Biochar and renewable energy generation from poultry litter waste: A technical and economic analysis based on computational simulations ☆

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HIGHLIGHTS

- A techno-economic analysis of the production of biochar and heat and power from poultry litter.
- The bio-waste pyrolysis/gasification system is modelled and simulated.
- The poultry litter biochar production system integrated with a CHP installation offers a significant CO_2 saving opportunity.
- Gate fees, Carbon Credits and ROCs have a significant impact on the breakeven selling price of biochar produced.

GRAPHICAL ABSTRACT
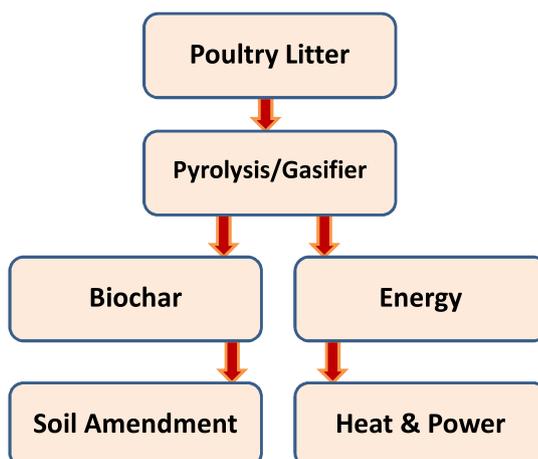
ARTICLE INFO

ABSTRACT

The technical and economic analysis of generating biochar together with electricity and/or heat from poultry litter (PL) waste is the subject of this study. To carry out this study, the process simulation software ECLIPSE is used. Modelling and simulation have been conducted over the selected system: the pyrolysis/gasification process integrated with an Organic Rankine Cycle (ORC). The facility will be capable of processing 1500 kg of PL every hour. The simulation shows that when a reference PL is used the yield of biochar from the process is around 398 kg/h with a 38% carbon content. Electricity generated by the ORC system is 388 kW h_e. Recovered low grade heat for space heating is estimated at 1831 kW h_{th}. The results of the economic analysis suggest that when paying £20/tonne for handling and storing the feedstock without any options of selling either heat or electricity, the break-even selling price (BESP) of biochar is around £218/tonne. If the sale of electricity and heat produced is considered to be around £60/MW he and £5/MW h_{th}, the BESP will decrease to £178/tonne. The case studies also indicate that when a gate fee of £10/tonne is introduced the BESP can be further reduced to £65/tonne, equivalent to a 63% reduction.

Nomenclature

AR	as received	LCOE	levelised cost of electricity
BESP	breakeven electricity selling price	NPV	net present value
CAPEX	capital expenditure	ORC	organic Rankine cycle
CHP	combined heat and power	O&M	operation and maintenance
CV	calorific value	P	phosphorus
DAF	dry and ash free	PL	poultry litter
DCFR	discounted cash flow rate	ROCs	renewable obligation certificates
EPC	engineering procurement and construction	TCI	total capital investment
FC	fixed carbon	VM	volatile matter
LHV	lower heating value		

On the other hand if biochar generated has an average price of £150/tonne in the market and the plant receives one Renewable Obligation Certificate (ROC) from the Government, the Levelised Cost of Electricity (LCOE) for the electricity generation will be £46/MW h_e, which is compatible with electricity generated by fossil fuel power plants.

1. Introduction

The broiler poultry production in Northern Ireland, UK is a significant part of the local economy, sustaining on-farm employment for over 1400 people, with a further 4600 people employed in processing [1]. Concentrated poultry farms, however, generate large quantities (around 260,000 tonnes per annum) of poultry litter (PL) waste which could rise to 400,000 tonnes per annum within 5–10 years [2] due to the constantly increasing demand, resulting in various problems especially in the environmental pollution and human health risk. The disposal of PL in NI has received a lot of media coverage recently. As things stand, there appears to be no agreed course of action to remediate this issue but with tightening EU legislation, a sustainable solution to deal with the increasing quantities of PL must be initiated as soon as feasibly possible. Common poultry litter, which is produced during the normal poultry farming operation, consists of a bedding material such as wood shavings, sawdust and straw, together with the spilled feed and accumulated droppings. When managed correctly, land application of PL on the farms is a viable and beneficial option to recycle relevant plant nutrients such as nitrogen (N), phosphorus (P) and potassium (K), thereby maintaining the fertility and texture of the soil cultivated. However excessive application of PL waste to land without an appropriate treatment causes serious social and environmental problems, the most prominent of which is the protection of the environmental resources as its leaching into groundwater or washing into surface waters in watersheds [3]. Relying heavily on spreading of poultry litter on agricultural land the poultry farms also create a high risk of transmitting of botulism to cattle which is urged against by DEFRA [4].

