Techno-economic assessment of municipal solid waste gasification for electricity generation: a case study of Kampala City, Uganda

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Abstract: This study was aimed at assessing the techno-economic potential of municipal solid waste (MSW) generated in Kampala City for electricity production through gasification. The quantity, characteristics and gasification parameters were determined. In addition, the gasifier- engine system components were sized, and an economic analysis was conducted to obtain the net present value (NPV) and the payback period. This study found that 523 t/d of MSW is collected in Kampala City. The biomass component of MSW was found to be 459.5 t/d with moisture content of 71.09% on as-received basis. The physical characteristics of the gasified biomass included 11.8% moisture content, 88.2% total solids, 25.9% ash content and 57.7 kg/m^3 bulk density. The resulting normalized producer gas constituted 11.64% H_2, 13.70% CO, 16.09% CO_2, 54.12% N_2, 4.45% CH_4 and lower heating value (LHV) of 4.75 MJ/Nm^3. The design fuel flow rate of 0.23 kg/s, specific gasification rate (SGR) of 5089.29 kg h^{-1} m^{-2} and specific energy demand of 42.75 GJ m^{-2} h^{-1} were obtained. This yields a net electrical power output of 425.17 kW with an overall efficiency of 15.6%. The net annual electricity generation from a single gasifier-engine system was found to be 2.97 GWh/a. The economic analysis for this system worth $887 333 of investment cost yielded a payback period of 6.57 years while the NPV at 6% interest rate was found to be nine years with a value of $316 47.

Keywords: municipal solid waste, biomass, gasification, economic analysis, producer gas, electricity

Citation: Bernard Kivumbi, Joseph Olwa, Andrew Martin, Emmanuel Menya. 2015. Techno-economic assessment of municipal solid waste gasification for electricity generation: a case study of Kampala City, Uganda. Agric Eng Int: CIGR Journal, 17(4):141-155.

1 Introduction

Within the waste management hierarchy, thermal disposal especially incineration is a viable and proven alternative. But, the dominating method, mass-burn grate incineration has drawbacks as well particularly hazardous emissions and harmful process residues. In recent years, pyrolysis and gasification technologies have emerged to address these issues and improve the energy output (Malkow, 2003). MSW disposal has been a controversial issue in many countries over the past years, due to disagreement among the various stakeholders on the waste management policies and technologies to be adopted. One of the ways of treating/disposing MSW is energy recovery, as waste is considered to contain a considerable amount of bio-waste and therefore can lead to renewable energy production (Rentizelas et al., 2013). Gasification of biomass for electricity generation is a proven technology in countries like Netherlands, Austria, Italy, Sweden, Finland, USA, Indonesia, Canada, Belgium and France (Hariie, 2005). Applications of producer gas from gasification include firing internal combustion engines, steam boilers, gas turbines and in synthetic fuel production such as dimethyl ether and methanol (Alameda, 2004). The conversion of biomass by gasification into a fuel suitable for use enhances the potential usefulness of biomass as a renewable resource

Received date: 2015-06-01 **Accepted date: 2015-10-14**
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(McKendry, 2002). Gasification can result into reduced need for disposal of MSW through landfilling as well as achieving emission limits (Umberto, 2012).

In Uganda, small scale gasification plants have been established at Muzizi Tea estate (250 kWe) (Ankur, 2009), Ankole Tea Estate, Forestry College Nyabyeya and Kings College Budo (Kasedde, 2009). Demonstration plants in Kampala City are located at Kyambogo University (10 kW) and Makerere University. Kampala City is currently experiencing rapid population growth due to immigration and natural increase and is estimated to have a population of 1.5 million inhabitants. The city has five divisions; Kawempe division, Central division, Makindye division, Rubaga division and Nakawa division (Komakech et al., 2014). The increasing population in Kampala City translates to increased MSW generation. In 2011, out of 1,200-1,500 t of MSW generated per day, only 400-500 t/d were collected and this represents a vast fuel source for gasification (WaterAid, 2011). MSW generated in Kampala City is collected in skips, transported by trucks to the landfill where it is deposited and left to decompose emitting gases such as methane and carbon dioxide which are potent greenhouse gases (U.S EPA, 1996). Furthermore, with the waste stabilization and compositing time of a conventional landfill being between 30years to 50 years or more, this leads to uneconomical usage of land (Sean et al., 2006). Consonni et al. (2012) reported that a number of waste gasification technologies are currently proposed as an alternative to conventional waste-to-energy (WtE) plants. Assessing their potential is made difficult by the scarce operating experience and the fragmentary data available. It is upon this background that a comprehensive gasification system is considered in this waste-to-energy application.

2 Materials and methods

2.1 MSW potential in Kampala City and its biomass characteristics as-received

Historical data for the period 2004-2008 regarding the quantity of MSW disposed of at Mpererwe landfill was collected (M. Mudanye, Personal communication, Mpererwe landfill, 2009) and analyzed using Microsoft Excel software to determine the average quantity of MSW collected per year. Data for the composition of MSW generated in Kampala City was obtained from Mudanye (Personal communication, Mpererwe landfill, 2009) and ERL (1990) which was used to compute the average composition of MSW using Microsoft Excel software. The moisture content and total solids of six samples of MSW on as-received basis were determined using the oven dry method according to FprEN 14774-3 (CEN, 2009) using a furnace (HRF 7/22) and an electronic weighing scale (Mettler PC 4400).

