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ORIGINAL RESEARCH

Multi-level framework for optimal operation of gasifier system utilising crop residues from small and medium-scale farms

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Abstract

Lack of techno-economic framework for optimal gasification and the identification of critical parameters for optimal operations is one of the major challenges restricting the gasification of crop residues. This study aims to develop an optimal techno-economic framework for the gasification of crop residues from clustered small/medium-scale farms. The developed model was applied to a case study in Adiembra, a farming community for a 10-kW gasifier engine system. Eight scenarios of individual feedstock and their blends were considered. The results revealed specific fuel consumption ranging from 1.79 – 3.53 kg/kWh. The economic analysis showed marginal profitability except for rice husk and straw which are not profitable. At the current grid electricity price, the minimum level of subsidies required to ensure the financial viability of the feedstocks is within the range of 30 – 70 % of the investment cost based on the various feedstock scenarios considered. The study revealed individual feedstocks with the best technical and economic prospects for optimal gasification to be cocoa pod husk, maize stalk and husk, maize cobs, rice straw and rice husk in the order of best to worst. The use of feedstock blends generally improved the overall syngas characteristics and financial viability. A total number of farms ranging between 107 – 532 are required to be clustered within a radius of 0.74 – 2.12 km with a cluster radius greater than 3.91 km not being financially viable. The fraction of each feedstock type in the blends were optimised with corresponding increase in syngas generation within the range of 9 – 35 % and decrease in the required number of farms within the range of 30 – 57 %. The outcome of the study demonstrates that sustainable gasification of crop residues for mini-grid electricity generation requires co-gasification of various residue types, valorisation of by-products and increase in the current feed-in-tariff rate in Ghana.

Keywords: Techno-economic, Crop Residues, Gasification, Farms, Optimisation

Introduction

Access to energy, particularly electricity, not only boosts socio-economic development but also helps to address challenges within other sectors of the economy, such as the provision of better healthcare, education, and employment among others. Ghana has seen an increase in electricity access from 23.5 % in 1990 to 85 % in 2019, however, access in rural areas remains lower, at about 70.5 % (Energy Commission Ghana, 2020). Efforts to ensure overall electricity access require an increase in electrification of rural communities by providing on and off-grid electricity solutions. Renewable energy is expected to play a critical role in this. However, only 1.1 % of total electricity in Ghana is generated from renewable energy mainly solar and biogas systems (Energy Commission Ghana, 2021). Biomass, as a renewable energy source, has a critical role to play in Ghana due to the unused feedstock generated annually (Osei *et al*., 2021; Kemausuor *et al*., 2015).

Traditionally, biomass in the form of firewood and charcoal accounts for 40.5 % of the total energy consumption in the country (Energy Commission Ghana, 2018). Currently, the consumption of firewood and charcoal as bioenergy feedstock is mostly done inefficiently and unsustainably and presents associated environmental and health issues (Anenberg *et al*., 2017). It contributes to climate change at regional and global levels. Due to the intensive agricultural activities in African countries, significant quantities of crop residues (e.g., rice husk, maize stalk and cobs, cassava peels, etc.) are generated annually. About 18,862,282 tonnes of field and processed-based agricultural residues are generated annually in Ghana (Kemausuor *et al*., 2015). These crop residues are often unused by farming communities (Arranz-Piera et al., 2017; Kemausuor *et al*., 2015). However, they can be used sustainably to provide off-grid energy solutions to rural communities using several conversion technologies including biogas, pyrolysis, gasification, and direct combustion among others (Osei *et al*., 2021).

Among the conversion technologies, gasification is one of the best for the reuse of crop residues and it is considered one of the most efficient ways of converting the energy embedded in biomass, as it provides room for small-scale applications for both electricity and heat generation with lower GHG (Akolgo *et al*., 2019; Pereira *et al*., 2012). Gasification is the thermal treatment of biomass at higher temperatures between 600 ^{o}C - 1200 ^{o}C and in oxygen-restricted environment which leads to the formation of a synthesis gas (syngas) with the constituent being hydrogen (H_2), carbon monoxide (CO), methane, (CH_4), carbon dioxide (CO_2) with lesser amount of water vapor (H_2O), tar, hydrogen sulfide (H_2S), carbonyl sulfide (COS) and other trace contaminants. Syngas can be used directly for heat applications such as cooking, drying crops, etc. Gasifier stoves for cooking are common in some developing countries, particularly in Asia (Ramamurthi *et al*., 2016). When syngas is appropriately cleaned to remove tar and carbon dioxide, it can be used in combustion engines. Even though the gasification technology is quite mature and reliable, it is not vastly deployed in Ghana, with few installations across the country due to some challenges (Osei *et al*., 2021; Akolgo *et al*., 2019).

The installed gasification systems in Ghana are mainly aimed at the efficient production of charcoal, heat, and power with little success (Akolgo *et al*., 2019). Four gasifier plants for institutional heat and electricity operations have been identified to be currently in operation in Ghana (Osei *et al*., 2021). The

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main challenges of installed gasifier plants have been categorised into social, technical, and economic ((Akolgo *et al*., 2019; Energy Commission Ghana, 2016; Kontor, 2013). Despite the reported availability of crop residues for energy generation (Kemausuor *et al*., 2015), unsustainable feedstock availability and supply have been identified as one of the major problems confronting installed gasifier plants in Ghana (Akolgo *et al*., 2019; Energy Commission Ghana, 2016). The feedstock types mostly used are low-density crop or wood processing residues (Osei *et al*., 2021). A good number of crop residues are available in Ghana which can serve as feedstocks for gasification, however, seasonal variation of residues, as well as logistical challenges, disrupt feedstock supply which poses a threat to the smooth operation of biomass gasification systems. Co-gasification of different feedstocks can however ensure smooth operations of the gasification system (Inayat *et al*., 2016). This has not been the subject of much discussion in literature, particularly for crop residue types available in Ghana (Inayat *et al*., 2016). The potential and viability of gasification of feedstock blends particularly for crop residues that can ensure optimal and sustainable gasification must therefore be investigated. Moreover, the current mode of operation of existing gasifier systems has been reported to be not technically and economically sustainable (Owen and Ripken, 2017).

The techno-economic study is the most important analysis of any biomass gasification system (Sansaniwal *et al*., 2017). It is used to identify the economic and social feasibility of the implementation of any energy generation system. It includes the performance evaluation of the designed system in terms of its efficiency, capital cost, operating and maintenance cost, gas production rate, payback periods, Internal Rate of Return (IRR), Net Present Value (NPV), acceptance of the technology and the cost-effectiveness of the entire system. Such investigations depend on many parameters such as feedstock type and availability, system capacity, gas production quantity and quality, design optimisation, and end-user applications. Several studies have presented techno-economic analysis of different gasification systems for different feedstock types (Porcu *et al*., 2019; Susanto *et al*., 2018; Lan *et al*., 2021). In the specific case of Ghana, techno-economic analysis on electricity production for crop residues from small and medium-scale clustered farms and agro-processing have been studied considering Combine Heat and Power generation (CHP) and gasification systems (Arranz-Piera *et al*., 2018; Arranz-Piera *et al*., 2017; Ramamurthi *et al*., 2016). The technical analysis aspects of the techno-economic analysis mostly involve the use of proximate, ultimate calorimetric and ash content analysis to determine syngas output and characteristics. Other studies also considered the use of technical parameters from operations of existing gasification plants. The economic analysis mostly employs the use of LCOE, NPV and IRR (Lan *et al*., 2021; Porcu *et al*., 2019; Arranz-Piera *et al*., 2018; Arranz-Piera *et al*., 2017; Ramamurthi *et al*., 2016).

The main research gaps identified from the available techno-economic analysis in literature is that most of the studies considered analysis on the gasification of single crop residue types, limiting the prospects of blended biomass feedstock systems (Porcu *et al*., 2019; Susanto *et al*., 2018; Ramamurthi *et al*., 2016). Some studies considered the use of multiple crop residues (Arranz-Piera *et al*., 2018; Arranz-Piera *et al*., 2017; Arranz-Piera *et al*., 2016). These studies however did not take into consideration the optimal fraction of each feedstock type in the blends and the optimisation of critical technical and economic parameters to ensure sustainable operations. The aim of this study is therefore to develop a techno-economic framework for systematic techno-economic analysis for the gasification of crop residues from small-scale farms for electricity generation based on the intrinsic feedstock characteristics with optimisation of syngas generation, feedstock supply and economic parameters. Comparative analysis of various feedstock types and blends for gasification is also investigated. Sensitivity analysis

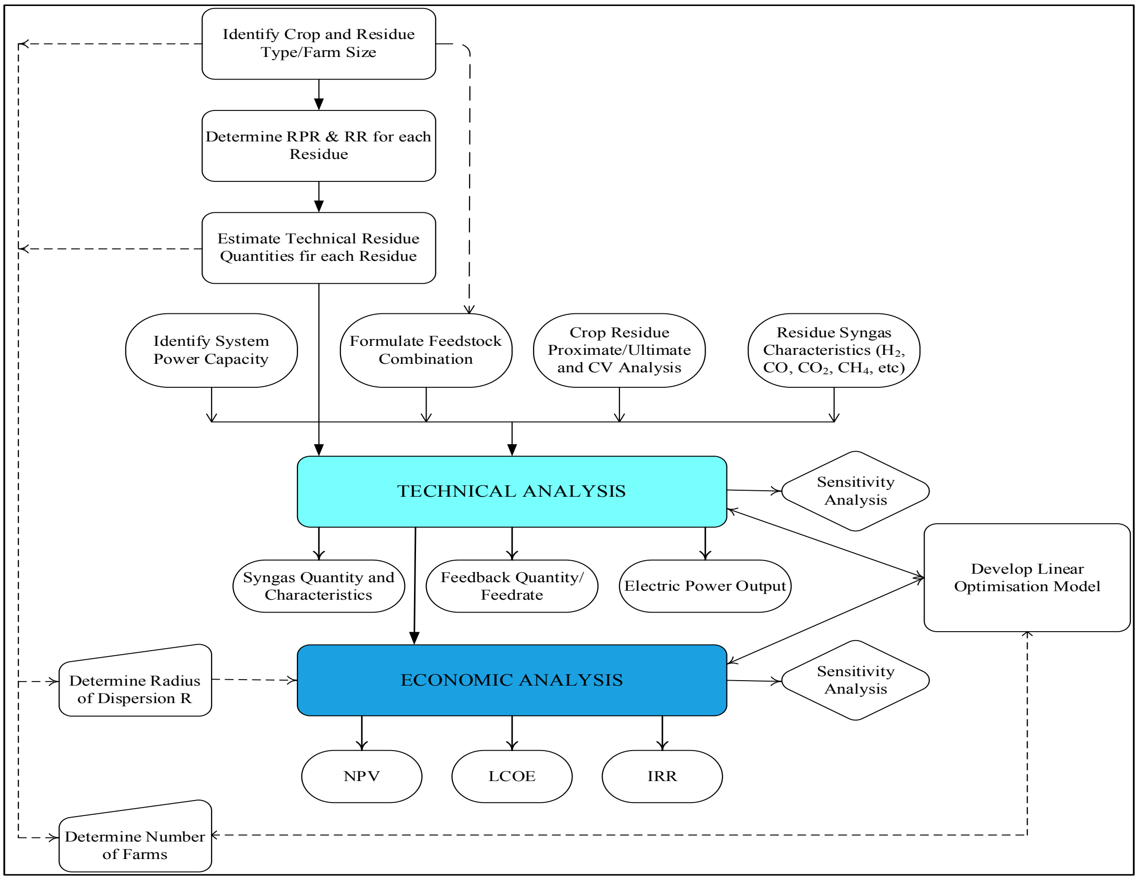

Figure 1 Framework for the development of the techno-economic model

is also performed on critical model parameters. The developed techno-economic model is implemented in an unelectrified farming community for a 10-kW gasifier engine system for electricity generation. The outcome of this study is also expected to present optimal technical parameters for the successful operations of gasifier systems which are essential for energy planners and investors in the gasification sector.

