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ORIGINAL PAPER

Gasification of Biowaste Based on Validated Computational Simulations: A Circular Economy Model to Handle Poultry Litter Waste

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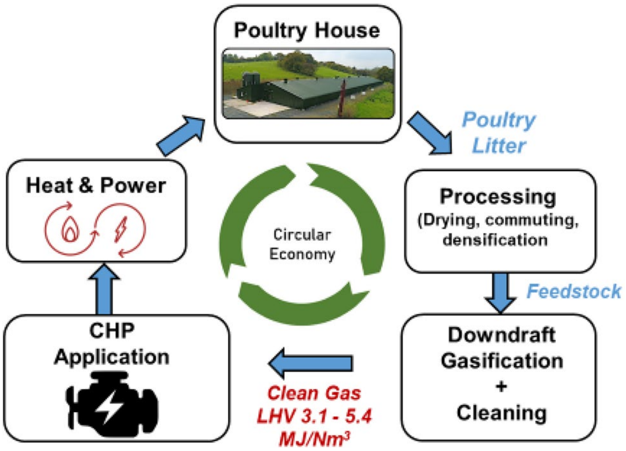
Abstract

Converting waste biomass resources through downdraft gasification can generate a producer gas for a combined heat and power unit. The study includes feedstock analysis, process modelling using ECLIPSE simulation software, and experimental analysis of materials in a pilot-scale fixed-bed downdraft gasifier. Anaerobic digestate and miscanthus were investigated for comparing the gasification potential of poultry litter as an energy source. Models validated through experimental analysis were applied to a case study based on a typical poultry farm in Northern Ireland.; Results found producer gas with a lower heating value up to 4.15 MJ/Nm^3 can be generated. Sufficient poultry waste is generated on-site to produce the required heat and electricity for each shed, allowing the farm to switch from fossil fuels to a local renewable resource and addressing the waste disposal issue.; Downdraft gasification coupled with cogeneration could have a payback period of 4–5 years given the correct conditions. The net present value is positive for all technologies considered (i.e. internal combustion engine and the Organic Rankine cycle combined heat and power unit) under different subsidies, showing the economic viability of the solution. The break-even selling price could be lower than the current grid electricity selling price (£120/MWh) when incentives such as: (i) avoiding disposal cost of £30/tonne, (ii) selling the biochar by-product at £200/tonne and (iii) fuel displacement costs of 1.5p/kWh are considered.

Graphical abstract



Keywords Downdraft gasification · Modelling and simulation · Poultry litter · Combined heat and power · Internal combustion engine · Organic rankine cycle

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Statement of Novelty

Using the circular economy method of thinking, waste material for energy generation purposes solves issues surrounding the disposal of potentially environmentally harmful material, as well as acting as a sustainable source of energy. Through a mass/energy balance modelling (ECLIPSE) of the downdraft gasification waste to energy process, we accurately predicted the energy produced through downstream application of the producer gas, the environmental benefit of utilising the proposed energy generation method through CO_2 saved as well as the key economic parameters of investing in the solution, such as payback period, net present value and break even selling price estimates. The research's case study will prove that this technology is suitable for small-scale rural applications ($< 250\ kW_e$) where waste is generated as a by-product from an industrial process.

Introduction

The poultry industry has significant output across the island of Ireland and the rest of Great Britain. Over 20 million birds a week are produced for market in the United Kingdom, leading to roughly 1400 tonnes of poultry litter (PL) by-product per week in an industry that directly employs over 37,000 people across the UK [1]. Sustainable development of this industry is critical for the UK economy, with production value being £2.7 billion in 2019 [2]. While consumer demand across individual industries such as food, textile and energy has increased around the globe due to growing populations, the desire for these demands to be met in more sustainable and environmentally friendly ways is critical for successful development. Clean energy technology has been at the forefront of most industries agendas across the UK since 1990 with government policy and legislation being a main driver [3]. A greater push towards renewable energy has been reasserted in recent years from the government's commitment to net zero carbon emissions by the year 2050 [4]. The use of a circular economy method of thinking could help the poultry industry to become more sustainable, lowering carbon emissions through utilising their own waste as an energy source on site [5]. Furthermore, it could contribute to the decarbonisation of the food industry sector, helping to achieve the net zero carbon farm goal that has been recently pledged by some international supermarket chains [6, 7].

Poultry litter has traditionally been utilised as a fertiliser on neighbouring tillage land for nutrient recycling, or disposed through landfilling with disposal costs approximately £30–£50 per tonne [8]. This is the associated cost for the removal and transport of waste material to a site for treatment or disposal. The application of poultry waste to land is a viable option for disposal, as it is a successful method of recycling important plant nutrients such as nitrogen (N), phosphorous (P) and potassium (K) [9]. However, an over application of PL to land as a fertiliser can lead to pollution of local waterways from excess nitrates. Northern Ireland introduced the Nutrient Action Programme in 2019 to protect water from agricultural nitrates [10]. Managing the amount of material spread on land is critical to ensure protection against pollution, such as eutrophication of local waterways. Other issues associated with land spreading of PL is the potential for airborne botulism to propagate between farms [11]. Due to the high volume of birds in Northern Ireland and relatively low land area, material has been sent across the border for spreading in the Republic of Ireland. Current waste shipment legislation between Northern Ireland and the UK remains unchanged due to the impact of Brexit, but future changes cannot be ruled out. Delays in ports for shipment of goods means companies may need greater storage areas for their waste before disposal can occur. More sustainable methods of disposal are therefore required, to ensure smooth operation. Advances in gasification technology and producer gas cleaning techniques have opened the door for PL to be used as on-farm energy feedstock. Previous research on solutions for disposal of PL have been carried out. Re-use of litter between batches in the houses has occurred but only means to delay the issue and increases chances of cross contamination among the birds. Feeding of the material to livestock can also be carried out in some parts of the world, but foreign objects such as plastics and glass can cause issues [12]. Currently, researchers agree that the use of PL as an energy source produces the greatest revenue streams for farms and avoids the previously mentioned contamination and disposal issues through on-site thermochemical treatment of material. Gasification of PL has attracted several interests in recent years. Dayanda [13] investigated the potential of fluidized bed technology in rural India. Jeswani [14] found out through a Life Cycle Assessment analysis that PL gasification had a lower impact in 14 out of 16 categories considered when comparing to fossil fuel alternatives, and Perondi [15] researched the potential of natural catalysts to increase gas yields. Other thermochemical conversion methods for PL researched include pyrolysis [16] and hydrothermal carbonisation and anaerobic digestion [17]. However, as discussed in [18] there is potential in using small scale (< 250 kW) gasification units for onsite heat and electricity production in poultry farms. Such concepts have already been demonstrated for the paper industry [19], oil waste [20] and the use of gasification by-products for onsite energy was researched by Vakalis [21] but has not been fully explored for the poultry industry.

