Modelling and Experimental Investigation of Small-Scale Gasification CHP Units for Enhancing the Use of Local Biowaste

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Abstract

Small-scale gasification Combined Heat and Power systems, fed by biowaste resources, have the potential to enhance local renewable energy production, reduce carbon emissions and address the challenges of waste disposal. However, there is a lack of understanding on the influence of challenging feedstocks, such as, for example, digestate, poultry litter and municipal solid waste, on the syngas quality and the incidence of the drying stage in the overall process. This paper addresses this gap by analysing and comparing 40 samples of the most common biowaste feedstocks. We developed a stoichiometric-thermodynamic one stage equilibrium model that was experimentally validated and calibrated by laboratory results, with a maximum error of 15% between real and predicted values. Simulation results show that the low heating value of the syngas produced from biowaste resources analysed ranges from 3.1 to 5.4 MJ/Nm^3 on a dry basis. Working at the optimal equivalence ratio increases the electricity and thermal output by up to 20%. To achieve a feedstock moisture content of 10%, the drying process may require up to 60% of the heat produced. Furthermore, results show that downdraft gasification based combined heat and power, is a feasible and interesting option to deal with biowaste resources which can potentially avoid the cost, risk and externalities of landfilling while it contributes to the increase of local electricity and heat production from renewable energy sources, both for grid and off-grid applications.

Keywords

Biowaste; Energy from waste; Gasification; Synthesis gas; Combined Heat and Power production

1. Introduction

The use of biowaste for energy generation can play a significant role in decarbonisation of the energy system and waste reduction (Cheng et al., 2020). The potential of biowastes in industrialized countries is vast but remains unexploited, as highlighted by new guidance in the EU for energy production from waste (European Commission (EC), 2017). Although the implementation of source separated collection and new management strategies is expected to help reduce mixed waste streams, recent studies (Kaza et al., 2018) suggest that the generation of waste will continue to increase in the EU. Therefore, it is necessary to look at technological solutions that can transform local biowaste (e.g., food & food processing waste, agriculture residues, sewage sludge) into energy. Among the technologies for energy recovery from biowaste, it has been recognized that small-scale gasification units (around 200kWe) can play a key role in energy recovery processes by enabling a better use of local and regional biomass resources (Situmorang et al., 2020). Gasification is the thermochemical conversion of solid fuel into gaseous products and is recognised as being among the highest technologies readiness level (TRL) systems for the conversion of biowaste into energy and fuels (Lovrak et al., 2020). Yao et al., (2018) found that compared to other thermochemical conversion methods, gasification technology has several advantages such as higher conversion efficiencies and minimal pollutants released to the atmosphere.

A significant increase in installed and operational downdraft gasifiers coupled with internal combustion engines (ICE's) around Europe recently is because of greater confidence in the technology, the availability of favourable subsidies and locally available biomass (Patuzzi et al., 2016). Installations can be found in Sweden, Germany, Finland and Italy (Patuzzi et al., 2021). Small-scale downdraft gasifiers have been identified as the most suitable set up for the feedstock types analysed in this study, as they have a simple design and can accept a wide variety of biomass materials (Elsner et al., 2017). Downdraft operation creates the least amount of tar, which can cause fouling in downstream equipment.

Many studies have discussed the potential of using biowastes, such as industrial wastes (Ayol et al., 2019; Galvagno et al., 2019), mixed solid waste (Arafat and Jijakli, 2013) and wood waste (Littlejohns et al., 2020) for syngas production. However, there is a scarcity of studies that have compared challenging biowaste resources (i.e., anaerobic digestate, poultry litter, municipal solid waste (MSW), agriculture and forestry residues) and investigated the main parameters influencing the quality of the syngas produced. While gasification of biowaste in small gasification ICE units has high potential to effectively generate heat and electricity, prior to the use of biowaste, especially wet waste, as a feedstock for gasification, a pre-treatment step is required to reduce its moisture content (MC) (Zhuang et al., 2020). Even fewer studies have discussed the incorporation of a drying stage in the whole gasification Combined Heat and Power (CHP) process, assuming it uses part of the heat produced by the CHP unit for pre-treatment purposes.

The paper aims to fill the gaps identified, by investigating optimal conditions for heat and electricity production from different types of biowastes using small-scale downdraft gasification coupled with ICE. Using a combination of experimental and mathematical modelling techniques, the paper analyses the performance of the entire system, when using challenging biowaste feedstocks and examines the opportunity to reuse the heat produced by the ICE system for pre-treatment purposes.

For the modelling efforts, we have chosen a thermodynamic model for the gasification process, as they are the simplest (from the viewpoint of their construction and solving) models developed and are most widely used in modelling studies (Ramos et al., 2019). They are easily customizable and converge rapidly, showing in most cases a good agreement with experimental data. The results produced by thermodynamic models are usually viewed as best case scenarios of gasification outcomes. We included small modifications (considering tar formation (Costa et al., 2015), assigning a fraction of the biomass carbon to char/methane formation (Li et al., 2001), adjusting the chemical reactions' equilibrium constants (Jarungthammachote and Dutta, 2007)) to improve the accuracy of a thermodynamic equilibrium model and make it more suitable for the purpose of this work. None of the studies referenced above considered ash as a component participating in gasification and neither used their own experimental data to calibrate the modified models. The combination of modelling and experimental studies proposed in this paper is implemented and tested for the first time.

The novelty of the paper arises from the prediction of the effect of 40 biowaste samples, which differ in either waste types or characteristics (e.g., carbon, moisture, ash content), on the combined gasification-CHP process performance. A recent review (Ramos et al., 2019) found that only about 8% of modelling studies on gasification are concerned with wastes, while the majority of studies have been focused on biomass gasification (37%), followed by coal (24%). The modelling results have been experimentally validated using two types of biowastes (i.e., poultry litter and digestate) and published literature data. This enabled the development of a wider picture of the real potential of using biowaste in small-scale gasification CHP systems. We were also able to contextualise the incidence of the pre-treatment process on the overall energy conversion process.

2. Materials & Methods

The work has been carried out through a combination of experimental analysis and mathematical modelling. This section discusses the models developed, the experimental apparatus, the rationale for feedstock selection and model validation efforts.

2.1 Simulation of the biomass gasification-ICE system

The modelled system consists of the following sub-systems: (a) biomass drying; (b) fixed-bed gasification reactor; (c) CHP module.

