Techno-Economic Analysis of Municipal Solid Waste Gasification for Electricity Generation

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ABSTRACT

Due to an overburdened national grid, chronic energy challenges, and the growing municipal solid waste menace, a unique opportunity to deploy waste-to-energy technology in Ghana is apparent. A techno-economic analysis was performed for meeting the primary electrical load of selected blocks at the University of Energy and Natural Resources through Municipal Solid Waste gasification. Three scenarios were simulated and assessed based on their Net Present Costs (NPC) and Levelised Cost of Energy (LCOE): a gasifier-standalone system, a grid-tied gasifier system and a grid-alone system. The grid-tied gasifier system was found to meet the 230.1 kWh/day electrical load at the least NPC ($2, 049790.00) and COE ($0.09426/kWh). The sensitivity analysis showed that the load factor, sell-back price of electricity and cost/ton of MSW had the most impact on the NPC of the gasification system. MSW gasification is, therefore, an economically viable alternative if grid-integrated. Finally, the study showed that Feed-in Tariffs, plant siting and demand response strategies are crucial to ensuring the cost-effectiveness of gasification systems.

Keywords: Techno-Economic Analysis, MSW, Gasification, Net Present Value, Levelized Cost of Energy
JEL Classifications: Q40, Q41, Q42, Q48, Q53

1. INTRODUCTION

Electricity is the bedrock on which rests every strong economy. The global electricity mix is still heavily dependent on fossil fuels, comprising 78% of total energy use as of 2017 (Koyama, 2017). The situation is no different in Ghana, where about 60% of power is met by fossil-fueled thermal power plants (GRIDCO, 2020). Growing concerns for climate change, however, make these sources of energy increasingly unpopular. Heavy reliance on the national grid also contribute to large infrastructural requirements and energy losses. At present, as much as 917.8GWh of energy is lost off transmission lines due in part to distant and centralized distribution. This loss represented at least 4.6% of the total energy projection for 2020 (GRIDCO, 2020).

Coupled with this energy situation, Ghana faces a growing Municipal Solid Waste (MSW) menace, with a typical regional

capital such as the city of Sunyani estimated to generate about 4270 tons of waste per day (Miezah et al., 2015). Of this chunk, about 52% of MSW are collected by sanitary agents for landfilling and only 2% is recycled. The remaining 46% are either improperly dumped or burnt (Ofori-boateng et al., 2013).

Distributed Generation (DG) systems powered by renewable energy have been found to be a cost beneficial alternative to large infrastructure requirements for grid extension. Assessing the costs of different technologies for distributed generation in India, Rajbongshi et al. (2016) found that biomass gasification was among the most cost-effective DG options. Biomass has been argued to be among our best bets at replacing fossil fuels because it is readily available and primarily classified as renewable (Ocquaye, 2012). Therefore, this study aims to perform a techno-economic analysis of offsetting part of the electrical load of the University of Energy and Natural

Resources through the gasification of MSW generated within the Sunyani Municipality.

Some work has been done on the feasibility of waste to energy conversion using biomass resources in Ghana for electricity generation. Präger et al. (2019) assessed the quantity and energy content of biomass in Sunyani across two main categories: forest biomass (comprising loggings and sawdust) and food waste (consisting of kitchen and cassava waste). Food and cassava waste was found to have the potential of generating 823 l/kg of biogas with a methane composition of 48.6Vol%. But the scope of the work did not include a detailed cost and technical analysis of meeting a typical electrical load through gasification in particular. Ofori-Boateng et al. (2013) assessed the feasibility of electricity generation from MSW through landfilling, landfilling without engineered sites and controlled incineration. The study found controlled incineration to be the most economically attractive among the four. The study, however, mainly focused on incineration in place of gasification, although gasification is less polluting as compared to incineration (Bhoi et al., 2018; Moshi et al., 2020).