2.2 Analysis of biomass characteristics & gasification parameters of dry MSW

MSW was sorted at the landfill to obtain the biomass portion which was then open-sun-dried for seven days until the moisture content (determined using the same procedure for the determination of the moisture content of the samples as-received) was less than 25% as required for gasification (Hariie, 2005). The dry biomass was then packed in twenty, 100 kg sand bags ready for experimentation on the downdraft gasifier test rig shown in Figure 1 and five runs each lasting for about 1 h were considered. The hot gas flowed through the system by the suction effect of the blower. Char/ash material was removed from the gasifier before each run. For each run, 7.6 kg of charcoal (to be used in the reduction stage) was weighed and added to the gasifier. The samples to be gasified were also weighed and recorded. A stirrer was used at intervals for pushing down the MSW. When the gasifier was full, the top cover was closed and the suction blower switched on. A flame placed at the air intake manifold was used to ignite the biomass fuel. The gasification parameters of MSW determined were temperature, gas composition and LHV. The temperature was recorded using a data logger (87623 SRP-6-1.5M) and measured using Chromel/Alumel

(K-type) thermocouples fixed at drying/pyrolysis zone, combustion/oxidation zone, reduction zone, ash zone, cyclone exit, sampling point, heater element and was monitored on a computer using Trend Reader software. The gas composition was determined by collecting producer gas using gas sampling bags (Tedlar® bags) and analyzed using a Micro Gas Chromatographer (Shimadzu GC-3BT) and a gas analysis Microsoft Excel sheet. The LHV of producer gas was determined using Equation (1) (Reed and Das, 1988);

$$LHV_{gas} = 11.2[H_2] + 13.1[CO] + 37.1[CH_4] + 83.8[C_nH_m] \quad (1)$$

Where, $[H_2]$ is the percentage concentration of hydrogen, $[CO]$ is the percentage concentration of carbon monoxide, $[CH_4]$ is the percentage concentration of methane and $[C_nH_m]$ is the percentage concentration of higher hydrocarbons. The moisture content of MSW was determined using the oven dry method as discussed under Section 2.1. The ash content was determined using a furnace (HRF 7/22) and electronic weighing scale (Mettler PC 4400) following the NREL/TP-510-42622 procedure (Sluiter et al., 2008) and bulk density was determined according to ASTM E873.

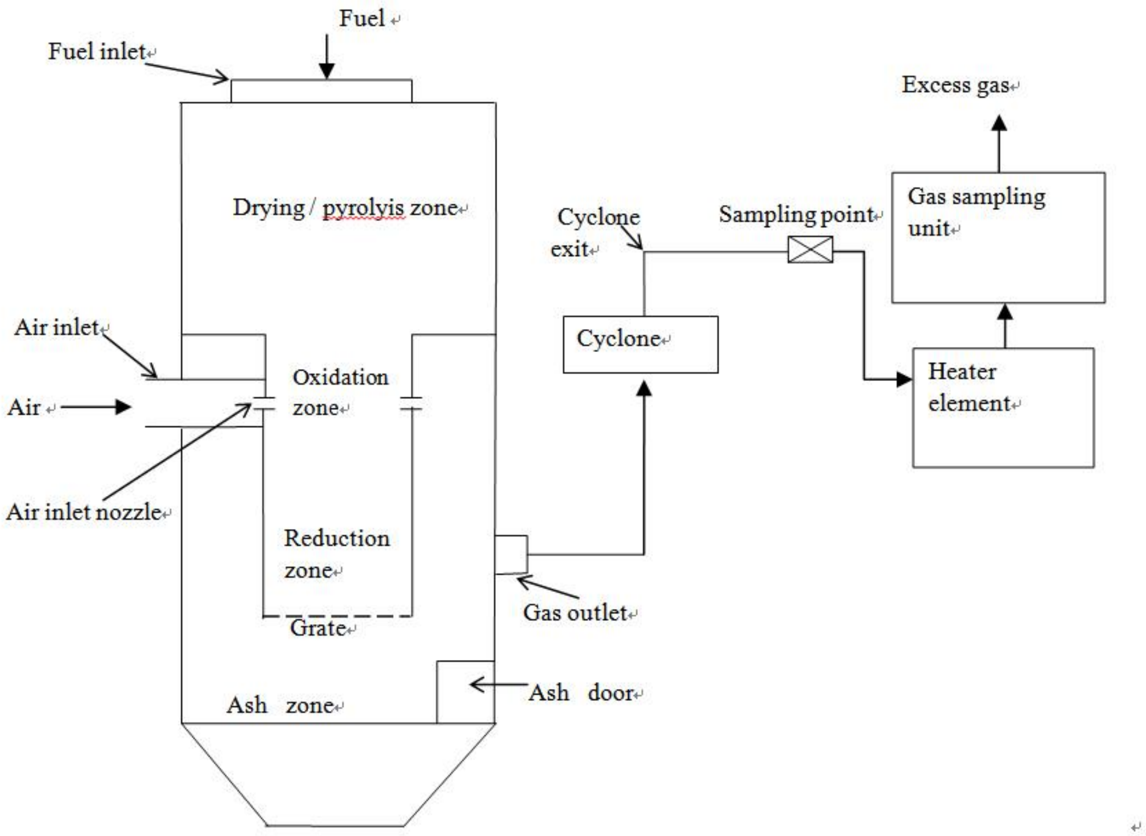

Figure 1: Sketch of the gasifier test rig showing the regions considered for temperature measurement

2.3 Sizing of the engine

The natural gas generator set QSV91 series engine in the range 1250-2000kWe was considered since the electrical power was not to exceed 0.5MWe using a downdraft gasifier (Hariie, 2005; Bridgewater, 2015; Cummins, 2008; FAO, 1986). Maximum air-producer gas intake, $\dot{V}_{ag}$ (m^3/s) was calculated using Equation (2).

$$\dot{V}_{ag} = 1/2 \times r \times D_{eg}/60 \quad (2)$$

Where, D_{eg} is the displacement of engine (m^3) and r is the revolutions per minute (r/min).

Air-producer gas ratio (stoichiometric) was 1.1: 1.0 (FAO, 1986). Maximum producer gas intake, $\dot{V}''_{ge}$ (m^3/s) was calculated using Equation (3).

$$\dot{V}''_{ge} = (1.0/2.1) \times \dot{V}_{ag} \quad (3)$$

Real producer gas intake, $\dot{V}'_{ge}$ (m^3/s) was determined using Equation (4).

$$\dot{V}'_{ge} = \dot{V}''_{ge} \times f_e \quad (4)$$

Where, f_e (%) is the fouling factor in the engine. $\dot{V}'_{ge}$ was converted to normal conditions (Nordstrand, 2009) using Equation (5).

$$\dot{V}_{ge} = \dot{V}'_{ge} \times T_{ge} / T'_{ge} \quad (5)$$

Where, T'_{ge} is the inlet temperature to engine (K), T_{ge} is the normal inlet temperature to engine (K) and $\dot{V}_{ge}$ is the normal volume flow rate of producer gas to engine (N m^3 s^{-1}). The thermal power, P_g (kW) in the gas was calculated using Equation (6).