Gasification technology allows for the conversion of solid biomass material into a producer gas in a low oxygen environment [22]. This producer gas can then be applied to a Combined Heat and Power, either Internal Combustion Engine (ICE) or Organic Rankine Cycle (ORC) unit to produce heat and electricity. Poultry litter has an inherent energy and fixed carbon content, which given the correct conditions can be exploited to meet the heat and electricity demands of rural farms. Changing from traditional energy generation methods such as fossil fuels to downdraft gasification coupled with applicable conversion technique, could potentially save thousands of pounds annually while increasing environmental performance and providing energy security. Environmental issues surrounding the increasing quantities of PL being produced and stored in large piles on site can be avoided using this thermochemical conversion process. These issues can include groundwater leaching from storage piles or land application, visual issues with large mounds, odour complaints and the spreading of diseases [23]. This paper aims to fill the gap with a complete performance and techno economic analysis of a downdraft gasification system utilising waste as feedstock, based on a poultry farm in Northern Ireland. The overall objective of this paper is to analyse the potential to use the poultry litter generated on site through small-scale (< 120 kW) integrated downdraft gasification and ICE or ORC to fulfil the energy requirements of the poultry farm. This sustainable conversion method would replace the necessity of fuel purchasing with PL as feedstock for production of the required heat and electricity on site. The study is based on a detailed feedstock analysis, lab-scale gasification experiments of feedstocks, and generation and validation of computational simulations using the results gathered. A typical farm in Northern Ireland is used to assess the economic viability of the solution, in terms of the Net Present Value (NPV) and Break-Even Selling Price (BESP) of the system.

Materials & Methods

The following section will detail the methodology through which the experimental and simulation work was carried out.

Analysis of the Feedstock

As a feedstock for gasification, poultry litter's physical characteristics will influence producer gas composition and quality. To understand how this will happen, a breakdown of these characteristics as well as elemental composition is required. To recognise the characteristics impact on performance, two other materials will also be investigated to compare the influence of moisture, energy and chemical composition. These will be digestate from a Northern Ireland based anaerobic digestion (AD) plant, and miscanthus. They've been chosen as digestate faces the same disposal difficulties as PL, whereas miscanthus can be grown on marginal land to provide extra income in Northern Ireland [24]. Estimates for digestate production are approximately 2.5 million tonnes available across the UK, with most currently spread on land for nutrient replacement [25]. Research carried out for the entire of the UK predict potential yield of 12 t ha^{-1} for miscanthus, generating between 0.09 and 0.034 EJ/year [26]. All materials are used in pellet form to increase energy density and avoid bridging issues in the grate. The proximate and ultimate analysis, along with calorific value of each material is presented in Table 1 Feedstock Properties. Standard methods of analysis which were carried out include moisture content (BS EN ISO 18134), ash content (BS EN ISO 18122), volatile matter (BE EN ISO 18123) and LHV (BS EN ISO 18125). Elemental components were identified by a PE 2400 CHNS Elemental Analyser, and oxygen was calculated by difference.

The relatively low moisture content of each material, between 7.15% and 10.27% can be attributed to the pelletisation process that each feedstock has gone through. Pelleting requires relatively dry material, as excess moisture would prevent the material from binding [27]. This low MC% will negatively affect the H_2 content of the producer gas and therefore the overall producer gas LHV, as H_2 in the gas stream is generated from the water gas shift reaction. Less moisture in the feedstock means less moisture for conversion into H_2 [28]. The ash content of PL (12.93%) is higher than the digestate (11.18%) or miscanthus (2.51%), with a much lower volatile matter (62.15%), implying that of the three streams PL will decompose into producer gas the least. Sulphur levels within the PL (0.43%) are relatively low, as is the amount of nitrogen (5.08%) in comparison with other biomasses. This means lower potential for the creation of harmful nitrogen oxides and sulphur dioxides.

