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TECHNO-ECONOMIC ASSESSMENT OF WASTE-TO-ENERGY TECHNOLOGIES IN GHANA

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Abstract - To reduce environmental degradation and improve energy security in Ghana, waste-to-energy (WtE) technologies will play a key role. This paper assesses the feasibility of municipal solid WtE technologies in Ghana using Accra as a case study. Technical feasibility, economic feasibility, and barrier analysis have been carried out to assess the feasibility of municipal solid WtE conversion technologies. Data from the Environmental Protection Agency of Ghana is used for the techno-economic analysis and a face-to-face interview is used to assess the barriers to the deployment of WtE technologies in the country. A power generation potential (PGP) of 530 kW/tMSW and an energy recovery potential (ERP) of 41.68 kWh/tMSW is recoverable from the waste in Accra when biochemical energy conversion is applied and a PGP of 1320 kW/tMSW and an ERP of 106 kWh/tMSW is recoverable when thermochemical energy conversion is applied. The economic analysis showed that the initial investment cost of WtE technologies is high, however, implementation of this technology is likely to have a good payback period of 8 years for the thermochemical processes and 4 years for the biochemical process. Additionally, the net present value and the sensitivity analysis conducted shows that WtE technologies are economically feasible in Ghana. The barrier analysis suggests that the main hindrance to the deployment of WtE technologies in Ghana is the high upfront cost.

Keywords: Anaerobic digestion; Gasification; Ghana; Municipal solid waste; Waste-to-energy technologies; Pyrolysis.

1. INTRODUCTION

The proliferation of municipal solid waste (MSW) and its attendant environmental impact has become a concern over the past decades [1]. High population growth rates, growing urbanization and industrialization, rapidly growing waste generation and characterization patterns, as well as increased standard of living, have resulted in the mass generation of MSW [2]. It is reported that nearly three-fourths of MSW is deposited in landfills or dump sites, and about a quarter of the total is still not being disposed of properly1. Developing countries with Ghana, not an exception are major integrators of this method of waste management because these landfills are a cheaper way of disposing wastes [3]. However, in Ghana, waste collection and transport, poor management and design of landfills still remain a huge challenge. Landfill wastes are a major source of methane (CH_4) emissions and other gases that affect the atmosphere to a higher scale, causing groundwater pollution, landfill fires and serious health problems.

Though MSW management is a major challenge, there is a great potential when these materials are reused, recycled, or properly managed [4]. Tapping into MSW to generate energy seems to be one of the most attractive options for energy supply in the future [5]. Modern energy access and economic development is a huge challenge in sub-Saharan Africa (SSA) [6]. The energy provided by MSWs has a great prospect especially in meeting local energy needs especially in SSA countries like Ghana where universal electrification is yet to be attained. Therefore, waste-to-energy (WtE) technologies which are now widespread in the world becomes vital for addressing sustainable Solid Waste Management (SWM). Though new treatment technologies have gained maturity in developed countries [7], these facilities cannot simply be transposed in developing countries because the performances of these technologies depend on the composition of the fuel used.

In order to curb the waste problem effectively, different ways have been adopted. This has led to the invention of WtE management techniques to retrieve the economic value from the waste. In the last three decades, plethora of studies have examined the societal perceptions towards a menu of energy technologies. The first challenge is the conceptualization of social and public acceptance of these technologies. This is because of the conception that WtE technologies are too expensive. The perceived restriction has caused many of developing countries to sideline strategies that can be used to harness the energy in these wastes, however, these new treatment technologies are now being developed on a smaller-scale to be applied in solving the problem of waste disposal as well as to tap valuable energy from the wastes [8].

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[1] www.gasification-syngas.org

MSW management is an essential element towards developing sustainable cities. It comprises the segregation of waste, storage, collection process, relocation of the waste, carry-age, processing of waste, and disposal to reduce its negative impacts on the environment. According to Ref. [8], the processes can be categorized as: biochemical and thermochemical. The biochemical process involves the use of anaerobic digestion technologies to generate biogas whereas the thermochemical processes are related to incineration technologies, gasification, pyrolysis, as well as landfill gas utilization technologies along with biorefineries [8]. Today, the various technologies are being discovered for the evaluation of energy recovery potentials from waste, and efforts are being made to improve existing technologies. This notwithstanding, the choice of a suitable WtE technology is not an easy task since the production of solid waste is determined by seasons and socio-economic levels of producers/consumers and thus should be selected based on the waste quality, composition assessment, as well as economics. Consequently, it is important to evaluate the techno-economic feasibility of WtE technologies at country level.

In literature, there have been a plethora of studies investigating the technical and economic potentials of WtE technologies in different parts of the world [9,10,19,11–18]. In Ghana, there have also been some studies on WtE over the years. Here, a snapshot of a few is taken. Abalo et al. [20] reviewed the gains from solid waste management in Ghana and suggested that with the application of appropriate technologies, the wastes generated in Ghana has the potential to generate renewable power and increase rural incomes. Ofori [21] suggested that around 8.7 million households in urban Ghana can have their monthly electricity consumption covered by using an estimated 2,975.6 million m3 of methane (CH4) biogas which can be technically generated from municipal solid and liquid waste, forestry residues, animal manure, and crop residues. Wikner [22] compared the benefits of WtE management systems and opined that incineration scenario produced maximum electricity of around 191000MWh/year. Dery et al. [23] conducted a waste audit in Ghana and suggested that solid waste compositions include papers, plastics, and food; thus, suggesting a strong potential for recycling. Mohammed et al. [24] examined the economic potential for a 9000 m3 biogas in Ghana and reported that biogas used for cooking is economically viable with a payback period of 5 years. Miezah et al. [25] argued that with the exception of Tamale, the average household waste generation rate among Ghanaian cities was high at around 0.72 kg/person/day. Abiti et al. [26] x-rayed the composition of MSW in Ga East Municipal Assembly (GEMA), Accra, Ghana and find that 48.8% of the MSW were organic materials, while the remaining 51.2% were inorganic materials. Samwine et al. [27] assessed the challenges and prospects of MSW management as well as the institutional framework to ensure environmental sustainability, while Yoada et al. [28] analysed the domestic waste practices, disposal methods, and the urban community perceptions on waste and human health.

