Energy Reports 13 (2025) 1537–1547

Contents lists available at ScienceDirect

Energy Reports

journal homepage: www.elsevier.com/locate/egyr

Sustainable agriculture: Assessing the feasibility of biogas derived energy generation on a UK mixed-model farm

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ARTICLE INFO

Keywords:
Sustainable agriculture
Farmyard manure
Straw
Biogas
CHP
Trigeneration
Net-zero

ABSTRACT

This paper investigates the technical, economic and environmental feasibility of implementing a combined energy generation system powered by anaerobic digestion on a UK mixed-model farm. Initially a case study farm was selected, followed by a research visit in which primary data collection was conducted. Characteristic data was then processed giving the technical and operational criteria to be met. Both CHP and Trigeneration systems were modelled and evaluated for three types of bio-waste feedstock input, consisting of farmyard cow manure (FYM) only, FYM with a low quantity of wheat straw (414.7 tonnes/year), and FYM and a high quantity of wheat straw (679.3 tonnes/year). Theoretical energy outputs were computed, and the financial characteristics of each configuration were found, consisting of capital costs and operational savings achieved and the resulting payback period (PP). The CHP configuration was recommended producing 41 kW electricity alongside 66 kW thermal energy at an overall efficiency of 87.8 % from FYM only. This case yielded a capital cost of £ 331,055 with a PP of 8.5 years.

1. Introduction

UK farming currently faces environmental, economic and legislative barriers to efficient and profitable operation. Recently, an increased emphasis has been placed on climate change, greenhouse gas emissions (GHG's), energy security and rising energy costs in the commercial sectors. To quantify this, farming currently utilises 71 % of UK land area (DEFRA, 2022) and is a contributor to 10 % of UK GHG emissions (DEFRA, 2022). GHG emissions include Nitrous oxide (NOx), Methane (CH_4) and Carbon dioxide (CO_2), each of which farming contributes 69 %, 48 % and 1.7 % (DEFRA, 2022) of total UK emissions respectively. NOx emissions result from nitrogen fertilizer application, pastureland manure application and bio-waste run-off (DEFRA, 2022), CH4 emissions from livestock digestive processes (DEFRA, 2022) and CO_2 emissions from fossil-fuel derived energy consumption. Government commitment to reducing emissions is evidenced by the 100 % reduction target in GHG emissions by 2050 (Tang et al., 2021), therefore sustainable practices are required. Furthermore, a typical UK farm is shown to produce approx. 6461 kg of CO_2 per annum assuming 0.20707 kg of CO_2 is emitted per kWh (Barclay, 2023) of UK grid electricity. Therefore, a reduced reliance on the national grid could improve CO_2 emission profiles.

A previous study showed that utilising anaerobic digestion (AD) process, where organic matter is decomposed by micro-organisms in a closed vessel to 'biogas', a combustible mixture of CH_4, CO_2 (Lamidi et al., 2017), which can be used to generate electricity, heating and cooling energy, either through combustion for direct generation, adopting combined heat and power (CHP) systems (Mertins and Wawer, 2022). Combined cooling, heat and power (also called trigeneration) systems can provide cooling, through the use of a waste heat driven chiller (Boukhanouf et al., 2008). To achieve 'net-zero' carbon farming, capturing the CH_4 emission from animal wastes and straws which are usually released into the atmosphere within a digester system and use it as the fuel to replace the energy supply from fossil fuels (O'Connor et al., 2021). Negative CO_2 emissions can also be achieved via post-combustion carbon capture (Li et al., 2017). Although there are some investigations into AD-derived energy generation systems, lack of feasibility evaluations of various generation systems suitable for mixed farming models incorporating diversified enterprises, with no crop growth solely for digester feedstocks, and evaluates the potential for carbon-negative operation via carbon capture. To fill in this research gap, [this] study provides an investigation into available bio-wastes on a

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https://doi.org/10.1016/j.egyr.2025.01.018
Received 13 July 2024; Received in revised form 26 December 2024; Accepted 8 January 2025
Available online 18 January 2025

UK mixed-model farm, and an evaluation of feasibility in the context of varied waste-usage and power system strategies to achieve net-zero and sustainable farming.