Table 1 Feedstock properties

	Poultry Litter pellet	Digestate pellet	Miscanthus pellet
Proximate analysis			
Moisture content	10.27	7.69	7.15
Ash content	12.93	11.18	2.51
Volatile matter	62.15	74.51	83.74
Fixed carbon	24.91	14.31	13.75
Ultimate analysis			
Carbon	41.97	44.49	50.53
Hydrogen	5.74	6.56	7.01
Nitrogen	5.08	2.51	1.41
Sulphur	0.43	0.34	0.34
Oxygen	46.78	46.09	40.70
LHV (MJ/kg)	17.20	20.96	19.95

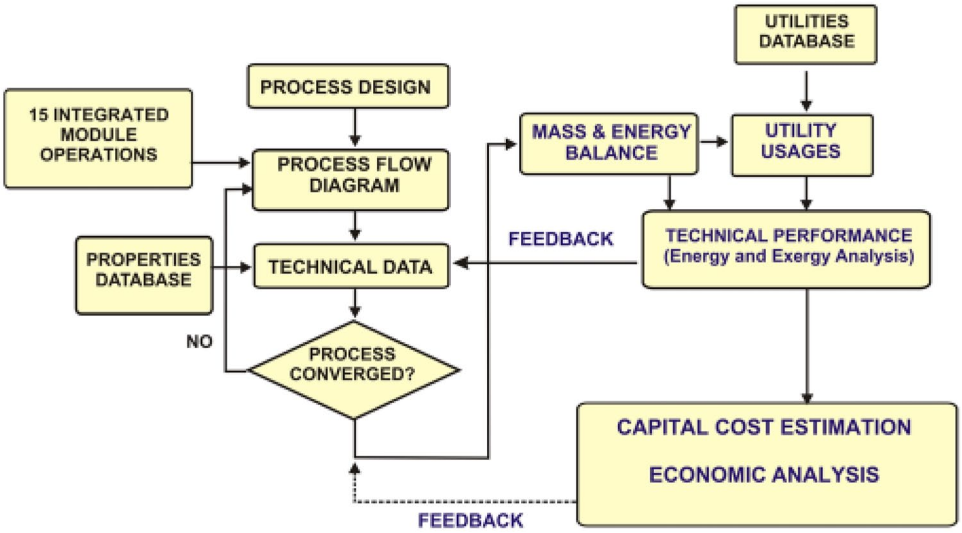

Fig. 1 ECLIPSE process modelling and simulation

Table 2 Gasification assumptions

	Poultry litter pellet	Digestate pellet	Miscanthus pellet
Input rate (kg/h)	120.0	90.0	89.1
Inlet temperature (°C)	15	15	15
Inlet pressure (bar)	1.013	1.013	1.013
Gasifying agent inlet temperature (°C)	15	15	15
Gasifying agent inlet pressure (bar)	1.013	1.013	1.013
Equivalence ratio	0.35	0.35	0.35

LHV of materials also has a wide range, from PL (17.20 MJ/kg) to digestate (20.96 MJ/kg). This range is down to the hydrogen content of each feedstock, with PL containing a lower amount of hydrogen (5.74%) in comparison to the other biomasses, with the miscanthus used containing 7%. The value could be related to the heterogenous mixture of material within the poultry litter such as bedding material, poultry excrement and feed.

2.2 Modelling and Simulation

For accurate prediction of producer gas composition along with reliable ICE and ORC system efficiencies, the modelling and simulation work was carried out using ECLIPSE process simulation package as shown in Fig. 1 [29]. ECLIPSE was designed by the energy research centre in Ulster University for a European Commission coal liquefaction project and since its development has been utilised for a range of industrial scale techno economic analysis, most recently in [30]. It is a computer-based software programme that carries out rapid and reliable mass, energy and exergy balances of complex thermochemical reactions. To accurately carry out the gasification reactions, a number of assumptions associated with the downdraft process are required and displayed in Table 2. These cover the basic system reaction characteristics.

Table 3 Producer gas conversion assumptions

	Parameter	Assumption
Air	Internal combustion engine excess air coefficient	1.8
	Input air temperature (°C)	15
	Input air pressure (bar)	1.013
CHP system	Fuel gas inlet temperature (°C)	25
	IC engine pressure ratio	22
	Engine polytropic efficiency (%)	90
	Hot water temperature (outlet) (°C)	70

Further assumptions which are required to carry out the producer gas conversion simulations are defined and displayed in Table 3. Assumptions for gas conversion are related to the air ratio for fuel consumption, along with air and gas temperatures and pressures. Any additional parameters which required definition such as separators, heat exchanger and expansion assumptions are displayed in the supplementary material, along with the gasification and combustion reaction which take place in Table S.1–5.

The techno-economic assessment is performed through a logical stepwise method. A process flow diagram is designed for the system, with technical details and experimental data used to carry out accurate mass and energy balance calculations based on the system enthalpy for each individual stream. When these individual streams have been defined the following stages are environmental impact analysis, cost estimations in terms of initial capital and daily operation costs, and finally economic analysis allowing for the calculation of the costs associated with the electricity generated from the proposed systems.

Economic modelling and evaluation of the system allowed for the identification of the NPV of the proposed systems along with the BESP for electricity generated. Total capital investment required along with other associated costs such as operation and maintenance fees were included. The lifespan of conventional energy conversion equipment such as traditional fossil fuel systems is approximately 25 years. During this time period components of the system would require regular maintenance and repair. A fixed value of 3.5% of capital cost has been included in economic assumption to agree with previous research in the field [9, 31]. Summarised in Table 9 System Components & Installed Costs are other key expenses which have been used in the economic assessment of the waste to energy system of interest.