From the foregoing literature, it is clear that studies aimed at evaluating the techno-economics of WtE in Ghana are limited. This paper addresses this knowledge gap by introducing one of the earliest case studies to evaluate the technical and economic implications of WtE technologies in Ghana, and in extension, sub-Sharan Africa. It has been observed that economic development contributes to environmental degradation as changes in lifestyle practices lead to increased consumption of goods/services which in turn, generates a large volume of MSW [29]. In the last few years, Ghana has recorded congestion in the cities and an increase in MSW due to the rise in urban population growth [30]. This study, therefore, seeks to examine the techno-economic feasibility of various WtE technologies in the market and assess the challenges of Ghana not adopting these technologies. To this end, Accra municipality is chosen as a case study because of the large volume of MSW that is generated and the poor waste management systems in the municipality. This study would, therefore, serve as a reference point for the government and waste management organizations in the country to reconsider their decisions on harnessing the energy potential of MSW and also lead to a clean environment devoid of health problems at the municipality.

The remainder of this paper is organized thus: section 2 presents a brief review of literature on WtE technologies. Section 3 describes the methodology employed in the study. Section four presents the results and analysis, while a few conclusions are drawn in section 5.

2. REVIEW OF WTE TECHNOLOGIES

2.1. Solid WtE treatment technologies

These technologies are used in the conversion of solid WtE like electricity, steam or heat. They are grouped into biochemical technologies and thermochemical technologies [31].

2.1.1 Biochemical technologies

These technologies convert WtE by using microorganisms to breakdown solid waste. An example of biochemical technology is anaerobic digestion. This is a biochemical process in which biogas is produced from biodegradable or organic material by microorganisms in the absence of oxygen [31]. The anaerobic digestion process is yields maximum gas especially if the wastes are containing a high quantity of organics. Primarily, this process generates CH_4, carbon monoxide (CO), and as well as a little fraction of other gas gases. Anaerobic digestion basically involves 3 steps. organic material is made by sorting the wastes, segregating them and reducing their sizes in the first step. Secondly, favourable ambient conditions are provided to facilitate the digestion process by microorganisms with pH up to 6.7 and maintain temperature around 55-60^{0}C. These components are well combined for anout 5-10 days. However, in colder climate, the slurry is combined at low temperature for a longer time. Finally, the residual sludge is disposed of in the third step.

The microorganisms which have a vital role are grouped into two: first is the acid-forming microbes and the second is the CH_4 forming microbes. The acid forming group is employed in breaking complex organic components into simple acids whereas the CH_4 forming group is employed to convert simple acids into CH_4. The CH_4 forming bacterial group is sensitive to different environmental conditions; temperature is the core component, control of oxygen and also prevention of toxic substances into the system. Generation of CH_4 can occur in two ways; it may be collected directly from the landfill sites (i.e. bioreactor landfill or sanitary landfill) or pre-treated refused in digesters. Digesters are dived into high-solid and low-solid digesters. The low-solid digester is well established as compared to high-solid digester but it requires a high amount of H_2O added to waste. Three by-products are obtained from this process namely, liquid digestate, fibre digestate and biogas. The biogas obtained is a mixture of 60% and 40% of CH_4 and Carbon Dioxide (CO_2) respectively, with traces of Hydrogen Sulphide (H_2S) and Ammonia (NH_3) [32]. The advantages of this technology are that it requires low capital and operational costs in comparison with the thermal technologies. Additionally, if the system is well maintained and controlled, it ensures a minimal level of environmental pollution. The key disadvantage of this process is that it generates contaminants that have a high proportion of metals like mercury.

2.1.2. Thermo-chemical technologies

These technologies convert WtE by the application of heat and chemicals. Examples are Pyrolysis, gasification, plasma arc gasification etc [33].

2.1.2.1. Pyrolysis

Pyrolysis involves the heating of MSW in an environment which is oxygen-deficient [32]. Pyrolysis thermally decomposes solid waste into solid char and volatile gases which consist of carbon and inorganic compounds in the feed. The Waste is heated at temperatures between 550-1300°F in the absence of oxygen in order to generate oils and syngas. There are two kinds of pyrolysis: slow and fast pyrolysis. The slow Pyrolysis requires that the biomass is heated gradually (400-800°C) for a relatively long time. The slow pyrolysis results in the production of more charcoal and tar and a small amount of gases. The fast pyrolysis yields more liquid or gases and less charcoal and tar. It involves the speedy heating of the biomass to an acceptable temperature of 650°C which is held constant at that temperature for some few seconds. Pyrolysis generates fewer air emissions due to the oxygen-deficient environment needed and allows easy control of air contamination as the Syngas is purified after production to take out all contaminant. However, it is a complex technology to deploy on a large scale and pyrolysis process also produces hazardous compounds and pollutants such as CO, hydrogen (H_2), and hydrocarbons.

2.1.2.2. Gasification

Gasification is the conversion of carbonaceous material such as MSW through the addition of heat (generally above 600C) in a starved-oxygen atmosphere by a physical and a chemical process [33]. Oxygen levels are kept low to prevent immediate combustion; instead, the carbon-based fraction of the solid waste decomposes into an end product of synthetic gas (syngas gas) made up of H_2, CO_2, CO and other contaminants such as slag and ash. Through an advanced pollution control system, the contaminants are removed and the syngas obtained is used as a fuel to power combustion engine or turbine to generate electricity. The impurities, like tars and articulates are removed from the end product. The conventional separation processes for the removal of particulate and tar are scrubbers, filters, cyclones, and electrostatic precipitators. The gas produced by this gasification process has heat content of about 25% to 40% like that of natural gas if ambient air or oxygen-rich air is used respectively. In the gasification process, MSW serves as a feedstock for the chemical conversion process.