Materials and Methods

Model formulation and description

The techno-economic model was developed for the gasification of crop residues from clustered small and medium-scale farms. Figure 1 presents a schematic of the model formulation and the conceptual framework. The model consists of five main sections: crop residue types and quantification, technical analysis, economic analysis, determination of the optimal radius of dispersion of farm and number of farms required and sensitivity analysis.

Identification of farm size, residue type and quantities

The various field and process-based residues available from each crop type within the study area are identified. The Residue to Product Ratio (RPR) and the Recoverability Ratio (RR) for the residue types are determined. For the case study, RPR and RR as determined by Kemausuor *et al.* (2015) in the study area were used. The total wet technical (Q_{RFW}) and dry technical residue potential (Q_{RFd}) from each farm were determined using Equations 1a and b respectively.

$$Q_{RFw} = \sum_{i=0}^{n} C_i \times RPR_i \times RR_i \quad (1a)$$

$$Q_{RFd} = \sum_{i=0}^{n} C_i \times RPR_i \times RR_i(1 - MC_i) \quad (1b)$$

Where:
Q_{RF} = Total technical residue per farm (t/farm)
n = Total number of residue types per farm
C = crop yield (t)
RPR=Residue to Product Ratio for each crop type
RR=Recoverability Ratio for each crop type
MC=Moisture fraction of each residue type

Methodology for technical analysis

The input parameters of this section include the capacity of the gasifier engine system, formulation of feedstock combination based on available feedstock types, chemical characteristics of feedstocks (proximate, ultimate analysis and calorific values), and syngas characteristics. In the case study, using methods described by Commeh *et al*. (2019), the proximate and ultimate analysis results are presented in Table A.1 in Appendix A. The model assumes a downdraft gasifier as the gasifier type due to its ability to work well with crop residues (Belonio, 2005). Therefore, optimal operating conditions (Equivalence ratio) and volumetric syngas composition (H_2 CH_4, CO, CO_2 and tar content of syngas) as determined from experiments of the same residue type in literature were used (see Table A.2 in Appendix A). The output syngas characteristics and optimal operating were determined using the following approaches.

1. **The stoichiometric amount of air and air fuel ratio required**
   The dry stoichiometric amount of air required for complete combustion of a unit weight of biomass and air-fuel ratio was determined using Eqs. 2a and 2b respectively.

$$DS_{air} = [0.1153C + 0.3434 (H - {}^{O}/_{8}) + 0.043] \quad (2a)$$

$$n_{air} = DS_{air} \times ER \quad (2b)$$

Where: C, H, O and S are the percentages of carbon, hydrogen, oxygen and sulphur respectively as determined from the ultimate analysis. Where ER is the optimal Equivalent Ratio from each feedstock as determined from Table A.2

2. **Determination of the lower heating value of syngas**
   The syngas heating values Q_{syngas} (MJ/Nm^3) for each feedstock type are estimated using the method described by Susastriawan *et al.* (2019).

3. **The energy released per kg of feedstock and specific gas yield Vg (Nm^3/kg)**
   The energy released per kg of each feedstock (E_g (*MJ/kg*) and specific gas yield V_g(Nm^3/kg) were estimated using the method described by Prasad *et al.* (2014) and Di Carlo *et al.* (2022) respectively.

4. **Determination of carbon, cold gas, thermal and overall efficiency**
   The carbon conversion (CCE), Cold gas (CGE), thermal (GTE) and overall conversion efficiencies were determined using the method described by Makwana *et al.* (2015), Susastriawan *et al.* (2019), Prasad *et al*. (2014) and Eq. 3 respectively.

$$\eta overall = \frac{CCE\ (\%) \times EF_E (\%)}{100\%} \quad (3)$$

Where EF_E = Efficiency of ICE, 22 % was used (All Power Labs, 2021)

Estimation of electricity, syngas, char, tar and feedstock quantities required

The annual electricity generated based on the system capacity was estimated using Eq. 3a. Similarly, the clean syngas power input (CSP) and syngas flow rate (FR_{syngas}) were determined using Eqs. 3b and 3c respectively.

$$EGA_{electricity} = EC_{gross}\ (kW) \times CF \times OH_{annual} \quad (3a)$$

$$CSP\ (kW) = \frac{C_E}{EF_E / 100\%} \quad (3b)$$

$$FR_{syngas}(m^3/h) = \frac{CSP\ (kw)}{Q_{syngas} \times 1000} \times 3600 \quad (3c)$$

Where:
EC_{gross} = Gross electrical capacity (kW)
CF = Capacity factor, 0.9 was used
OH_{annual} = Annual Operational Hours. 8000hrs were used (Rahimi et al, 2020) and
C_E = Capacity of Internal Combustion Engine (ICE) system (kW)

The biomass feed rate (BFR) dry basis (kg/h), air feed rate (m^3/h), specific fuel consumption (SFC) (kg/kWh) and annual biomass consumption (BC_{annual}) dry basis (kg/yr) were determined using Equations 4 a, b, c and d respectively.

$$BFR\ (kg/h) = \frac{CSP \times 3600}{(CGE/100\%) \times 1000 \times CV\ feedstock} \quad (4a)$$

$$Air\ Feed\ rate\ (m^3/h) = \frac{BFR\ (kg/h) \times n\ air}{1.223\ (kg/m3)} \quad (4b)$$

$$SFC\ (kg/kWh) = \frac{BCA\ feedstock\ (kg/yr)\ x}{EGA\ electricity\ (KWh/yr)} \quad (4c)$$

$$BC\ annual\ (kg/yr) = BFR\ (kg/h) \times OH\ annual \quad (4d)$$

The unreacted char production rate (CPR) (kg/hr) was determined using Eq. 5. The quantity of tar generated (TG) was also estimated using Eq. 6.

$$CPR\ (kg/hr) = BFR \times (CP/100\% \quad (5)$$

$$G\ (kg/hr) = \frac{FR_{syngas} \times TC}{1000} \quad (6)$$

Where CP is the percentage of unreacted char generated as a percentage of biomass feed rate. A value of 5 % was used as suggested by All Power Labs (2021). TC is the quantity of tar generated for each m^3 of syngas produced in g/Nm^3.

Determination of the number of farms required and radius of dispersion crop residues

The total number of farms (N_f) needed to provide the required residue quantities for each scenario considered was determined using Eq. 7a. The ideal radius of dispersion of the residues from the power plant was determined using Eq. 7b as presented by Velo (2011).

$$N_f = \frac{BC_{annual} \times 1000\ (t/y)}{_{QRF}\ (t/farm)} \quad (7a)$$

$$R_{dispersion} = \sqrt{\frac{(C_E \times 1000)(MWe)/_{\eta_{overall}} 3600 \times 24}{CV_{feedstock}(MJ/kg) \times d \times \pi}} \quad (7b)$$

Where d is sustainable residue production (kg/km^2 day). In this study, the sustainable residue production (d) was determined from residue densities as presented by kemausuor *et al.* (2015).

Methodology for economic analysis

Table A.3 in Appendix A presents the assumptions and data sources used to perform the economic analysis. The main revenue streams considered in the analysis are the sale of electricity and unburnt char as a soil amendment as suggested by Ripken and Owen (2017). The Internal Rate of Return (IRR), the Net Present Value (NPV) and the Levelised Cost of Energy (LCOE) were used to ascertain the financial viability of each scenario considered. These parameters were determined using methods described by Arranz-Piera *et al.* (2017) for IRR and NPV and Ramamurthi *et al.* (2016) for LCOE.

Sensitivity analysis

RR and RPR were subjected to sensitivity analysis using a range of values as presented in Table A.4. Various farm sizes of cocoa (3, 5 and 10 ha), rice (0.96, 5,10 ha) and maize (2, 5 and 10 ha) were also considered for the sensitivity analysis. The cost of biomass, electricity subsidy and electricity tariffs were also subjected to sensitivity analysis. Similarly, the volumetric concentration of syngas gas species was subjected to sensitivity analysis using Table A.6 in Appendix A. Moreover, a discount rate in the range of 18 – 30 % were also considered for the sensitivity analysis.

Development of linear programming optimization models

Based on the outcomes of the techno-economic models, a multi-objective linear programming model was developed which consists of three objective functions (see Eq. 8a) and four constraints (C1 to C4). For the scenarios that considered the various feedstock blends, the optimal composition of each feedstock quantity in the blend was optimised to maximise annual syngas output (Eq. 8b) maximising NPV (Eq. 8c) and minimising the total number of farms required to provide the needed feedstock quantities (Eq. 8d).

$$F(x) = (f_1(x), f_2(x), f_3(x)) \quad (8a)$$

1. **Objective Function 1 (f_1 (x))**

$$Z_1 = Maximise\ (FRA_{syngas}) = a_1 X_1 + a_2 X_2 + a_3 X_3 \ldots a\_n\ X_n \quad (8b)$$

Where

n = Total number of feedstocks within the blends

a = specific gas yield for each feedstock (m^3/kg)

X = Optimal total annual quantities of each feed stock in the blend (kg)

Z_1= Optimal total annual quantities of syngas (m^3)

2. **Objective Function 2 *($f_2(x)$)***

Where:

$$Z_2 = Minimise\ (N_f) = \frac{1}{y_1}X_1 + \frac{1}{y_2}X_2 + \frac{1}{y_3}X_3 \ldots \frac{1}{y_n}X_n \quad (8c)$$

y_i = Total quantity of feedstock generated per farm size

Z_2 = Total number of clustered farms required under each feedstock blend category

3. **Objective Function 3 (f_3(x))**

$$Z_3 = Maximise\ (NPV) = p_1 X_1 + p_2 X_2 + p_3 X_3 \ldots p\_n\ X\_n \quad (8d)$$

Where

Z_3 = Maximum NPV (USD)

p = Net Present value (NPV) per kg of individual feedstock (USD/kg)

4. **Constraints for Objective Functions 1, 2 and 3**

$0 < X_1, X_2, X_3 \ldots X_n \leq b_1, b_2, b_3 \ldots b_n$:C1

$X_1 + X_2 + X_3 \ldots X_n = T$: C2

$0.1T \leq X_1, X_2, X_3 \ldots X_n \leq 0.7T$:C3

$Z_1 \geq d$:C4

Where: $b_1..b_n$ =Total annual quantities of feedstock used individually (kg)

T=Total annual quantities of feedstock in the combined feedstock blend (kg)

d = Total quantity of syngas generated for the combined feedstock (m^3)

Each of the three objective functions together with the constraints was solved individually using the Simplex LP method in excel. They were then solved together using the MiniMax function to determine the optimal composition of feedstock in the blends that can satisfy all three objective functions and constraints.