Motivated by the availability of biomass resources, Commeh et al. (2019) experimented with comparing the power outputs from the gasification of charcoal produced from teak, bamboo, sugar cane and wood pellets using a downdraft gasifier. Bamboo was found to produce the highest power output, whilst wood pellets produced the least. The study concluded that biomass gasification holds tremendous potential to contribute towards energy security in Ghana due to biomass resources availability. In another study, Indrawan et al. (2020) assessed the economics of MSW and forest biomass co-gasification. They found that a 40%wt of MSW had a positive Net Present Value (NPV) of US$84,550.00, indicating that they are cost-effective. This study, however, discounted the cost of transporting the biomass.

There is no known biomass power plant in Ghana as of 2019 (Ministry of Energy et al., 2019). However, biomass gasification holds enormous potential to contribute towards energy security in Ghana due to the vast availability of biomass resources (Ocquaye, 2012).

Literature, therefore, indicates a research gap as no research exists or has been sighted on techno-economic analysis of MSW gasification for electricity generation in Ghana.

2. DESCRIPTION OF STUDY AREA

In this section, the general study area of Sunyani and the specific location where this study is focused on is discussed. The discussion includes data on the MSW generation rate and the cost of transporting waste to the University of Energy and Natural Resources, where the gasification plant is being assessed.

Sunyani is the study area for this research. It is the capital of the Sunyani Municipality and the capital of the newly created Bono Region of Ghana (Anane, 2013). Sunyani lies between Latitudes 70.20°N and 70.05°N and Longitudes 20.30°W and 20.10W, Sunyani can also be found in the middle belt of Ghana between 750 (229 meters) to 1235 feet (376 meters) above sea level (Höflinger et al., 2020). Given a population of 230,000 in the Sunyani Municipality as of 2010 and an average household size of 4.4, the total number of households is about 52,000 (Ghana Statistical Service, 2013). The city also has a high relative humidity of 70-80%, and is, therefore, a very suitable place for growing vegetables and is, therefore, a central agricultural hub in Ghana (Anane, 2013). Nearly 70% of the landmass in the Municipality is agricultural land (Höflinger et al., 2020).

2.1. MSW Characterization in the Sunyani Municipality

The city of Sunyani generates over 12,010 tons/day of waste (Anane, 2013). Like many Ghanaian cities, more than 60% of this waste is organic (Aboagye et al., 2021), and 55-80% of this waste is contributed by households (Miezah et al., 2015). Food waste has also been found to constitute more than 40% of all MSW generated in the city and similar cities in Ghana (Indrawan et al., 2020; Miezah et al., 2015). The high organic contents of the vast tonnage of municipal solid waste generated in the city make it suitable for use in waste-to-energy applications through one of many biomass conversion processes. This would curb the waste menace while producing energy. Preliminary organic waste collection from 100 households in the city reveals a per-capita organic waste generation of 0.61 kg/person/day. This is consistent with the range of 0.3-0.8 suggested by (Gyam et al., 2015; Hensley et al., 2011; Ketibuah et al., 2004; Miezah et al., 2015). The Lower Heating values (LHVs) of producer gases resulting from the gasification of MSW from municipalities in Sunyani and similar municipalities have been determined by many researchers. Table 1 presents some of these findings.

Table 1 shows that the heating value of producer gases from the gasification of MSW is mainly within the range of 4 and 6. In a biomass-MSW co-gasification, Indrawan et al. (2018) found that a 20 Wt.% of MSW recorded the highest LHV (7.74 MJ/m^3), followed by a 0 Wt.% of MSW (6.91 MJ/m^3). A 40 Wt. % of MSW recorded the lowest LHV of 6.78 MJ/m^3.

3. METHODOLOGY

This section describes how the electrical load of the selected blocks of the University of Energy and Natural Resources (UENR) were assessed. It also describes how the techno-economic assessment was done and the input data used.