Experimental Set Up

The experimental apparatus selected is a Fluidyne Micro-Lab Class Gasifier, an air blown fixed-bed downdraft gasifier that operates at atmospheric pressure. Downdraft has been selected for this research as it is widely accepted as the technology of choice for small scale applications with low moisture content material. A simple and proven technology that produces a gas with moderate calorific value, but importantly, low tar content which is critical for successful downstream engine application of the gas. Downdraft also accepts the widest range of biomass materials, ideal for research into underutilised biowastes [32]. The downdraft gasifier of choice is a pilot scale one, for experimental analysis. Six air inlet manifolds allow air into the heart module of the gasifier where the reactor is, with an external handle controlling the flow rate. Solid biomass is converted into producer gas in the hearth, before passing along the system to the cyclones for removal of tar and particulates. From here the gas can pass two ways: to the test flare where gas is siphoned from for further cleaning and analysis or through an internal condenser and filtration system for engine application. Clean-out ports on each module allow for the removal of tar and other unwanted particulates. Manometers and thermocouples are connected to each module to measure pressure and temperature changes across the system respectively. A Grant 2020 series data logger is connected to the thermocouples for accurate recording. Apparatus layout is displayed in Fig. 2 Experimental System Set Up along with an image of the gasifier.

For producer gas composition analysis, it is fed through the ETG PSS 100 Portable Sampling System Gas Treatment which has a scrubber unit along with an additional gas drying filter unit for the removal of final tar, particulates and other unwanted by-products. The cleaned producer gas is then fed into an ETG MCA 100 Syn Biogas Multigas Analyzer, which accurately record the CO, CO_2, H_2, N_2 and O_2 as volumetric percentage (vol.%).

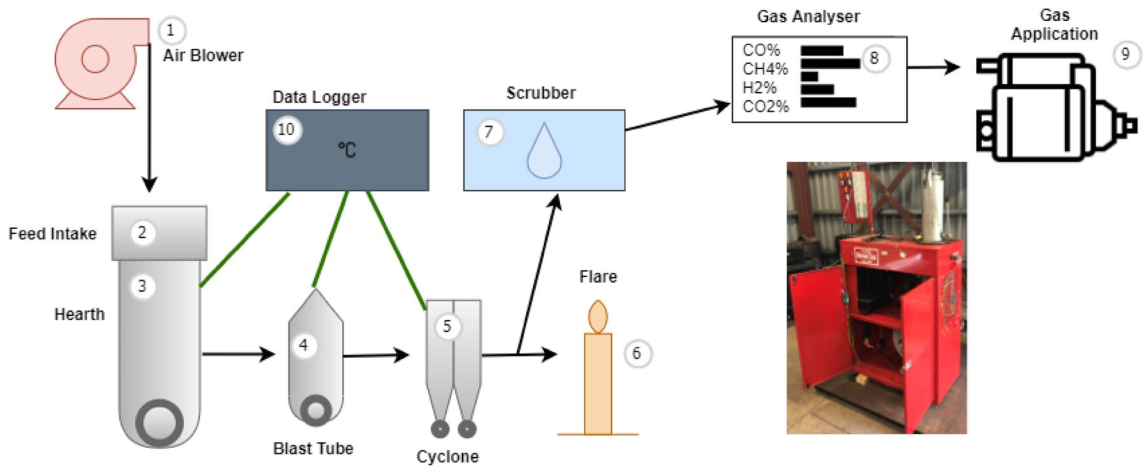

Fig. 2 Experimental system set up and gasifier image

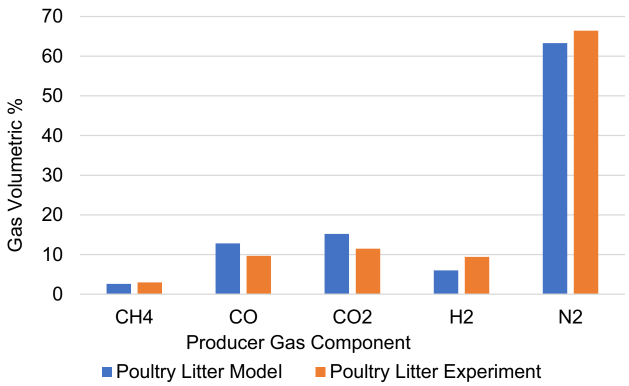

Fig. 3 Model results vs. experimental results

Process Validation

Experimental analysis of feedstocks was performed in triplicate, to ensure the validity of the collected results. Average values for each of the gaseous components of interest (CH_4, CO, CO_2, H_2 & N_2) were obtained. The ECLIPSE model generated was then adjusted to accurately represent the producer gas found. This was carried out through alterations of the mass balance equations until volumetric composition from the ECLIPSE model agreed with experimental results. The mass balance equations within the model could be adjusted to favour particular products from the defined reactions. Increasing or decreasing the percentage of reaction products allowed for accurate composition to be generated. A comparison of model results and experimental results can be seen in Fig. 3 Model Results vs. Experimental Results. A maximum difference of 3% variation in gas composition was identified. To ensure accuracy of both the model and the experimental results, the data was compared to that found within the literature of previous research [33–35]. Results agreed with what has been previously identified as good quality gas. LHV was found for the poultry litter producer gas. Using air as the carrier gas, the resulting gas with diluted with inert nitrogen. Overall producer gas LHV for the poultry litter pellets was found to be between 2.84 and 4.15 MJ/Nm^3. Gasification efficiency was calculated through sample weight calculation. Ash, char and tar produced during the reaction was collected and weighed to identify the total biomass conversion. It was found that 68% of the total weight input was converted to gaseous components.

Economic Indices and Assumptions

For the economic analysis carried out to investigate the impact of a variety of scenarios on the systems profitability and electricity production costs, two financial indices were employed. These are NPV and BESP. These are defined in Eqs. (1) and (2) as follows:

$$NPV = \sum\nolimits_{n=1}^{t} \frac{CF_n}{(1+r)^n} - C_c, \tag{1}$$

where CF_n is the annual total cash flow, which is the difference between revenues and expenditures, r is the discount rate, C_c is the total capital costs of the system and t is the lifetime of the equipment (22 years) [36].