Case study and application of developed model

The techno-economic and optimisation models were applied to a case study in the Asante Akyem North District of the Ashanti region, Ghana. This is an unelectrified farming community. The main crops cultivated are maize, rice, and cocoa among others. Based on the need for electricity for rice milling and irrigation

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purposes, a 10-kW gasifier engine system was considered as the system capacity. Table 1 presents the various feedstock scenarios considered based on the available feedstocks. The various scenarios were considered in order to investigates the prospects of individual and co-gasification of the various feedstocks in the study area.

Results and Discussion

Determination of syngas characteristics and conversion efficiency of feedstock

The syngas heating value and the volumetric composition of H_2, CH_4 and CO play a critical role in determining the syngas quality and ultimately its suitability for electricity generation (Indrawan *et al*., 2017). Values for the individual feedstock were within the range of 4.51 – 6.77 MJ/Nm^3. Cocoa pod husk had a favourable composition of H_2, CO, and CH_4 which resulted in the highest syngas heating value of 6.77 MJ/Nm^3. The differences in the volumetric composition of the various gas species can be attributed to the inherent characteristics of each feedstock type as well as optimal operating gasifier parameters (Kirsanovs *et al.,* 2017). The volumetric syngas composition was determined as the average percentage composition for each gas specie in the blends. Overall, the use of feedstock combination generally presented improved volumetric syngas characteristics and heating value (ranging between 4.4 to 6.8 MJ/Nm^3), particularly for individual feedstock with poor characteristics (see Figure 2). Co-gasification of different biomass resources has been reported to reduce high ash content by mixing different feedstocks which can mitigate the ash melting problem in the gasification process (Akkache *et al*., 2016). Co-gasification of oil palm fronds (OPF) and coconut shells (CS) at different blending ratio showed an increase in the percentage volumetric composition of H_2, CO and CH_4, gas yield and syngas heating value compared to the gasification of individual feedstocks (Inayat *et al*., 2016).

Table 1 Residue categories and scenarios considered

Residue categories	Residue type in the category
F1	cocoa pod husk, rice husk & straw, maize stalk, husk and cobs
F2	Cocoa pod husk
F3	Maize stalk, husk and cobs
F4	Rice straw & husk
F5	Cocoa pod husk & Maize stalk, husk and cobs
F6	cocoa pod husk & Rice straw & husk
F7	Maize stalk, husk and cobs& Rice straw & husk
F8	Rice husk

Similarly, Cao *et al.* (2022) reported improved H_2 and Heating values of co-gasification rice husk, sawdust and bamboo dust. Rice husk has the lowest syngas heating value of 4.36 MJ/Nm^3 but as part of feedstock blends in F1, F4 and F6 the overall characteristics improved due to the favourable syngas property of the other feedstocks types in the blends. Table 2 presents syngas characteristics for the various feedstock categories considered. The specific gas yield presents the quantity of syngas yield per each unit of feedstocks. Feedstock blends F3 (maize stalk, husk and cobs) have the highest specific gas yield of 1.63 Nm^3/kg.

Among the individual feedstocks, cocoa pod husk in all

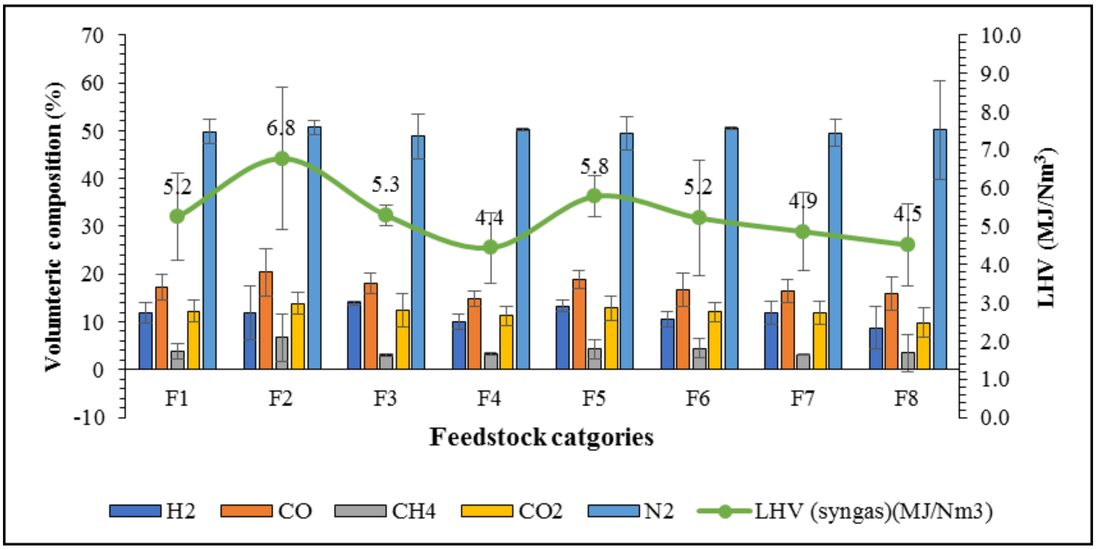

Figure 2 Volumetric syngas composition and heating values for residue category

Table 2 Producer gas parameters for various feedstock categories

Parameter	F1	F2	F3	F4	F5	F6	F7	F8
Stoichiometric amount of air required	5.24	5.04	5.54	4.89	5.41	4.94	5.28	5.00
Fuel Equivalent ratio (ER)	0.28	0.34	0.31	0.23	0.32	0.26	0.27	0.23
Actual air-fuel ratio	1.48	1.69	1.70	1.12	1.71	1.31	1.42	1.17
Fraction of tar generated in g/Nm^3	23.75	3.57	43.07	4.86	33.19	4.43	27.78	3.57
Molecular Weight of gas (MWg)(g/mol)	25.01	27.32	25.00	23.88	25.77	25.03	24.44	23.56
Specific mass of the producer gas (kg gas/kg feedstock)	1.51	1.69	1.70	1.21	1.71	1.36	1.25	1.23
The density of the producer gas (kg gas/Nm^3 gas)	1.04	1.14	1.04	1.00	1.07	1.04	1.02	0.98
Energy released per kg of feedstock (MJ/kg)	7.58	10.06	8.61	5.37	9.19	6.81	5.96	5.63
Specific gas yield Vg (Nm^3/kg feedstock)	1.45	1.48	1.63	1.21	1.59	1.31	1.23	1.25

cases had the highest cold gas, carbon conversion and thermal efficiencies of 70.39 %, 77.35 % and 63.42 % respectively. Cold gas efficiency has been identified as one of the key indicators of gasifier performance (Basu 2018). It shows the chemical energy contained in the product gas (syngas lower heating value) to the energy contained in the initial solid fuel (lower heating of each feedstock). It is affected by feedstock characteristics, gasifier design and operating conditions. Worall *et al.* (2021) reported lower cold gas efficiency for cocoa pod husk of 55.7 %. The cold gas efficiency of rice husk was determined to be 43.7 % lower than the reported efficiency within the range of 50 –70 % (Ma *et al*., 2015). The results of the feedstock categories revealed that a feedstock combination containing cocoa pod husk has better efficiencies (see Figure 3). Similar to these findings, Susastriawan *et al.* (2019) reported an improvement in cold gas efficiency with a mixture of rice husk and sawdust as compared to the individual feedstock. The overall conversion efficiency represents the percentage of the energy in the biomass that is converted to electricity. The results of the feedstock categories revealed overall conversion efficiency in the range of 7.83 to 14.08 % with F4 (rice straw and husk) and F2 (cocoa pod husk) with the lowest and highest efficiencies respectively. The overall efficiencies of rice straw and husk are improved as part of feedstock blends in F1 and F7.

Syngas yield and characteristics for the various feedstock categories

The expected syngas flow rate for each of the feedstock categories is presented in Figure 4. The results revealed that feedstock categories with higher syngas heating values had lower syngas flow rates. A higher syngas flow rate implies a higher biomass feed rate and correspondingly higher quantity of feedstock required for energy generation. Low feedstock quantities have been identified to affect the sustainable operations of gasification systems in Ghana (Osei *et al*., 2021), therefore lower syngas flow rate with a corresponding higher heating value is preferred for optimal gasification.

Biomass feed rate, specific fuel consumption and syngas yield

The biomass feed rate for the feedstocks considered was within the range of 16.11 – 28.77 kg/hr respectively (see Table 3). Specific fuel consumption is the quantity of feedstock required to produce 1 Nm^3 of syngas or 1 kWh of electricity. For optimal and sustainable gasification, lower specific fuel consumption is preferred. Specific fuel consumption of 1.9 kg/kWh has been reported for low-density biomass feedstocks (Indrawan *et al*., 2017). Susanto *et al*. (2018) reported specific fuel consumption within the range of 1.5-2.5 kg/kWh depending on the biomass quality. The results for this study were determined to be in the range of 1.79 – 3.52 kg/kWh. A similar observation in the improvement of specific fuel consumption for feedstock