$$P_g = \dot{V}_{ge} \times LHV_{gas} \quad (6)$$

Where, LHV_{gas} is the lower heating value of producer gas (MJ Nm^{-3}). The maximum mechanical output, P_m (kW) of this engine was obtained using Equation (7).

$$P_m = P_g \times \eta_m \quad (7)$$

Where, η_m is the mechanical efficiency of engine (%). The maximum electrical output, P_e (kW) was obtained using Equation (8).

$$P_e = P_m \times \eta_e \quad (8)$$

Where, η_e is the electrical efficiency of engine (%)

2.4 Sizing of the gasifier

Since small scale applications (≤ 0.5 MWe) were considered, the throatless downdraft gasifier was then selected for ease of movement of MSW in the reactor (Hariie, 2005; Bridgewater, 2015). The thermal power consumption (full load), P'_g (kW) was calculated using Equation (9).

$$P'_g = P_g / \eta_g \quad (9)$$

Where, η_g is the efficiency of gasifier (%). Biomass consumption, $\dot{m}_g$ (kg/s) of gasifier was computed using Equation (10).

$$\dot{m}_g = P'_g / LHV_{msw} \quad (10)$$

Where, LHV_{msw} is the lower heating value of municipal solid waste (MJ/kg). Specific fuel consumption (sfc) was computed using Equation (11).

$$sfc = \dot{m}_g / P_e \quad (11)$$

The fuel flow at moisture content, B_t (%) was calculated using Equation (12).

$$(1 - B_t) \times \dot{m}_t = (1 - B_{tw}) \times \dot{m}_{tw} \quad (12)$$

Where, B_{tw} (%) and B_t (%) are the moisture contents of MSW as-received and the sun dried MSW respectively , $\dot{m}_{tw}$ (kg/s) and $\dot{m}_t$ (kg/s) are the mass flows of MSW as-received and the sun-dried MSW respectively. The total number of gasifiers, n_g needed to gasify all the waste was obtained using Equation (13).

$$n_g = \dot{m}_t / \dot{m}_g \quad (13)$$

The gas production, $\dot{V}_{gg}$ (N m^3 s^{-1}) from the gasifier was obtained using Equation (14).

$$\dot{V}_{gg} = \dot{V}'_{ge} \times T_{gg} / T'_{ge} \quad (14)$$

Where, T_{gg} is the outlet temperature of producer gas from gasifier (K). Thus, cross-sectional area, A_h (m^2) of the air inlet was obtained using Equation (15).

$$A_h = \dot{V}_{gg} / B_h \quad (15)$$

Where, B_h (Nm^3 m^{-2} h^{-1}) is the hearth load. The diameter of the air inlet, d_t (mm) was calculated using Equation (16).

$$d_t = \sqrt{4A_h/\pi} \quad (16)$$

Once d_t was fixed, further important gasifier dimensions were derived as follows (Reed and Das, 1988);

Height, h (cm) of the nozzle plane above the smallest cross-section of the throat was obtained using Equation (17)

$$h = 0.48d_t \quad (17)$$

Diameter, d_r (mm) of the fire box was obtained using Equation (18).

$$d_r = 2.1d_t \quad (18)$$

Nozzle diameter, d_n (mm) was obtained on the assumption that the gasifier was to be equipped with five nozzles (Reed and Das, 1988). The nozzle diameter was determined using Equation (19).

$$4.7 = (100\times 5\times 0.25\times \pi \times d_n^2)/(0.25\times \pi \times d_t^2) \quad (19)$$

Specific gasification rate, SGR (kg h^{-1} m^{-2}) was obtained using Equation (20).

$$SGR = \dot{m}_g / A_h \quad (20)$$

Specific gas production rate, $SGPR$ (m^3/h) was obtained using Equation (21).

$$SGPR = \dot{V}_{gg} / A_h \quad (21)$$

Specific energy demand, SED (GJ m^{-2} h^{-1}) was obtained using Equation (22).

$$SED = \dot{V}_{gg} \times LHV_{gas} / A_h \quad (22)$$

Overall efficiency, η_o (%) of the system was obtained using Equation (23)

$$\eta_o = P_e / LHV_{msw} \times \dot{m}_g \quad (23)$$

2.5 Sizing of gas cleaning system

2.5.1 Sizing of cyclone

The volume flow rate, $\dot{V}_c'$ (m^3/s) at the cyclone inlet was calculated using Equation (24).

$$\dot{V}_c' = \dot{V}_{ge}' \times T_c' / T_{ge}' \quad (24)$$

Where T_c' is the cyclone inlet temperature (K). Thus, a pipe with diameter, D_p (m) should provide a gas velocity, V_{gd} (m/s) which was determined using Equation (25).

$$V_{gd} = 4\dot{V}_c' / \pi D_p^2 \quad (25)$$

Selecting the cyclone inlet width, B_c (cm) equal to the gas pipe diameter (Reed and Das,1988), the cyclone was designed using Equations (26)-(32).

$$B_c = D_c/4 \quad (26)$$

$$D_e = D_c/2 \quad (27)$$

$$H_c = D_c/2 \quad (28)$$

$$L_c = 2D_c \quad (29)$$

$$S_c = D_c/8 \quad (30)$$

$$Z_c = 2D_c \quad (31)$$

$$J_c = D_c/4 \quad (32)$$

For inlet width, B_c and inlet height, H_c (cm) the cyclone inlet velocity, V_{ic} (m/s) was determined using Equation (33).

$$V_{ic} = \dot{V}_c' / B_c \times H_c \quad (33)$$

Cyclone cut size, d_{pc} (μm) was computed using Equation (34).

$$d_{pc} = \sqrt{9\mu_g B_c / 2N_e V_{ic}(\rho_p - \rho_g)\pi} \quad (34)$$

Where V_{ic} is the inlet gas velocity to the cyclone (m/s), μ_g is the dynamic gas viscosity (kg m^{-1} s^{-1}), N_e is the effective number of turns in a cyclone, ρ_g is the gas density at inlet (kg/m^3), ρ_p is the actual particle density (kg/m^3). The pressure drop, ΔP across the cyclone was estimated using Equation (35).

$$\Delta P = 6.5 \times \rho_g \times V_{ic}^2 \times A_d \big/ D_e^2 \quad (35)$$

Where, A_d is the inlet duct area (m^2) and D_e is the diameter of the cyclone exit duct (m).

