, respectively. There were also changes observed with a 10% variation in electricity generation efficiency for LFGTE with approximately 7–9% decrease in the LCOE and PBP due to a 10% increase in electricity generation efficiency and 8–10% increase in the two parameters with 10% electricity generation efficiency decrease in both cities. For the LCC, NPV and IRR, there are increases and decreases of approx. 2%, 58% and 11%, respectively, with 10% variation for Lagos as well as an estimated 2%, 16% and 26% increase or decrease in Abuja. For both incineration and LFGTE, the results reveal that the LCOE decreases with the electricity generation efficiency. The result also shows that with increased generation efficiency, the NPV become more positive indicating a better economic viability of the projects (except for LFGTE in Abuja, which still did not become positive). The payback period decreases with improved generation efficiency.

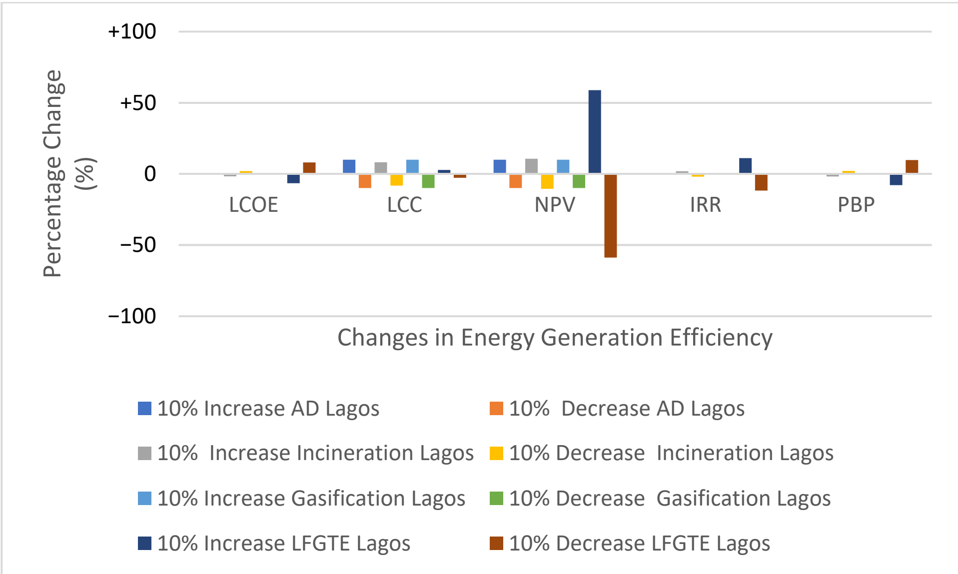

Figure 11. Sensitivity Analysis: Changes in Energy Generation Efficiency for WtE Systems in Lagos.

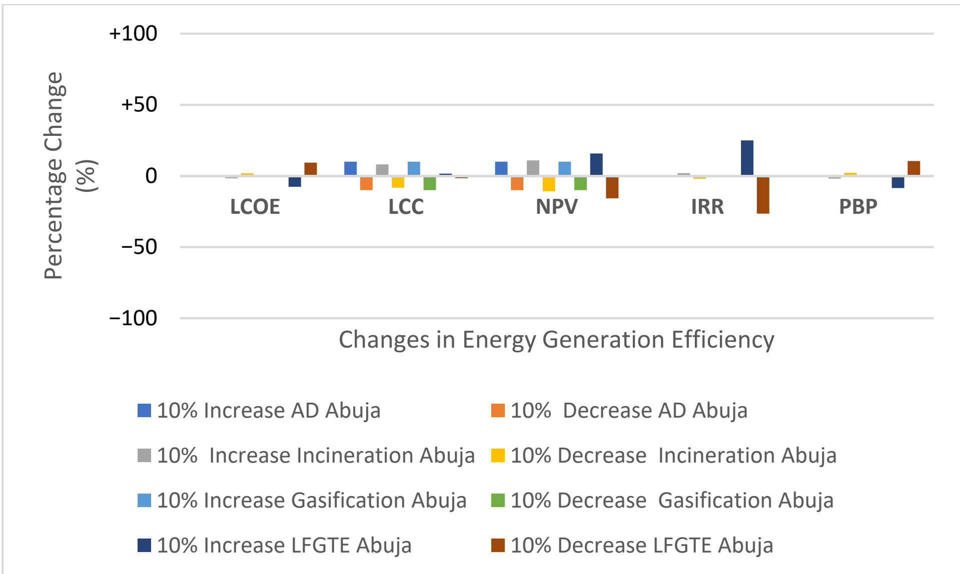

Figure 12. Sensitivity Analysis: Changes in Energy Generation Efficiency for WtE Systems in Abuja.