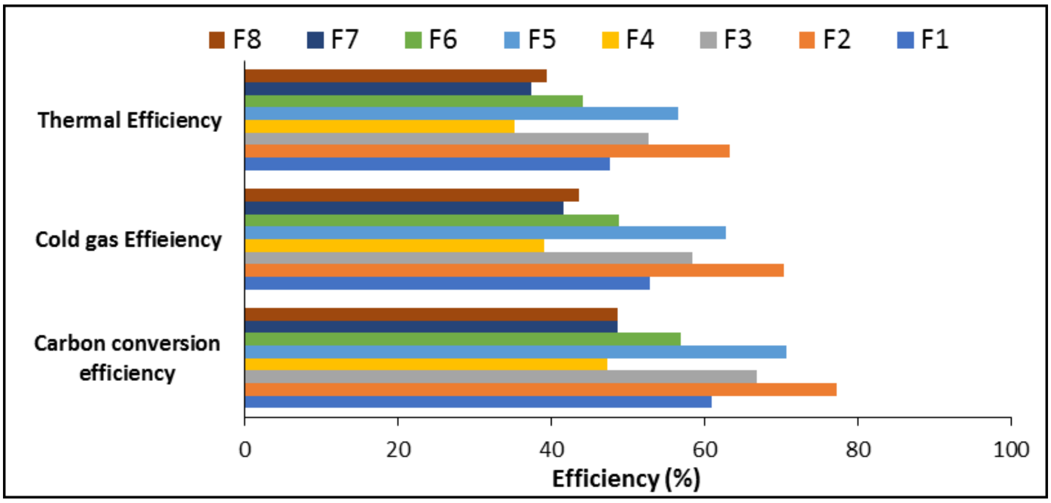

Figure 3 Efficiencies of feedstock categories

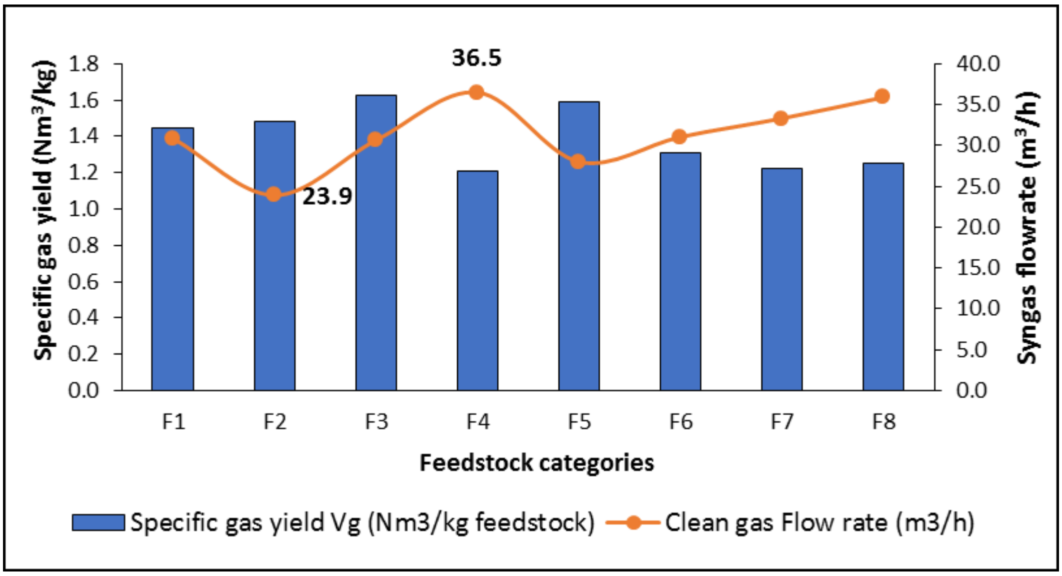

Figure 4 Specific gas and syngas flow rate of various feedstock categories

combination was also observed (see Table 3). Much lower SFC (0.8-1.5 kg/kWh) for low-density biomass mixtures consisting of rice husk, sawdust and bamboo dust has been reported (Buragohain *et al*., 2010). To meet the electric generator engine capacity, due to low syngas heating value, feedstock categories F4 requires 292,102 Nm^3/yr of clean syngas whiles that of F2 needs 191,318 Nm^3/yr of syngas due to high syngas heating values (see Table 3).

Determination of feedstock quantity, required number of farms and radius of dispersion

The annual feedstock quantities for individual feedstocks were determined to be in the range of 128.85 – 253.90 tonnes based on the required syngas quantities. Cocoa pod husk had the lowest quantities due to the superior syngas characteristics. Maize stalk and husk and maize cobs also had low annual biomass quantity. On the other hand, rice husk and rice straw had the highest annual biomass quantities. This is due to the unfavourable syngas characteristics which resulted in high biomass feed rate and corresponding annual biomass quantities. In the feedstock categories considered, similar patterns were observed (see Table 3). Average farm sizes of 1 ha each of cocoa, rice and maize farms were considered in the base case scenario with corresponding crop yields of 0.4, 2.5 and 2.05 t/ha based on average values in the study area. Even though rice straw has unfavourable syngas characteristics compared to the other feedstocks, it had the highest dry technical residue potential of 1.11 tonnes/farm due to the high RPR and RR ratios. On the other hand, cocoa pod husk with favourable syngas characteristics had the lowest technical residue potential of 0.27 tonnes/farm (Figure 5). This unequal characteristic of the various feedstock presents the need to use multiple feedstocks to ensure sustainable gasification.

The total number of farms and the corresponding radius of dispersion for the individual feedstocks are presented in Figure 6. The radius of dispersion is defined as the distance from a central point where the gasifier plant is to be positioned to the farthest farm. The results show that to obtain the required quantities of cocoa pod husk (128.85 t/yr), 532 cocoa farms (1 ha size each) are required within a cluster radius of 1.12 km. The use of rice straw required the least number of farms (251) but with a radius of dispersion of 2.16 km. The disparities with the radius of dispersion are accounted for by the differences in the sustainable residue densities for the various feedstock types. Whiles, the sustainable residue density of cocoa pod husk of 109.58 kg/km^2.day, that of rice straws is 57.57 kg/km^2.day. The radius of dispersion plays an important role in determining the economic viability of the gasification systems. Higher values increase the biomass transportation cost and therefore lower value is ideal to ensure optimal operations of the gasification systems.

The use of feedstock combination reduced the total number of clustered farms as well as the radius of dispersion (see Figure 7). Rice straw and husk as individual feedstock resulted in farm requirements of 462 and 251 respectively, however, as a feedstock combination (F4), 159 farms are required within a cluster radius of 2.11 km. Similarly, cocoa pod husk as part of the feedstock combination in F1, F5 and F6 resulted in a lower number of farms (see Figure 7). The observed lower number of farms and cluster radius for feedstock combination is generally contributed by higher sustainable residue density (values between 57 – 329 kg/m^2.day). The high sustainable residue density for feedstock is a result of the farming systems in Ghana, where monocropping is often practiced. Moreover, different crops are cultivated within a specific farming area increasing the sustainable residue densities. Arranz-Piera *et al*. (2017) reported that, for 1000 kWe CHP plants, a minimum number of farms ranging from 223-3185 with land size of 1 ha are required for the various feedstock types across districts in Ghana. Their study revealed that, for 1 ha maize, rice, cassava and cocoa farm, 50 tonnes of residue are generated annually per year, however, lower technical residues were determined in this study (3.4 tonnes for 1ha each of maize, cocoa and rice). The differences can be attributed to variations in the crop yield, RPR and RR. Secondly, their study presented an ideal radius of dispersion ranging between 0.8 to 3.2 km for farms ranging between 223-3185 kg/m^2.day. These values are lower compared to the outcomes of this study with an ideal radius of cluster between 0.74 – 2.12 km for 107 to 532 farms. The differences are as a result of the use of different technology types and sustainable residue densities.

Gasifier capacity and electricity generated

The total gasifier fuel power input was determined to be 45 kWe based on the ICE efficiency of 22 %. Based on the ICE capacity of 10 kW and with characteristics as presented in Table B.2 in Appendix B. The daily electricity generation was estimated to be 81 kWh for daily operational hours 9 (from 8 am to 5 pm). A total annual net electricity generation of 72,000 kWh taken into consideration annual operational hours of 8000. A 20 kWh 48V lead acid Flooded Battery was considered for energy storage. In the base case scenario and based on the energy need of the study area, electricity generated is considered to be used for rice milling (with a 5.5 kW electric motor) and maize milling (3 kW) and water pump (1.1 kW) for irrigation purposes.

Economic analysis

The investment cost for the base case financial analysis for all feedstock scenarios was estimated to be USD 33,053. The major differences in the cost for the various feedstock types is mainly due to differences in the cost of biomass (due to the differences in the quantities required) and biomass transportation cost (due to variations in the cluster radius). In this study, total biomass cost consists of the purchase price of biomass and the transportation cost to the energy generation site. At a biomass cost of 5 USD/tonne and a biomass transportation cost of USD 3.35 per tonne/km, rice straw had the highest biomass

Table 3 Annual syngas, biomass, char and tar yield

Parameters	F1	F2	F3	F4	F5	F6	F7	F8
Annual clean gas consumption (m^3/y)	247,129	191,318	245,143	292,102	224,125	248,471	266,570	287,283
Biomass feed rate dry basis (kg/h)	21.37	16.11	18.81	30.14	17.62	23.78	27.19	28.77
SFC (kg/kWh)	2.37	1.79	2.09	3.35	1.96	2.64	3.02	3.20
Air feed rate in (m^3/h)	25.74	22.21	26.14	27.56	24.66	25.35	31.42	27.40
Annual Biomass Consumption (t/y) dry basis	170.99	128.85	150.46	241.13	140.98	190.26	217.48	230.13
Annual Char Production (t/y) dry	8.55	6.44	7.52	12.06	7.05	9.51	10.87	11.51
Total tar quantities generated annually (kg/yr)	5868.91	683.00	10557.49	1419.61	7439.26	1100.73	7406.38	1025.60