The BESP for the electricity generated can be calculated using the following equation:

$$BESP = \frac{\sum\nolimits_{i=0}^{N} \frac{(I_i+O_i+M_i+F_i)}{(1+DCF)^i}}{\sum\nolimits_{i=0}^{N} \frac{E_i}{(1+DCF)^i}}, \tag{2}$$

where Ii is investment expenditures in the year i, Oi and Mi are operation and maintenance costs in the year i, Fi is the fuel cost, DCF is the discounted cash flow rate, and Ei is the electricity produced in the year i, N is the expected lifetime of the system [37].

A number of economic factors and indices which required definition for accurate economic analysis to be carried out utilising the ECLIPSE software package are defined within Table 4. These are based on previous work carried out in the field of techno-economic analysis of biomass power generation plants [9, 38].

The model was applied to a case study of a typical farm in Northern Ireland to assess the potential benefits of small-scale gasification systems. A comparison of three different set ups for energy generation have been undertaken, considering: (i) to use all the poultry waste available for heat and electricity production (120 kW ICE), leading to an excess of electricity sold back to the grid, (ii) to use an Organic Rankine Cycle, that is a CHP technology with a higher heat to power ratio (36 kW ORC) to meet the thermal demand and limit the export of electricity to the grid, (iii) to use an ICE (21 kW) to meet the electricity demand on site, in combination with a gas boiler, using excess producer gas to meet the heat demand not covered by the ICE unit. The NPV and BESP for each system was identified through use of the ECLIPSE simulation software.

Table 4 Economic factors and indices

Project life (years)	22
Discounted cash flow rate (DCFR) (%)	8.0
Owners cost (% EPC)	10.0
Project contingencies (% TCI)	10.0
Plant occupancy (%)	75.0
Operating cost (%TCI)	5.0
Maintenance cost (% TCI)	3.0
Insurance cost (% TCI)	1.5

Table 5 Net present value of the defined scenarios (*k*£)

Scenarios defined	£ 120 kW ICE–CHP	£ 36 kW ORC–CHP	£ 21 kW Standalone ICE
Base case	515.45	396.61	244.71
Case 1	747.14	555.04	403.15
Case 2	1017.17	819.08	667.21
Case 3	1140.97	937.12	697.04
Case 4	1378.63	1174.75	748.03

Table 6 Break even selling price of electricity (£/MWh)

Scenarios defined	£/MWh 120 kW ICECHP	£/MWh 36 kW ORC–CHP	£/MWh 21 kW Standalone ICE
Base Case	123.85	317.6	336
Case 1	93.84	250.85	221.74
Case 2	60.52	139.8	31.22
Case 3	44.88	90.09	10.99
Case 4	14.88	− 9.89	− 27.1

Table 7 Payback period (years) of CHP systems

Scenarios defined	Years 120 kW ICE–CHP	Years 36 kW ORC–CHP	Years 21 kW Standalone ICE
Base Case	19.3	19.3	19.3
Case 1	11	12	9
Case 2	7	7	5
Case 3	6	6	5
Case 4	5	4	4

Table 8 System technical & environmental performance

	Poultry Litter pellet	Digestate pellet	Miscanthus pellet	LPG [39, 40]
Input (kg/h)	120.0	90.0	89.1	62.7
Gas production (m^3/h)	250.1	209.6	236.6	N/A
Heat output (kW)	163.6	160.3	161.1	150.6
Electrical output (kWh)	120.0	120.0	120.0	120.0
CO_2 emissions (kg/h)	179.5	135.5	124.3	188.0
Electrical efficiency (%)	20.34	22.89	24.30	16.8
CHP efficiency (%)	48.06	53.47	56.94	38.3

Results and Discussion

Results from the economic analysis of the three individual CHP systems that were proposed was generated using the relevant ECLIPSE simulation software packages. Results are displayed in Tables 5, 6, and 7 for the NPV, BESP and PBP calculated for each scenario defined within Table 11. NPV results are in thousands of pounds (k£), BESP is shown as £/MWh while PBP is in years.

The proposed system was successfully assessed through the utilisation of ECLIPSE simulation package. An overview of the technical and environmental performance of the system is presented in Table 8 System Technical & Environmental Performance. Biomass flowrate in based on a DAF basis, which influences the variation in rate, with PL having the highest flowrate, of 123.5 kg/h, compared to miscanthus with the lowest flowrate, 89.1 kg/h. The reason being that PL has the highest ash and moisture content (12.93% and 10.27% respectively). Ash and moisture content don't have the expected influence on gas production. Miscanthus has the highest volatile matter (83.74%), meaning it breaks down into its gaseous components easiest, but this does not translate into the gas production rate here as PL creates the highest amount of gas even with its lower VM, of 62.15%.

Heat output varies slightly between feedstocks, with digestate gasification and ICE producing marginally less heat than PL, 160.3 kW vs 163.6 kW, while miscanthus sits between, with a heat output of 161.1 kW. This is noteworthy as despite having a higher gas production rate than digestate, the efficiency for PL is much lower. Electrical efficiency of the ICE is 20.34% with an overall heat and electrical efficiency of 48.06% for PL. Although the performance is lower than natural gas fed ICE's, in this case, waste is used with the additional advantage of overcoming disposal issues.

CO_2 emissions from the system are a critical reference point, to compare the environmental performance to existing systems. From the authors experience and existing literature [41], poultry farms across the UK utilise LPG or biomass systems for their energy needs. LPG systems have lower efficiencies than those found for the biomass gasification systems of interest, as well as increased

CO_2 emissions as can be seen in Table 8. Environmental improvements will therefore be found from changing to the proposed gasification system.