2.5.2 Sizing of venturi scrubber

Gas volume flow rate at the inlet to the venturi scrubber, $\dot{V}_s'$ (m^3/s) was calculated using Equation (36).

$$\dot{V}_s' = \dot{V}_c' \times T_s' / T_c' \quad (36)$$

Where, T_s' is the scrubber inlet temperature (K). Gas volume flow rate at the outlet to the venturi scrubber, $\dot{V}_s$ (m^3/s) was calculated using Equation (37).

$$\dot{V}_s = \dot{V}_s' \times f_v \quad (37)$$

Where, f_v is the volume correction factor.

2.5.3 Sizing of pump for the venturi scrubber

Liquid-gas ratio, considered was 6.7L/m^3 for efficient scrubbing of the gas (Wikimedia, 2009). The water flow rate, Q_L (m^3/s) was computed using Equation (38).

$$Q_L = 6.7 \times \dot{V}_s' \quad (38)$$

The water velocity, V_w (m/s) was computed using Equation (39).

$$V_w = 4Q_L \big/ \pi d_i^2 \quad (39)$$

Where, d_i is the inside diameter of scrubber (m). The density of water, ρ_w (kg/m^3) was computed using Equation (40).

$$\rho_w = 741.966 + 1.9613 \times T - 0.00371211 \times T^2 \quad (40)$$

Where, T is the room temperature (K). The kinematic viscosity, ν (m^2 /s) of water was computed using Equation (41).

$$\nu = 10^{\left[-13.73 + 1830/T + 0.0197 \times T - 0.0000147 \times T^2\right]} \quad (41)$$

The Reynolds number, Re was computed using Equation (42).

$$\mathrm{Re} = d_i V_w / \nu \quad (42)$$

The friction factor, f was computed using Equation (43).

$$f = 64/\mathrm{Re} \quad (43)$$

The frictional pressure drop, $\Delta P_{f,f}$ (N/m^2) in pipes was calculated using Equation (44) (Jonsson, 2007).

$$\Delta P_{f,f} = f \times L/d_i \times \rho_w V_w^2 \big/ 2 \quad (44)$$

Where, L is the length of pipe (m). The Pump power, P_{pump} (kW) was computed using Equation (45) (Jonsson, 2007).

$$P_{pump} = Q_L \times \Delta P_{f,f} \big/ \eta_p \quad (45)$$

Where, η_p is the efficiency of pump (%)

2.5.4 Sizing of fine filter

For the sizing of the fine filter, filter parameters like bed height, filtering material, retention time, and gas flow were considered (Mandwe et al., 2006). The velocity of gas in the fine filter, V_{gf} (m/s) was calculated using Equation (46).

$$V_{gf} = B_H \big/ R_T \quad (46)$$

Where, R_T is the retention time (s), B_H is the bed height (m). The diameter of the filter, D_f (m) was estimated using Equation (47).

$$D_f = \sqrt{\dot{V}_{ge}' / V_{gf} \times \pi/4} \quad (47)$$

Where, V_{gf} is the velocity of gas in the filter (m/s).

2.5.5 Sizing of bag-house/ fabric filter

The shaking mechanism was considered. The total gross cloth area, A_c (cm^2) was computed using Equation (48).

$$A_c = \dot{V}_{ge}' / V_f \quad (48)$$

Where, V_f is the filtration velocity (cm/s). The bag height, H_{cb} (m) was computed using Equation (49).

$$H_{cb} = A_c / \pi D_{cb} \quad (49)$$

Where, D_{cb} is the bag diameter (cm)

2.6 Economic analysis

Economic evaluations must often cover at least 10 years and often up to 25-40 years (Kjellström, 2007). A single gasifier-engine system was considered. The economic analysis assessed costs such as investment, feed-in tariffs, annual electricity production costs, annual revenues and annual benefits. The annual benefits were used to estimate the payback period as well as the NPV of the investment.

2.6.1 Electricity generation costs, E_c ($)

The costs of electricity generation were computed using Equations (50)-(59) (Reed and Das, 1988). The annual electricity generation, E_{ag} (kWh/a), from a single gasifier-engine system was computed using Equation (50).

$$E_{ag} = P_e \times d_u \times 365 \times 24 \quad (50)$$

Where, d_u is duty cycle (%). The auxiliary energy consumption, E_{ax} (kWh/a) of the pump was computed using Equation (51).

$$E_{ax} = P_{pump} \times d_u \times 365 \times 24 \quad (51)$$

The net annual electricity generation, E_{net} (kWh/a) was computed using Equation (52).

$$E_{net} = E_{ag} - E_{ax} \quad (52)$$

The total cost of electricity generation, C_{total} ($/kWh) was computed using Equation (53).

$$C_{total} = C_{\text{int}} + C_{fuel} + C_{wear} + C_{labour} + C_{ma\text{int}} \quad (53)$$

Where, C_{int} is the cost on interest ($/kWh), C_{fuel} is the cost of fuel ($/kWh), C_{wear} is the cost of wear ($/kWh), C_{labour} is the cost of labour ($/kWh), $C_{ma\text{int}}$ is the cost of maintenance ($/kWh).

C_{int} was computed using Equation (54).

$$C_{\text{int}} = (E_q \times r)/(365 \times 24 \times d_u) \quad (54)$$

Where, E_q is equipment cost ($/kW), r is loan interest (%/a). C_{fuel} was computed using Equation (55).

$$C_{fuel} = (f_p \times sfc)/907.18 \times (1 - B_t) \quad (55)$$

Where, f_p is the fuel price ($\$/t$), sfc is the specific fuel consumption (kg/kWh). C_{wear} was computed using Equation (56).

$$C_{wear} = r_c / (e_c \times e_l) \quad (56)$$

Where, r_c is the rebuild cost ($), e_c is the engine capacity (kW), e_l is the engine life (h). C_{labour} was computed using Equation (57).

$$C_{labour} = (w_r \times h_{as})/(e_c \times h_s) \quad (57)$$

Where, w_r is the wage rate ($/h), h_{as} is the attention hours per shift (h), h_s is the hours per shift (h). $C_{ma\text{int}}$ was computed using Equation (58).

$$C_{ma\text{int}} = (c_p + c_l + c_o)/(e_c \times m_i) \quad (58)$$

Where, c_p is the cost of parts ($), c_l is the cost of labour ($), c_o is the cost for oil analysis ($), m_i is the maintenance interval (h).