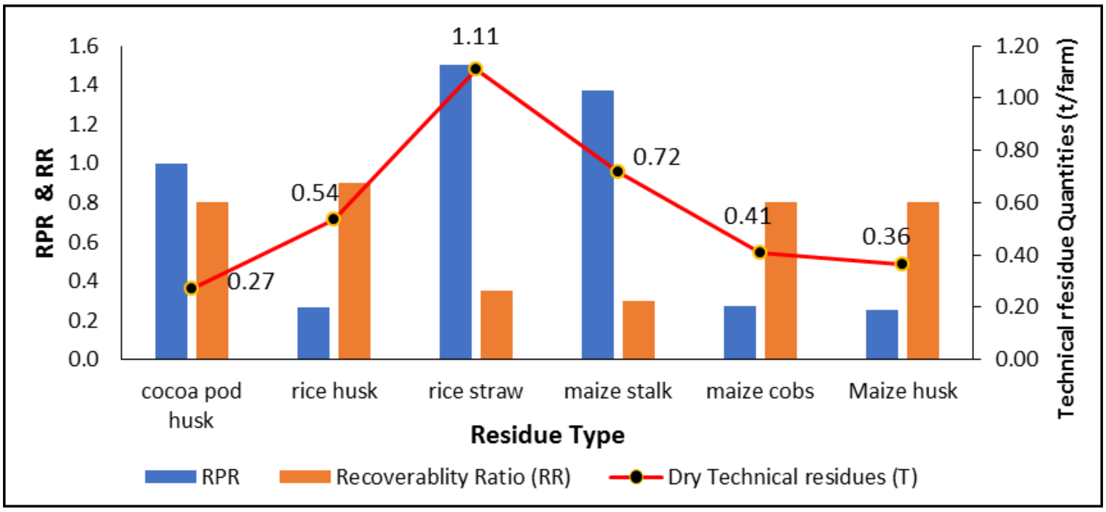

Figure 5 RPR, RR and technical residue potential per farm

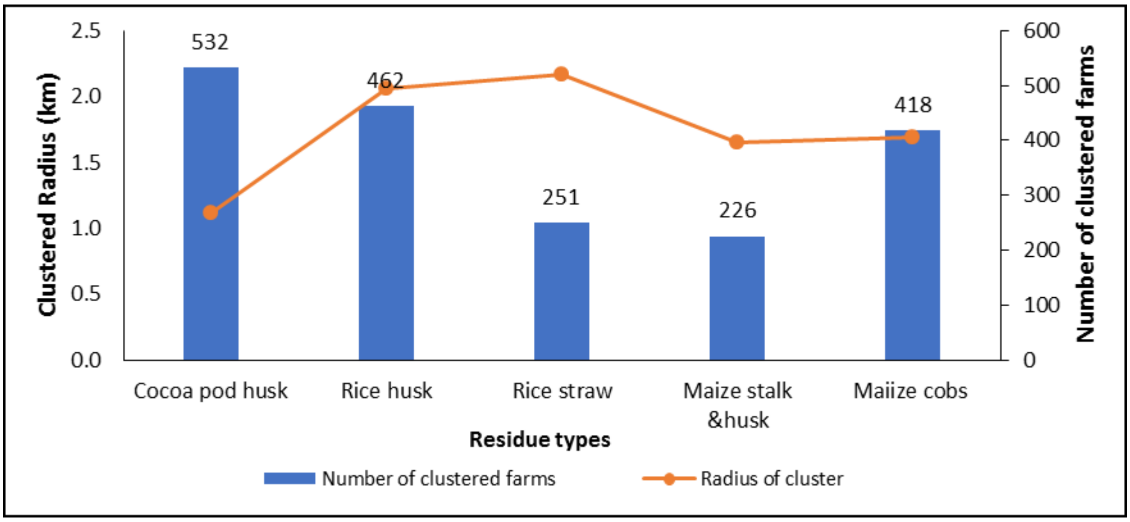

Figure 6 Number of clustered farms and required radius for various residue types

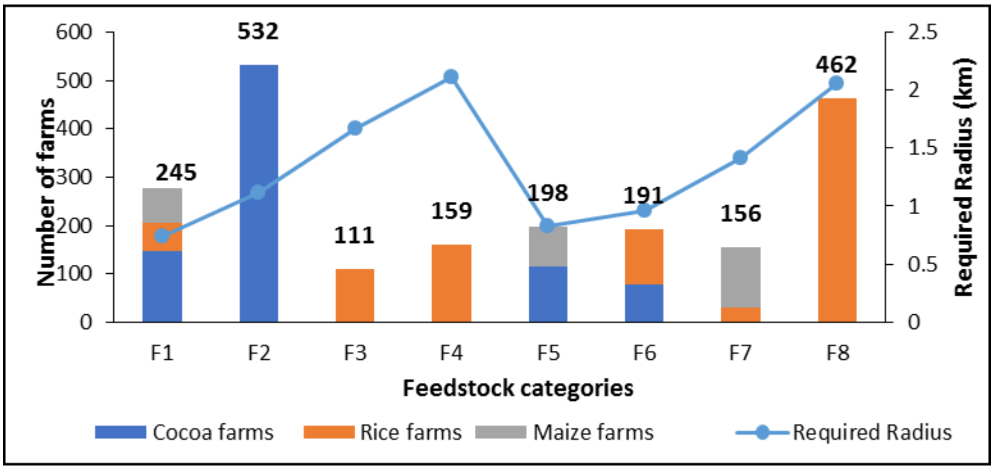

Figure 7 Number of clustered farms and required radius for Feedstock categories

Table 4 Parameters for the various feedstock categories

Parameter	F1	F2	F3	F4	F5	F6	F7	F8
Investment cost	33,053	33,053	33,053	33,053	33,053	33,053	33,053	33,053
Labour cost	1,608	1,608	1,608	1,608	1,608	1,608	1,608	1,608
Biomass cost	1,403	1,265	1,740	3,159	1,205	1,716	2,311	2,950
Maintenance cost	4,113	3,975	4,450	5,869	3,915	4,426	5,020	5,660
Revenue	14,291	14,044	14,171	14,702	14,115	14,404	14,564	14,638

Table 5 Economic viability indicators for individual feedstock

	Cocoa pod husk	Rice husk	Rice straw	Maize stalk and husk	Maize cobs
LCOE (USD/kWh)	0.21	0.23	0.24	0.21	0.21
NPV (USD)	3,825	-2,712	-4,585	1,828	1,383
IRR (%)	20.07	16.50	15.45	19.00	18.75

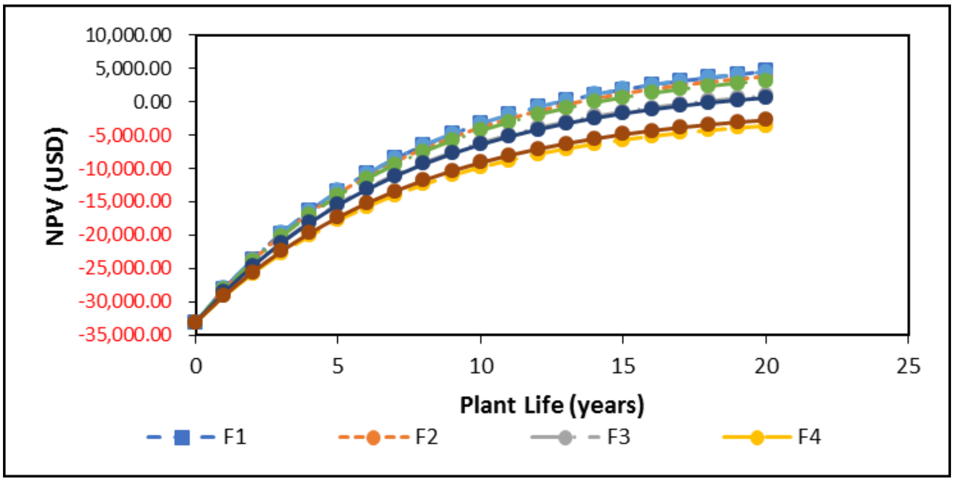

Figure 8 Variation of NPV for project lifetime for feedstock categories

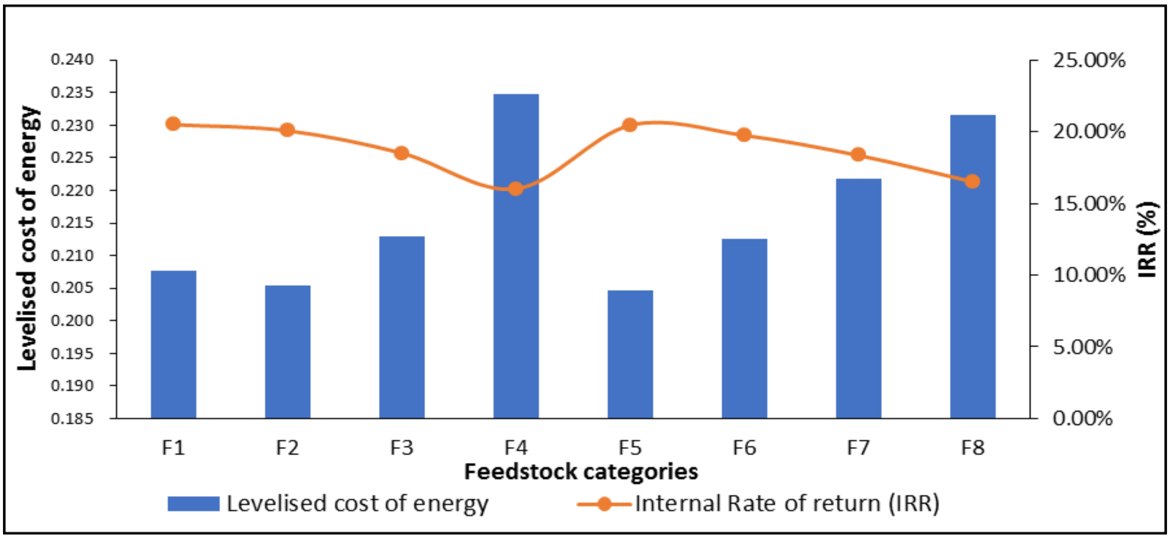

Figure 9 Levelized cost of energy and IRR for feedstock categories

cost of USD 3,406. Rice straw had the highest radius of dispersion of 2.16 km and therefore contributed to the increase in transportation cost.

In the base case analysis, the Feed-in-Tariff (FiT) rate as reported by the Public Utility Regulatory Commission (PURC) Ghana as of 2016 of USD 0.13/kWh was used (PURC Ghana, 2016). Electricity sale of USD13,288.68 was estimated to be generated annually with corresponding char sale ranging between USD 750 - 1,400 for the various feedstock types. The use of char as a soil amendment for USD 5.86 per 50 kg (10 % of the current price of NPK fertilizer) was considered. Rice husk had the highest revenue among the individual feedstock of USD 14,777 (see Table 4). Reduction in biomass cost and increase in revenue for some feedstock types when used in blends as compared to individual scenarios were also observed. For example, cocoa pod husk in F1, F5 and F6, and rice straw in F4.

With a project lifetime of 20 years, the results of the financial analysis revealed marginal profitability for maize stalk & husk, cocoa pod husk and maize cobs (see Table 5). However, rice straw and rice husk are not financially viable with NPV of USD -4,585 and –2,712 respectively. Despite the marginal profitability for some feedstock types using the NPV as the economic indicator, LCOE and IRR showed non-viability for all feedstock types. The Levelised cost of energy (LCOE) indicates the minimum selling price of the electricity based on the cost incurred in the electricity generation. Values between 0.21 - 0.24 USD/kWh were determined which is higher compared to the current FiT in Ghana of 0.185 USD/kWh. Ramamurthi *et al.* (2016) reported a lower LCOE of 0.116 - 0.13 USD/kWh for the CHP system using rice husk as feedstock. The IRR also shows non-viability, particularly when compared with other possible streams of investment such as the treasury bill (which is above 25 %). In situations where the revenues are considered to be generated from only the sale of electricity, all the feedstock types are not financially viable. This result is in line with reported findings which indicate that gasification systems are not profitable in Ghana from the point of view of the investor particularly when electricity generation is the only stream of revenue generation (Arranz-Piera *et al.*, 2018; Owen and Ripken, 2017).

All the feedstock categories considered were marginally viable except F4 (consisting of rice straw and husk) which is not profitable (see Figure 8 and Figure 9). The radius of dispersion was observed to play a critical role in the financial viability of the feedstock blends. F1, F5, F6 and F7 have a radius of dispersion lower than the individual feedstock types. The role of the radius of dispersion on the financial viability of the projects is further emphasized as the best two profitable feedstock scenarios F1 and F5 have the least cluster radius of 0.74 and 0.82 respectively. Similarly, all the feedstock combinations considered are not viable at the current grid electricity price of USD 0.13/kWh.

Sensitivity analysis

Effects of RPR, RR and farm sizes on the number of clustered farms

The total number of farms needed to provide the required residue quantities is an important parameter to ensure sustainable operations of gasification systems. As the number of farms increases, it becomes impractical to obtain the required number within the cluster radius. An increase in the RPR and RR decreases the number of farms required. The number of farms for maize cobs (maize farms) and rice husks (rice farms) was not significantly affected by the changes in the RPR. On the other hand, there was a significant variation in the number of cocoa farms from 165 to 67 farms for RPR of 0.90 and 2.20 respectively. Similar trends were also observed for maize stalks & husks and rice straws. This finding implies that the use of realistic and correct RPR values is critical in ensuring sustainable operations of gasifier systems. The effects of RR on the number of clustered farms show similar trends to that of the RPR. Similar trends on the effect of RPR and RR on the number of farms were observed for the other feedstock categories. An increase in the farm sizes resulted in a decrease on the number of clustered farms required under feedstock categories. Considering an increase in the farm size to 10 ha each for cocoa, maize and rice results in a corresponding number of farms of 15, 8 and 3 respectively. Comparing the base case number of farms of 148, 74 and 23 shows a significant decrease.