3.1. Calculating the Load Profile

A techno-economic analysis was performed to assess the feasibility of meeting the electrical load of the Administration and Odum blocks of the UENR. The Administration block houses the Vice and Pro-Vice chancellors' offices and offices for other administrative duties. Load components comprise mainly lighting, refrigeration, air-conditioning and printing. On the other hand, the Odum block houses most of the offices of Senior lecturers and has a similar load as that of the administration block. Because both blocks are already connected to the national grid, the monthly electricity consumptions and bills were obtained from the Northern

Table 1: Heating values of producer gases from the gasification of MSW

Parameter	(Park et al., 2020)	(Indrawan et al., 2020)	(Homdoung et al., 2019)	(Commeh et al., 2019)	(Khosasaeng and Suntivarakorn, 2017)	(Ofori-boateng et al., 2013)
LHV (MJ/m³)	6.2	5.4	4-6	4.9	5.87	5.6
Ash (%W)	NA	NA	NA	NA	4.8	NA
Carbon (%W)	NA	NA	NA	NA	9.73	NA
Density (kg/m³)	NA	NA	9.02	NA	9.3	NA

Electricity Distribution Company (NEDCO). NEDCo is the critical distributor of power to the Northern sectors of Ghana (Dramani and Tewari, 2014). Figure 1 shows the monthly load profile of the Administration block for the years 2018, 2019 and 2020.

Over the last three years, these monthly load profiles at the Administration block show a yearly growth in electricity consumption. Monthly consumptions reflect peak demands in February and May for 2018 and 2019, showing very similar trends. For 2020, however, electricity demand peaked in March instead, followed by a steep drop in consumption until September. Average growth in yearly demand increased by about 40% between 2018 and 2019 but reduced by about 27% between 2019 and 2020.

The average monthly and yearly energy consumptions are 2985.611 kWh and 35827.33kWh, respectively. This translates into a daily consumption of 98.16 kWh/day. The load profile of the Odum block is also presented in Figure 2.

Figure 2 depicts a consistent growth in energy consumption over the years 2018, 2019 and 2020. Energy consumption rises steadily from January through April (for 2020) and through June for 2018 and 2019. Energy consumption peaks in April 2020 and peaks at around June in 2018 and 2019. Consumption drops steeply from June to August and then rises sharply from September through December for all years. The average monthly and yearly energy consumptions for the Odum block are 4013.273 kWh and 48159.27kWh, respectively. This translates into a daily consumption of 131.94kWh/day. Also, based on the utility bills sourced from NEDco, the average yearly amount paid for electricity at the administration and Odum blocks over the years 2018, 2019 and 2020 were US$8,816.852 and US$ 11, 617.64 respectively. The total average yearly cost of electricity for both blocks is, therefore, US$ 20, 434.492.

3.2. Gasifier System Design
A 60KW internal cyclonic downdraft gasifier (60 KW ICDG) shown in Figure 3 was used for this study.

This type of gasifier is suited for this study because of its low tar rate, tolerance to moisture and suitability for small scale applications (Khosasaeng and Suntivarakorn, 2017). It is also able to handle biomass flowrates of 100 kg/h. to generate producer gas of heating values within the range of 6-6.8MJ/m³ whilst releasing tar contents of 300-400 mg/m³ at a moisture tolerance of 40 wt.% (Indrawan et al., 2020).

The system's yearly operation and maintenance costs (OMC) comprise the cost of labour, USD 895.32; energy consumption of the 1hp conveyor belt, USD 892.00; and the cost of souring the organic