The annual electricity generation costs, E_c ($/a) were computed using Equation (59).

$$E_c = E_{ag} \times C_{total} \quad (59)$$

2.6.2 Payback period

The payback period was computed using Equation (60).

$$P_b = I_o / A_b \quad (60)$$

Where, P_b is the payback (years), I_o is the investment ($), and A_b is the annual benefits ($ a^{-1}). I_o was computed using Equation (61).

Where, I means income amount for a specific year; 0, 1, n mean year numbers, where I_o is negative for investment costs.

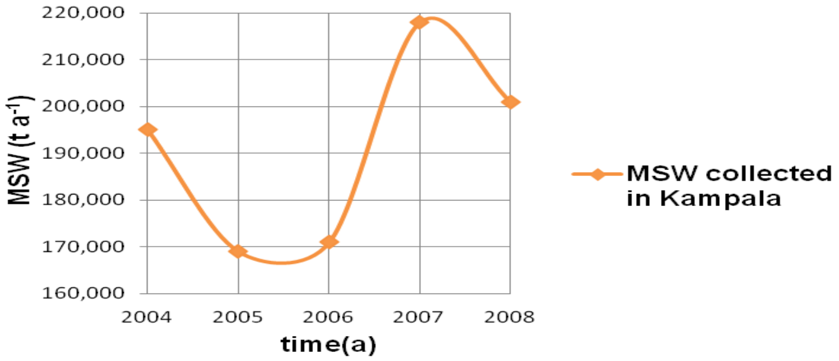

Figure 2 Quantity of MSW collected at Mpererwe landfill from 2004-2008

$$I_o = E_q \times P_e \quad (61)$$

A_b was computed using Equation (62).

$$A_b = R_v - E_c \quad (62)$$

Where, R_v is the annual revenue ($/a). R_v was computed using Equation (63).

$$R_v = E_{net} \times F_t \quad (63)$$

Where, F_t is the feed-in tariff ($/kWh)

2.6.3 Net present value (NPV)

The NPV was computed using Equation (64).

$$NPV = I_0 + \frac{I_1}{1+r} + \frac{I_2}{(1+r)^2} + \dots\dots\dots\dots\dots\dots\dots \frac{I_n}{(1+r)^n} \quad (64)$$

3 Results and discussion

3.1 MSW potential in Kampala

Figure 2 shows the quantities of MSW collected at Mpererwe landfill from 2004 to 2008. The results show a fluctuation in the amount of MSW collected over these years and this is attributed to the seasonal changes in MSW collection. The analysis of data obtained from Mpererwe landfill showed 523 t/d of MSW collected and this is close to the range of 400-500 t/d reported by WaterAid (2011). However, this is lower than the value of 933 t/d reported by Komakech et al. (2014). The increase may be attributed to the improvement of the quantity of MSW collected in Kampala city.

3.2 Characteristics of MSW on as-received basis

Table 1 shows the composition of MSW on as-received basis. The composition was found to be 87.85% biomass, 1.125% Glass, 4.10% plastics, 2.425% metal and 4.25% street debris. In a similar study, Komakech et al. (2014) reported the following composition of MSW from Kampala City; 93.1% biomass, 0.6% glass, 5% plastics, 0.15% metal and 1.15% street debris. The results reported by Komakech et al. (2014) are close to those obtained in this study.

Table 1 Composition of MSW on as-received basis

Type of waste	Mean percentage composition (%)	Amount(kg/s)
Biomass	87.85	5.317
Glass	1.125	0.068
Plastics	4.10	0.248
Metal	2.425	0.147
Street debris	4.25	0.257

Table 2 shows the moisture content and total solids of MSW on as-received basis computed using Microsoft Excel. The average moisture content of the MSW obtained was 71.09%w.b which was close to 71.1% w.b reported by Komakech et al. (2014). On the other hand, the average total solids content of the MSW was found to be 28.91%w.b.

Table 2 Moisture content and total solids of MSW as-received

Sample No.	Moisture content(%)	Total solids(%)
1	63.06	36.94
2	74.31	25.69
3	73.46	26.54
4	73.31	26.69
5	73.11	26.89
6	69.27	30.73
Mean	71.09	28.91
Standard deviation	3.93	3.93

3.3 Analysis of biomass characteristics & gasification parameters of dry MSW

3.3.1 Biomass characteristics of dry MSW related to gasification

Table 3 shows the biomass characteristics of dry MSW related to gasification. The results show that the low bulk density is attributed to MSW being very light and its high standard deviation was as a result of the heterogeneous nature of MSW. In addition, the low bulk density of MSW implies that gasification proceeds very fast thus continuous feeding of the gasifier is required. The material gasified contained a moisture content of 11.8%. Furthermore, the moisture content plays a significant part in the water gas reaction and water gas shift reaction (Hariie, 2005; Akii, 2003; Jared and John, 2002). The material gasified contained total solids of 88.20% and this determines the amount of solid biomass available for gasification. The ash composition of MSW was above 20% (Reed and Das, 1988) and likewise, its high standard deviation is attributed to the heterogeneous nature of MSW. In addition, the higher the ash composition the lower the amount of available total solids for gasification.

Table 3 Biomass characteristics of dry MSW related to gasification

	Bulk density (kg/m^3)	Moisture content (%)	Total solids (%)	Ash content (%)
Mean	57.67	11.80	88.20	25.94
Standard deviation	20.21	2.00	2.00	7.78

3.3.2 Gasification parameters of MSW

3.3.2.1Temperature

Table 4 shows the temperature recorded during gasification of MSW. The results show that the temperature profiles were fluctuating between 29.73-834^0 C. The fluctuation of temperatures inside the gasifier is attributed to MSW continuously flowing down the gasifier as gasification proceeds. Furthermore, the heat generated from the combustion zone was transferred to other zones which also affected the temperatures at the cyclone exit and at the sampling point. The high temperature at the ash zone was attributed to the red-hot charcoal that dropped through the grate.