Gasification is not an incineration system but a combustion technology, where efficient energy is recovered from the system [33]. This technology is more attractive due to the high production of energy. Gasification is also an improved pyrolysis system, which uses less Oxygen (O_2) to generate enough heat such that the system is self-sustained. In a conventional gasification process, the system consists of solid waste drying, pyrolysis, oxidation and reduction steps. Large hydrocarbon molecules of biomass are breakdown into smaller ones in the oxygen-starved pyrolysis chamber. This results in a volatile compound of biomass under a temperature ranging 400-650°C which is being removed from the char. Gasification technologies are currently of three types namely, Fluidized bed combustion, High-temperature gasification technology which has a commercial scale value, and the fixed bed. Gasification process is economical on a smaller-scale and emits fewer toxic chemicals. However, this technology is relatively not efficient and the CO released into the atmosphere is harmful and can cause health discomfort.

2.1.2.3. Plasma Gasification

In Plasma gasification, hot plasma gas is fed into the reactor to gasify MSW and to melt down the inorganic materials [33]. The gasifier is then injected with a carbonaceous substance such as coke and coal. This carbonaceous substance reacts rapidly with oxygen to generate heat for the pyrolysis reactions in an oxygen-deficient atmosphere. The reactor is fed with steam to speed-up syngas reactions. Heat with extra heat from the plasma arc torches for the pyrolysis reactions is produced from the combustion reactions. Plasma which is the fourth state of matter is produced when an electrical discharge flows through a gaseous medium. Plasma is also known as an ionized gas such as the lightning flash in the atmosphere. This is why Plasma as very feasible in treating waste. Plasma torches are used when plasma is needed at atmospheric pressure. The high temperature ranging from 2000-5000°C (3632-9032°F) of Plasma gasifiers makes it suitable to treat MSW due to the heterogeneous nature of MSW which is difficult to be gasified by other gasifiers. Hence plasma gasifiers are more efficient in treating MSW as compared to other gasifiers.

Plasma arcs or torches with its high energy input can be adjusted depending on the quantity and quality of MSW fed into the Plasma gasifier. The high temperature needs to be maintained for the gasification reactions to breakdown the chemical bonds of the MSW and subsequent conversion into syngas. Plasma technologies though, new, yet has been in use for over 30 years. It has been deployed by industry predominantly to ensure the safe decomposition of hazardous waste as well as the melting of ash from incinerators into a safe, non-leachable slag. The Plasma Arc Gasification is characterized by its efficiency and It requires limited land resources. Its key disadvantage is that the technology is capital intensive.

In Ghana, both biochemical and thermochemical WtE technologies are technically feasible. However, thermochemical processes such as gasification and plasma arc gasification are more expensive and are used principally in developed countries, therefore it may not be economically feasible for implementation in developing countries such as Ghana. This notwithstanding, the Pyrolysis technique has been found to be more feasible technically and economically in developing countries. Also, biochemical techniques (biomethanation or anaerobic digestion, landfill gas utilization) are more feasible in developing countries and have found implementation even in Ghana for the past few years. Therefore, this study would estimate the general technical energy-producing potential and the economic analysis of both biochemical and thermochemical technologies to assess their feasibility in Ghana.

3. METHODOLOGY

This section presents the methods used in the assessment of the techno-economic feasibility of WtE technologies in Ghana. The various WtE technologies are analyzed to assess the potential of energy production from MSW based on different conversion technologies. Their economic analysis, as well as barrier analysis, are also carried out.

3.1. Description of the study area

Accra is a city located in the coastal area of Ghana and has an estimated population of around 3 million persons [34]. Accra covers a land area of around 894 km^2 which is approximately 25% of the Greater Accra Region total landmass. The city's population has been growing on average of 4.2% per annum owing to the increased rural-urban migration [35]. Ghana's capital city, Accra, is the city considered for the energy potential estimation and technical feasibility assessment. This is because the city has available data for the feasibility analysis. Moreover, it is the highly populated area in Ghana and therefore a major producer of MSW. Its population distribution patterns, livelihoods, as well as its prominent role within the Ghanaian economy also makes it a good case study for the country. Figure 1 shows the map of Accra.

Figure 1. Map of the study area (Accra) [36]

3.2. Data collection

The energy potential of WtE technologies has been estimated in this work. A detailed study of solid waste data collected from the Environmental Protection Agency of Ghana has been done. There is unavailability of current waste data in Ghana, thus, the 2010 data on the composition of waste, method of waste collection, population and the amount of waste generated is been used for the analysis. The data were organized, analyzed and presented in tables, pie charts, bar charts in the form of average values and percentages.

Table 1. Data collected from Environmental Protection Agency [37]

Characteristics	Accra
Population (thousand)	1904
MSW generated (kg/capita/day)	0.79
MSW generated (tons/year)	1500
MSW collected (tons/day)	950
Percent collected (%)	63
Collection cost (US$/ton)	10.0
Disposal cost (US$/ton)	2.0
Total cost (US$/ton)	12.0

3.3. Technical Analysis

The amount of biogas emission from the waste generated in Accra is estimated using the US-EPA Landfill Gas Emissions Model (LandGEM). The LandGEM software is a first-order decomposition rate equation used for quantifying emissions generated from of MSW landfills. The software provides a relatively simple method to estimating landfill gas emissions. The software is an automated estimation tool embedded with Microsoft Excel interface which can be applied to estimate the emission rates for total landfill gas, carbon dioxide, methane, non-methane organic compounds, and individual air pollutants from MSW landfills. The software comprises of two sets of default parameters: the Clean Air Act (CAA) and the inventory defaults. The CAA defaults are developed based on the US federal regulations for MSW landfills as outlined by the CAA. It can also be used to determine whether a landfill is subject to the control requirements of the US federal regulations. The inventory defaults are based upon the EPA's emission factors which can as well be applied in generating emission estimates for in the absence of site-specific test data such as in Ghana. For detailed documentation of the LandGEM software, see Ref. [38].

Accordingly, the MSWs from the study location are classified as organic matter for the biochemical energy potential estimation and inorganic matter for the thermochemical energy potential estimation. The waste data is shown to have 0.79 kg/capita/day MSW generated and contains 950 thousand tons of waste and it consists of 60% organic matter and 40% inorganic matter [37]. Therefore, the waste contains 570 thousand tons of organic matter and this has been used in the LandGEM software to estimate the biogas emissions for the biochemical energy potential. For the energy potential in the thermochemical energy conversion, the estimation is done using the dry municipal waste constituent of 380 thousand tons.