Case Study

While gasification at large scale has yet to take off across the UK, there are examples of plants across Europe, North America and Asia that are successfully operational [42]. Small scale ($< 250kW_e$) is currently a more attractive method for the UK market due to the simpler technology and lack of expertise required to run. The application of this system would be particularly suitable for a rural poultry farm, capable of using their farm waste to generate heat and electricity for the site and avoid any contamination issues associated with the transportation of poultry litter. Using the efficiencies found through the ECLIPSE modelling, we have assessed the potential of using poultry litter waste as the energy source for a typical poultry farm in Northern Ireland. The evaluation will consist of three different scenarios, as explained above, containing a fixed bed downdraft gasifier, along with: (1) 120 kW ICE – CHP, (2) 36 kW ORC–CHP and (3) 21 kW standalone ICE with a boiler to generate any additional heat required. The mechanism of operation is the collection of fresh poultry litter from the onsite sheds and fed into the drying system for processing, before feeding to the gasifier for energy conversion. A standard sized poultry shed of 73 m × 18 m, holds approximately 27,000 birds at any given time. The shed requires 240 MWh_{th} and 35 MWh_e annually [43]. An average poultry farm containing 4 sheds, will have a resulting net annual demand on site of 960 MWh_{th} and 140 MWh_e.

Table 9 System components and installed costs were generated using values found through the ECLIPSE modelling software. ICE total capital costs are marginally higher than the ORC equivalent due to the increased cost of the power generation process. ICE system also has an increased grid connection cost due to the amount of electricity generated. Feedstock preparation costs are those associated with drying, commuting or pelleting. The gasification system for both set ups is the downdraft gasifier which would include reactor bed, cyclone, heat exchanger and ceramic filter system. Contingency costs could be any associated works required such as material handling, disposal or filtration. Total installed cost for the proposed 120 kW ICE system would be £487,835, while the 36 kW ORC system is lower at £375,331.

From Table 9 we can see the overall cost of the proposed system for a rural poultry farm based in Northern Ireland. For the case study, we assume that in the standard scenario the heat and electricity currently utilised on site is provided by an LPG system. To understand the potential of these three technologies, the current operational capacity along with performance analysis are displayed in Table 10 Operational Capacity and Performance for Downdraft Gasification CHP Systems. Increased thermal output in Table 10 compared to Table 8 is from the introduction of a heat recovery system.

Table 9 System components & installed costs

Components	Gasifier & 120 kW ICE	Gasifier & 36 kW ORC	Gasifier, 21 kW ICE + Boiler
Feedstock preparation	£25,835	£20,353	£19,661
Gasification system	£129,178	£101,767	£98,292
Power generation process	£115,929	£83,064	£17,661
Grid connection cost	£51,558	£14,137	N/A
Heat recovery circuit	£52,758	£50,709	£20,831
Gas burner	N/A	£18,686	N/A
Biomass boiler (117 kW)	N/A	N/A	£21,579
Total equipment cost	£375,257	£288,716	£178,024
Integration cost	£75,051	£57,743	£35,605
Contingency	£37,526	£28,872	£17,802
Total installed cost	£487,835	£375,331	£231,431

The material produced on site is approximately 378 tonnes of wet PL per shed, as material contains an as received moisture of approximately 60%. This equates to 226 tonnes of dried material per shed when reduced to 15–20% moisture, giving a total of 907 tonnes of dry material per annum. Downdraft gasification of this material could produce up to 2565 MWh/annum, enough to meet the heat and electricity demands of the site, as well as covering the excess needed for material drying.

When considering the 120 kW ICE–CHP for heat and electricity production, sized based on the thermal demand, as previously mentioned, a large proportion of the electricity generated will need to be sold to the grid as the electricity demand onsite is only 18% of the amount produced. Selling 82% of the electricity generated, or 97.5 kW_e would require a grid connection and permission from the local authority. This may be difficult to achieve, as well as having an associated cost that could be avoided. Heat generated from an ICE engine is much closer to that of the onsite demand, with 91.6% of all heat produced required for heating of the poultry sheds or for pre-treatment drying of PL. Excess heat generated here could be used for further heating onsite, to increase poultry comfort, to supply hot water for cleaning or other specific onsite needs.

To avoid the large excess of electricity and potential grid connection problems, an ORC system characterised by a more flexible system where the power to heat ratio can be adjusted and by a higher heat to power ratio, more in line with the on-site heat to power demand, could be used. Under the 36 kW ORC–CHP conditions modelled, 59.5% of the

Table 10 Operational capacity and performance for downdraft gasification CHP systems

	120 kW ICE–CHP	36 kW ORC–CHP	21 kW Standalone ICE
CV (kWh/kg)	4.16		
Input (kg/h)	120.0	84.5	78.0
Thermal input (kW_{th})	499.1	351.4	324.4
Gasification efficiency (%)	68.0%	68.0%	68.0%
Producer gas energy (kW)	339.4	239.0	220.6
To CHP system (%)	100.0%	100.0%	32.3%
Total CHP energy input (kW)	339.4	239.0	71.3
Heat recovery efficiency (%)	85.0%	85.0%	85.0%
Thermal energy recovered from engine (kW_{th})	187.5	172.7	42.4
Electrical efficiency (%)	35.0%	15.0%	30.0%
Electrical power (kW_e)	118.8	35.9	21.4
Drying heat consumption (MWh_{th}/year)	163	115	106
Electric consumption (MWh_e/year)	140	140	140
Heat used (MWh_{th}/year)	1,123	1,075	1,066
Electric for export (MWh_e/year)	640	96	N/A
Producer gas energy diverted to boiler	–	–	67.7%
Boiler thermal energy (kW_{th})	–	–	149.3
Boiler efficiency (%)	–	–	85.0%
Thermal energy from boiler (MWh_{th}/year)	–	–	834
Sent to the grid (MWh_e/year)	640.6	95.3	–