Table 4 Temperature data recorded during gasification of MSW

Description	Maximum (^{0}C)	Minimum (^{0}C)	Mean (^{0}C)	Range (^{0}C)	Standard deviation (^{0}C)
Ambient temperature	32.09	29.73	31.10	2.37	0.78
Drying/pyrolysis zone	583.98	52.50	236.92	531.49	173.18
Combustion zone	829.88	77.70	673.30	752.18	184.43
Reduction zone	825.15	181.29	683.30	643.85	160.67
Ash zone	834.00	500.84	709.99	333.15	92.71
Cyclone exit	575.86	129.75	367.46	446.10	104.44
Sampling point	428.82	131.10	306.51	297.72	90.53
Heater element	74.11	51.55	60.28	22.56	7.52

3.3.2.2 Gas analysis

Table 5 shows the percentage composition of the dry normalized producer gas from MSW, calibration gas and air obtained using Gas Chromatography. Using Equation (1) and the values in Table 5, the LHV of producer gas was determined as 4.75 MJ/Nm^3 which compares well with values of 2.0- 6.0 for air blown gasifiers (Hariie, 2005; Akii, 2003).

Table 5 Normalized Producer gas from MSW, calibration gas and air

	H_2	O_2	N_2	CO	CH_4	CO_2	C_2H_4	Total
Producer gas (%)	11.64	0	54.12	13.70	4.45	16.09	0	100.00
Calibration Gas (%)	8.05	0.61	58.97	9.93	5.09	17.96	0	100.61
Air (%)		20.9	78					98.9

3.4 Sizing of engine

$\dot{V}_{ag}$ was 1.145 m^3/s while $\dot{V}''_{ge}$ was 0.545 m^3/s. f_e was taken as 0.8 (FAO, 1986) while a T'_{ge} of 298 K was considered (Kaupp,1984). $\dot{V}'_{ge}$ at 298 K and 1 atm was 0.436 m^3/s while $\dot{V}_{ge}$ was 0.4 Nm^3/s. P_g was 1898.09 kW. P_m was 531.4 kW. P_e was 425.17 kW. Since P_e was only 425.17 kW, then the 1250 kW engine was selected (Cummins, 2008).

3.5 Sizing of gasifier

MSW with $\dot{m}_{tw}$ of 5.317 kg/s and B_{tw} of 71.09% was converted to $\dot{m}_t$ of 1.743 kg/s and B_t of 11.8% suitable for gasification. The η_g of the gasifer was taken as 70% (FAO, 1986) and LHV_{msw} as 12000 kJ/kg (Fakhrai, 2007). The n_g needed to gasify this waste was approximately eight gasifiers. The η_O was 15.68%. The B_h value of 9000 Nm^3 m^{-2} h^{-1} was considered (Reed and Das, 1988; FAO, 1986). Table 6 shows additional parameters determined. The $\dot{m}_g$ of 0.226 kg/s is close to the practical upper limit of 0.139 kg/s for downdraft gasification reported by Bridgewater (1994).

Table 6 Additional parameters for the sizing of the gasifier

Biomass consumption						
P_g (kW)	$\dot{m}_g$ (kg/s)	sfc (kg/kWh)	SED (GJ m^{-2} h^{-1})			
2711.55	0.226	1.913	42.75			
Reactor Design						
GPR (m^3/h)	A_h (m^2)	d_t (mm)	h (cm)	d_r (mm)	d_n (mm)	SGR(kg h^{-1}m^{-2})
5127.14	0.16	451	21.7	948	43.7	5089.29

3.6 Sizing of cyclone

T'_c was assumed to be 573 K giving a $\dot{V}'_c$ of 0.839 m^3/s. A D_p of 0.15 m inside diameter resulted in a V_{gd} of 47.4 m/s which was above the recommended minimum velocity of 15 m/s for conveying medium density dust (Reed and Das, 1988). For B_c of 15 cm, D_c was 60 cm, H_c was 30 cm, J_c was 15 cm, L_c was 120 cm, S_c was 7.5 cm, Z_c was 120 cm, D_e was 30 cm. For B_c of 15 cm and H_c of 30 cm, V_{ic} was 18.64 m/s. Using the T'_c of 300^0 C ρ_g and μ_g were obtained as 0.489 kg/m^3 and 255 × 10^{-7} kg m^{-1} s^{-1} respectively. With a ρ_p of 2000 kg/m^3 (Reed and Das, 1988), d_{pc} was 5.42 µm for ash. The ΔP across the cyclone was 552.07 N/m^2. Thus, this cyclone would achieve the desired particulate removal without excessive pressure drop. Figure 3 shows a cyclone with the various proportions.

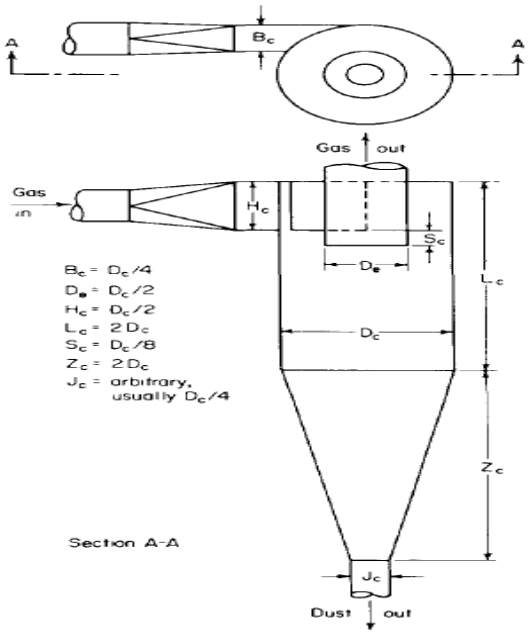

Figure 3 High-efficiency cyclone proportions (Reed and Das, 1988).