The biochemical energy potential is calculated using Equation 1 and 2 [39].

$$PGP = \frac{BGS \times NCV \times r}{1000} \qquad (1)$$

$$ERP = \frac{BGS \times NCV}{0.042} \qquad (2)$$

Where:

PGP is the Power Generation Potential (MW/tMSW); ERP is the Energy Recovery Potential (kWh/tMSW); NCV the Net Calorific Value (Kcal/kgMSW)

(In the biochemical potential, NCV lies in the range 0.194–0.242 kW/m^3 of biogas) [40]

BGS is biogas (m^3 of CH_4/year) and it is calculated from the LandGEM software using Equation 3.

$$BGS = \sum_{i=1}^{n} kLoMi(e^{-kt}) * (Tmsw/y) \qquad (3)$$

The parameters used in the LandGEM software are:

Ŋ=conversion efficiency of biochemical process; k = methane generation constant; L_0 = methane generation potential; Mi = mass of waste in i section (Mg); ti = age of the i increment section; TMSW/y = total production of MSW per year (tMWS/year).

The thermochemical energy potential is also estimated using equation 4 and 5 [41]

$$RP = 1.16 \times NCV \times MSWx \qquad (4)$$

$$PGP = \frac{0.048 \times NCV \times MSWx \times \eta Th}{1000} \qquad (5)$$

Where:

PGP is the Power Generation Potential (MW/tMSW); ERP the Energy Recovery Potential (kWh/tMSW); NCV the Net Calorific Value (Kcal/kgMSW);

(For thermochemical potential, NCV also lies between 0.194–0.242 kW/m^3 of biogas, [40].

MSWx = Municipal solid waste dried quantity (tons/day)

ηTh = Conversion efficiency of thermochemical process [42]

3.4. Economic analysis

In the economic analysis, the capital cost and operation cost of both biochemical and thermochemical WtE technologies are estimated and financial analysis is carried out to calculate the NPV, the payback period, and the internal rate of return using the power capacity of waste in the study area. The annual power generation of each technology is estimated using the plant efficiency and the amount of power generated within the year. These estimates are then used in financial analysis. The financial model also considers the potential income from selling the electricity produced and the benefit of landfill savings. In other to estimate the capital cost of the various WtE technologies, the data for the unit price of the technologies were taken from the US industry trade journal [43], that gave the typical cost range of WtE technologies in developing countries like Ghana. The power generation capacity is then used to estimate the total capital cost. The operation and maintenance (O&M) costs are estimated using the lifespan of WtE plants as 25 years. The maintenance cost is assumed to be 6% of the capital cost for biochemical technologies and 11% of the capital cost for thermochemical technologies. According to the literature [44], these costs are around 3% and 8% for biochemical and thermochemical technologies respectively, but the additional 3% here includes the cost of emissions monitoring which is a requirement of the European Union [44], waste management cost, and cost for contingencies. The operation cost which is the labour cost is assumed to be the pay of 24 workers.

Table 2. Data used in the biochemical and thermochemical calculation

Parameter	Value
Biochemical potential	
NCV	0.218
k	0.04
Lo	100
Ŋ	30%
Thermochemical	
NCV	0.242
MSWx	380
Ŋ	30%

Table 3. Capital Cost of WtE technologies [43]

Capital cost of WtE technology	Unit cost per kW for low range (US$)	Unit cost per kW for high range (US$)	Average cost per kW (US$)
Anaerobic digestion	7,000	10,000	8,500
Pyrolysis	8,000	11,500	9,750
Gasification	7,500	11,000	9,250
Plasma Arc Gasification	8,000	11,500	9,750

3.5. Net Present Value (NPV)

The NPV is calculated by taking the difference between the present values of cash inflows to the present value of cash outflows (Equation 6)

$$NPV = \sum_{1}^{T} \frac{C_w}{(1+r)^t} - C_i \qquad (6)$$

Where C_w is the net cash inflow during period t, C_i the initial investment cost, r the discount rate, t the number of time periods, and T the life cycle of plant.

3.6. Internal rate of return

This is the discount rate that makes the NPV zero and it is calculated using Equation 7.

$$\sum_1^T \frac{C_W}{(1+r)^t} - C_i = 0 \qquad (7)$$

3.7. Levelized cost of Electricity (LCOE)

In calculating the LCOE, Equation 8 is used to estimate the sum of cost over the lifetime of the plants over the sum of the power output of the plants over their lifetimes [45].

$$LCOE - \frac{\sum_1^T \frac{I_i+OP}{(1+r)^t}}{\sum_1^T \frac{E_t}{(1+r)^t}} \qquad (8)$$

Where OP is the operation cost

3.8. Barrier analysis

In the analysis of the barriers to the adoption of WtE technologies in Ghana, a survey was conducted through face-to-face interviews and phone calls with 5 experts in WtE technologies; 2 managers of waste management institutions; and 13 workers at waste management institutions. Solid waste management sites in Accra were visited to assess the barriers or challenges to the deployment of WtE technologies in the country. In the interview, respondents were asked various challenges that have hindered the implementation of WtE technologies in developing countries. The results were then analyzed using Microsoft Excel. The questionnaire used for the barrier analysis is given in Appendix A.

4. RESULTS AND ANALYSIS

In this section, the results of the economic and technical feasibility analysis of the various WtE technologies are presented. The results of the barriers to adopting WtE technologies in Ghana is also presented and analyzed.

4.1. Average composition of solid waste

Figure 2 illustrates the average solid waste composition in the study area. The waste in the study area has a high percentage of organic matter and inorganic matter that can be used for both biochemical and thermochemical plants respectively. It can be observed that organic wastes are the highest with a share of around 60%, while glass is the lowest with a share of just around 2%.

4.2. Estimation of the sources of solid waste

The sources of generated waste in the study area is shown in Figure 3. The solid waste from the figure shows that a high percentage of the waste that would be used for the WtE conversion would be collected from the market, lorry parks and public areas, followed by the solid waste from households. It can also be seen that factories/industries produce the least waste materials in the city. Thus, the current result suggests that there is a need to establish stringent measures for MSW management across public areas in Ghana.