To minimise health and environmental concerns in relation to the increasing quantities of poultry litter waste without adversely impacting on the farming communities, it is urgent for the poultry industry to develop and adopt green and sustainable solutions to deal with the issues. Since the poultry farm waste has been shown to be a type of wastes derived from agricultural biomass and contains the relatively high energy content and fixed carbon, the use of PL as a way of producing both bioenergy and sustainable biochar is a promising alternative for waste management [5]. As proposed this project is to produce biochar from PL waste. Different from the direct incineration/combustion process which is typically used to convert PL waste into heat/or power with small amounts of biochar, this option can be implemented by the combined pyrolysis/ gasification of poultry litter in an oxygen restricted environment, whereby organic materials are converted into combustible gas (synthesis gas) and the rest is transformed into biochar containing a relatively high carbon content. Because of its high in phosphorous, potassium, calcium and other valuable micronutrients, biochar obtained from the pyrolysis/gasification process can be realised as a soil amendment which boosts soil fertility [6] and has the potential to help mitigate climate change by carbon sequestration in soils [7].

The overall objective of this paper is to perform a comparative techno-economic analysis of the small-scale integrated pyrolysis and gasification of poultry litter to give rise to both biochar and energy products. To achieve these objectives, the work begins with an investigation of the property of PL as a gasification feedstock using the information obtained from experiments. An integrated pyrolysis/updraft gasifier is then selected. Taking extremely high levels of tar content in the producer gas generated by a updraft gasifier into account an Organic Rankine Cycle (ORC) is configured to generate electricity. This implementation can avoid using the complicated scrubbing system, resulting in lower capital costs. Technical data are obtained from the test facilities and European Commission projects to adapt the models for PL waste conversion and applications and to ensure that the models are realistic. The process modelling and simulation are done using the ECLIPSE process simulation package [8]. Based on the results of mass-energy balances, an economic analysis of the options is then carried out together with a sensitivity study.

2. Materials and methods

2.1. Analysis of the feedstock

As a pyrolysis/gasification feedstock, the PL properties will influence the process operation and biochar product quality. In order to investigate the impact of variations in energy content, moisture level and chemical composition on the overall technical performance of the process two PL samples are chosen for the modelling and simulation. In addition, for the purpose of comparison a willow biomass is also included in this study. The ultimate and proximate analyses and lower heating values of the feedstock used are shown in Table 1. In this study, the PL Sample #2 is selected as the reference feedstock. This PL has a medium ash

Table 1
Feedstock properties: poultry litters vs. willow chips.

	Poultry litter samples		Willow chips
	PL Sample #1	PL Sample #2[a]	
Proximate analysis			
Moisture content	30.0	25.4	29.2
Ash content	22.4	17.3	0.6
Volatile matter	42.8	50.4	55.1
Fixed carbon	4.8	6.9	15.1
Ultimate analysis			
Carbon	50.8	44.8	51.0
Hydrogen	6.2	6.0	6.0
Nitrogen	8.0	8.9	0.1
Sulphur	1.3	0.8	0
Oxygen	33.7	39.5	42.9
LHV (MJ/kg)	17.23	16.02	17.37

[a] PL Sample #2 is also specified as a reference feedstock.