From the sensitivity analyses, it was clear that the LCOE and LCC were very sensitive to changes in the capital cost for the WtE systems while the NPV for the LFGTE for both cities were sensitive to all the changes in the various parameters considered. In addition, the analysis shows that the NPV value of all the WtE scenarios has an inverse relationship with the changes in the capital costs as well as with O&M costs. For the collection rate, the results of the sensitivity analyses indicate that an effective waste collection is one of the ways to ensure a viable WtE project. Given this, it is very important to employ a wide system of selective waste collection in the cities, where MSW are segregated in homes and collected by the municipal selective collection system [72]. This selective waste collection will improve on the collection efficiency and in turn ensure an effective functioning of the WtE plant. For the electricity generating efficiency, the use of improved turbines could increase the electricity generation efficiency and invariably have a positive effect on the economic viability of WtE system.

4. Discussion

This paper has presented the results of an LCC-based assessment of the potential economic impacts arising from the adoption of WtE systems in Lagos and Abuja, Nigeria. In both cities, the projected rise in the amount of waste generated was due to economic and population growth as stated by [63], and the calculations made in this study are predicated on the expectation that there will be a rise in the amount of MSW generation in Lagos and Abuja by 87% and 200%, respectively, over a 20-year period from 2022 considering both their population growth rate and waste generation rate. Such assumptions will be context-specific, of course, and may vary from city to city. For example, Huang and Fooladi [73], have estimated a growth in MSW in Tehran and Beijing of 340 and 240%, respectively. In terms of electricity generation, the results suggest AD had the highest potential and this is consistent with the findings of Ogunjuyigbe et al. [41], who concluded that AD is the optimum electricity generation technology for the South-Western and North Central parts of Nigeria (where Lagos and Abuja are located). This could be attributed to the high percentage of putrescible (food waste) in their waste streams which would yield a high generation of biogas of electricity production, particularly in Lagos. LFGTE on the other hand had the lowest electricity generating potential compared to the other WtE scenarios in this present study, and this finding agrees with findings generated by Alzate et al. [55], on the techno-economic evaluation of MSW for electricity generation in Colombia. Alzate et al. [55] noted that LFGTE had the lowest electricity generating potential compared to AD, gasification, and incineration (the highest) for three different cities in Colombia.

The ranking in this present study of incineration as being the most economically favourable WtE option based on its NPV, IRR, PBP and LCOE agrees with the findings of Abdallah et al. [74] who concluded in their financial feasibility study of WtE strategies in the United Arab Emirates that an incineration-based strategy was more financially feasible than other WtE systems such as AD. Abushammala and Qazi [75], in their study of the financial feasibility of WtE technologies for MSW management in Oman also demonstrated that incineration was the most preferred option compared with gasification and AD based on the system having the lowest LCOE of 0.06 USD/kWh; a value very similar to that derived for both Abuja and Lagos in this study. The findings of the present study that incineration had the lowest LCC when compared with other WtE systems such as AD and LFGTE were also consistent with those of Slorach et al. [28] but contradicted the findings of [41] who indicated from the perspective of economic viability that AD was the best option while incineration was the least preferred for electricity generation from MSW in Nigeria based on LCC, NPV, PBP, LCOE. For the PBP, most of the WtE systems in the two cities had a value of 7 years or less, the exception being LFGTE in Abuja, and Goosen [76] and Mabalane et al. [67] have noted that a payback period of seven or less years is considered economically feasible for any WtE project.