2. Methodology

2.1. Agricultural case study

In order to evaluate the real-world feasibility of a renewable combined-energy generation plant, a farm is selected as the case study, which is a recently established mixed-model cattle and arable farm (named as 'WF') in South-East Oxfordshire, UK. The farm comprises 242.8-hectares of arable land and 242.8-hectare of pasture land on a milling wheat and grass species rotation to optimise yields and soil performance. The farm also keeps a herd of 600 beef cows at varying stages of development, with typical weights of between 500 and 700 kg (Owners and employees, 2023). A herd of 300 ewes are also kept for grazing purposes, however the lack of a housed period prevents sheep bio-waste collection and usage. WF also includes a farm shop, where WF and local produce are prepared, stored and sold in a direct-to-customer (D2C) market.

2.2. WF energy demand

Energy demand data was investigated/collected from WF. Consumption on WF is categorised into heating and electrical power needs across the farm shop, farm house and arable farm infrastructure. Electricity is currently supplied by grid electricity and heating by a single boiler and 800 litre domestic oil tank (Owners and employees, 2023). Electrical power is required for the majority of WF operations including lighting, refrigeration, domestic and shop appliance operation. Heating is required only for domestic purposes. Heating consumption profile is mainly for domestic use, with sustained peaks occurring November to February (Watson et al., 2019), provided by a single 26 kW (maximum rated output) oil boiler operating at a maximum 75°C flow temperature (Grant Engineering Ltd, 2024), reflecting existing farm heating demand. Cooling is provided by standalone fridges and a refrigerated cool room, totalling an electricity demand of 6.51 kW. Appliances use the Vapour Compression Refrigeration Cycle (VCRS), therefore the coefficient of-performance (COP) was used to estimate actual useful cooling duty Q_{out}, with power input W_{in}:

$$COP = \frac{Qout}{Win} \tag{1}$$

where, Q_{out} was the required cooling duty which was calculated for required appliances, giving a total Q_{out}= 4.6 kW.

Annual electricity consumption can be seen in Fig. 1. It shows that the farm shop is the primary electricity load, with peak demand occurring in September. In order to derive actual electrical power demand

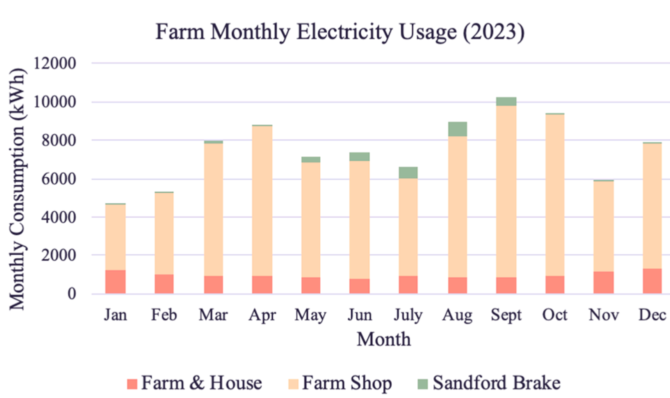


Fig. 1. Monthly breakdown of 2023 electricity consumption.

(kW), details of each appliance utilised in the farm shop was recorded, and a weighted average (WA) method was used to determine operational hours based on power consumption.

Table 1 displays resulting instant electricity demand values for each farm area, and total values considered in this investigation. It is also found that the maximum electrical power load of the whole farm during a day was 38.93 kW, if all of the electrical appliances were switched on. Therefore, the system hardware was specified in accordance with the WF's demand across electricity, heat and cooling energies. A CHP generator manufactured by *2 G Energy Company* was then selected to meet electricity and heating requirements. The model of 'g-box 50plus BG mager' was capable of outputs of up to 45 kW electricity and 75 kW heating (2G Energy AG, 2023), both sufficient to meet maximum potential WF requirements, with surplus to meet reasonable increased future demand as a result of enterprise expansion. For upgrading to a trigeneration system, a Robur heat driven ammonia absorption chiller was chosen. The single 'GA ACF' model in a standalone configuration is selected for cooling which can generate maximum 17.72 kW cooling with a minimum stream outlet temperature of 3°C (Robur, 2023), therefore sufficient to meet WF demand.