content of 17.3% (as received: AR), a high moisture content of 25.4% (AR), a calorific value of 16.02 MJ/kg (lower heating value: LHV, dry ash free basis: DAF) [9]. Although this LHV lies below most fossil fuels ($\sim$35 MJ/kg) it is still compatible with most biomass (17–18 MJ/kg) [10]. With 8.9% nitrogen (DAF), the proportion of this component is considerably higher than most biomass. Thus there would appear to be significant potential for fuel nitrogen oxides formation from the conversion process at high temperatures. The sulphur content of the reference PL is 0.8% (DAF), higher than many biomass fuels. In fact most PL contains relatively high proportions of calcium compounds. These would react with sulphur dioxides to produce calcium sulphates and thereby reduce gaseous emissions. If additional measures still need to be taken limestone injection in the process is a primary option to fully comply with environmental legislative limits [11]. The volatile matter of the reference PL is around 88.0%. This has an implication that the PL materials can be easily decomposed into producer gas. As selected PL Sample #1 and willow chips have calorific values of 17.23 MJ/kg and 17.37 MJ/kg (LHV, DAF) and moisture contents of 30.0% and 29.2% (AR), slightly higher than the reference PL. In general the feedstock with high moisture content may need to be dried before the feedstock is used for gasification. However, according to the pilot plant test results it is probably not worth including a pre-drying process in the system if the feedstock is delivered at the moisture content of up to 30%. So that the drying equipment cost can be avoided. With 22.4% ash content of PL Sample #1, the percentage of this component is much higher than that of willow chips (0.6%). The volatile matters of PL Sample #1 and willow chips are 90.0% and 78.5%.

2.2. Carbon sequestration

The application of PL to field soils as a fertiliser can cause a rapid decomposition of organic matter resulting in carbon dioxides (CO_2) and other greenhouse gas emissions. The consequence is that the bulk of carbon added as PL is rapidly released back to the atmosphere as CO_2. Adding carbon rich biochar made from PL to field soils is a means of sequestering atmospheric CO_2 because natural soil degradation of biochar is an extremely slow process that may last for hundreds of years [12]. Therefore, PL biochar increases terrestrial carbon stocks and converting PL biomass carbon to biochar carbon enables up to 50% of the initial organic carbon to be sequestered in a much more stable form.

2.3. The carbon content of PL biochar

The poultry litter biochar is produced by thermal decomposition of PL organic matter in the PL. The biochar product composi-

tion will be affected by the feedstock properties. Since the PL feedstock contains relatively high ash content (typically 30% on dry basis) the biochar will have lower carbon contents than biochar made from biomass. From a literature review on biochar certification and other carbon materials it is found that there are some discrepancies among the different international initiatives [13,14]. The British Biochar Foundation appears to accept lower carbon materials (e.g. manure biochars) within the definition of "Biochars". However the European Biochar Certificate states biochar must contain above 50% carbon, with other materials classified as "Bio-Carbon Minerals". This latter definition will permit identification of products with higher mineral content with potential as fertilisers. Depending on how the biochar market develops, our biochar product in the future may be called a bio carbon mineral. For the purposes of this study we will term our product a biochar. However, whatever classification it achieves ultimately in the future, this will have no effect on its value or benefits.

2.4. Fertiliser value of PL biochar

During the process of gasification of PL, the volume is reduced by approximately 60–70%, no P is lost and the risk of botulism and other pathogens are eradicated due to the high temperatures. On the basis of a 60% reduction in volume, biochar has approximate 17.5 kg P/tonne compared to 7.0 kg P/tonne in PL. As a result PL biochar is a dry stable product, with the potential to be a high value fertiliser, available for application to grassland and arable land in Northern Ireland and for export to the UK and/or Republic of Ireland.

2.5. Modelling boundary and economic assumption

The economic evaluation of the selected process was carried out using the net present value (NPV) concepts. As the main indicator, the break-even selling price (BESP) of the biochar was calculated using the financial modelling of ECLIPSE. This computational software is used to estimate capital investment along with the fixed and variable operating and maintenance (O&M) costs. Conventional fossil fuels and biomass conversion systems usually have life spans between 20 and 25 years. The poultry litter pyrolysis/gasification and ancillary equipment in the biochar production system would be expected to have similar lifetimes. Therefore, the project life of the selected process was set to 25 years. This implies that some components would need to be repaired/or replaced a number of times through the lifetime of the system. Although the designed system is going to be run automatically a relatively high operating and maintenance costs are still incurred due to its small size, the time and effort needed for handling of PL and environmental costs. Basically the PL has a very low financial value in the market itself

Table 2
Economic factor and indices.