Effects of sustainable density on radius of dispersion

The sustainable residue density plays a critical role in determining the radius of dispersion of the feedstocks which intern affects the economic prospects of the gasification system. An increase in the sustainable residue densities results in a decrease in the radius of dispersion (see Figure 10). For feedstock category F1, a sustainable residue density of 1,298 kg/km^{2}day results in a radius of dispersion (cluster radius) of 0.37 km compared to the base case of 0.74 km. A decrease in the radius of dispersion of the feedstock even though may reduce biomass transportation costs can also be a challenge to identify the required number of farms within the required cluster radius across farming communities in Ghana. The sustainable residue density is affected by the proximity of the farms to each other, the number of crops cultivated and the technical residue potential from each farm. The various feedstock categories are not financially viable from radius of dispersion as presented in Table 6.

Table 6 Radius of dispersion from which feedstock is not technically viable

Feedstock categories	The radius of dispersion (R)
F1	2.08
F2	3.13
F3	3.17
F4	1.48
F5	2.40
F6	1.82
F7	1.50
F8	1.65

Effects of Syngas Composition on NPV

The effects of the volumetric composition of CO, H_2 and CH_4 on the NPV were investigated. An increase in the volumetric composition especially CH_4 resulted in a significant increase in the NPV (see Figure 11). This can be attributed to the higher energy content of methane which increased the syngas heating value and decreased the quantity of feedstock required. Even though F7 is profitable in the base case, a 21 % decrease in H_2 volumetric concentration (which is 9.38 % of H_2 concentration in syngas) yielded a negative NPV of USD -21.20. Feedstock category F8 is not profitable in the base case scenario, however, an increase in the concentration of CH_4 beyond 5.90 % volumetric concentration of the syngas yields financial viability. This result shows optimal syngas generation plays a critical role in the smooth running of gasification of crop residues. Even though the chemical characteristics of the feedstock affect the volumetric composition of the various gas species in the syngas, the optimal gasifier design and operating conditions are essential in improving the composition of the gas species

Effects of changes in capital, biomass cost, debt ratio and electricity price on NPV

A 10 % increase in the current feed-in-tariff rate (i.e USD 0.203/kWh) can ensure economic viability for all the individual and feedstock blends considered (see Figure 12). The result further shows that at the current grid electricity price of USD 0.137/kWh, all the feedstock categories considered are not fi-

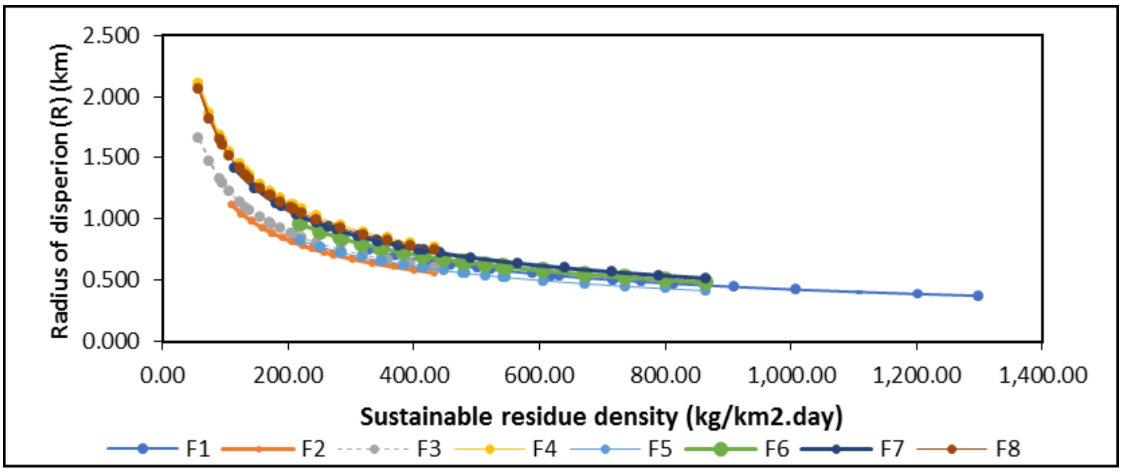

Figure 10 Effects of sustainable residue density (d) on the radius of the cluster (R)

nancially viable implying that the gasification system cannot directly compete with national grid electricity and therefore unelectrified communities or hard to reach areas where grid extension will be expensive or impractical should be explored. However, in the quest to increase renewable energy in the national energy mix and to ensure sustainability in energy generation as stipulated in the renewable energy masterplan of Ghana, the provision of subsidies on the capital cost can ensure project viability at the current national grid electricity price. The results show that, at the current grid electricity price, the minimal level of subsidies required to ensure project viability is within the range of 30 – 70 % of the investment cost (see Table 7). Similar findings of the need for subsidies of up to 65 % to ensure the financial viability of biomass gasification projects in Ghana have been reported (Arranz-Piera *et al*., 2018). An increase in biomass cost beyond the range of 10 % - 90 % (USD 5.5 – 9.5/ tonnes) of the base case price results in non-financial viability for all feedstock categories.

Optimisation of feedstock blends

Optimal composition of feedstocks in the blends

The highest quantity of each feedstock in the blends for the various objective functions was not the same. For feedstock category F1, maximizing syngas generation resulted in maize cobs with the highest feedstock composition of 112.414 tonnes, minimizing the number of farms had rice husk with the highest contribution of 93.68 tonnes and finally maximising NPV, cocoa pod husk had the highest feedstock quantity of 112.41

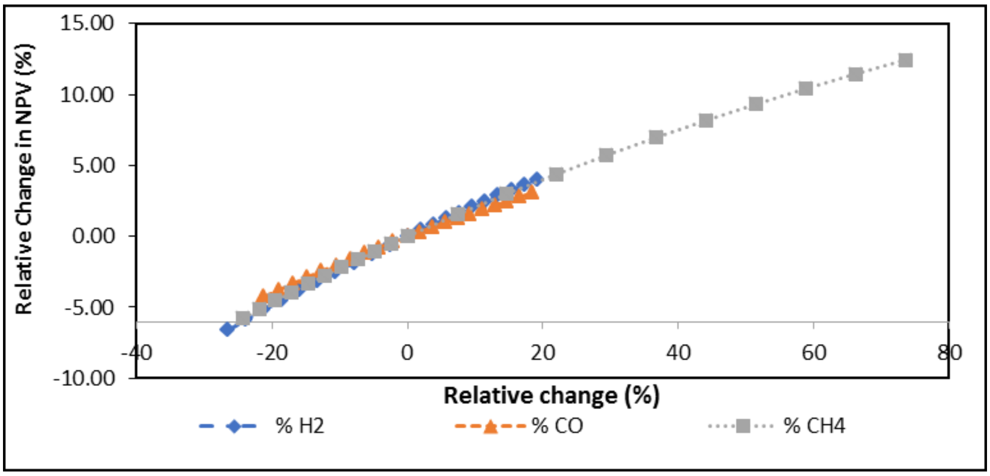

Figure 11 Effects of syngas volumetric composition on NPV for F1

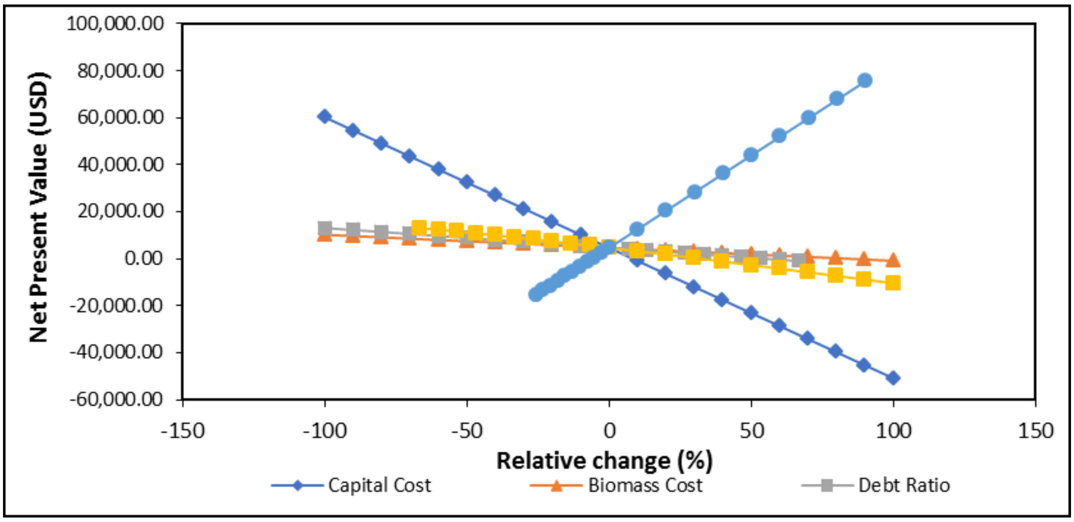

Figure 12 Effects of critical cost parameters on the NPV for F1

Table 7 Minimum subsidies for profitability at national grid electricity price

Feedstock Category	Required subsidies (% of the capital cost)
F1	30
F2	40
F3	50
F4	50
F5	30
F6	60
F7	60
F8	70

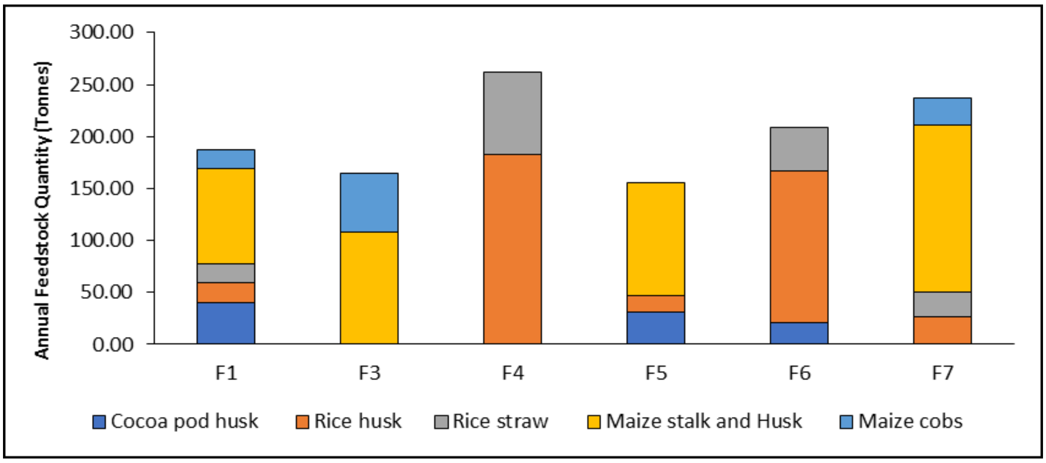

Figure 13 Optimal composition of feedstock under the various feedstock categories