2.3. Bio-waste availability

WF produces three major categories of agricultural bio-waste: Cow manure, wheat straw and unused grass silage. Cattle are housed over a 6-month period from October-April annually, with manure only being collected over this period and stored in existing covered areas. Manure is mixed with quantities of wheat straw (WS) and removed from the cattle barn monthly as farm-yard manure (FYM), which is currently spread over arable crops, negating the use of chemical fertiliser at WF. WS is produced as a by-product of arable milling wheat harvesting operations, with an assumed yield of 4.00 tonnes/hectare (Department for Environment Food and Rural Affairs, 2022). Grass silage is produced from cut grass on WF pastureland, with a covered storage area (clamp) being loaded twice annually. Grass silage is primarily a cattle feed, however surplus supply does exist. Table 2 displays quantities of excess biomass available for disposal via Anaerobic Digestion in a given calendar year. Owing to varied production rates and usage requirements of wheat straw, low-case and high-case estimates were found for surplus availability.

The quantity of cow manure produced as dictated by WF was 0.23 m^3 manure produced/cow/week, averaged across variation in livestock weight. Samples of each bio-waste were collected, and laboratory ultimate analysis was carried out to determine Carbon (C), Nitrogen (N) and Hydrogen (H) composition, in order to accurately assess biogas generation potential. Further analysis was used to determine moisture and volatile solids (VS) content, with VS indicating the quantity of digestible organic matter in a sample (Meegoda et al., 2018).

2.4. Generation system design

An end-to-end combined energy generation system was theorised to assess implementation feasibility on WF, replacing existing grid electricity and fossil fuel heating. Key priorities of any proposed solution included sufficient generation capacity, high quality and reliable equipment, reasonable payback period and cost, and support for future business expansion. The complete system was to be housed on site,

Table 1
Electricity demand.

Location	WA Hours (hrs)	Average (kW)	Recorded Peak (kW)
Farm House	16.0	2.0	2.6
Farm Shop	12.6	16.4	23.7
Arable Ops.	12.0	0.7	2.0
Overall Net	N/A	19.1	26.8

Table 2
Bio-waste availability.

Bio-waste	Surplus (tonnes/ year)	Mass flow rate (kg/s)
FYM	2000.0	0.0634
WS (Conservative – Low case)	414.7	0.0132
WS (Non-conservative – High case)	679.3	0.0215
Grass Silage	384.0	0.0122

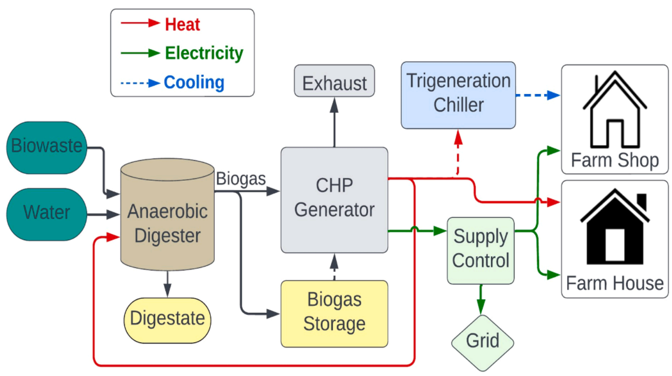


Fig. 2. End-to-end system schematic.

adjacent to the farm house and shop, and a short distance from the combined cattle housing barn and straw bale storage areas. Fig. 2 displays a schematic of the proposed system, with the optional inclusion of a heat-driven chiller to upgrade a cogeneration or CHP system to a trigeneration system.