For the sensitivity analysis, the conclusion that LCC varies with changes in the capital cost and O&M cost as well as discount rate are all in line with the results of the sensitivity analysis conducted as part of the LCC analysis of MSW management scenarios in Mumbai, India, by Sharma and Chandel, [77]. Here, it was inferred that the net LCC of all scenarios changed significantly under the effect of variation in the discount rate and a higher discount rate resulted in a lower LCC. In the research reported here, the finding that LCC for all scenarios reduced with a decrease in capital and O&M cost (and vice versa) was in line with the findings of [77]. Additionally, the increase in electricity generation efficiency resulting in increases in the NPV can be related to the finding of Ayodele et al. [29] where it was noted that the NPV becomes more positive with an increased generation efficiency, thus indicating better economic viability for the WtE systems. The implication of this is that WtE technologies will be more profitable if the electricity generation efficiency is increased by the application of innovative and improved technology to the engine design [29].

The similarity in the LCC results for the two cities is of interest in the present study. This implies that the geographic and socio-economic differences that exist between the two cities did not have any considerable effect on the possible economic impacts of adopting WtE for both. This similarity could, at least in part, be attributed primarily to their similar waste compositions, and it is possible that similar findings will be expected for other cities of the country considering that local differences may not influence the economic impacts from different WtE scenarios. Huang and Fooladi [73] came to a similar conclusion with their work on the economic viability of solar thermal systems in cities as diverse as Beijing and Tehran.

However, it does need to be noted that there were various assumptions in the analysis presented here that can be open to question. For example, it was assumed that the MSW composition is consistent throughout the study period, while in reality it could be influenced by many factors such as culture and tradition, economic development, and climatic conditions [5]. Such variation is important as, for instance, in the case of AD and LFGTE, it may generate uncertainty in biogas production. This is because biogas production for these WtE systems is supported by the waste stream with high moisture content and organic component such as food waste and any change to the flow of such waste due to climatic condition may have effects on biogas production [29]. Additionally, variation in capital cost and O&M cost of conversion into electricity with time may also affect the overall economics of the WtE scenarios. Given that most of the parameters used in this present study were assumed to be constant throughout the entire 20-year period, it is important for future studies to consider the uncertainty factors in waste composition of the MSW, landfill gas collection efficiency as well as variation in conversion technologies [29].

Additionally, the WtE systems were researched as standalone scenarios for the purpose of simplicity, and this was considered appropriate for such a prospective analysis conducted in the absence of site-specific data. However, in practice it may be better to have a mix of WtE technologies on each site. Future research could, therefore, explore the economic benefits of such 'hybrid' and/or optimised applications of these WtE systems that sees the strength of one balancing the weakness of the other to enhance the utilization of waste. For example, Mabalane et al. [67] concluded that a combination of two WtE systems (AD and gasification) would yield positive results on the whole set of financial indicators, thus increasing the overall financial and technical feasibility of the WtE system.

Such an extended analysis could also include value recovery from co-products of the WtE systems such as recyclables and digestates, all of which have been ignored in the study reported here. For effective adoption and implementation of these WtE scenarios in Nigeria, adequate policies and regulations must be put in place. This should come with the government creating an environment that will encourage local and foreign investors to participate in such projects through clear strategies for legislation and policy implementation and enforcement.

This is followed by the government strengthen financial institution as well as providing adequate incentives such as subsidies and carbon credit to attract the necessary private sector investments. Given this, the implementation of WtE is one strategy that should be integrated into policies such as the Renewable Energy Master Plan (REMP) which seeks to increase the supply of renewable electricity to 36% by 2030 [78], as well as that of the National Environmental Sanitation Policy (NESP) aimed at making the environment clean and healthy as well as safeguarding the welfare of the public by making solid waste management methods economical, efficient and sustainable [79]. According to Ogbonnaya et al. [80], this integration can also serve as an opportunity for investments that will encourage not only local participation but that of foreign as well in electricity generation. For a WtE system such as incineration which was considered as the most favourable from an economic perspective, government could introduce tipping fees which will also be of huge financial benefits to the operators of the WtE plants given that large amount of wastes will be processed. However, this also depends on certain legislations coming into effect in the future as Nigeria's waste management sector is still at a developing stage. So far, the poor implementation of these policies has been a major challenge in both sectors. Regardless, it is important that appropriate policies based on the best possible analysis particularly that of economic analysis are made when selecting the appropriate WtE technologies. For this reason, LCC analysis can assist the decision-making process in terms of cost estimation and planning of MSW management /WtE systems [77], and the introduction of appropriate, sustainable WtE technologies in combination with other MSW management practices such as enhanced collection systems should be encouraged as part of an integrated solid waste management strategy. This is relevant in supporting some of the Sustainable Development Goals (SDGs) such as clean energy (SDG 7), good health and well-being (SDG 3), quality education (SDG 4), economic growth (SDG 8) [81] as well as SDG 11 (sustainable cities and communities) and SDG 12 (responsible consumption and production) [82].