Construction time (years)	1
Project life (years)	25
Discounted cash flow rate (DCFR) (%)	8
Owner's cost (% EPC[a])	15
Project contingencies (% TCI[b])	10
Plant occupancy (%)	80
Operating cost (% TCI)	6
Maintenance cost (% TCI)	2
Insurance cost (% TCI)	1
Poultry litter receiving and handling cost (£/tonne)	20
Potential heat unit price (£/MW h$_{th}$)	5
Renewable Obligation Certificates (ROCs), £/MW h	43.3

[a] EPC: Engineering Procurement and Construction.
[b] TCI: Total Capital Investment.

as a fuel feedstock. Typical costs are around £5/tonne collected at the poultry house in Britain [15]. However, transportation costs from farms to the plant location for the PL feedstock will be relatively large due to their bulkiness and low energy densities. To have a reasonable modelling of feedstock costs the value of £20/tonne for the receiving, handling and storing of PL is assumed. As a large amount of low grade heat is recovered in the plant site the potential heat unit price of £5/MW h$_{th}$ is also assumed [16]. The key economic factors and indices as used in this assessment are given in Table 2.

2.6. Modelling and simulation options

The production of biochar from PL by pyrolysis/gasification at this scale is still a novel process and there is currently no available biochar produced from UK PL. Although PL is currently being converted to biochar using gasification in the US neither the PL itself nor the resultant biochar are comparable. To allow suitable analyses associated with the biochar production systems four options are created. The criteria for selecting options include being technically viable and being placed in commercial applications, both in the short-term and long-term. For each option, the likely capital expenditures, operating and maintenance costs along with the BESP for the plant under certain conditions will be determined. To summarise, these options are as follows:

Option 1: biochar production along with a heat utilisation installation (heat is utilised for composting and drying with no commercial value);
Option 2: biochar production along with a heat utilisation installation (heat is sold for space heating in residential buildings);
Option 3: biochar production along with an electricity generation installation (heat is utilised for composting and drying with no commercial value);
Option 4: biochar production along with a combined heat and power (CHP) installation.

2.7. The software – a brief introduction of ECLIPSE

To ensure the evaluations and comparisons were carried out in a consistent and reliable manner, the modelling and simulation were performed using the ECLIPSE process simulation package. ECLIPSE was developed for the European Commission by the Research Centre of the University of Ulster and has been successfully used to analyse a wide range of energy conversion systems using biomass and waste, such as biomass combustion plants [17] and biomass fuelled combined heat and power [18]. ECLIPSE, as shown in Fig. 1, is a personal-computer-based package containing all of the program modules necessary to complete rapid and reliable step-by-step technical, environmental and economic evaluations of chemical and allied processes including mass, energy and exergy balance, capital costing and economic analyses.

At the initial stage, process flow diagrams composed of modules and streams are generated within ECLIPSE. After specifying the stream inputs and technical features of individual modules, the mass and energy balance is determined via enthalpy calculations for each stream. This is achieved by converging the information specified in the compound database, as well as in the input streams and modules. The information gained during this second stage of simulation forms the base for identifying critical components within the plants that may be subjected to extreme physical and chemical exposure conditions. In the third stage, the package computes the amount of energy consumed by individual utilities and compounds and provides the power plant net output. Finally, the economic viability of the examined systems is evaluated. Whilst every effort is made to validate the capital cost estimation data, using published information and actual quotations from equipment vendors, the absolute accuracy of this type of capital cost estimation procedure has been estimated at about ±30%. However, although the absolute accuracy of a single cost estimate may be only ±30%, what has been done in these studies is to compare families of similar technologies, composed of similar types of equipment. Therefore, the comparative capital cost estimates, which are based on the accurate calculation of a difference in a basic design by the mass and energy balance program, should be valid.