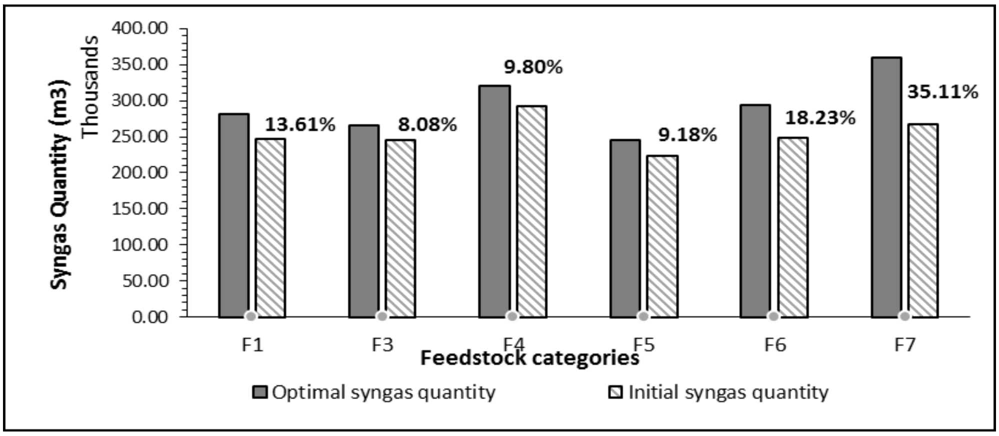

Figure 14 Optimal and initial syngas quantity

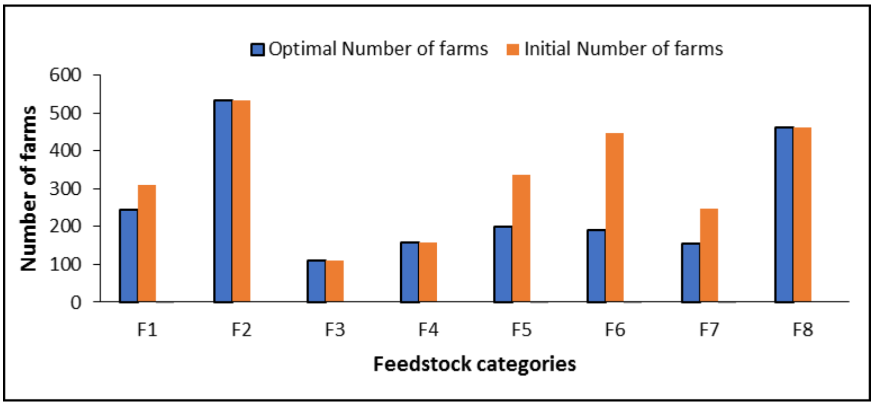

Figure 15 Optimal number of farms

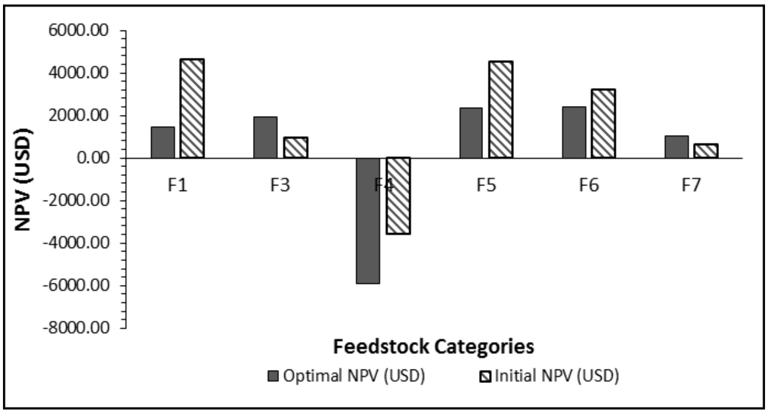

Figure 16 Optimal and initial NPV

tonnes. However, to satisfy all three objective functions, the optimal composition of the feedstock types in the blends requires the annual composition of maize stalk & husk, cocoa pod husk, maize cobs, rice straw and rice husk of 90.86, 40.29, 18.74, 18.74, 18.74 and 18.74 tonnes respectively. The results of the optimisation show that maize stalk & husk generally satisfies all three objective functions as it contributes the highest feedstock quantities in all cases where it's part of the feedstock blends (see F1, F3, F5 and F7) (see Figure 13). This is followed by cocoa pod husk, rice husk, rice straw and maize cobs. The optimal composition of each feedstock type in the various feedstock categories varies depending on the feedstock types in the blends.

Optimal syngas generation

In the linear programming optimisation model, it was assumed that, the effect of blended feedstocks on syngas yield behaves as a simple linear combination of the individual feedstock in the blends as reported for thermochemical reactions (Edmunds *et al*., 2018). Similar linear correlation between individual and co-gasified feedstock for syngas yield of palm trunk and oil palm fronds have been reported by Umar *et al.* (2021) with a deviation of 2.8 % between experimental and estimated values. Generally, there was a 9 to 35 % increase in the syngas generation with the highest increase of 35.1 % determined for feedstock category F7 (see Figure 14). The results indicate that annual syngas generation can increase with the optimal gasification of feedstock blends.

Optimisation of the number of farms

The optimisation of the number of farms resulted in a percentage reduction ranging between 30 – 57 % (see Figure 15.). The highest farm reduction was observed in feedstock category F6. In a situation where equal feedstock quantities are required, 448 farms consisting of 384 cocoa and 63 rice farms are needed. However, based on the optimal feedstock composition, the total optimal number of farms needed is 191 consisting of 77 and 114 cocoa and rice farms respectively.

Optimisation of NPV

The initial NPV for the various feedstock blends in most cases (F1, F4, F5 and F6) were higher than the optimal NPV to satisfy all the objective functions. Higher optimal NPV as compared to the base case was however observed for feedstock categories F3 and F7 (see Figure 16). The lower optimal NPV observed is generally contributed by the high cluster radius for the individual feedstock, which increased biomass cost. In the base case analysis for the feedstock categories, higher sustainable residue densities were considered (with the assumption that the feedstock in the blends is in clusters) which therefore contributed to higher NPV.

Conclusion

The aim of this study was to develop an optimal techno-economic model for the gasification of crop residues from clustered small/medium-scale farms. The developed framework consists of a systematic approach to performing techno-economic analysis for the gasification of crop residues for electricity generation based on feedstock characteristics with optimisation of syngas generation, feedstock supply and economic parameters. The results revealed specific fuel consumption ranging from 1.79 – 3.53 kg/kWh. The economic analysis showed marginal profitability except for rice husk and straw which are not profitable at the current Feed-in-tariff rate in Ghana. At the current grid electricity price, the minimum level of subsidies required to ensure the financial viability of the feedstocks is within the range of 30 – 70 % of the investment cost. A total number of farms ranging between 107-532 are required to be clustered within a radius of 0.74 – 2.12 km to obtain the right quantity of feedstock with a cluster radius greater than 3.91 km not being financially viable.

The developed linear programming optimisation model optimised the fraction of each feedstock type in the blends with a corresponding increase in syngas generation within the range of 9 to 35 % and a decrease in the number of farms required within a range of 30 – 57 %. The outcome of the study demonstrates that sustainable gasification of crop residues for mini-grid electricity generation requires co-gasification of the various residue types, valorisation of by-products such as unburnt char increase in the current feed-in-tariff rate in Ghana and provision of necessary subsidies on the investment cost to ensure financial viability. Based on the outcomes of the techno-economic model, specific rural farming communities that can meet the conditions of the techno-economic model to ensure technical and economic viability should be identified.

Conflict of Interest Declarations

The authors declare no conflict of interest.

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APPENDICES

Appendix A

Table A.1 Proximate, ultimate and calorific values of crop residues

Alternatives	MCd (wt.%)	PA (wt.%)	PC (wt.%)	PV (wt.%)	C (wt.%)	H (wt.%)	O (wt.%)	S (wt.%)	N (wt.%)	CV (MJ/kg)
Rice husk	7.15	20	12.8	59.97	40.1	5.2	34	0.7	0.16	12.9
Rice straw	8.68	9.46	9.76	72.11	39.9	5.9	43	0.6	0.85	14.6
Maize stalk &husk	8.27	7.92	12.8	71.01	44.1	6.5	40	0.4	0.99	14.3
Maize cobs	9.05	2.21	13	75.72	43.5	6.9	47	0.2	0.64	15.7
Cocoa pod husk	10.98	7.86	16.6	64.57	42.1	5.7	42	0.8	1.49	14.3

Table A.2 Sources for volumetric syngas composition, equivalence ratio and tar content of the various feedstock types

Feedstock type	Reference
Cocoa pod husk	(Susanto *et al*., 2018; Worall *et al*., 2021; Ma et al., 2015; Gunasekaran *et al*., 2021)
Rice husk	(Susastriawan *et al*., 2019; Ma *et al*., 2015; Copa *et al*., 2020; Murugan and Sekhar 2017; Salisu *et al*. (2019))
Rice straw	(Dalmiş *et al*., 2018; Belonio *et al*., 2018)
Maize stalk&husk	(Atiya *et al*., 2017; El-Sattar *et al*., 2020)
Maize cobs	(Lubwama, 2010; Suhartono et al., 2016; Biagini, *et al.* 2015; Martínez *et al.* (2020))

Table A.3 Parameters and assumptions for the economic analysis

Parameter	Value	Unit	Reference
Gasifier biomass power plant (fixed bed downdraft gasifier, cleaning unit, battery bank)	2000	USD/kW	(Copa *et al*., 2020)
Installation cost	10 %	Cost of gasifier plant	(Copa *et al*., 2020)
Auxiliary costs (piping, civil and structure, electrical, etc.)	15%	Investment cost	(Rahimi *et al*., 2020)
Cost of engine system and electric generator	504.32	USD/kW	(Copa *et al*., 2020)
Contingency cost	10%	Investment cost	(Yassin *et al*., 2009)
Cost of biomass	5	USD/tonne	(Arranz-Piera *et al*., 2017)
Staff cost management and operations	1,608	USD/year	Determined based on minimum wage in Ghana for 1 skilled and 2 unskilled staff
Biomass transportation cost	3.35	USD/km	Field data
Annual escalation rate for other operating and maintenance cost aside fuel cost (2%)	2%	Operating and maintenance	(Arranz-Piera *et al*., 2017)
Annual fuel cost escalation rate	2%		
Salvage value of plant	15%	Investment cost	(Indrawan *et al*., 2020)
Project life time	years	20	(Rahimi *et al*., 2020)
Feed-in-tariff rate (Reference October 2016)	0.185	USD/kWh	(PURC Ghana, 2016)
Annual plant operational hours	hours	8000	(Rahimi *et al*., 2020)
Discount rate	0.18	-	(Osei *et al*., 2016)

Table A.4 RPR and RR values for the sensitivity analysis

Residue types	RPR	RR
cocoa pod husk	2.2-0.9	0.4-0.88
rice husk	0.23-0.28	0.45-0.99
rice straw	1.28-3.05	0.18-0.80
maize stalk	1-4.75	0.15-0.8
maize cobs	0.25-0.3	0.4-0.88
Maize husk	0.2-0.26	0.4-0.88