The research reported here has demonstrated that WtE not only provides an effective strategy to diversify the energy mix but also can be economically profitable under certain operating and market conditions. Given that the implementation of this strategy can be confronted with numerous challenges, there are some relevant recommendations that can be made, and these include:

- Good quality data are required for proper decision-making as the reliability of feasibility studies can be affected by lack and/or uncertainties of local data.
- The employment of economies of scale for WTE facilities whereby decreasing capital and operating costs are reduced by increasing plant capacity.
- The establishment of effective legislative and institutional frameworks involving relevant stakeholders should be made to promote the implementation of WTE systems and encourage private sector participation.
- For WtE systems such as AD, more flexible criteria are required regarding the use of fertilizers originating from waste treatment processes. The production of such fertilizer from the digestate significantly improves the economics of AD systems.
- For the success of WTE systems, it is essential that participation rate in source separation programs is increased through incentives and awareness programs managed by municipalities and non-profit organizations.
- It is crucial to build a skilled educated workforce able to operate the WtE systems.
- Public awareness campaigns should be conducted to alleviate community concerns about the environmental impacts of WtE facilities.
- The Federal Government in Nigeria should embark on pilot WtE projects first before introducing large scale projects. This is due to the high investment cost required to establish a large scale WtE facilities as well as the lack of technological knowledge and experience for handling and operating such facilities.
- Relevant research institutions should be empowered through adequate budget allocation to explore WtE in Nigeria.

5. Conclusions

In conclusion, this study found that over a 20-year period (spanning 2022 to 2042), the waste generation in Lagos was approximately four times more than that in Abuja with cities showing 87% and 200% increase in waste generated due to economic development and population growth. It then goes on to reveal that AD was the highest electricity generating potential amongst the four WtE systems considered for both cities while LFGTE had the lowest electricity generating potential. In terms economic viability, all the WtE systems in Lagos were considered viable while all except for LFGTE in Abuja were viable. Overall, the study showed that incineration was the most favourable WtE system from an economic perspective. The sensitive analysis results on the other hand indicated that the LCC was most sensitive to variation to the capital cost and was least sensitive to O&M costs.

In addition, the findings from the present study indicate that differences between the two cities did not have any substantial effect on the economic impacts of adopting WtE in Lagos and Abuja. Finally, this present study provides important quantitative insights and informative results for decision-makers for the optimal investment in WtE systems in Nigeria.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/su142013293/s1, Table S1: The parameters for the projection of the Population and Waste Generated and Collected; Table S2. The waste fraction for WtE Processes; Table S3. The energy generating potential of the WtE Processes; Table S4. The average population, waste generated and wasted collected over a 20-year period; Table S5. The amount of waste processed for the WtE systems; Table S6. The amount of energy generated from the WtE systems; Table S7. The plant size/kW capacity for the WtE systems; Table S8. The economic assessment for the WtE systems for Lagos; Table S9. The economic assessment for the WtE systems for Abuja; Table S10. The economic assessment on a per tonne basis for the WtE systems for Lagos; Table S11. The economic assessment on a per tonne basis for the WtE systems for Abuja; Table S12. The projected population for Lagos and Abuja; Table S13 The projected waste generation for Lagos and Abuja; Table S14 Sensitivity Analysis: Variation of Capital Cost of WtE systems for Lagos and Abuja; Table S15 Sensitivity Analysis: Variation of O&M Cost of WtE systems for Lagos and Abuja; Table S16 Sensitivity Analysis: Variation of Discount Rate of WtE systems for Lagos and Abuja; Table S17 Sensitivity Analysis: Variation of Collection Rate of WtE systems for Lagos and Abuja; Table S18 Sensitivity Analysis: Variation of Energy Generating Efficiency of WtE systems for Lagos and Abuja; Table S19. The Waste Composition of Lagos and Abuja (after [1] and [2]; complied by the authors). References [43,45] are cited in the supplementary materials.

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