3. Process configuration and description

3.1. Integrated pyrolysis and gasification process

A schematic presentation of the proposed biochar production system is shown in Fig. 2. The thermal conversion process mainly consists of a feedstock hopper, auger feeder, drying and pyrolysing
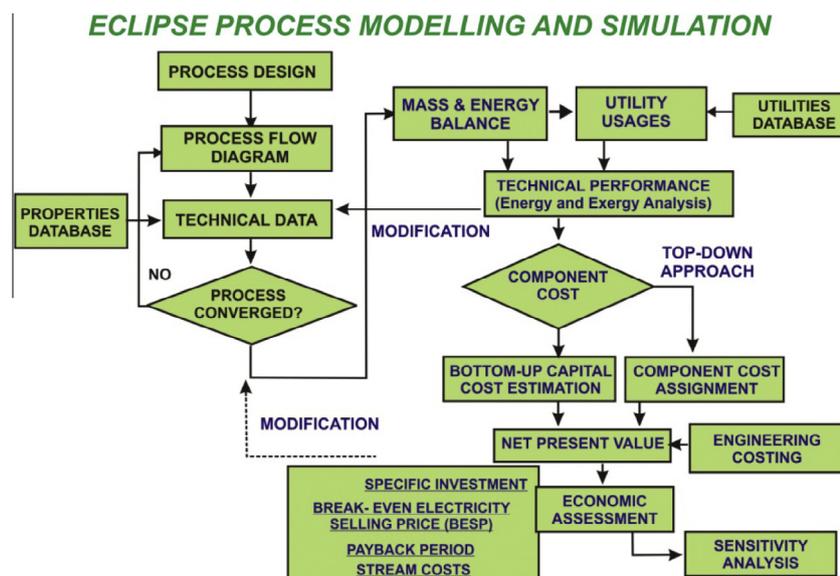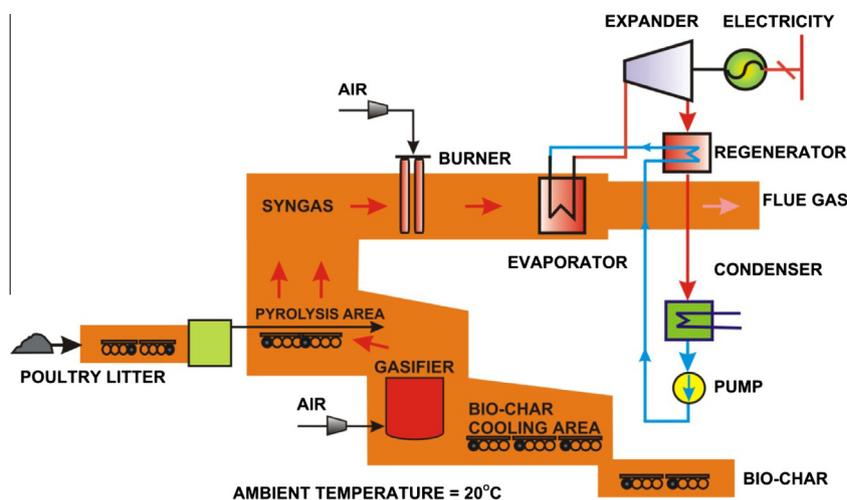

Fig. 1. ECLIPSE process modelling and simulation.

BIOCHAR AND POWER FROM POULTRY LITTER

Fig. 2. Schematic diagram of pyrolysis/gasification integrated with an ORC process.

area, reactor, updraft gasifier and biochar cooler. The work process is as follows: poultry litter is delivered with the moisture content approximately 30% to the pyrolysis area through an auger system which means no pre drying equipment is included. Poultry litter feedstock is then undergone the thermal decomposition at temperature of 500–550 °C in the absence of oxygen where a stream of carbon monoxide (CO), methane (CH_4) and hydrogen (H_2) is driven off from the PL feedstock. After the incomplete pyrolysis of PL the remaining solid contents are passed to an updraft gasifier where they are reacted with a gasification medium (air or oxygen) under conditions such that the carbon content of biochar can be controlled. In the above context the producer gas created by the pyrolysis and gasification is burnt in a thermal oxidiser and the majority of heat generated is recovered for space heating applications. In general, the system gives the biochar product with carbon content from PL wastes, typically ranging 25–40%.