electricity generated would cover onsite demand, reducing the amount of exported electricity from 640 to 95 MWh. In terms of heat almost 95% of the heat energy supplied from the ORC system will be used on site. The final proposed system was sized to generate only the required electricity, avoiding a grid connection cost and supplementing the heat required with a gas boiler to meet the farm needs. This meant a 21 kW ICE system, which utilises 100% of the electricity generated on site. An additional 149.34kWh_{th} was generated from the combustion of excess producer gas in a gas boiler. The proposed systems will save the case study farm heating costs (£0.015/kWh), grid electric costs (£0.12/kWh) and waste disposal costs of £30/tonne [44]. CO_2 savings available to the system could displace up to 0.21 kg CO_2/kWh of net energy generated when compared to the CO_2 emissions from grid electricity network and LPG systems [45]. Savings related to the heat generation system are not solely from the purchase cost of the LPG, but also from the avoidance of additional equipment such as heat exchangers or related ancillary equipment. The saving per kWh of heat generated will therefore be greater than the £0.015/kWh from the cost of LPG alone.

Sensitivity Study: Net Present Value & Break-Even Selling Price

To evaluate the potential profitability of the proposed energy generation system and identify under what conditions the system will offer a positive return on investment, the NPV of the CHP conversion systems were identified utilising the economic analysis package of ECLIPSE [46]. NPV allows for the assessment of the economic viability of the project over the equipment's lifetime, using the initial investment and any subsequent cash flow generated by the system [47]. To generate the NPV of the project over time, 5 scenarios were identified. In all but the base case additional income for the system could be generated. These scenarios are defined within Table 11. Biochar pricing of £200/tonne is an estimated figure based off prices from [48]. The 1.5p/kWh is

Table 11 NPV scenarios for CHP system

Base case	Basic configuration without any incomes/incentives from outside the farm
Case 1	Disposal of poultry litter material at £30/tonne
Case 2	Selling of biochar generated from process, approximately 20% of input feedstock. £200/tonne
Case 3	Displacement of LPG fuel required for heating purposes 10p/kWh
Case 4	Carbon tax on CO_2 emissions, £20/tonne

an projected tariff at which the heat could be sold for from [49]. For the analysis carried out, the cases were added with a cumulative reasoning, adding additional incomes with increasing cases. Further economic factors and indices which required definition for the economic analysis carried out by ECLIPSE are displayed in Table 4 of the in Sect. 2.5 of materials and methods.

While payback period varies between each scenario, a positive economic performance can be identified for cases 2–4. From Fig. 4 the payback period of each case can be seen, and, in most cases, it is swift with payback period below 10 years identified for two thirds of them. Base cases each begin with a payback period of 19 years, close to the lifetime of the equipment. Payback period decreases with increasing income sources, as would be expected. From this analysis it can be derived that the conversion of PL waste to electricity is a financially viable project, offering relatively low payback periods for the initial investment. Biomass conversion systems have a life span of between 20 and 25 years, and under most scenarios the payback period for this system is below 10 years, offering a solid return on the initial investment [38].

To understand the NPV of the proposed systems, analysis of the proposed scenarios was carried out using ECLIPSE's economic analysis software. As is displayed within Fig. 5 the NPV of each scenario increases with increasing revenue generated by the power generation system. The impact of each individual scenario is influenced by the size and rating of the system. Disposal of poultry litter has a greater impact on the NPV of the 120 kW ICE – CHP system than the 21 kW standalone ICE as it displaces a much larger amount of material from this scenario.

The final financial aspect of the research carried out was the BESP of the electricity generated from the proposed CHP systems. BESP shows the minimum price for which each MWh of electricity must be sold to recover the initial capital investment of the system [35]. This would equate to the NPV of the project over the course of its lifetime being equal to zero.

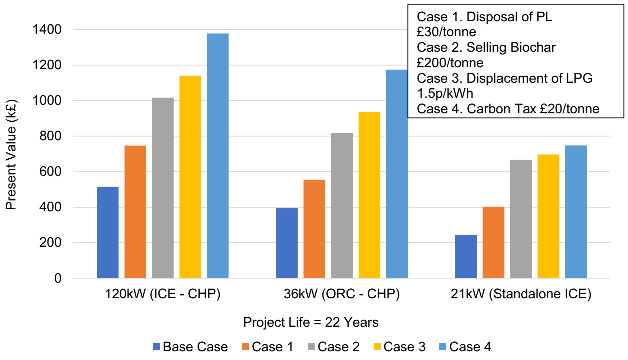

Fig. 5 NPV for the proposed energy generation systems

Figure 6 displays the BESP of the electricity produced in £/MWh with a range of prices dependant on the scenario. Scenarios are the same as those defined within Table 11. BESP is dependent on the income from various stream available to the system, where the lower the BESP, the greater the profitability of the system. BESP for the 120 kW ICE system varies between 123.9 £/MWh to 14.9 £/MWh, while for the 36 kW ORC system it is between 317.6 £/MWh and − 9.9 £/MWh. The 21 kW standalone ICE system requires between 336 £/MWh and − 27.1 £/MWh. All systems offer a swift payback period under the correct conditions, with each having their own benefits. The ICE system requires slightly higher initial investment for a greater energy output, but the ORC system flexibility may be more attractive to prospective investors, although keeping the problem of exporting part of the electricity to the grid network.