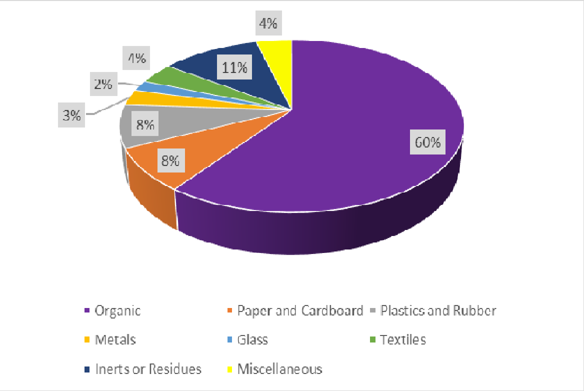

Figure 2. Average solid waste composition in Accra

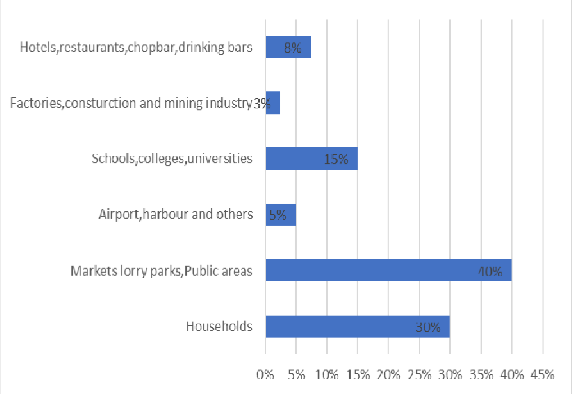

Figure 3. Estimation of primary sources of solid waste

4.3. Results of technical analysis of WtE technologies

Table 4 depicts the results of the technical analysis for both biochemical and thermochemical energy conversions. The results of the technical analysis show that the power generation potential of the waste using the thermochemical energy conversion is higher than that of the biochemical energy conversion. Also, the energy recovery potential of thermochemical processes is far higher than the biochemical process. The biochemical technology gives a power generation potential of around 530 kW/tMSW while that of the thermochemical capacity is 1320 kW/tMSW. This shows that there is far more production capacity when the waste in energy is converted to electricity using thermochemical technologies.

Table 4. Energy generation potential from MSW in Accra (t/MSW).

Biochemical potential	
Biogas emission	8.03
Power Generation Potential (PGP) (kW per tMSW)	530.00
ERP (kWh per tMSW)	41.68
Thermochemical potential	
PGP (kW per tMSW)	1320.00
ERP (kW per tMSW)	106.00

4.4. Results of economic analysis of WtE technologies.

Capital and O&M cost

Capital cost of WtE technologies is shown in Table 5. The results show that the initial investment of WtE technologies are expensive with plasma arc gasification having the highest initial capital just as confirmed by literature. Table 6 gives the O&M cost of WtE technologies. The results of the O&M cost as shown in Table 6 prove that the O&M cost of plasma arc gasification is higher than all the other thermochemical technologies. The thermochemical technologies have higher maintenance cost far above that of the biochemical technologies.

Table 5. Capital Cost of WtE Technology

Capital cost of WtE technology	Cost of low range	Cost of low range	Average cost
Anaerobic digestion	$3.710,000	$5,300,000	4,505,000
Pyrolysis	$10,560,000	$15,180,000	12,870,000
Gasification	$9,900,000	$14,520,000	12,210,000
Plasma Arc Gasification	$10,560,000	$15,180,000	12,870,000

Table 6. O&M cost [25]

Capital cost of WtE technology	Labor cost per annum	Maintenance cost per annum	Total O&M cost
Anaerobic digestion	$ 58050	$ 270,300	328,350
Pyrolysis	$ 58050	$ 1,415,700	1,473,750
Gasification	$ 58050	$ 1,343,100	1,401,150
Plasma Arc Gasification	$ 58050	$ 1,544,400	1,602,450

LCOE analysis

The performance parameters of the WtE technologies and its generation capacities are shown in Table 7 and their corresponding LCOEs are shown in Table 8. The LCOE shows that gasification has the least LCOE followed by the plasma arc gasification methods. With a transmission and distribution cost of 0.055US$/kWh in Ghana, the total LCOE production by these WtE technologies would be around 0.19 US$/kWh for gasification, 0.40 US$/kWh for plasma arc gasification, 0.47 US$/kWh for anaerobic digestion, and 0.48 US$/kWh for pyrolysis technologies. These shows that gasification technology has the least LCOE.

Table 7. Generation capacities of WtE technologies

WtE technology	Conversion efficiency [46]	Generation capacity (kW/tMSW)	Energy generation per annum (GWh/year)
Anaerobic digestion	0.5	530	2.32
Pyrolysis	0.3	1320	3.47
Gasification	0.9	1320	10.41
Plasma Arc Gasification	0.4	1320	4.63

Table 8. LCOEs of WtE technologies

Capital cost of WtE technology	Total O&M cost per annum (US$)	Generation per annum (GWh)	LCOE (US$/kWh)
Anaerobic digestion	328,350	2.32	0.415
Pyrolysis	1,473,750	3.47	0.425
Gasification	1,401,150	10.41	0.135
Plasma Arc Gasification	1,602,450	4.63	0.346

Financial analysis of WtE technologies

Table 9 shows the cost of electricity for financial analysis. The results of the financial model show that the NPV for all the considered WtE technologies (anaerobic digestion, pyrolysis, gasification, and plasma arc gasification) are greater than zero. Meaning all these projects are feasible and investors would yield a positive financial benefit when they invest in the implementation of these WtE technologies in Ghana. The $9.06 million NPV of the biochemical technology shows that it would yield the greatest financial benefits when this technology is used in the conversion of WtE in Ghana. Moreover, the biochemical technologies seem to have the least payback period of a little over 4years after which investors can start getting enough financial benefit from the plants. All the thermochemical energy conversion schemes had a payback period over 8years. Pyrolysis would have a payback period of 8.73years and gasification and plasma arc gasification would have 8.69- and 8.03-years payback periods respectively. However, it is a good time to make enough benefits from these technologies over the 25years life cycle of the plants. The internal rate of return was 21.20% for anaerobic digestion, 11.66% for plasma arc gasification, 10.58% for gasification and 10.52% for the pyrolysis technology. The higher internal rate of return for the anaerobic digestion technology shows that it is more desirable to undertake this technology to generate electricity.