3.2. Organic Rankine Cycle (ORC)

The ORC process is similar to a traditional steam Rankine cycle process, where, instead of water a refrigerant circulates as working fluid within an ORC process. The major advantage is that the vapour of the organic working fluid can be used to extract energy from a low temperature source and it allows the system to work more efficiently than conventional steam cycle technology at small scale [19,20]. The electrical efficiency of the ORC process lies between 6% and 17% [21]. From economic point of view, as operated at low temperatures, the ORC system is less costly than steam cycle boilers. The proposed ORC cycle, as shown in Fig. 2, consists of five major components: evaporator, expander, regenerator, condenser and pump. The working fluid chosen within the cycle is R245fa [22]. The heat recovered by producer gas combustion is transferred via a thermal oil loop into the organic medium in an evaporator, where the pressurised working fluid is vaporised and slightly superheated (up to 150 °C). The organic steam leaving the evaporator is then expanded in a turbine which is connected with a generator. Since the turbine exhaust vapour has not reached the two-phase state at the end of the expansion, its temperature at this point is still much higher than the condensing temperature. To recover this heat the expanded vapour is forced to pass a regenerator to preheat the cold condensed working fluid before entering the condenser. The main advantage for recuperative implementation is to reduce the impact of irreversibility on the ORC thermal efficiency. As an air cooled condenser condensing temperature is given by 45 °C. The condensate is pumped to the regenerator and economiser before returning to the evaporator and completing the cycle.

4. Results and discussion

4.1. Technical data overview

The proposed systems were successfully evaluated using the ECLIPSE process simulator. The technical and environmental performance results are illustrated in Table 3. The results show that when the feed rate is set to 1500 kg/h (AR), the yields of biochar are 429 kg/h and 398 kg/h using PL Samples #1 and #2 respectively. The carbon content of biochar generated, as a function of ash content, increases from 25% to 38% as the ash content declines from 22.3% to 17.3%. As compared with the biochar made from willow chips it may be seen that biochars made from PL contains much less carbon content (up to 75% less). This can almost certainly be attributed to the higher ash content of feedstocks. When operating on PL Samples #1 and #2 the calorific values of producer gas are 4.21 MJ/Nm³ and 4.72 MJ/Nm³ respectively. On willow chips the calorific value of the gas rises to 5.52 MJ/Nm³. This suggests that the feedstock heating value seems to have little influence on the calorific value of producer gas. For the CHP options, the total available waste heat recovered will be 1777 kW h_{th} and 1831 kW h_{th} and electricity outputs are 376 kW h_e and 388 kW h_e giving efficiencies of around 63% and 58% (on LHV basis) from PL Samples #1 and #2 respectively. Since the pyrolysis/gasification processes convert PL waste to heat, biochar and producer gas, a lot of carbon content is likely to remain in solids. As a result it is not surprising that the mean efficiencies are well below normal CHP processes fuelled by biomass.

With regard to the environmental performance, the results show that for the CHP system the CO_2 emissions from the stack are found in the simulation to be 433 g/kW h and 387 g/kW h from PL Samples #1 and #2 respectively. As compared with willow chips (365 g CO_2/kW h) the use of PL as feedstocks may increase CO_2 emissions but is not significant. The SO_2 emissions from PL Samples #1 and #2 are 224 ppm and 161 ppm at 8% O_2 respectively. While these emissions are relatively high, they are still within

Table 3
Technical and environmental results.

	PL Sample #1 Options 1–4				PL Sample #2 Options 1–4				Willow chips Options 1–4
Poultry litter input, kg/h	1500				1500				1500
Biochar product, kg/h	429				398				254
Carbon content of biochar, %	25				38				96
Producer gas CV, MJ/Nm^3	4.15				4.81				5.52
	Option 1	Option 2	Option 3	Option 4	Option 1	Option 2	Option 3	Option 4	Option 4
Low grade heat output, kWth[a]	–	2541	–	1777	–	2622	–	1831	2140
Electrical power output, kWe	–	–	376	376	–	–	388	388	453
CO_2 emissions, g/kW h	–	366	2479	433	–	328	2213	387	368
Avoided CO_2 emissions, tonne CO_2/tonne biochar	0.92				1.39				3.52
SO_2 emissions, ppm (@ 8 O_2 vol.%)[b]	224				161				–

[a] The flue gas leaving Waste Heat Recovery Unit has a temperature of 130 °C.
[b] Without Flue Gas Desulphurisation (FGD) installation.

the emission limit value defined in the Large Combustion Plant Directive (LCPD) [23]. When biochar is applied to field soils the avoided and sequestered CO_2 emissions of 0.92 tonne CO_2/tonne biochar and 1.39 tonne CO_2/tonne biochar are estimated with PL Samples #1 and #2 as feedstocks, respectively. These figures will be financially beneficial for the biochar production if the Carbon Credits are introduced.