The CHP module is modelled using a black box. We assume that the ICE and heat recovery unit efficiencies are 30% (η_{el}) and 52% (Patuzzi et al., 2016), respectively. For the CHP module, thermal energy discharged from the engine can be recovered using an engine coolant/water heat exchanger and an exhaust/water heat exchanger and used in the drying process (Caresana et al., 2011). We assume that the parasitic load represents 15% of the electricity production (Patuzzi et al., 2016)

The construction of the mathematical models for drying and gasification are detailed in the following sub-sections, a schematic of the fully coupled drying-gasification-CHP system is presented in the Supplementary Material, Figure S1.

2.1.1. Biomass drying model

Most common types of biomass and biowaste have a high MC, negatively impacting on their gasification behaviour and resulting syngas yield and quality (Tuomi et al., 2019). While preliminary drying is necessary for proper gasification performance, it is a costly and energy intensive process (Cummer and Brown, 2002).The choice of drying equipment and optimization of drying conditions are essential for improving energy efficiency and profitability of a biomass cogeneration plant.

For the small-scale CHP gasification installation studied, we developed the modelling around the use of a belt dryer with hot air as the drying agent. Belt dryers are favoured for smaller drying applications, and can treat various materials, useful for co-gasification of biowastes (Fagernäs et al., 2010).

The dryer model is assembled writing the corresponding mass and energy balances, assuming the belt dryer uses hot air as the drying agent, adapting the system proposed by Holmberg and Ahtila (2005) to exclude a thermal recovery unit. The humid air exiting the drier is recirculated and heat losses are assumed to be 30% (Galvagno et al., 2016).

The schematics and full system of drying equations are presented in the Supplementary Material, Figure S1 and Table S1, respectively.

We assume the humid air exiting the dryer is fully saturated, and its humidity (Hum_{air}) can be expressed function of the saturated vapour pressure (P_{sat}), using Eq. 1.

$$Hum_{air} = 0.622 \cdot P_{sat} / P_{air} \quad (1)$$

The saturated vapour pressure is expressed function of the air saturation pressure T_{air}, using Antoine's law, Eq. 2, where A, B and C are the values for the Antoine's coefficient.

$$P_{sat} = 10^{A - \frac{B}{C + T_{air}}} \quad (2)$$

We assume that the temperature of biomass exiting the dryer is 10 °C lower than humid air. The full system of equations, together with drying parameters and values/ranges used in the calculations are supplied in the Supplementary Material, Table S1. The system of non-linear equations is solved using Matlab's built in function *fsolve*.

2.1.2 Gasification model implementation and calibration

Several reviews have been published, detailing thermodynamic models' construction (La Villetta et al., 2017; Safarian et al., 2019), applications (Baruah and Baruah, 2014; Puig-Arnavat et al., 2010), solving algorithms (Ramos et al., 2019). While we do not intend to reproduce them in this study, we highlight several references consulted to justify our choice of the mathematical model.

Thermodynamic models have been employed to compare biomass types and link biomass elemental composition to gasification performance: Vaezi et al. (2012) used a thermodynamic model to predict the heating values of syngas generated based on the ultimate analysis of 80 biomass types. Despite successfully validating their model against other literature sources, they did not consider ash as a biomass constituent nor tar or char formation. Soltani et al., (2013) proposed and analysed a biomass integrated fired combined-cycle, comparing the performance of five materials: wood, paper, MSW, paddy husks and coal. Xu et al. (2017) investigated the gasification behaviour of seven types of MSW and three gasifying agents (air, hydrogen and steam). Both studies have successfully validated their models against published literature data.

Thermodynamic models have been employed to optimise operating conditions, saving time and expense associated with experimental efforts. Using a non-stoichiometric model, Gambarotta et al. (2018) investigated the influence of forestry waste characteristics and operating parameters on the syngas heating values. They found that lower gasification temperatures produce higher calorific value syngas (but did not report the temperature effect on gas yield) and higher concentrations of minor pollutants (ammonia, cyanide, COS).

Several assumptions inherent to thermodynamic models (i.e. reaching thermodynamic equilibrium, assuming no tar and char formation, isothermal gasification reaction) make them over-predict the formation of H_2 and CO and under-predict CH_4.

Analysing the balance between the advantages (ease of implementation and solving, satisfactory accuracy, flexibility) and disadvantages (over-estimation of hydrogen production and under-estimation of methane formation), we have decided to use a stoichiometric thermodynamic equilibrium model in this study, and modify it, to enhance its prediction capability.

The equilibrium model developed follows a classic approach, proposed by Zainal et al. (2001), which assumes gasification to be a one-stage process and combines all the reactions into a general equation.

There are several underlying assumptions used for the general gasification equation. Firstly, biomass can be represented as three components: dry ash-free biomass with generic elemental formula $CH_xO_yN_zS_u$, ash and moisture (received from the drying unit). Ash does not take part in gasification and is included only in the heat balance equation. If the gasification temperature reaches ash melting temperature, it can lead to bed agglomeration and slagging phenomena, as noted by several experimental works (Gregorio et al., 2014; Katsaros et al., 2019). For biowastes with a high ash content this can lead to significant operating problems. Another issue related to ash is its heavy metal content, which can lead to corrosion problems. Heavy metals can accumulate in the ash and char residue, making their valorisation or disposal difficult (Chen et al., 2017). Chlorine content poses another problem for biowaste gasification, as HCl content in syngas varies according to experimental conditions and biomass type, from as low as 12 ppm (Hervy et al., 2021) to over 1000 ppm (Turn, 2007).

We assume the sulphur biomass content is recovered as H_2S, while nitrogen biomass content is transformed solely to nitrogen gas. While several studies have reported ammonia and hydrogen cyanide formation from the nitrogen content in biomass, this varies according to biomass type: Vonk et al. (2019) reported syngas ammonia concentrations ranging from 619 to 2107 μmol/mol . Hervy et al. (2021) reported ammonia concentration of 115 mg/Nm^3 in syngas following solid recovered fuel gasification but higher concentrations of hydrogen cyanide (310 – 470 mg/Nm^3). These values are sufficiently small to justify neglecting NH_3 and HCN contribution to gasification modelling.

Despite no limits being given for the syngas content of H_2S, NH_3 or HCl in ICE's, the pollutants have a negative effect on the environment and equipment. The consideration of pollutants' fate doesn't significantly affect model performance (and thus was neglected in the modelling effort) but must be kept in mind when considering gas cleaning.