4.5. Sensitivity analysis for WtE technologies.

Table 11 shows the sensitivity analysis results. The results of the sensitivity analysis show that with a low rate of waste products which would lead to low capacity and therefore a low cost of WtE plants, all the WtE technologies still yield a positive NPV showing that these technologies are still feasible and would give enough financial benefits. More so, the higher cost and the base cost scenario have their NPV also greater than zero and proofs the technologies feasibility. The NPV yield higher values even in the low-cost scenario; depicting that the project would be still attractive to investors even with a small-scale plant capacity of the technologies. The IRR for the low cost, base cost and high-cost scenario for anaerobic digestion technology gives the highest percentage showing it has good benefits for implementation.

Table 9. Capital cost and electricity cost for waste to electricity production

Capital cost of WtE technology	Capital cost (US$)	Cost of electricity
Anaerobic digestion	4,505,000	962,800
Pyrolysis	12,870,000	1,474,750
Gasification	12,210,000	1,405,350
Plasma Arc Gasification	12,870,000	1,601,980

Table 10. Financial analysis parameters

Technology	Initial investment	NPV at 5%	IRR (%)	Payback period (years)
Anaerobic digestion (US$)	4,505,000	9,064,649.83	21.20	4.68
Pyrolysis (US$)	12,870,000	7,915,044.75	10.52	8.73
Gasification (US$)	12,210,000	7,596,925	10.58	8.69
Plasma arc gasification (US$)	12,870,000	8,683,570	11.66	8.03

Table 11. Sensitivity analysis of WtE technologies

Technology	Level	Amount	NPV (US$)	IRR
Anaerobic digestion	Low	3,710,000	9,859,649.83	25.87
	Base	4,505,000	9,064,649.83	21.20
	High	5,300,000	8,269,649.83	17.87
Pyrolysis	Low	10,560,000	10,225,044.75	13.36
	Base	12,870,000	7,915,044.75	10.52
	High	15,180,000	5,605,044.75	8.43
Gasification	Low	9,900,000	9,906,925.00	13.61
	Base	12,210,000	7,596,925.00	10.58
	High	14,520,000	5,286,925.00	8.39
Plasma arc gasification	Low	10,560,000	10,993,569.77	14.68
	Base	12,870,000	8,683,569.77	11.66
	High	15,180,000	6,373,569.77	9.45

4.6 Results of the barrier analysis of WtE technologies

Figure 4 shows the results of the barriers to WtE technologies in Ghana. It was discovered from the analysis that a high percentage of the respondents see that the reason why WtE technologies have not been adopted in Ghana is that, WtE technologies are too expensive followed by the argument that there is difficulty in the segregation of waste. The initial cost of WtE technologies followed closely with 80% of the respondents seeing this as a problem for the non-feasibility of WtE technologies in the country. Only a few considered the non-environmental friendliness of WTE technologies and lastly the ideology that the waste in Ghana could not generate enough energy for the country.

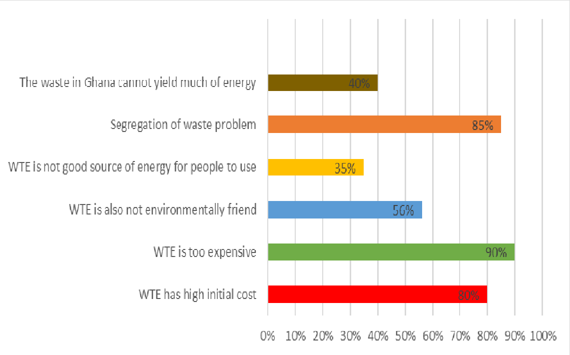

Figure 4. Barriers to WtE technologies in Ghana

5. CONCLUSIONS

This paper has assessed the feasibility of municipal solid WtE technologies for sustainable management in Ghana by using Accra as a case study. A detailed literature review has been done on the various WtE technologies and the feasibility of these technologies in other countries have also been assessed. Technical feasibility analysis, economic feasibility analysis and barrier analysis has been done to assess the feasibility of municipal solid waste. It can be concluded that the waste in Ghana is feasible for both biochemical and thermochemical processes. A power generation potential of 530 kW/tMSW and an energy recovery potential of 41.68 kWh/tMSW is recoverable from the waste in Accra when biochemical energy conversion is applied. A power generation potential of 1320 kW/tMSW and an energy recovery potential of 106 kWh/tMSW is recoverable from the waste in Accra when thermochemical energy conversion is applied. A yearly generation of 10.41, 4.63, 3.47, and 2.23 GWh of electricity are recoverable from the waste in Ghana using gasification, plasma arc gasification, pyrolysis, and anaerobic digestion technologies respectively. This shows that gasification has the highest energy yield. The economic analysis showed that the initial investment cost of WtE technologies is high, however implementation of this technology is likely to have a payback period of a little over 8 years for gasification, plasma arc gasification and pyrolysis and a little over 4years for the biochemical process.

The total LCOE by these WtE technologies is around 0.19$/kWh for gasification, 0.40$/kWh for plasma arc gasification, 0.47$/kWh for anaerobic digestion and 0.48$/kWh for pyrolysis technologies. These shows that gasification technology has the least LCOE cost and therefore more feasible. The internal rate of return shows that anaerobic digestion would yield better financial benefits. The barrier analysis shows that the hindrance to the implementation of WtE technology is the problem of high initial cost and waste segregation problem. The paper shows that the deployment of WtE technologies in Ghana is both technically and economically feasible. The study is not without limitations. The main drawback of this study is the availability of appropriate data for the feasibility assessment as well as the limitation of respondents ready to fill the questionnaire and go through a face-to-face interview. It is recommended that future work should look at a detailed techno-economic analysis of each technology for economic benefit and there should be further work to analyze the current Ghanaian waste constituents.

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REFERENCES

[1] Joeng H, Kim K. KOICA-WorldBank Joint Study on Solid Waste Management in Punjab, Pakistan. 2007.