4.2. Economic simulation results

An economic analysis, as shown in Table 4, was done to determine the BESP of biochar produced. Since economic results are too detailed to be discussed here, certain parameters have been selected to assess the technology used.

4.2.1. Options 1 and 2

With regard to Options 1 and 2 we use the same configuration to generate biochar and low grade heat. Therefore the capital cost of each option will remain the same. Based on the process components and capacity it is estimated that the minimum capital investment is around £1,610,000 including the equipment of the pyrolysis/gasification system, feedstock handling and storage, all necessary environmental controls and 15% of owners' cost. Taking an annual operation and maintenance (O&M) and insurance cost of £353,000 and a capital expenditure (CAPEX) return of £164,000 into account the BESP of biochar is £202/tonne from PL Sample #1 and £218/tonne from PL Sample #2 when recovered waste heat is used onsite composting (Option 1). While using the same conditions but recovered waste heat has possible pricing of £5/MW hth

(Option 2), the BESP of biochar is £173/tonne from PL Sample #1 and £184/tonne are calculated from PL Sample #2. Compared with Option 1, this can reduce the BESP of biochar by around 15%. If a gate fee of £10/tonne is charged at the plant gate the BESP is reduced by up to 63%. If a carbon credit of £10/tonne of CO_2 is considered to offset CO_2 emissions through biochar and soil carbon sequestration, the BESP can be further reduced, equivalent to a 5% reduction.

4.2.2. Options 3 and 4

Although Option 3 is a power-only generation and Option 4 is a cogeneration configuration, both systems can be expected to have similar process operating components. As a result overall capital costs will remain the same. The capital investment of the plant for either Option 3 or 4 can be estimated to be around £2,771,000, costing an additional £1.16 million compared to the cost of Option 1 or 2. This increase in the capital investment is caused by the ORC system. Like Options 1 and 2 the total annual O&M and insurance costs and CAPEX return are estimated at £405,000 and £282,200, respectively. For Option 3, electricity generated is sold back to the grid at £60/MW h$_e$ and recovered waste heat is used in composting without commercial value. This gives an additional income of around £150,000. As a result, the BESP of biochar is estimated at £188/tonne and £201/tonne from PL Samples #1 and #2 respectively. For Option 4, based on a heat price of £5/MW h$_{th}$, and an electricity price of £60/MW h$_e$ the BESP of biochar is estimated at £167/tonne and £178/tonne from PL Samples #1 and #2 respectively. As compared with Option 3 this accounts for an 11% reduction. The results also show that the

Table 4
Economic results.

	Options 1 and 2		Options 3 and 4					
Total capital investment (£k)	1610		2771					
Present value of initial capital cost (£k)	1890		3254					
Annual O&M and insurance costs (£k)	353		405					
Annual electricity cost (£k)	57		–					
Annual CAPEX return (£k)	164		282					
	Option 1		Option 2		Option 3		Option 4	
	Sample #1	Sample #2	Sample #1	Sample #2	Sample #1	Sample #2	Sample #1	Sample #2
Annual income from heat/electricity sales (£k)	–	–	82	85	148	151	206	211
Break-even selling price (BESP) (£/tonne biochar)	202	218	173	184	188	201	167	178
BESP (£/tonne of biochar) at a gate fee of 10£/tonne PL	98	107	68	73	83	88	62	65
BESP (£/tonne of biochar) at a gate fee of 10£/tonne PL and carbon credit of 10£/tonne CO_2	88	96	59	62	74	75	53	53
LCOE (£/MW h) with the biochar price of 150£/tonne, feedstock charges of 20£/tonne and 1 ROC (£43.3/MW h) issued by the UK Government	–	–	–	–	60	70	36	46

impact of gate fee and carbon credit on the BESP of biochar is similar to each option, up to a 65% reduction. For Option 4 if biochar made from the reference PL is assumed to have an average price of £150/tonne in the market and the plant is still paying a receiving and handling fee of £20/tonne for the PL feedstock but will receive one Renewable Obligation Certificate (ROC) from the UK Government [24], the Levelised Cost of Electricity (LCOE) for the electricity generation will be £46/MW h_e. Clearly this figure is compatible with electricity generated by most fossil fuel power plants [25].