Figure 1: Monthly load profile of the administration block (based on data obtained from NEDCo)
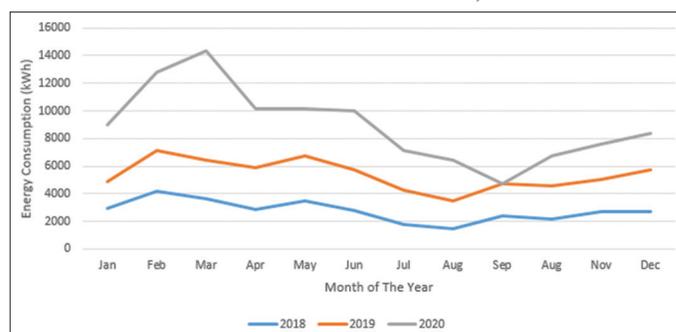
Figure 2: Monthly load profile of the Odum block (based on data obtained from NEDCo
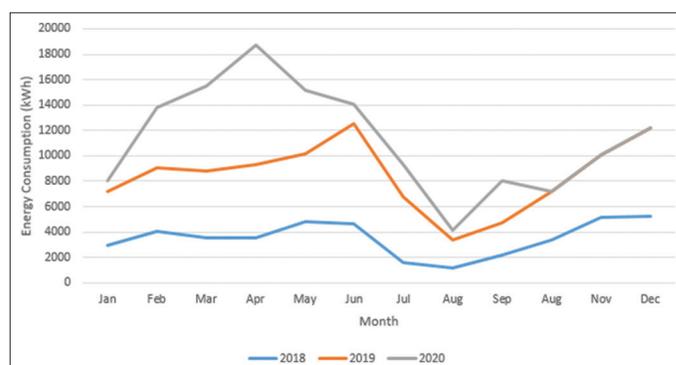
waste USD 12585.20. The labour cost was estimated at 50% more than the Ghanaian minimum wage of US$49.74/month (Starr, 1981; LRPI, 2018). The conveyor belt consumes 6,516k Wh/year. This translates to a yearly cost of US$ 892.00 based on Ghana's current electricity tariff of US$0.137/kWh. Obtaining the cost/ton of the waste sourced was quite challenging. This is because there are no established biomass/MSW markets (Montuori et al., 2014). Since the cost of MSW is usually priced negatively (Klein, 2002), the cost/ton of biomass was calculated based only on the cost of transporting waste from households to the UENR. Based on firsthand experience, it costs Ghc15.00 to transport a 100 kg weight of waste (Ghc0.15/kg) to UENR. This translates into USD 0.026/kg and USD 26.00/ton, using a conversion rate of Ghc5.8/USD (Forex Rates – 19, 2021).

The capital cost breakdown of the various components of this system in their US Dollar rates as suggested by Indrawan et al. (2020) are shown in Table 2.

3.4. HOMER Simulation
3.4.1. About the HOMER pro software
The HOMER Pro MicroGrid Software was the primary tool used for the analysis. HOMER was developed by the National

Renewable Energy Laboratory of the United States and uses energy balance calculus to complete computations (Montuori et al., 2014). HOMER is particularly suited for practical micro-grid systems modelling because it provides a fair balance between minimum complexity and detail. It has also been known to be the most flexible of micro-grid modelling tools due to the wide range of systems it can simulate (Lambert et al., 2006).

For analysis, three different cases were considered: A standalone gasifier system, a grid-tied gasifier system and a grid-only system. The schematics involved specifying the primary load; selecting the required equipment, i.e. the grid and biomass-fired Genset; specifying the costs and fuel requirements of the selected components; describing the availability, cost and characteristics of the biomass resource used; defining economics and constraints, and performing simulation and sensitivity analysis. Table 3 shows the sensitivity variables used in the simulation.

A sensitivity analysis was performed to determine the performance of the systems for specific variables that are subject to change throughout the project's lifetime. The primary electrical loads were adjusted by ±20% to account for any unforeseen increase in demand or decrease in any demand response programs in the future.

Table 2: Capital cost of gasifier system

Equipment	Cost ($)
Reactor and control system	60,000
Belt conveyor	10,000
Ash removal system	10,000
Air compressor	10,000
Gas scrubbing system	4,500
100 kW power generating unit (biogas generator)	18,000
Total	112,500.00

(Indrawan et al., 2020).

Table 3: Sensitivity variables used in the simulation (generated from HOMER)

Biomass price ($/tonne)	Biomass biogas lower heating value (MJ/Kg)	Sellback rate ($/kWh)	Electric load at administration block (kWh/day)	Electric load at odum block (kWh/day)	Capacity shortage (%)	Renewable energy fraction (%)	Operating reserve (%)	Expected inflation (%)	Nominal discount (%)
26	55	0	98.16	131.939976	5	0	10	9.8	0
40	4.9	0.137	117.792	158.328	10	50	20	10	10
	4	78.528	105.552	0					

Table 4: Comparative costs and reliability of the three configurations over a 25 years' lifecycle

Configuration	Renewable energy fraction	NPC ($)	COE ($/kWh)	Capital Cost($)	Operation cost ($/year)	Unmet load (%)	Excess electricity (%)	Capacity shortage (%)
Grid-only system	0.00	2,875,531.00	0.137	0.00	25,540.64	0	0	0
Gasifier-only system	100	3,310,574.00	0.5277	121,500.00	29,478.85	28.90	62.70	37.10
Grid-tied gasifier system	79.70	2,049,790.00	0.09426	121,500.00	17,824.54	0.00	0.00	0.00