We have included three of the model modification methods outlined above (tar formation, biomass carbon fraction to char and methane, and adjusting chemical reaction equilibrium constants), to bring model results closer to experimental ones. To the best of the authors' knowledge, Aydin et al., (2017) is the only study that proposed similar model modifications, while Costa et al. (2015) only considered tar formation and multiplicative factors for the equilibrium constants.

We amend the general equation to account for tar production (assuming tar can be represented by benzene), using the equation proposed by Costa et al. (2015) to calculate the corresponding tar coefficient (Eq.3).

$$n_{tar} = 35.98exp(-0.0029 * T) \quad (3)$$

where T is the gasification temperature (°C)

Then, we modify the model to assign part of the original biomass carbon content to the formation of char (assumed to consist only of carbon) and methane, as proposed by Li et al. (2001) and Aydin et al. (2017).

The modified general gasification reaction equation is written according to Eq. 4, further enabling us to write the corresponding elemental mass balance for carbon, oxygen and hydrogen.

$$CH_xO_yN_zS_u + m \cdot H_2O + n_1(O_2 + 3.76N_2) \rightarrow n_2CO + n_3CO_2 + n_4H_2 + n_5CH_4 +$$
$$n_6\, H_2O + n_7\, H_2S + n_8\, N_2 + n_{tar}C_6H_6 + n_{char}C \qquad (4)$$

Sulphur contribution is low in the biowastes considered (<1% wt) and can be neglected in the energy balance equation. The amount of H_2S formed during gasification is computed directly from the elemental balance of the general gasification equation. We assume H_2S can be recovered entirely during gas cleaning and doesn't impact the CHP engine's functioning. Poultry litter's high calcium content will assist with reduction of sulphur emissions, through sequestration of sulphur in the ash (Dalólio et al., 2017). Similarly, the calcium/potassium content in the ash can catalyse ammonia decomposition to N_2.

We consider two chemical reactions representative of the gasification phenomena: the homogeneous water – gas shift reaction (Eq.6) and the methanation reaction (Eq. 7).

$$CO + H_2O \leftrightarrow CO_2 + H_2 \qquad \Delta H_{298} = -41.1\ kJ/mol \qquad (5)$$

$$C + 2H_2 \leftrightarrow CH_4 \qquad \Delta H_{298} = -74.5\ kJ/mol \qquad (6)$$

The values for their equilibrium constants (K_1 and K_2) are expressed as a function of temperature, according to Trninić et al. (2020), Eq. 8 and 9:

$$lnK_1 = 4276/T - 3.961 \qquad (7)$$

$$lnK_2 = \frac{7082.848}{T} - 6.567 \cdot lnT + 3.733e-3 \cdot T - 0.3067e-6 \cdot T^2 + 0.355e-5/T^2 + 32.541 \quad (8)$$

Equilibrium equations for the two reactions are appended to the elemental mass balances, with two further modelling assumptions: biomass and air are fed to the reactor at atmospheric pressure and pressure drop in the reactor is negligible.

The final step in assembling the model is adding the heat balance equation (Eq. 9).

$$\sum_{i=reactants} n_i h_{f,i}^0 = \sum_{i=products} n_i \left(h_{f,i}^0 + \Delta h_{T,i}^0\right) \quad (9)$$

where $h_{f,i}^0$ represents the formation enthalpy for reactants (including ash) and products and $\Delta h_{T,i}^0$ is the enthalpy difference between the initial state (inlet to the gasification reactor) and the gasification state (Eq. 10).

$$\Delta h_{T,i}^0 = \Delta T \cdot C_{P,i} \quad (10)$$

Where ΔT represents the difference between inlet temperature to the gasifier and the gasification temperature and $C_{P,i}$ is the specific heat capacity of the participating species.

We also consider heat losses in the reactor and assume they represent 20% of inlet thermal energy.

To solve the thermodynamic model, either the gasification temperature or the equivalence ratio (ER) must be specified. Workings and merits of both these algorithms are comprehensively detailed in Mendiburu et al. (2014).

For the simulations presented in this paper we specify the air ER and compute the resulting gasification temperature, together with syngas composition. We chose to use the ER as an input to the model, instead of temperature because, depending on reactor geometry and operating conditions, temperature may not be constant in the reduction zone of the gasifier. In contrast, for continuously operated gasifiers, the ER remains constant throughout the process. Thus, we decouple the mass and energy balances and starting with a guess temperature we solve the mass balance system of 5 equations to compute the coefficients for H_2, CO, CO_2, CH_4 and H_2O. Using the determined coefficients, we solve the energy balance equation to compute temperature. If the difference between the initial and computed temperature is smaller than 1K we assume the solving algorithm has converged successfully. If not, we compute a new guess temperature (the mean value between the former guess temperature and its calculated value) and perform another calculation step.

To examine the efficiency of the gasification system, we compute the syngas lower heating value (LHV_{gas}) and the cold gas efficiency (CGE), Eq. 11-12.

$$LHV_{gas} = 10.8\, x_{H2} + 12.64\, x_{CO} + 35.82\, x_{CH4},\ MJ/Nm^3 \qquad (11)$$

where *x* represents the molar fraction of the component in the gas mixture

We do not consider tar contribution to the syngas' LHV, assuming tars can be completely removed through syngas cleaning.

$$CGE = \frac{LHV_{gas} \cdot G_{m,gas}}{LHV_{biomass} \cdot G_{m,biomass}} \cdot 100\% \qquad (12)$$

2.2 Experimental Apparatus

The Fluidyne MicroLab Class Gasifier is an air blown gasifier operating at atmospheric pressure, as presented in Figure 1.

The internal reactor diameter is 155 mm and height 165mm. The heart module houses the throat plate, reduction tube and grate. Six air inlet manifolds introduce the gasification agent (air) to the reactor, with flow rate controlled by an external handle. Syngas passes from the heart to the blast tube where cooling occurs before the cyclone. The cyclones direct gas two ways: one toward the test flare where a tap siphons it for cleaning and analysis, the other to an internal condenser and filtration system for engine application. Each module contains an outlet port for particulate removal. Pressure changes across the system are monitored using manometer connections. Thermocouples connected to the hearth, blast and cyclones record temperature evolution across the system, using a Grant 2020 series Squirrel data logger.

For analysis, gas is fed through the ETG PSS 100 Portable Sampling System Gas treatment equipped with Dreschel and Chiller scrubber system to remove remaining tar and particulates. Cleaned gas passes through the ETG MCA 100 Syn Biogas Multigas Analyzer, returning the CO_2, CO, H_2, N_2 and O_2 content as volumetric percentages.