Both the option of a CHP (cogeneration) and a trigeneration system was to be evaluated for suitability, with each system powered by biogas generated from different feedstock combinations. Grass silage was discounted from consideration as a feedstock primarily due to its importance as a cattle feed resulting in a requirement to hold a certain quantity in reserve, diminishing surplus availability. Three feedstock configurations were therefore investigated; FYM only, FYM combined with low-case WS quantity, and FYM combined with high-case WS quantity. Co-digestion of feedstocks was considered due to the enhanced biological system stability and biogas yields offered (Karki et al., 2021). Anaerobic digester parameters were selected as follows: An assumed 30-day hydraulic retention time (HRT) was chosen (Ahlberg-Eliasson et al., 2021), in line with literature estimates for efficient cow FYM digestion, and in order to suit the waste collection schedule of WF operations. For operational simplicity and reliability, a mesophilic temperature range value was selected of 30°C (de Mes et al., 2003). Due to the low water content of the available feedstocks, a dry fermentation type strategy was adopted (implying a total solids content of approximately 30 %) as such real-world plants have already shown promising results (de Mes et al., 2003). Given the assumed temperature of digestion, WF heating requirements should include anaerobic digester heat demand in order to ensure operational self-sufficiency. Overall demand was calculated as $Q_{tot} = Q_{feed} + Q_{loss}$ as given in Eq. 2 and Eq. 3, where Q_{feed} = heat required to increase feedstock temperature (W), Q_{loss} = digester heat loss (W), k_{dig} = overall digester wall heat transfer coefficient (W/m^3 °C), A = heat transfer area (m^2), $\dot{m}$ = input mass flow rate (kg/s), C_p = feedstock specific heat (kJ/kg/°C), T_{AD} = digestion temperature (°C), T_{in} = input temperature (°C) and T_{ext} = average WF external temperature (°C) (Zupancic and Ros, 2003).

$$Q_{feed} = m\ C_p\ (T_{AD} - T_{in}) \tag{2}$$

$$Q_{loss} = k_{dig}\ A\ (T_{AD} - T_{ext}) \tag{3}$$

C_p was taken as 4.13 kJ/kg/°C (Chen, 1983) for cow manure feedstock, and 1.63 kJ/kg/°C (Kahr et al., 2012) for wheat straw feedstock. Parameter k_{dig} was taken as 0.265 W/$m^{3\circ}$C (Chen, 1983). A was defined in accordance with expected digester size. Overall demand was calculated as Q_{tot} = 6.82 kW. A mechanism for excess biogas storage is also included, to provide a reserve source of biogas to supply energy in the event of increased demand or a digester failure. Naturally, biogas value will be subject to fluctuation however a conservative range of values were assigned at £ 0.242–0.589 /m^3 (Rosa, 2020; International Renewable Energy Agency, 2017).

2.5. Carbon capture

As secondary investigation, post combustion carbon capture (PCCC) technology can be implemented at the point of the generator exhaust to create a carbon-negative energy generation system. Chemical absorption processes post combustion can provide a 90 % CO_2 recovery rate (Li et al., 2017), although research and development previously undertaken in the area has focused on larger scale applications of circa 5000 tonnes/day of flue gas for processing (Zanco et al., 2021). As a result, little information is available concerning micro-scale systems suitable for WF application. For this analysis, investigation has shown for flue gas flow rates of 200 m^3/hour, a heat duty for CO_2 desorption and solvent regeneration was 3.00 MJ/kg CO_2 (Tatarczuk et al., 2023). Environmental implications of PCCC will be evaluated later in this study.

2.6. Computational simulation

In order to assess energy generation potential and validate the theory, anaerobic digestion, CHP and trigeneration systems were individually modelled and evaluated in ECLIPSE, a process simulator software developed by the Energy Research Centre of Ulster University (Energy Research Centre Ulster University, 1992). The simulation process was conducted in four stages: initially a process flow diagram incorporates the system components and connections. Secondly, compounds involved in the simulation are defined in a compound database. Thirdly, component parameters are defined and a mass-energy balance simulation is run, providing quantitative system results. Finally, utilities usage data is inputted, and utilities calculations are completed, in this case providing electrical energy produced.