Figure 3: Schematics of the 60kW ICDG used in this study (Indrawan, Simkins, et al., 2020)
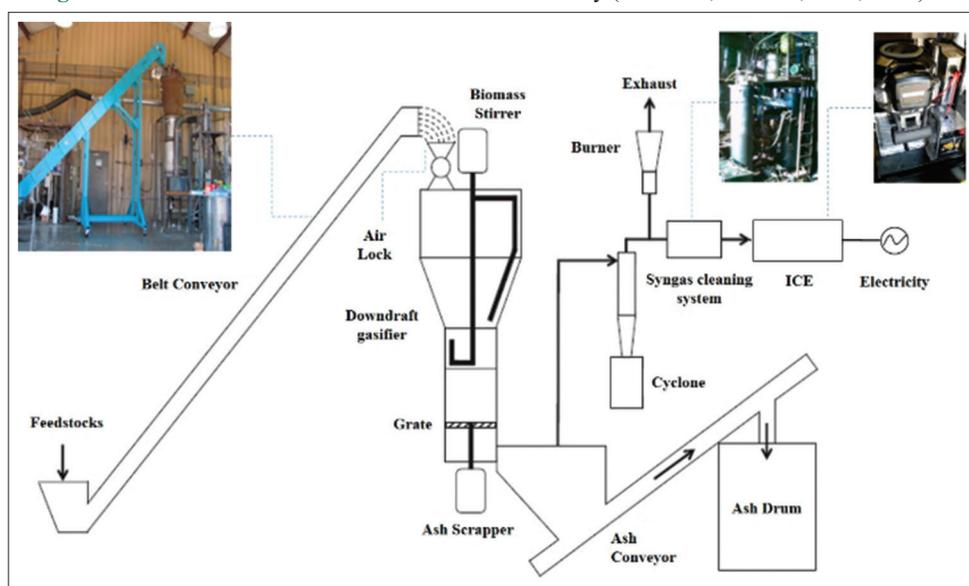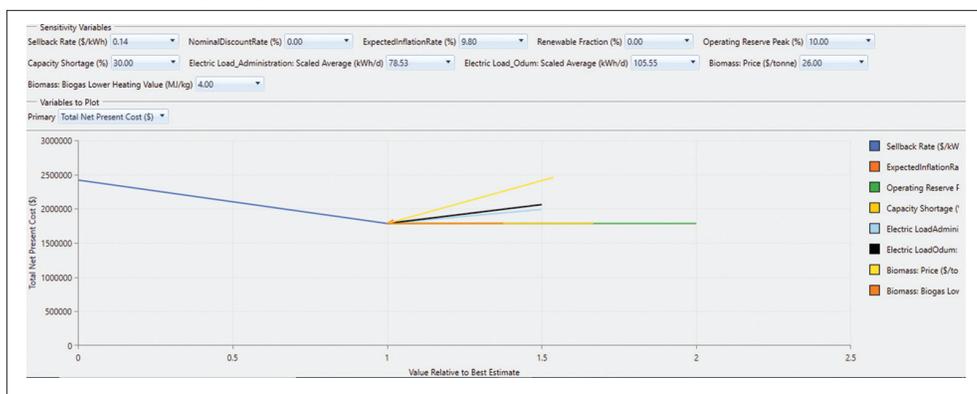
Figure 4: Spider plot showing sensitivity analysis of the grid-tied gasifier configuration

4. RESULTS AND DISCUSSION

The results of the costs and reliability of supply for each configuration are shown in Table 4.