4.3. Sensitivity analysis

The impact of PL feedstock costs and biochar carbon contents on the BESP of biochar is presented in Figs. 3 and 4. It can be seen from Fig. 3 that if a reduction of feedstock costs of 10£/tonne can be obtained then the BESP is reduced by around 38£/tonne of biochar for each option. The sensitivity of the BESP with regard to changes in the carbon content of biochar generated is also illustrated in
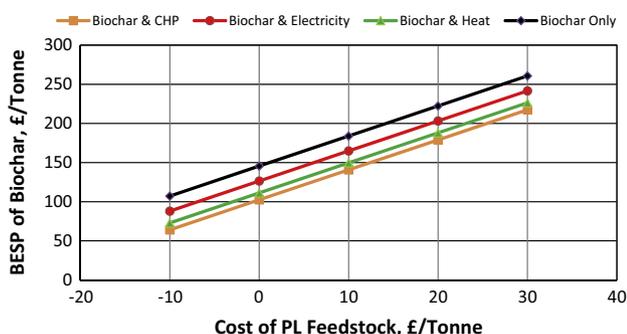

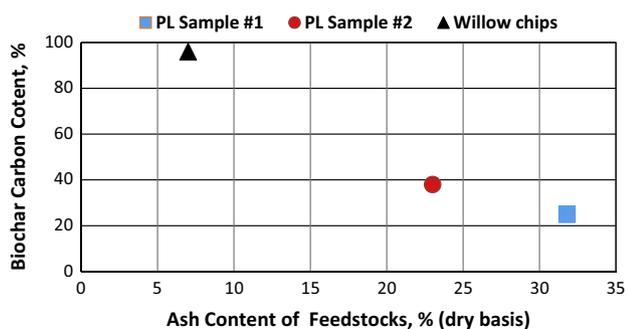**Fig. 3.** Variation of BESP versus the cost of the PL feedstock.

Fig. 4. Variations of biochar carbon content versus ash content of feedstocks.
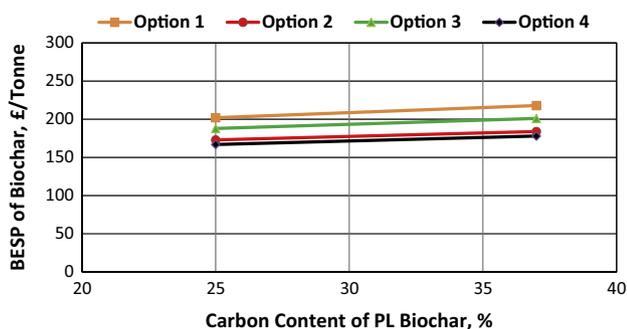

Fig. 5. Variations of BESP versus the carbon content of PL biochars.

Fig. 4. In general PL feedstock composition, including ash and moisture contents have an impact on the quality of the biochar product. The carbon content, which is one of indicators of biochar quality increases as the ash content decreases. In comparison with the reference PL (PL ash content of 23% on dry basis) PL Sample #1 displays a 34% decrease in carbon content of biochar when the ash content of the PL feedstock is increased by 39%. The BESP of biochar, as illustrated in Fig. 5, is increased by 10% when the carbon content of biochar is raised from 25% to 38%. From an economic point of view this has an implication that the carbon content of biochar made from PL may has a positive impact on the BESP.

5. Conclusion

A number of options have been modelled and simulated to assess the technical and economic viability of the production of biochar from PL waste. The following are the main conclusions from this study.

- It is technically and economically feasible to use PL as the feedstock to generate biochar together with heat and power based on a pyrolysis/gasification process.
- Among four options the combination of biochar and CHP will be the most financially attractive because of its highest profit margins.
- The ash content of PL will have a strong negative impact on the quality of biochar in the process.
- Due to its low CO_2 emissions on the basis of heat generation/or cogeneration and biochar carbon sequestration in soils, the PL biochar production system integrated with a CHP installation offers a significant CO_2 saving opportunity.
- The BESP of biochar is dominated by the feedstock cost and CAPEX return.
- The additional income, such as Gate fees, Carbon Credits and ROCs has a significant impact on the BESP of biochar produced.

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