[2] Beyene HD, Werkneh AA, Ambaye TG. Current updates on waste to energy (WtE) technologies: a review. Renew Energy Focus 2018;24:1–11. doi:10.1016/J.REF.2017.11.001.

[3] Xu Q, Jin X, Ma Z, Tao H, Ko JH. Methane production in simulated hybrid bioreactor landfill. Bioresour Technol 2014;168:92–6. doi:10.1016/J.BIORTECH.2014.03.036.

[4] Triyono B, Prawisudha P, Mardiyati M, Pasek AD, Pasek AD. Experimental Study on Utilization of Indonesian Non-Recycled Organic Waste as Renewable Solid Fuel Using Wet Torrefaction Process. Eng J 2018;22:81–92. doi:10.4186/ej.2018.22.6.81.

[5] AlQattan N, Acheampong M, Jaward FM, Ertem FC, Vijayakumar N, Bello T. Reviewing the potential of Waste-to-Energy (WTE) technologies for Sustainable Development Goal (SDG) numbers seven and eleven. Renew Energy Focus 2018;27:97–110. doi:10.1016/J.REF.2018.09.005.

[6] Dioha MO. Energy System Models for Sub-Saharan African Countries-A Systematic Review. J Sustain Energy 2017;8:159–68.

[7] Malinauskaite J, Jouhara H, Czajczyńska D, Stanchev P, Katsou E, Rostkowski P, et al. Municipal solid waste management and waste-to-energy in the context of a circular economy and energy recycling in Europe. Energy 2017;141:2013–44. doi:10.1016/J.ENERGY.2017.11.128.

[8] Korai MS, Mahar RB, Uqaili MA. Optimization of waste to energy routes through biochemical and thermochemical treatment options of municipal solid waste in Hyderabad, Pakistan. Energy Convers Manag 2016;124:333–43. doi:10.1016/J.ENCONMAN.2016.07.032.

[9] Sobamowo GM, Ojolo SJ. Techno-Economic Analysis of Biomass Energy Utilization through Gasification Technology for Sustainable Energy Production and Economic Development in Nigeria. J Energy 2018;2018:1–16. doi:10.1155/2018/4860252.

[10] Saini S, Rao P, Patil Y. City Based Analysis of MSW to Energy Generation in India, Calculation of State-Wise Potential and Tariff Comparison with EU. Procedia - Soc Behav Sci 2012;37:407–16. doi:10.1016/J.SBSPRO.2012.03.306.

[11] Luz FC, Rocha MH, Lora EES, Venturini OJ, Andrade RV, Leme MMV, et al. Techno-economic analysis of municipal solid waste gasification for electricity generation in Brazil. Energy Convers Manag 2015;103:321–37. doi:10.1016/J.ENCONMAN.2015.06.074.

[12] Leme MMV, Rocha MH, Lora EES, Venturini OJ, Lopes BM, Ferreira CH. Techno-economic analysis and environmental impact assessment of energy recovery from Municipal Solid Waste (MSW) in Brazil. Resour Conserv Recycl 2014;87:8–20. doi:10.1016/J.RESCONREC.2014.03.003.

[13] Tozlu A, Özahi E, Abuşoğlu A. Waste to energy technologies for municipal solid waste management in Gaziantep. Renew Sustain Energy Rev 2016;54:809–15. doi:10.1016/J.RSER.2015.10.097.

[14] Dong J, Tang Y, Nzihou A, Chi Y, Weiss-Hortala E, Ni M. Life cycle assessment of pyrolysis, gasification and incineration waste-to-energy technologies: Theoretical analysis and case study of commercial plants. Sci Total Environ 2018;626:744–53. doi:10.1016/J.SCITOTENV.2018.01.151.

[15] Moya D, Aldás C, Jaramillo D, Játiva E, Kaparaju P. Waste-To-Energy Technologies: an opportunity of energy recovery from Municipal Solid Waste, using Quito - Ecuador as case study. Energy Procedia 2017;134:327–36. doi:10.1016/J.EGYPRO.2017.09.537.

[16] Dong J, Tang Y, Nzihou A, Chi Y, Weiss-Hortala E, Ni M, et al. Comparison of waste-to-energy technologies of gasification and incineration using life cycle assessment: Case studies in Finland, France and China. J Clean Prod 2018;203:287–300. doi:10.1016/J.JCLEPRO.2018.08.139.

[17] Khalil M, Berawi MA, Heryanto R, Rizalie A. Waste to energy technology: The potential of sustainable biogas production from animal waste in Indonesia. Renew Sustain Energy Rev 2019;105:323–31. doi:10.1016/J.RSER.2019.02.011.

[18] Katinas V, Marčiukaitis M, Perednis E, Dzenajavičienė EF. Analysis of biodegradable waste use for energy generation in Lithuania. Renew Sustain Energy Rev 2019;101:559–67. doi:10.1016/J.RSER.2018.11.022.

[19] Barros RM, Tiago Filho GL, Santos AHM, Ferreira CH, Pieroni MF, Moura JS, et al. A potential of the biogas generating and energy recovering from municipal solid waste. Renew Energy Focus 2018;25:4–16. doi:10.1016/J.REF.2018.02.001.

[20] Abalo EM, Peprah P, Nyonyo J, Ampomah-Sarpong R, Agyemang-Duah W. A Review of the Triple Gains of Waste and the Way Forward for Ghana. J Renew Energy 2018;2018:1–12. doi:10.1155/2018/9737683.

[21] Ofori GM-L. Waste to Energy: an alternate energy source for Ghana. Lund University, 2016.

[22] Wikner E. Modeling Waste to Energy systems in Kumasi, Ghana. Swedish University of Agricultural Sciences, 2009.

[23] Dery FA, Kuusaana ED, Owusu-Sekyere E. Solid Waste Characterization and Recycling Potential for University Campuses in Ghana: Case Study of Two Ghanaian Universities. J Waste Recycl 2018;3.

[24] Mohammed M, Egyir IS, Donkor AK, Amoah P, Nyarko S, Boateng KK, et al. Feasibility study for biogas integration into waste treatment plants in Ghana. Egypt J Pet 2017;26:695–703. doi:10.1016/J.EJPE.2016.10.004.