2.3 Feedstocks

Poultry litter and AD digestate were selected for the analysis. All materials were pelletized to increase energy density and avoid bridging in the grate. Digestate was obtained from an AD plant run on a mixture of animal manure and green waste, the most common feedstock across Northern Ireland. Physical and chemical properties of the biowastes were analysed using relevant standard methods: MC (BS-EN ISO 18134), ash content (BS-EN ISO 18122) and volatile matter (VM) (BS-EN ISO 18123), through a Carbolite AAF 1100 Oven. Fixed carbon (FC) content was calculated by difference. Calorific Value (BS-EN ISO 18125) was determined using an IKA C200 calorimeter. Ash Melting (BS-EN ISO 21404) was carried out using a Carbolite CAF Digital Ash Melting Oven. Major elemental components Carbon (C), Hydrogen (H), Nitrogen (N) and Sulphur (S) were identified by means of a PE 2400 CHNS Elemental Analyser. Oxygen (O) content was calculated by difference. A laboratory in Belfast (ASEP, 2019) carried out the ultimate analysis for the two biowastes used for model validation. Results showed that poultry litter carbon content was 41.97%, while digestate pellets contained 44.49% carbon. This difference could be due to the heterogenous mix of materials in each biowaste such as feathers and bedding material in the poultry litter. Similar observations can be made regarding the hydrogen content of the materials. The determined higher heating values (HHV) (dry and ash free) are 18.15 MJ/kg for the poultry litter pellet and 22.32 MJ/kg for the digestate. The LHVs are 17.19 MJ/kg for the poultry litter pellet, 20.44 MJ/kg for miscanthus, and 20.97 MJ/kg for the digestate pellet. MC was 10.27% and 7.70% respectively, while ash content was 12.93% and 11.18% for each. Full results of the analysis are presented in supplementary material Table S4.

2.4 Model Validation

To perform model validation experiments, the gasification reactor was initially fed with approximately 0.6 kg of poultry litter/digestate pellets. We operated the reactor autothermally, initially heating the feedstock to 120 – 150 °C using a heat gun. After reaching this initial temperature, the heat gun is removed, and air is supplied to the gasifier. After an initial warm-up period (5 – 15 minutes, depending on biowaste type), the temperature reaches 850 – 950 °C. To ensure longer and consistent operation, we refilled the reactor, whenever the temperature probes recorded steep increases/decreases in temperature. On average, the gasifier was refilled every 15-20 minutes with ~ 200 g fresh biowaste. After each experiment, the contents of the reactor and gas cooling and cleaning system were inspected. The reactor was cleaned, and the amount of char, ash and tar was weighted.

The experimental results show on average a relatively consistent quality syngas with LHVs between 3.14 – 3.8 MJ/Nm^3 in the case of digestate and 2.84 – 4.15 MJ/Nm^3 in the case of poultry litter. This low heating value is due to the experimental conditions, where the air flowrate was relatively high, diluting the syngas and lowering its overall calorific value. Because of the small scale of the experimental set-up, the air flow rate to the gasifier was difficult to control and optimize during experimental operation.

For model calibration/validation, we recorded the operation intervals in which the syngas composition and temperature read-outs remained relatively constant and the initial model outcomes were compared to the average experimental values.

Figure 2 shows the comparison between the percentage of CH_4, CO, CO_2, H_2 obtained using the experimental set up and the model. The results are reported on a dry basis, nitrogen making up the rest to 100% of the syngas. The experimental outcomes reported in Figure 2 are the average of three experimental runs in similar conditions.

The model calibration was performed using an ER of 0.48, which was found to best represent the experimental results. As this is a batch process it is difficult to determine the ER using the experimental setup accurately: when biomass is consumed during gasification, the ER increases (the air flow rate remaining constant). When the reactor is refilled, the ER decreases. The high value comes from the fact that the gasifier deployed is not equipped with a system to control the air intake and has high thermal losses. The ER of 0.48 was obtained comparing the experimental results (gas composition, gasification temperature) with those obtained through modelling, choosing the ER value which minimised the departure between modelling and experimental results. Despite this being high for a gasification process, the corresponding temperature calculated using the thermodynamic model was a 1175°C in the case of the digestate and 1285 °C for the chicken litter pellets. The temperature ranges in which the experimental results were recorded were 820 – 1030 °C for digestate and 920 – 980 °C for the chicken litter experiments. The temperature sensor was placed above the gasification zone, so the temperature recorded was lower than the one registered in the gasifier. Additionally, the ±10% experimental error makes us confident to use of the proposed ER in the model validation efforts. Due to the difficulty in controlling the air supply to the reactor, we were unable to optimize the experimental runs further to obtain a higher gas quality. We used the validated mathematical model to simulate what would happen in a larger scale reactor with proper air supply control and similar design characteristics to our laboratory set-up.

The operation temperature being higher than the ash melting temperature determined experimentally, but we did not observe any ash agglomeration in the reactor.

To bring the model results closer to experimental ones, we used the method proposed by Jarungthammachote and Dutta (2007), multiplying the values of the equilibrium constants for the two chemical reactions rates (K_1 and K_2 presented in Eq. 8 and 9, respectively) considered in the model with two model coefficients (p_1 and p_2). To determine the values of the two coefficients, we employed genetic algorithm optimisation (Houck et al., 1995). We chose to use genetic algorithms, as they are less likely to converge to local minima and can search a larger parameter space; they are more flexible because they do not depend on the structure of the optimization problem and they do not require a continuous parameter space. Genetic algorithm optimization has been shown to outperform classical methods in several fields (Martínez et al., 1996). For the minimization function we used the root mean square deviation between model and experimental data. We used Matlab’s own genetic algorithm optimization function *ga* (“Genetic Algorithm Homepage,” R2021a.). The values of the two regression coefficients were $p_1 = 4.69$ and $p_2 = 4.26$.

Following model calibration, there is a very good model-experiment agreement in the case of the digestate: the standard relative error between modelling and experimental values is between 2 and 28% and the root mean squared deviation is 1.99. The largest model experiment departure is observed in the case of hydrogen. The poultry litter data also shows good performance (with standard errors between 6.5 and 15.5%) with a root mean squared deviation of 2.42. To verify the model predictions against independent literature sources, we selected several of the references presented in Trninić et al.(2020) and Aydin et al. (2017), and compared our own model predictions against them. Results, showing a good agreement between model and experiments, similar to other modelling studies, are listed in Table S2.