Anaerobic digestion is modelled here as a chemical process, following a condensed overall equation representing a multi stage reaction process given in Eqs. 4 and 5, displaying the conversion of organic matter to soluble molecules to biogas (Uddin and Wright, 2022).

$$n(C_6H_{10}O_5) + n(H_2O) \rightarrow n(C_6H_{12}O_6) + n(H_2) \tag{4}$$

$$n(C_6H_{12}O_6) + n(H_2) \rightarrow CH_4 + CO_2 + 2H_2O \tag{5}$$

Given the complex bio-chemical nature of real world AD, assumptions were employed in the process simulation. Literature details conservative digestion/material conversion efficiencies of volatile (organic) solids to be between 42.17 %, 45.36 % and 50 % (Rosenberg and Kornelius, 2017; Kadam et al., 2024; Alkhrissat, 2023) for cow manure. Considering the properties of the dry mass (DM) input of FYM used in this investigation, overall conversion efficiency was calculated as between 30 % and 40 %, with 35 % selected as the simulation parameter.

Material conversion efficiency was taken as 50 % for WS as found by Gao et al (Gao et al., 2020). Process temperature was defined as 30°C in the mesophilic range (de Mes et al., 2003), and water input was defined in accordance with feedstock input quantity. The process flow diagram of the AD model is shown in Appendix A.

Both CHP and chiller sections of the generation models were validated against the selected *2 G CHP* and Robur ACF hardware specifications (2G Energy AG, 2023; Robur, 2023) to ensure accuracy and repeatability of results. Validation was completed by model component parameter adjustment for manufacturer specified inputs and outputs. The table of validation is shown in Appendix B3.

$$CH_4 + 2O_2 + N_2 \rightarrow CO_2 + 2H_2O + N_2 \tag{6}$$

The combustion of biogas completed in the energy generation process is given by Eq. 6 (Wresta and Saepudin, 2018). ECLIPSE simulation diagrams of the trigeneration and CHP models are included in Appendices B & C.

2.7. Environmental analysis

The adoption of the AD-derived combined energy generation system here is renewable biomass-based, which can result in the displacement of fossil-fuel emissions emitted from traditional energy generation. Therefore this energy generation method is notably reducing the impact of agriculture on the environment by reducing/eliminating the carbon emissions of WF's consumed energy to climate change.

The environmental impact of existing energy consumption at WF is split into carbon-positive CO_2 emissions produced from UK grid electricity generation, and emissions from heating oil combustion on site. Grid electricity emissions are approximately 0.207 kg CO_2/kWh (Barclay, 2023) and oil combustion releases circa 2.692 kg CO_2/litre (US Energy Information Administration, 2023). Therefore, annual CO_2 emissions attributed to WF, total a grid electricity derived 18, 712 kg/year, and direct oil boiler derived 2154 kg/year. It is seen that the grid electricity consumption is a greater contributor to the total emissions, due to the unusually high electricity demand created by the farm shop food preparation and storage appliances, by comparison to more traditional farming enterprises. As a result, the total farm CO_2 emissions are 20,866 kg/year, or can otherwise be identified as the baseline CO_2 emissions reduction (kg/year) in the event of the adoption of a renewable combined energy generation system, and the complete removal of fossil fuel and grid reliance. Besides, addition of a post-combustion carbon capture system would allow for a greater annual CO_2emissions reduction (kg/year) through the creation of a carbon-negative process.