3.7 Sizing of venturi scrubber

T_s' was estimated at 200^0 C thus $\dot{V}_s'$ was 0.692 m^3/s. From the volume correction chart, for 0.15 kg/H_2O kg of dry air (Sly Inc., 1998), f_v was 0.775 and $\dot{V}_s$ was 0.537 m^3/s. The value of 0.537 m^3/s was closest to the nominal capacity range of 1.227/1.699 m^3/s (Sly Inc., 1998). Figure 4 shows the venturi scrubber while Table 7 shows the dimensions selected.

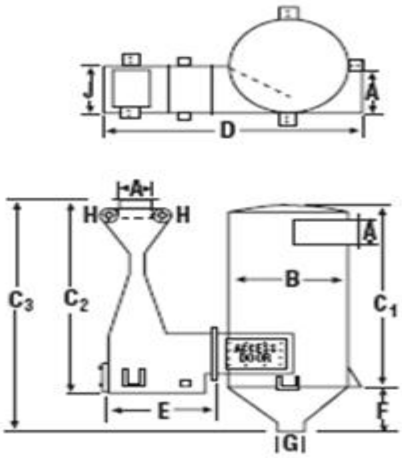

Figure 4 Schematic drawing of the scrubber (Sly Inc., 1998).

Table 7 Scrubber dimensions (Sly Inc., 1998).

Nominal capacity/ saturated (m^3/s)	1.227/1.699
inlet ×outlet A	13×13
separation diameter B(m)	1.118
separation C_1 (m)	1.981
Vent C_2 (m)	2.002
Overall height C_3 (m)	2.189
overall width D(m)	2.019
venturi width E(m)	0.711
Separation cone F(m)	0.394
drain pipe G(m)	0.076 2
water pipe H(m)	0.050 8
venturi depth J(m)	0.431 8

3.8 Sizing of pump for the venturi scrubber

A $\dot{V}_s'$ of 0.692 m^3/s required a Q_L of 0.004 64 m^3/s. The T of 295.5 K (USMA, 2010) for the water in the scrubber pond was considered giving a ρ_w of 997.39 kg/m and ν of 0.001 001 m^2/s. From Table 7, a d_i of 0.050 8 m was selected and an L of 5m was considered. The V_w was 2.29 m/s with a Re of 116.15 and since $\mathrm{Re} < 2300$, then the flow was laminar thus, f was calculated as 0.55. The $\Delta P_{f,f}$ in the pipe was 141 804 N/m and assuming η_p of 50% (Jonsson, 2007), P_{pump} was 1.316 kW. This power can be supplied from the net power output of 425.17 kW obtained from a single gasifier-engine system.

3.9 Sizing of fine filter

An R_T of 10 s for a gas in the B_H of 50 cm was considered (Mandwe et al., 2006). The V_{gf} in the filter was 0.05 m/s. V_{ge}' in the fine filter was 0.436 m^3/s. The D_f of the filter was 3.334 m. The filtering material recommended was rice husks. Figure 5 shows a sketch of the fine filter drawn using Microsoft Word.

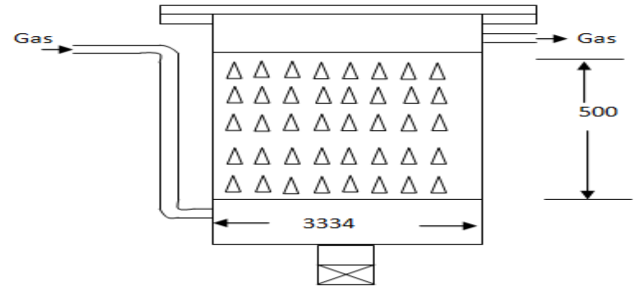

Figure 5 Sketch of the fine filter (all dimensions in mm)

3.10 Sizing of bag-house/fabric filter

V'_{ge} considered was 436 000 cm^3/s. The V_f of 3 cm/s was considered giving an A_c of 145 396 cm^2. For space considerations the D_{cb} of 30.48 cm was considered (David et al., 2005) and the calculated H_{cb} was 2.44 m. Figure 6 shows a sketch of a fabric filter. The layout of the system was drawn using SOLID-EDGE software and it is shown in Figure 7.

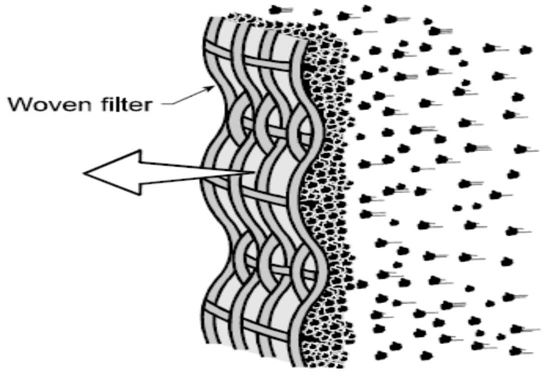

Figure 6 Sieving (on a woven filter) (David et al., 2005).