Table A.5 Range of cost components considered for sensitivity analysis

Parameter	Base case	Minimum	Maximum
Biomass cost	5	0.00	10
Level of subsidy of Initial Investment cost (%)	0	50.00	100.00
Electricity selling tariffs	0.185	0.137	0.240

Table A.6 Syngas composition and sustainable residue density for sensitivity analysis

Scenario	Volumetric syngas composition (%)		d (kg/km^2 day)
F1	H_2	8.75-14.18	328.77-1298.63
	CO	13.57-20.39	
	CH_4	2.92-6.70	
F2	H_2	2.66-17.33	109.59-432.88
	CO	13.60-24.67	
	CH_4	3.80-14.18	
F3	H_2	13.63-14.18	57.53-432.88
	CO	16.64-19.61	
	CH_4	2.92-3.15	
F4	H_2	8.75-11.05	57.53-432.88
	CO	13.57-15.90	
	CH_4	3.08-3.45	
F5	H_2	11.90-14.18	219.18- 865.75
	CO	16.64-20.39	
	CH_4	2.92-6.70	
F6	H_2	8.75-11.90	219.18-865.75
	CH_4	3.08-6.70	
F7	H_2	8.75-14.18	115.07-865.75
	CO	13.57-19.61	
	CH_4	2.92-3.45	
F8	H_2	2.12-14.00	57.53-432.88
	CO	10.83-22.00	
	CH_4	0.17-11.60	

Appendix B

Table B.1 Syngas characteristics of individual feedstock types

Parameters	cocoa pod husk	Rice husk	Rice straw	Maize stalk and husk	maize cobs
Specific gas yield Vg (Nm3/kg feedstock)	1.48	1.25	1.17	1.59	1.64
Carbon conversion efficiency (%)	77.35	48.66	45.92	63.50	69.68
Cold Gas Efficiency (%)	70.39	43.75	34.96	61.31	53.32
Gasifier Efficiency (Coefficient of thermal conversion)	0.63	0.39	0.32	0.55	0.48
Overall System Efficiency (%)	14.08	8.75	6.99	12.26	10.66
Clean gas Flow rate (m^3/h)	23.91	35.91	37.14	29.53	31.84
Biomass feed rate dry basis (kg/h)	16.11	28.77	31.74	18.53	19.38
Specific Fuel consumption in (kg/kWh)	1.79	3.20	3.53	2.06	2.15
Char Production Rate (kg/h) dry	0.805	1.438	1.587	0.926	0.969
Total quantity of tar generated (kg/hr)	0.09	0.13	0.23	1.88	0.07

Table B.2 Parameters for electricity generation

Parameter	**Value**
Gross Electrical Capacity (kWe)	10 (50 HZ)
Capacity Factor (%)	90
Net Electrical Capacity (kWe)	9
Parasitic Load (kWe)	1
Annual Hours	8000
Annual Net Electricity Generation (kWh)	72000
Engine characteristics	
Model	GM Vortec 3.0 L
Number of strokes	4
Compression value	9.4:1
Max power (kW)	37
Max power torque (Nm)	73
Max rotation (rpm)	3000
Generator characteristics	0
Model	Mecc Alte NPE 32
Frequency	50 HZ
Voltage (V)	220

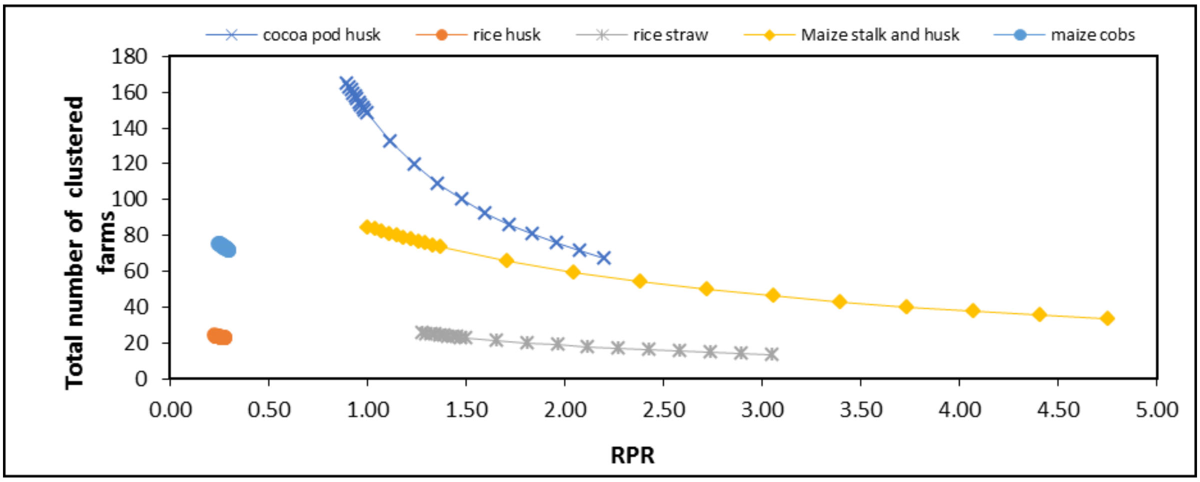

Figure B.1 Effects of changes in RPR on the number of farms for F1

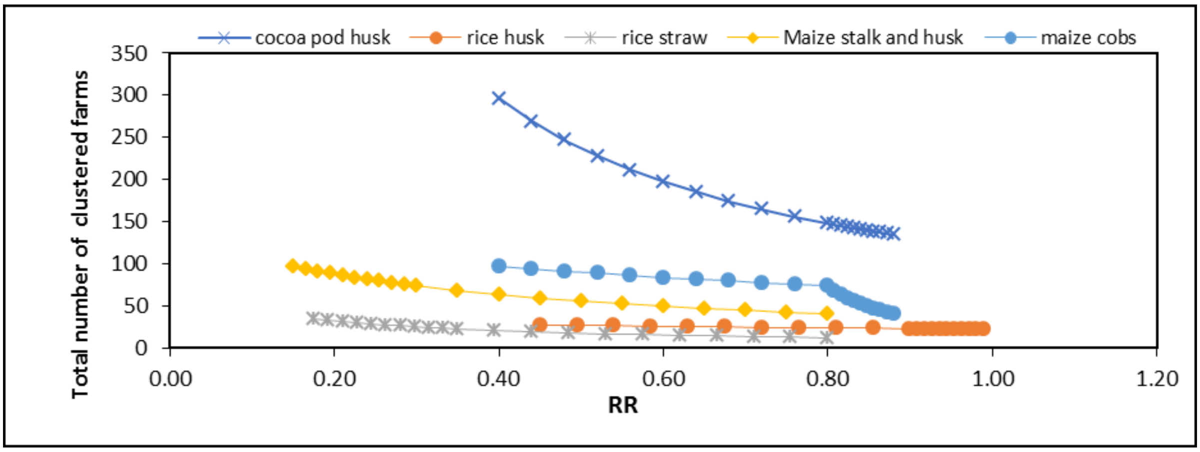

Figure B.2 Effects of changes in RR on the number of farms for F1

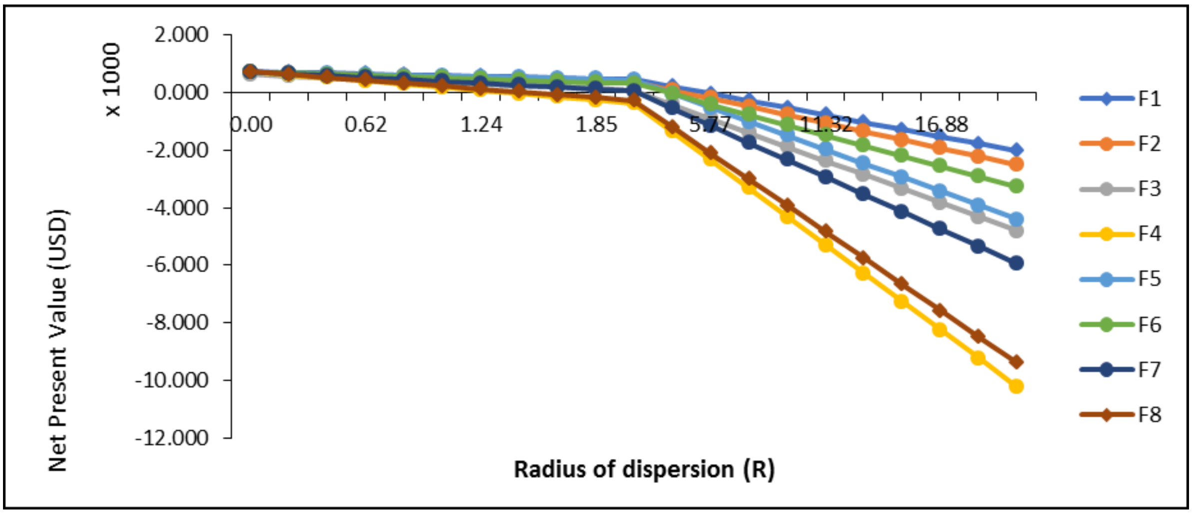

Figure B.3 Effects of variation of Ideal Radius of dispersion on the NPV

Table B.3 Optimization values for individual objective funcions

Feedstock Categories	Feedstock Types	Optimal feedstock composition for Individual Objective Function			Optimal feedstock composition for all three Objective Functions		
		F (X_1)	F(X_2)	F(X_3)	F (X_1)	F(X_2)	F(X_3)
F1	Cocoa pod husk (kg)	18736	18736	112414	40287		
	Rice husk (kg)	18736	93679	18736	18736		
	Rice straw (kg)	18736	37471	18736	18736		
	Maize stalk and Husk (kg)	18736	18736	18736	90863		
	Maize cobs (kg)	112414	18736	18736	18736		
	Function value optimization	**287687**	**174**	**2442**	**280752**	**245**	**1447**
F3	Maize stalk and Husk (kg)	49347	49347	115143	108392		
	Maize cobs (kg)	115143	115143	49347	56098		
	Function value optimization	**267837**	**111**	**1926**	**264951**	**111**	**1905**
F4	Rice husk (kg)	183302	183302	183302	183302		
	Rice straw (kg)	78558	78558	78558	78558		
	Function value optimization	**320740**	**159**	**-5923**	**320740**	**159**	**-5923**
F5	Maize stalk &husk	31033	31033	31033	108410		
	Rice husk	108617	108617	15517	15517		
	Cocoa pod husk	15517	15517	108617	31241		
	Function value optimization	**250962**	**151**	**3411**	**244692**	**198**	**2343**
F6	Rice husk (kg)	146249	146249	146249	146249		
	Rice straw (kg)	41786	41786	41786	41786		
	Cocoa pod husk (kg)	20893	20893	20893	20893		
	Function value optimization	293759	191	2420	**293759**	**191**	**2420**
F7	Maize stalk & husk (kg)	23713	23713	161574	161574		
	Maize cobs (kg)	165990	23713	28129	25707		
	Rice husk (kg)	23713	23713	23713	26135		
	Rice straw (kg)	23713	165990	23713	23713		
	Function value optimization	**367861**	**147**	**1114**	**360166**	**156**	**1046**