3. Results and Discussion

Aiming to understand the potential of heat and electricity production from local biowaste through small gasification units combined with ICE, we identified the most common biowaste types and divided them into five categories: poultry litter, digestate, MSW, agricultural wastes and forestry residues. The potential of these biowastes in the UK is presented in the supplementary material, Table S3, to provide an idea of local resources available for energy production from waste.

We have analysed multiple literature sources and identified 40 different biowaste resources for the different categories considered. For each biowaste category, we have considered multiple samples as their ultimate and proximate composition can vary widely, depending on origin, time of year, weather and cultivation conditions. It is worth noting that poultry litter, digestate and MSW show the highest variability of parameters considered, and for this reason we selected a higher number of samples. We selected 12 samples for MSW, 9 for digestate and poultry litter, 8 for agricultural residues and 2 for forestry residues. The full table with the different biowaste resources, their ash, moisture and elemental compositions, together with the references consulted, is provided in the Supplementary Material, Table S4.

To investigate and quantify the influence of varying biowaste composition on the biowaste gasification suitability, we simulated their gasification behaviour in similar conditions: using an ER of 0.35 and assuming all biomass types have been dried prior to gasification to a MC of 10%. We analysed the effect of each biowaste ash content, nitrogen content, C:H and C:O ratio on the syngas yield and calorific value. The full results from the simulations (gas compositions, heating value and dry yield) for each biowaste samples are presented in the Supplementary Material, Table S5.

3.2.1. Ash content

While ash does not actually take part in the gasification reactions (as long as the gasification temperature does not reach ash melting temperature), it has a significant impact of gasification performance. Firstly, biowastes with low ash content, have a higher amount of 'true' biomass available for gasification and thus will produce higher gas yields. This is shown in Figure 3a, where the dry syngas yield shows a relatively linear decrease with increasing biowaste ash content.

Biowaste ash acts as a heat sink during the gasification process and lowers the gasification temperature. Lower gasification temperature results in a decreased formation of hydrogen and carbon monoxide, which in turn lowers the heating value of the syngas. Methane concentration increases at lower temperatures, but the increase is not sufficient to overcome the lower concentrations of both hydrogen and carbon monoxide. As a result, the calorific value of the syngas will decrease at high biowaste ash content.

As seen in Figure 3b, biowastes with high ash content generally produce syngas with lower heating value. For example, the digestate sample, characterised by an ash content of 65%, shows one of the lowest values of LHV (3.5 MJ/Nm^3).

Exceptions are given by samples that are characterised by either high or low level of carbon content that can offset the effect of the ash content. An example is one of the samples of MSW (i.e. organic waste, carbon content 53% w) that shows one of the highest LHV (5.4 MJ/Nm^3), although the ash content is 40% (w). Other examples are the samples of poultry litter and MSW with a low carbon content, around 29% (w) and, although the ash content is below 20%, the LHV is below 4 MJ/Nm^3.

3.2.2. Ultimate composition analysis

The elemental composition of biomass plays an important role in the evaluation of syngas composition and calorific value. The gasification knowledge predicts that biowastes with low C:H ratio, high C:O ratios and as well as a low N content will produce the highest LHV syngas. However, the model results show that the amount of any single element does not have a clear influence on the LHV of the syngas produced, but rather the combination of them all. It is therefore important to run several experiments before assessing the real gasification potential of a specific biowaste.

While biowastes with a high oxygen content (low C:O ratio) typically have lower heating values, the simulation results indicate that the same does not hold true for the heating values of the syngas produced via gasification (Figure 4a). Neither the C:O nor C:H ratio (Figure 4b) appear to have a distinguishable effect on the distribution of syngas LHVs. The influence of nitrogen is also puzzling: while for most biowaste types high N-content lowers the syngas LHV, the poultry litter samples with high nitrogen content (6-8%) do not appear to follow this downward trend (Figure 4c). Simulation results confirm that the higher the hydrogen content of the biowaste (lower C:H ratio), the higher the H_2 concentration in the syngas (Figure 4d).

3.2.3. Moisture content and drying performance

Operational experience requires a maximum MC of 20% for a downdraft gasifier. However, based on empirical experience, the recommended value to allow the smooth operation of the gasifier is 10%. We have tested the influence of MC on gasification performance for biowastes with final MC in the range 5 – 20%, assuming an ER of 0.25 The results were similar for all biowaste types, but for clarity we focused on the poultry litter sample which produced the highest LHV syngas and cold gas efficiency, selected from Katsaros et al. (2019).

For higher MC, the syngas composition is characterised by higher H_2 concentrations, as well as higher CO_2. Despite this, the decrease in CO concentration leads to a small overall decrease in the syngas heating value, accompanied by incrementally higher gas yield and lower cold gas efficiency (Table 1).

Overall, as shown in Table 1, a higher biomass MC entering the gasification reactor has little impact on the amounts of heat and electricity generated through the ICE. The heat requirement for drying the biomass from its initial MC increases significantly as the target moisture becomes lower, reaching the 25% of the heat recovered by the CHP unit when a 5% MC is required. Unless better heat integration is considered (e.g. using the flue gases as the drying medium, employing solar drying) the need to reduce the MC to such a level could lower the plant's profit margins.

3.2.4. Equivalence Ratio

To investigate the influence of the ER, we selected the best performing poultry litter sample, with a MC of 10% and varied the ER between 0.15 and 0.5. High ERs lead to high gasification temperatures, which promote the formation of CO from the water gas shift reaction (to the detriment of H_2 formation) and lower the rate of the methanation reaction. As a result, the syngas LHV will decrease with increasing ERs (Figure 5a). On the other hand, low ERs (and thus lower temperatures) favour pyrolysis reactions and result in low gas yields (Figure 5a).

Figure 5a. shows that there is an optimum equivalence ratio to maximise the gasification efficiency, as well as overall CHP performance, shown in Figure 5b. Working at the optimal

ER (Figure 5b) can provide an increase in the electricity and heat produced, with a difference between the minimum and maximum energy output achievable by more than 20%.

3.2.5. Overall Performance Comparison

To compare the different feedstocks and understand their potential for electricity and heat production, we assumed a 100 kg/h of as received biomass, optimized the ER for all categories. Full results for each biowaste sample (syngas yield, LHV and CHP output) are presented in the Supplementary Material, Table S5.