The lowest BESP for the electricity generated is from case 4 of the 21 kW standalone ICE system, due to the relatively low initial investment costs associated with it. Both the 36 kW ORC system and the 21 kW ICE system have a

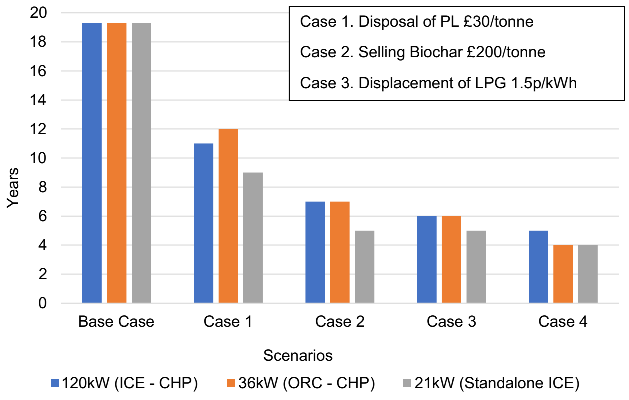

Fig. 4 Payback period for downdraft gasification and CHP systems

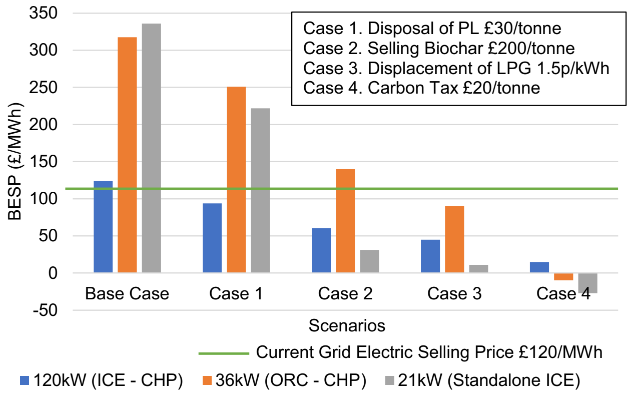

Fig. 6 BESP for electricity from poultry litter gasification based CHP systems

negative BESP of – 9.9 £/MWh and – 27.1 £/MWh respectively. When compared to the grid electricity selling price, £120/MWh, the production cost of electricity is lower in 9 of the 12 cases described. For the 120 kW ICE–CHP the cost varies from 123.85 to 14.88 £/MWh. For the 36 kW ORC–CHP the price begins at an expensive 317.6 £/MWh but becomes a negative price of – 9.89 £/MWh by case 4, where producing electricity becomes profitable. The 21 kW standalone ICE follows a similar trend, beginning at 336 £/MWh and ending with – 27.1 £/MWh, showing in case 4 a high margin that demonstrates the profitability of the solution. This means that under 75% of the cases modelled, electricity is cheaper to generate than to purchase from the national electricity grid. The results from this analysis show that Northern Ireland's poultry industry is a suitable candidate for the proposed energy generation system, due to the quick payback period offered, the low BESP for most scenarios and the need to address the problem of PL disposal as soon as possible as a result of Brexit [50]. The large number of birds nationally, and relatively low amount of land for spreading means the use of material on the site of production is the most environmentally and economically sustainable method of disposal. If poultry waste can no longer be transported across the Irish border, the only available option may be to transport to the island of Great Britain for disposal through either landfilling or spreading. Handling and transport costs for shipping to mainland GB are significant, with prices being £30 per tonne in 2012 and potentially rising due to higher gate fees in future [8]. With over application of nutrients to land already an issue in Northern Ireland, gasification coupled with downstream application offers a practical solution to avoid high disposals costs, as well as ensuring the sustainability of the industry.

Conclusion

The use of poultry litter for onsite heat and electricity production is an interesting example of circular economy, utilising a waste from the poultry industry to generate the energy required to run it. The paper has investigated the potential of using small-scale downdraft gasification along with a heat and electricity production unit on a rural poultry farm in Northern Ireland. The elemental analysis of three types of pellets was carried out (poultry litter, AD digestate and miscanthus) to understand their potential as a fuel for gasification. Simulation modelling of the gasification reactions along with heat and power systems were carried out and validated using the averaged results obtained from experimental analysis. Gasification efficiency was found to be 68% for material conversion along with producer gas with a LHV of up to 4.15 MJ/Nm^3.

Poultry litter was compared to other locally available feedstock in Northern Ireland and the rest of the UK to understand their gasification potential, with obvious differences arising from the moisture, ash and volatile matter content of each biomass feedstock. Through simulation of the ICE and ORC application of the producer gas, it was found that enough waste material is generated on site to meet the energy demands, both electrical and thermal, of the farm from the waste to energy conversion process.

NPV and the BESP of electricity generated for the three proposed CHP systems were identified utilising further ECLIPSE economic analysis software. Results displayed a positive return on investment for the technologies, with a payback period of less than 12 years identified for each scenario of CHP application of the producer gas after the base case. BESP for each system was dependent on the scenario defined but could be as low as – 27.1 £/MWh for the 21 kW Standalone ICE or – 9.9 £/MWh for the 36 kW ORC–CHP in case of a carbon tax of £20/tonne of CO_2. With an estimated 22-year lifetime of the equipment, each proposed system offers great promise as a technology for lowering disposal costs, avoiding over application of nutrients to land and ensuring biosecurity of individual farms through avoiding transport off site of potentially harmful material. Optimum system choice will depend on electricity and heat demand of the farm. Literature shows that the 90% of GHG emissions of a poultry farm comes from the fuel used to satisfy the energy needs [51]. The solution of fuel switching studied in the present paper is a technical and economic viable option that will help farmers to achieve a nearly zero carbon goal.

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Code Availability Not applicable.

Declarations

Conflict of interest The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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