[25] Miezah K, Obiri-Danso K, Kádár Z, Fei-Baffoe B, Mensah MY. Municipal solid waste characterization and quantification as a measure towards effective waste management in Ghana. Waste Manag 2015;46:15–27. doi:10.1016/J.WASMAN.2015.09.009.

[26] Abiti B, Hartard S, Bradl HB, Pishva D, Ahiakpa JK. Resource Prospects of Municipal Solid Wastes

Generatedin the Ga East Municipal Assembly of Ghana. J Heal Pollut 2017;7:37–47. doi:10.5696/2156-9614-7.14.37.

[27] Samwine T, Wu P, Xu L, Shen Y, Appiah E, Yaoqi W. Challenges and Prospects of Solid Waste Management in Ghana. Int J Environ Monit Anal 2017;5:96. doi:10.11648/j.ijema.20170504.11.

[28] Yoada RM, Chirawurah D, Adongo PB. Domestic waste disposal practice and perceptions of private sector waste management in urban Accra. BMC Public Health 2014;14:697. doi:10.1186/1471-2458-14-697.

[29] Singh A, Raj P. Sustainable recycling model for municipal solid waste in Patna. Energy Environ 2019;30:212–34. doi:10.1177/0958305X18787335.

[30] Fei-Baffoe B, Nyankson EA, Gorkeh-Miah J. Municipal Solid Waste Management in Sekondi-Takoradi Metropolis, Ghana. J Waste Manag 2014;2014:1–9. doi:10.1155/2014/823752.

[31] Carlos Escobar Palacio J, Joaquim Conceição Soares Santos J, Luiza Grillo Renó M, Corrêa Furtado Júnior J, Carvalho M, Martín Martínez Reyes A, et al. Municipal Solid Waste Management and Energy Recovery. Energy Convers. - Curr. Technol. Futur. Trends, IntechOpen; 2019. doi:10.5772/intechopen.79235.

[32] GIZ. Waste-to-Energy Options in Municipal Solid Waste Management 2017:57. https://www.giz.de/en/downloads/GIZ_WasteToEnergy_Guidelines_2017.pdf (accessed September 18, 2018).

[33] Themelis NJ, Barriga MED, Estevez P, Velasco MG. Guidebook for the Application of Waste to Energy Technologies in Latin America and the Caribbean. Inter-American Dev Bank 2013:228. http://www.seas.columbia.edu/earth/wtert/pressreleases/Guidebook_WTE_v5_July25_2013.pdf (accessed September 11, 2018).

[34] Rain D, Engstrom R, Ludlow C, Sarah Antos. Accra Ghana: A City Vulnerable to Flooding and Drought-Induced Migration. Case study prepared for Cities and Climate Change: Global Report on Human Settlements 2011; 2011.

[35] Fagariba CJ, Song S. Assessment of Impediments and Factors Affecting Waste Management: A Case of Accra Metropolis. Acad J Environ Sci 2016;4:144–62.

[36] Aryee MK, Pumijumnong N, Punwong P, Roachanakanan R. Assessment of the Sustainability of Accra Metropolitan Area, Ghana. Appl Environ Res 2018;40:27–39.

[37] Huober AL. Moving Towards Sustainable Solid Waste Management in Accra: Bridging the Formal-Informal Divide. Amherst College, 2010.

[38] Alexander A, Burklin C, Singleton A. Landfill Gas EmissionsModel (LandGEM) Version3.02 User's Guide. United States Environ Prot Agency 2005:48. https://www3.epa.gov/ttn/catc/dir1/landgem-v302-guide.pdf (accessed January 23, 2018).

[39] Moya D, Aldás C, Jaramillo D, Játiva E, Kaparaju P. Waste-To-Energy Technologies: an opportunity of energy recovery from Municipal Solid Waste, using Quito - Ecuador as case study. Energy Procedia 2017;134:327–36. doi:10.1016/J.EGYPRO.2017.09.537.

[40] Chakraborty M, Sharma C, Pandey J, Gupta PK. Assessment of energy generation potentials of MSW in Delhi under different technological options. Energy Convers Manag 2013;75:249–55. doi:10.1016/J.ENCONMAN.2013.06.027.

[41] Rafat A., Omar K., Syed A. Potential Value of Waste-to-Energy Facility in Riyadh City, Saudi Arabia. 8th Jordanian Int. Mech. Eng. Conf., Amman, Jordan: 2014. doi:DOI: 10.13140/2.1.2668.6720.

[42] Scharff H, Jacobs J. Applying guidance for methane emission estimation for landfills. Waste Manag 2006;26:417–29. doi:10.1016/J.WASMAN.2005.11.015.

[43] Tangri N, Wilson M. W aste Gasification & Pyr olysis: High Risk, Low Yield Pr ocessesfor W aste Management. 2017.

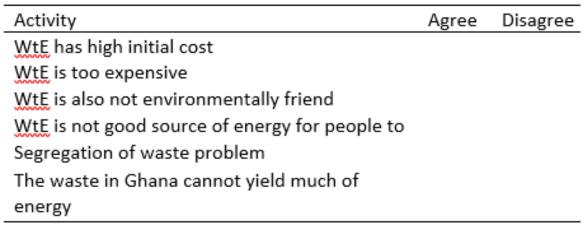
[44] Pueyo A, Bawakyillenuo S, Osiolo H. Cost and Returns of Renewable Energy in Sub-Saharan Africa: A Comparison of Kenya and Ghana. Evidence Report, No. 190: Pro-Poor Electricity Provision. 2016.

[45] Peerapong P, Limmeechokchai B. Waste to Electricity Generation in Thailand: Technology, Policy, Generation Cost, and Incentives of Investment. Eng J 2016;20:171–7. doi:10.4186/ej.2016.20.4.171.

[46] Purser R. A financial feasibility study of waste to energy generation in the City of Cape Town. University of Cape Town, 2011.

Appendix A: Interview questions for barrier analysis

Do you agree or disagree to the following barriers as reasons why waste to energy technologies have not been harnessed in Ghana?



Activity	Agree	Disagree
WtE has high initial cost		
WtE is too expensive		
WtE is also not environmentally friend		
WtE is not good source of energy for people to		
Segregation of waste problem		
The waste in Ghana cannot yield much of energy		