Table 2 shows the main output of the gasification process combined with an ICE for the best performing biowaste samples in the categories considered. The difference between biowastes that require drying prior to gasification (digestate, poultry litter, food and garden waste) and those that do not (forestry and agricultural residues) is highlighted. For forestry and agriculture residues, the natural drying process in an open area would be enough to bring the MC below 20% (Ramachandran et al., 2017).

The MC of the digestate, poultry litter sample and MSW is of 40%, 30% and 50%, respectively. Meaning that for 100 kg/h of as received feedstock, the dried biomass represents only 40, 70, and 50 kg/h, respectively. Consequently, the syngas energy content available for samples of the digestate, poultry litter and MSW is lower than the ones for agriculture and forestry residues. The digestate requires the highest percentage of the heat produced, that is almost 60%.

Results show that using biowaste in gasification cogeneration systems is feasible, providing electricity and heat that can contribute to low carbon energy production. The economy of the investment depends on the specific case study, but increasing cost of waste disposal, as shown by the UK value of the gate fee (Letsrecycle, 2021) will further help the business case. Furthermore, the solution investigated in this study provides an alternative pathway to landfilling. There are applications where investing in gasification cogeneration systems is already economically viable. We provide an example using a poultry litter gasification CHP system for electricity and heat production.

To understand the economic feasibility, we assumed a case study with four standard broiler sheds (73m x 18m) containing 27,000 birds per shed (Caslin, 2016) and developed a simplified techno-economic analysis. Each shed host 8 crops of birds annually. Technical and economic parameters used are summarised in Table 3.

We considered the poultry litter previously analysed and assumed to run the gasifier at the optimal ER. Through on-site conversion of biowaste to energy, a farm switching to a small-scale downdraft plant combined with an ICE could introduce a 350kW gasifier coupled to a 120kW ICE. The CO_2 savings would be of about 490 tonnes of CO_2 per year. Savings are from avoiding the purchase of LPG and grid electric for energy needs. Further savings come from exporting electric back to the grid. The farm would be, therefore, able to cover the cost for the thermal and electrical demand of the poultry houses shown in Table 5, with some revenue coming from the electricity produced that is not used on site. For the exporting tariff, we assumed a value of £0.03/kWh, that could be agreed with the energy provider. It is worth noting that selling a high amount of electricity to the grid would be challenging and not feasible in congested areas. In our simplified case study, the return of investment would be below 11 years, due to the high cost of LPG that is commonly used to cover the energy needs of poultry houses, and export prices per tonne of poultry litter for disposal (Assembly, 2012).

4. Conclusions

The study analysed the production of electricity and heat from biowaste resources in a small gasification unit with the aim of showing the potential for reusing local renewable sources to address the problem of waste disposal. The authors acknowledge that thermodynamic models are limited in their predictions, as they cannot consider reactor set-up, mass, heat and momentum transfer limitations or the entire set of chemical reactions that occur. However, we believe the findings of this paper can be used as a benchmark for the performances of small-scale gasification units combined with ICE.

Results show that the drying is essential for biowastes with high MC (50 – 60%), such as poultry litter, digestate and MSW. The incidence of the drying stage on the whole process could be high. The heat required to reduce the MC to 10% for the samples analysed ranges from 19% to 60% of the thermal energy produced by the CHP, with the maximum value required by digestate.

In cases of high thermal demand, the use of alternative low-energy drying systems, such as solar energy and microwave pre-heating systems is critical to allow for all the heat generated to be used for the local heating load.

The LHV of the syngas produced by the 40 feedstocks ranges from 3.1 to 5.4 MJ/Nm^3. Although this value is low, the syngas produced must be considered as a value-added product of a waste resource. Some biowastes, such as digestate and poultry litter, will also avoid the environmental impact and the externalities of disposing of hazardous biomaterials directly to the environment.

Results highlight the importance of running a preliminary test for assessing the real syngas potential of any biowaste resource. The single amount of oxygen, carbon, hydrogen, or nitrogen, do not allow for an accurate prediction of the gasification potential.

Rather than the single element composition, it is the mix of different elements which determine the LHV of the syngas produced.

Running the gasifier at the optimal ER is important, with a 20% difference in the energy outcomes from the CHP unit between best and worst-case scenarios.

Agriculture and forestry residues do not require any pre-treatment drying process and can produce a useful quantity of electricity. The finding highlights the potential applications of such biowastes for off-grid electricity and heat production as discussed in Verkerk et al., (2019)

Acknowledgements

The authors acknowledge the support of the Bryden Centre project. The Bryden Centre project is supported by the European Union's INTERREG VA Programme, managed by the Special EU Programmes Body (SEUPB).

Disclaimer

The views and opinions expressed in this paper do not necessarily reflect those of the European Commission or the Special EU Programmes Body (SEUPB).

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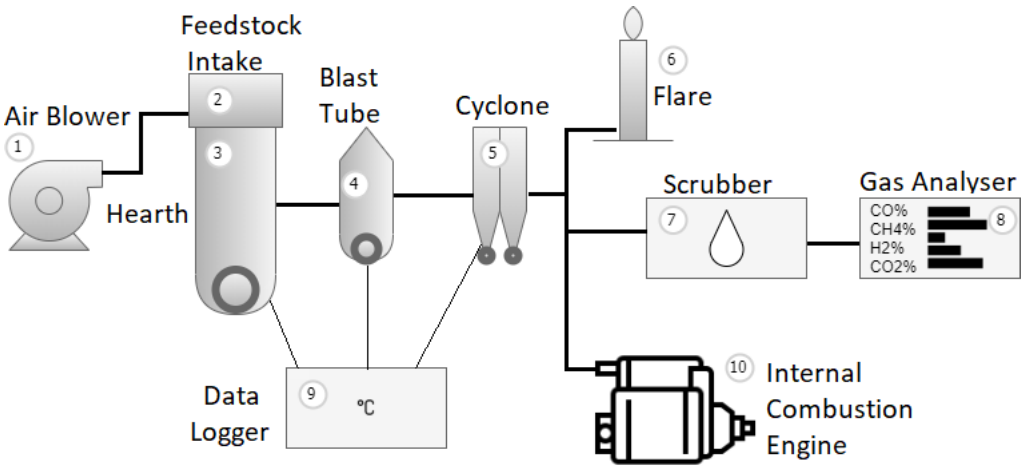