All the other systems were able to meet the load demand of the system except the gasifier-only system, which recorded an unmet load of 23,533 kWh/year (28.9% of yearly electrical load). The standalone gasifier system also showed a 37.1% capacity shortage and recorded the highest NPC of US$3310574.00, making it the least economically feasible option. This result agrees with several other studies: Cattolica and Lin (2009) found that off-grid biomass mini-grid gasification systems were not cost-effective. In a similar study using HOMER simulations, Chambon et al. (2020) also concluded that standalone gasifier systems were not cost-effective unless integrated into a hybrid system, or unless tipping fees were charged for waste collected and processed (Dowaki et al., 2005). The grid-tied gasifier system performed the best in NPC and COE, meeting the electrical load at the least NPC of $2, 049,790.00 and COE of $0.09426/kWh. The producer gas-fired generator in the grid-tied gasifier system operated 79.7% of the time, consuming 489 tons of MSW over the project lifecycle to deliver 160,215 kWh/year of energy. The standalone gasifier system consumed the same tonnage of waste and delivered a slightly lower energy per year: 155,600 kWh/year. At efficiencies of 34.4% and 33.4%, respectively, the grid-tied gasifier system also proved marginally more efficient than the standalone gasifier system. Thus, whilst the grid-tied system consumed 2.14 kg/kWh of MSW, the standalone system consumed 2.2 kg/kWh. Table 5 shows the performance of each system on a random day (241st day of the 1st year) and a random time, 9:00 AM.

From Table 5, on day 241 of year 1, at 9:00 AM, the grid-only system had a 0 KW power output from the generator, simply because there was no generator connected. 13.25 kW of power was purchased from the grid with no power sold to the grid and no MSW used. The gasifier-only system consumed 55 kg of MSW to produce 25 kW of power from the producer gas-fired generator. No power was purchased or sold to the grid because it is a standalone system. The grid-tied gasifier system would consume 78.17 kg of MSW to produce 36.58 Kw of power. No power is being purchased from the national grid. Rather 23.33 kWh of electricity was sold to the grid.

Table 5: Time-step analysis of the three configurations (241st day, 9 am)

Configuration	Generator output (kW)	Electricity purchased from grid (kW)	Electricity sold to the grid (kWh)	MSW use (kg)
Grid-only system	0.00	13.25	0.00	0.00
Gasifier-only system	25 kW	0.00	0.00	55.00
Grid-tied gasifier system	36.58 kW	0.00	23.33	78.17 kg

4.1. Sensitivity Analysis

A sensitivity analysis was performed for the most cost-effective configuration to determine the effects of the sensitivity variables listed in Figure 4 on the NPC and COE. A spider plot showing the sensitivity analysis for the grid-tied gasifier system is shown in Table 4.

Based on the steepness of the slopes, it can be observed from the Spider Plot in Figure 4 that, sell-back rate of electricity, biomass price/ton, and load factor (primary electric load) had the most impact on the total NPC of the system. A 50% increase in the sell-back rate of electricity reduces the total NPC by about 8% whilst a 100% increase reduces it by a little over 20%; increasing the cost of MSW/ton by 50%, however, increased the total NPC by as much as 30%.

Finally, a 50% increase in the load factor increased the total NPC by close to 12.5%. On the contrary, the Capacity shortage, operating reserve peak and producer gas lower heating values (surprisingly) had a negligible effect on the NPC and COE.

5. CONCLUSIONS AND RECOMMENDATIONS

The results showed that a standalone gasifier system is not technically or economically advisable using MSW gasification. A grid-tied gasification system is more economically feasible and technically advisable than the current status quo of grid-only. A grid-tied gasifier system also has a cheaper annual operational cost of US$17,824.54/year compared to 25,540.64/year, as is

currently the case with the two blocks powered by the national grid. This leads to an annual savings of US$ 7, 716.10/year. Based on this, the simple pay-back time of the system is 15.7 years. A future plan for a biomass gasification plant in the Municipality should consider either a grid-tied or hybrid system.

This study, therefore, further empathizes the importance of Feed-in-Tariffs in encouraging and ensuring the profitability of renewable energy integration since the NPC was very sensitive to the sell back rate of electricity. Also, the findings indicate that plant siting is very crucial to the economic feasibility of MSW gasification as transportation adds significantly to the cost/ton of waste which has a negative impact on the economic viability of MSW gasification systems. The findings of this study further calls for the integration of demand response strategies to reduce the load factor as these have been established to have significant positive effect on the NPC and LCOE of MSW gasifier systems.

6. ACKNOWLEDGMENT

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