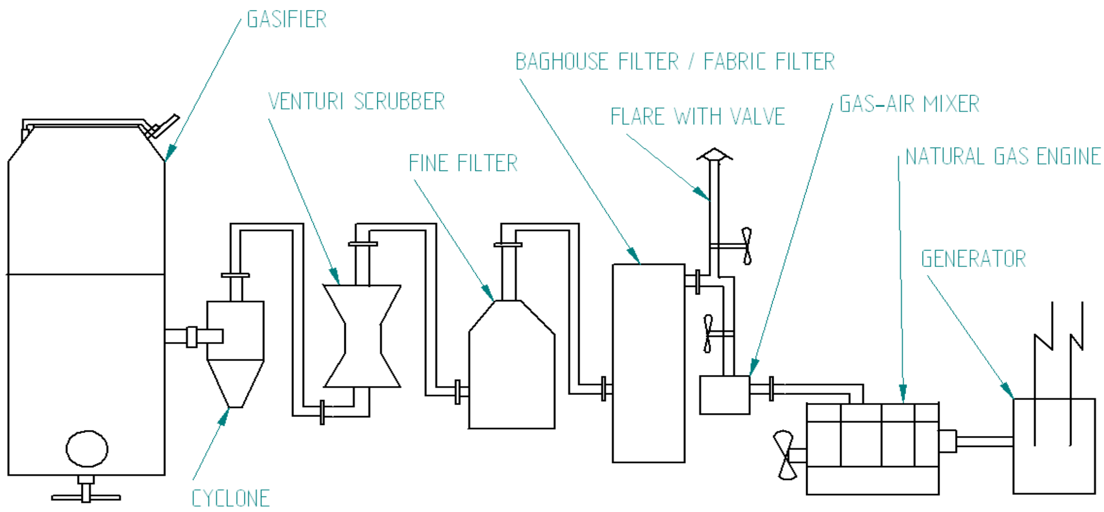

Figure 7 Layout of the gasifier-engine system

3.11 Economic analysis

3.11.1 Electricity generation costs and Payback

For a P_e of 425.17 kW and d_u of 80% (Reed and Das, 1988), E_{ag} was 297 960 2.2 kWh/ a. For a P_{pump} of 1.316 kW, E_{ax} was 921 9.58 kWh/a and the resulting E_{net} was 2 970 382.6 kWh/a. The E_q considered was $ 2087/kW (Buchholz and Volk, 2007). For an r of 6% (Boyle, 2004), C_{int} was $ 0.017 87/kWh. For a f_p of -2 $\$/t$, sfc of 0.454 kg/kWh and B_t of 11.8%, C_{fuel} was $ -0.004 78/kWh. For an r_c of $ 4500, e_c of 1250 kW and e_l of 10 000 h (Africa Motors and Machinery, 2010), C_{wear} was $0.000 36/kWh. For a w_r of $ 0.5 /h, h_{as} of 0.5 h and h_s of 8 h, C_{labour} was $ 0.000 025/kWh. For c_p of $97.9 ($82.9 for 20L oil capacity and $15 plugs), c_l of $37 for 1 h labour, c_o of $15 and m_i of 200 h, C_{maint} was $ 0.000 60/kWh, C_{total} was $ 0.014 07 /kWh. The resulting E_c was $ 41 924.31/a. I_o was $887 333.01.

The F_t considered was \$ 0.059 6/kWh (MEMD, 2007) leading to R_v of \$ 177 034.80/a. Thus, A_b was \$135 110.50/a. The payback was 6.57 a.

3.11.2 NPV

Boyle (2004), recommends discount rates of 6%-15% for economic evaluation of renewable energy projects. BOU (2010), issued interest rates to commercial banks in the range 16%-21% as at January, 2007. The income amount, I of \$135 110.50/a was considered. Using Microsoft Excel, the NPV was computed for values of interest rates, r from 6% to 21% for n years. At an r of 6%, the NPV was positive after 9 years with a value of \$316 47.033. Figure 8 shows the NPV calculated at different interest rates and years.

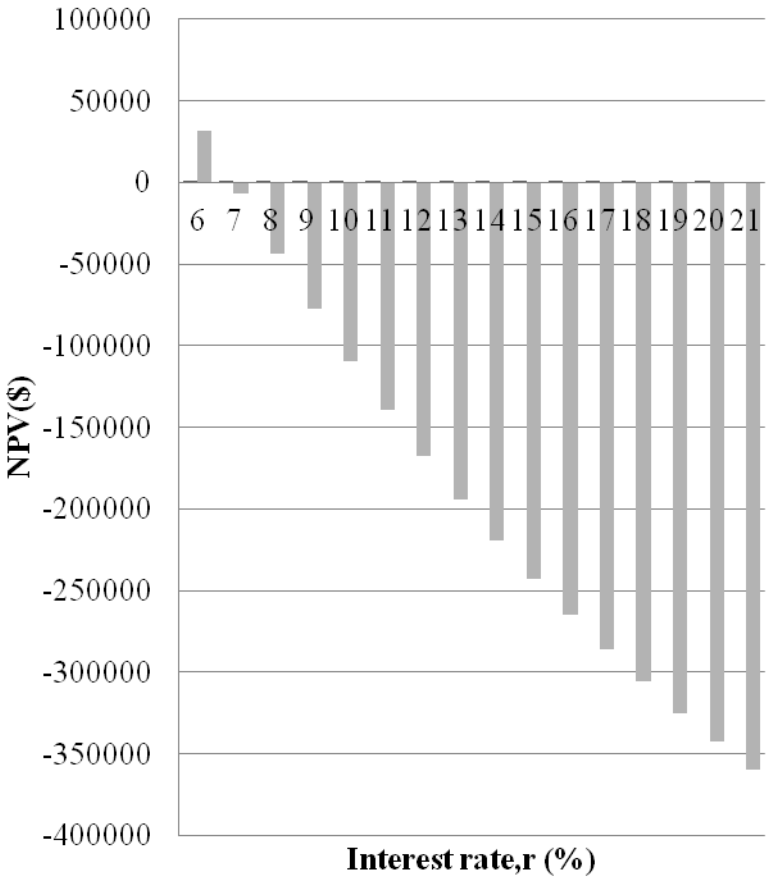

Figure 8 NPV at different interest rates for nine years

4 Conclusions

The MSW generated in Kampala City has potential to power up to eight gasifier-engine systems each with capacity 2711.55 kW. However, MSW needs to be sorted to obtain the biomass component which is suitable for gasification while other components such as plastics, metal and glass can be recycled by setting up recycling plants. Furthermore, the biomass collected from Kampala City has high moisture content and has to be dried by open-sun-drying or through heat recovery to optimum moisture content suitable for gasification before feeding it to the system. The total cost of equipment was found to be \$887 333.01 with a return on investment of 9 years at 6% interest rate which showed that the project was worth the investment. Furthermore, for higher interest rates the return on investment would take a longer time which may not be feasible considering that this is a small scale power generation project. The project could be implemented considering factors such as increasing the energy supply and provision of employment in Kampala City. The implementation of the project could consider installation of a system in each of the five divisions of Kampala City i.e. Kawempe, Rubaga, Makindye, Nakawa and Kampala Central. This would greatly reduce on the costs of transporting the waste over long distances to a single location as well as minimize on the resulting emissions from the transport facilities. Furthermore, due to the heterogenous nature and low bulk density of MSW, briquetting of the fuel should be considered to improve on the handling and gasification.

Acknowledgements

The authors wish to extend their sincere gratitude to the Swedish International Development Agency (SIDA), KTH, Royal Institute of Technology and the College of Engineering, Design, Art and Technology (CEDAT) at Makerere University for the financial and technical support .

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