Figure 1. Experimental Apparatus Set Up

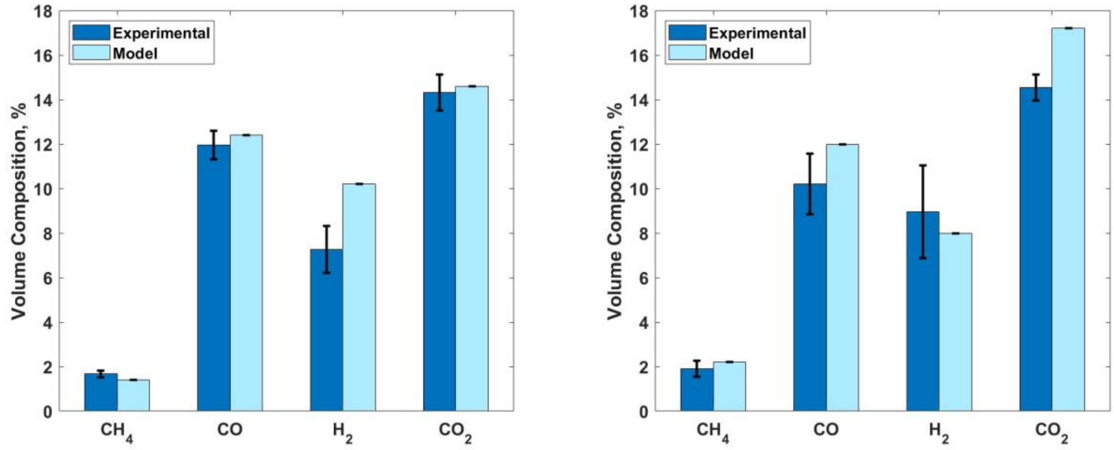

Figure 2. Model Validation for a. Digestate and b. Poultry Litter experiments

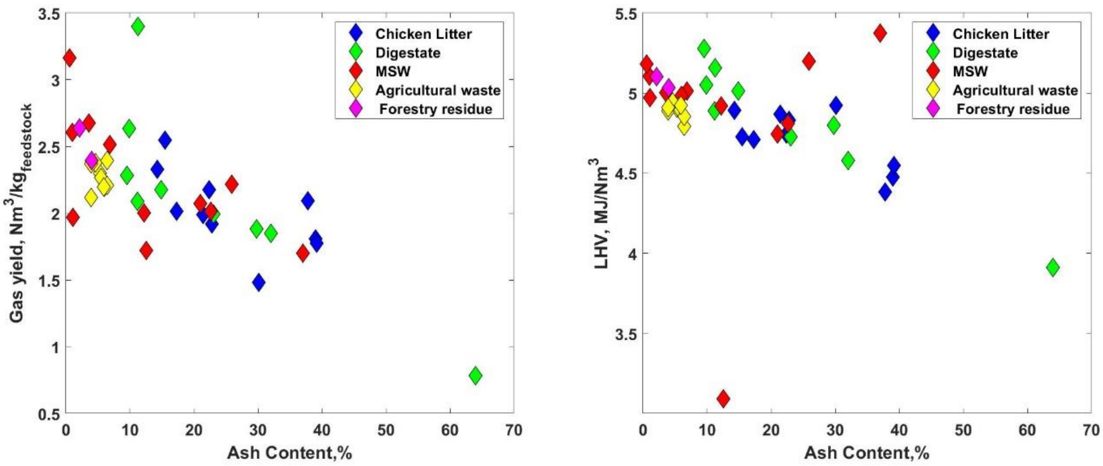

Figure 3. Influence of biomass ash content on a. dry syngas yield and b. syngas LHV

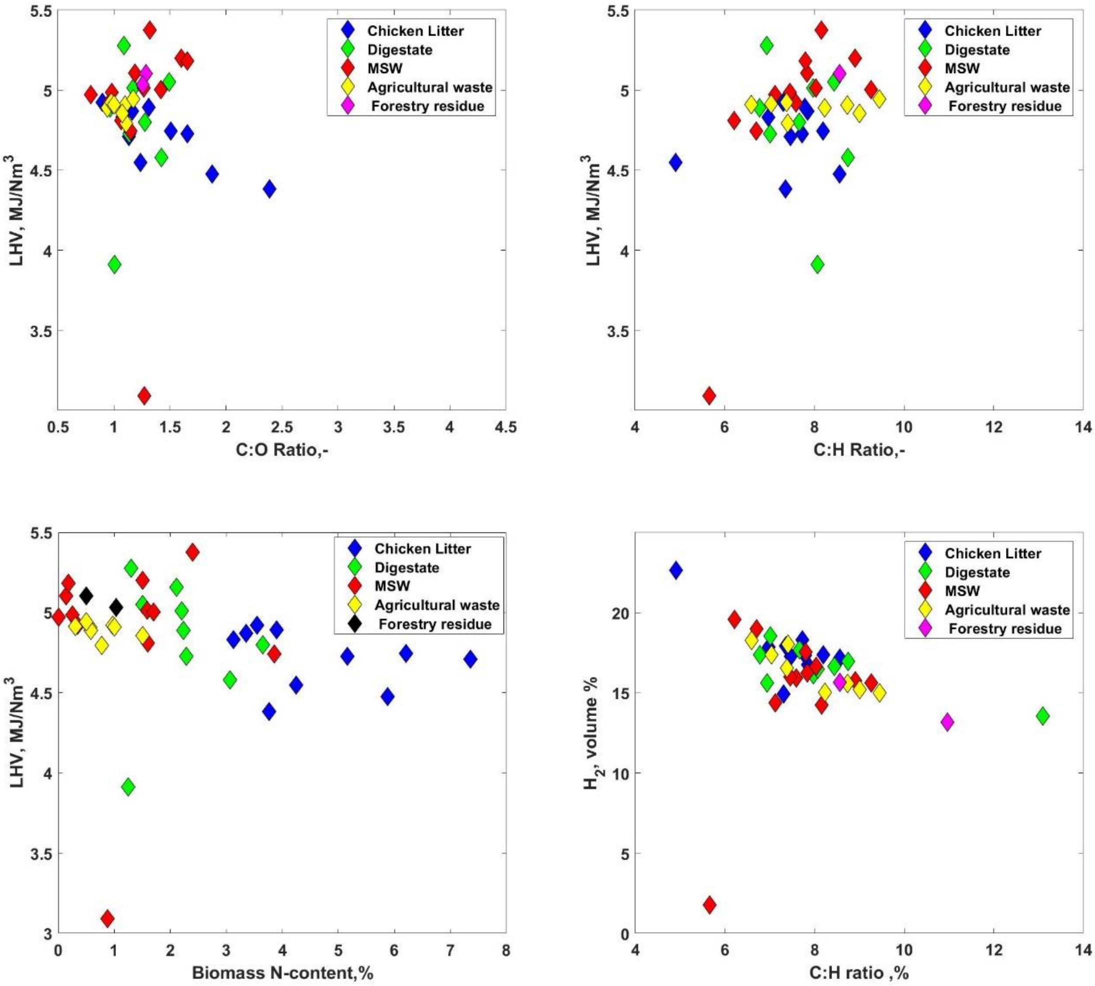

Figure 4. Influence of a. C:O ratio, b. C:H ratio c. N-Content on syngas LHV and d. influence of C:H ratio on the syngas H_2 content

Table 1. Influence of moisture content on gasification-CHP performance for poultry litter defined in Katsaros et al. (2019).

	Moisture content = 5%	Moisture content = 10%	Moisture content =15%	Moisture content = 20%
H_2 (%vol)	19.7	20.6	21.4	22.2
CO (%vol)	20.6	19.4	18.3	17.3
CO_2 (%vol)	9.8	10.7	11.5	12.3
CH_4 (%vol)	2.3	2.3	2.2	2.2
LHV (MJ/Nm^3)	5.55	5.49	5.42	5.36
Gas yield (Nm^3/kg dry biomass)	2.17	2.19	2.22	2.24
Cold gas efficiency (%)	73.40	73.38	73.38	73.36

Heat for drying (kW)	29.25	23.74	18.22	12.67
Electricity (kW)	59.65	59.64	59.64	59.62
Hot water from ICE (kW)	61.41	61.39	61.39	61.37
Heat from flue gases (kW)	55.56	55.54	55.54	55.53

*Boundary condition: 15ºC and 1.013 bar

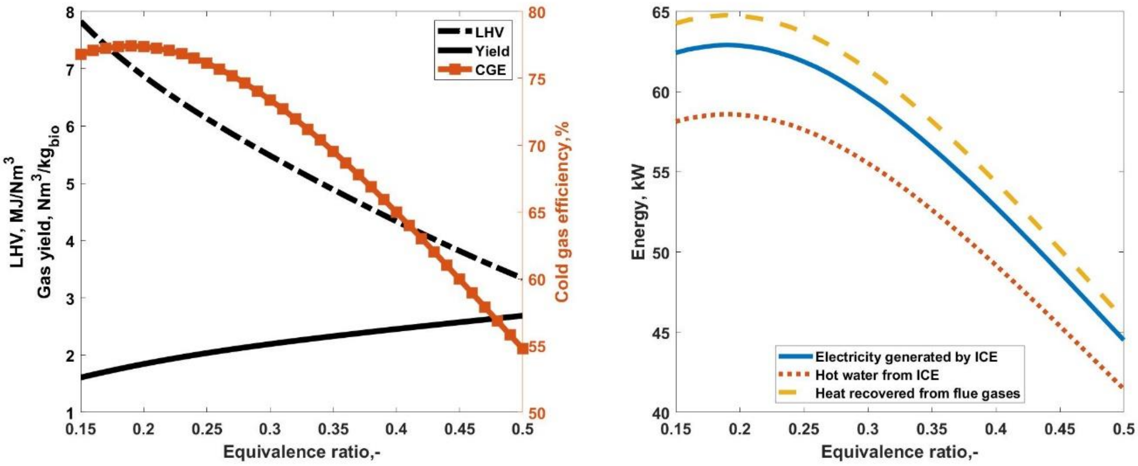

Figure 5. Influence of equivalence ratio on a. syngas heating value, yield and cold gas efficiency. and b. CHP energy output for the sample defined in Katsaros et al. (2019)

Table 2. Comparison between different biowastes assuming a flow rate of 100 kg/h of as received biomass (best performing biowaste samples)

Biowaste type	Moisture content (%)	Feedstock LHV** (MJ/kg)	Syngas energy content (kW)	Drying requirement (kW) (%on the total heat)	Net electricity (kW)	Heat as hot water (kW)	Heat from flue gases (kW)
Drying process required (10% MC target)							
Poultry litter	30%	16.4	246.3	23.7 (19%)	62.8	58.52	64.86
Digestate	60%	25.1	200.1	57.6 (58%)	51.01	47.51	52.51

Municipal Solid Waste	50%	23.2	260.5	46.3 (30%)	79.7	74.24	82.05
Drying process not required							
Agriculture residue (Wheat straw)	/	16.9	346.2	-	88.28	82.2	90.9
Forestry residues	/	19.4	390.4	-	99.56	92.7	102.5

**Dry basis

*** T 15°C and 1.013 bar

Table 3. Techno-economic parameters used for assessing the poultry litter case study

Technical parameters	
Parameter	**Value**
Boundary condition	**15 °C, 1.013 bar**
Baseline scenario (Caslin, 2016)	
Birds per shed	27,000
Electricity demand per shed [MWh/year]	35
Thermal demand per shed [MWh/year]	240
Number of sheds	4
Poultry litter annually gathered per shed [tonne per year]	227
Electricity tariff [pence/kWh]	15.52
LPG cost [£/kWh]	0.07
CO_2 emission factor for the electricity bought from the grid kgCO_2/kWh (DEFRA, 2020)	0.283
CO_2 emission factor LPG [kgCO_2/kWh] (DEFRA, 2020)	0.23
Poultry litter gasification CHP application	
Gasifier efficiency at the optimal equivalence ratio	73%
Poultry litter LHV [kWh/kg]	4.16
Gasifier capacity for 4 Sheds [kW]	350
CHP capacity for 4 Sheds [kWe]	120
Annual Operational Hours	7,056
Electricity produced by the CHP for the entire site [MWh]	966
Thermal energy produced by the CHP for the entire site [MWh]	1,450
Electricity exported to the grid [MWh]	826
Gasification CHP Initial Investment [£] (Jeswani et al., 2019)	1,059,824
Maintenance Cost [£]	39,413
Contingency Cost [£]	105,982
Integration Cost [£]	317,947
Material Storage Cost [£]	20,000
Material Handling Cost [£/tonne]	4.00

Exported electricity tariff [£/kWh]	0.03
Tariff for litter disposal in Northern Ireland [£/tonne]	30
Simple Pay Back [years]	<11