2.8. Financial analysis

Economic metrics are of paramount importance to the evaluation of project feasibility in the agricultural industry. Key financial performance requirements were specified by WF, a payback period of no longer than 10 years, the option of loan-based financing included, and the minimising of total capital expenditure (CAPEX) where possible. Financial data was tabulated into standard operational expenditure (OPEX) and CAPEX categories per annum, and performance and cost data for each system configuration option was inputted against the current basis of the existing grid electricity and oil boiler energy supply systems. Totals of CAPEX and annual savings over the existing system are then compared to calculate the payback period (years). Payback periods were then compared alongside total CAPEX values to select the best performing configurations in a wider context. A further metric of the Levelised Cost of Energy (LCOE) was also considered. This value provides a net present value (NPV) based comparative data point between energy generation systems representing the lifetime costs of implementation with respect to the energy production over the lifetime, giving a cost per unit energy value (£/kWh) (Aldersey-Williams and Rubert, 2019). LCOE values are calculated by Eq. 7, where t = total active period in years, n = expected years of operation or project lifetime, C = CAPEX cost in the considered annual period, O = the annual fixed OPEX cost, V = the variable OPEX cost in the annual period (e.g. fuel input), E = the annual generated energy, and d = the discount rate (Aldersey-Williams and Rubert, 2019).

$$LCOE = \frac{\sum_{t=1}^{n} \frac{(C+O+V)}{(1+d)^t}}{\sum_{t=1}^{n} \frac{E}{(1+d)^t}} \tag{7}$$

Table 3
Ultimate (wt%, DAF*) and Proximate (%AR**) Analysis Results.

	C	H	N	DM (%)	VS (%)
FYM	35.10	4.32	2.59	63.30	47.17
Wheat Straw	43.41	5.57	0.71	93.00	82.00
Grass Silage	24.14	8.75	0.00	67.93	53.85

* Percentage by weight; Dry, Ash-Free Basis. * * 'As received'.

3. Results and discussion

3.1. Generation system

Table 3 displays the results of the ultimate and proximate analysis undertaken on the feedstock samples from WF. These values for carbon (C), hydrogen, (H) and nitrogen (N) were subsequently inputted into the compound database of the ECLIPSE software package to enhance the accuracy of the simulations for this particular case study.

Results for the AD simulation for varied feedstock parameters are displayed in Table 4. Feedstock option 1 represents a FYM only biomass input, option 2 represents FYM co-digested with the low-case quantity of WS. Option 3 represents co-digestion of FYM and high-case WS quantity. Biomass input was taken as the DM input of the available feedstock, with biogas yields shown to increase with increased feedstock quantity. The quality of produced biogas is determined by CH4 content (%), and conservative results of circa 47 % CH4 and 53 % CO_2 by volume are quoted here. This is in line with likely ranges of between 40 % and 70 % CH4 by volume (Tauseef et al., 2013).

Table 4 also shows that the BG mass flow rate produced for all feedstock combinations is in excess of fuel mass flow requirements for the commercially available CHP generator modelled in this investigation, of 0.0099 kgBG/s (2G Energy AG, 2023). This allowed for excess BG produced to be supplied to the BG storage system instead, providing further income to WF and to allow for continued energy generation in the event of a reduced BG production.

Table 5 displays results for the CHP generation simulation run for the manufacturer quoted BG input. It shows that potential electrical and thermal energies produced can meet the WF requirements of 38.93 kW and 26 kW respectively, confirming the technical feasibility of a combined renewable energy generation system. All three feedstock options are able to provide in excess of this value, increasing surplus electricity available for Smart export guarantee (SEG) grid sale or business expansion, and surplus thermal energy for application at WF's discretion. Such excess heat could be utilised for farm shop or barn heating

Table 4
Biogas production and quality from varied biomass feedstocks.

Option	Biomass (kgDM/s)	Biogas (kg/s)	CH4 (kg/s)	CH4 (%)
1	0.040	0.015	0.004	47.445
2	0.052	0.019	0.005	47.148
3	0.060	0.023	0.006	47.082

Table 5
CHP energy generation and efficiency.

	Energy Output (kW)		LHV Efficiency (%)	
Option	Electrical	Thermal	Electrical	Overall
1	41.42	66.00	33.87	87.84
2	41.22	66.00	34.01	88.47
3	40.84	65.00	33.77	87.51

Table 6
Trigeneration energy production and efficiency.

	Energy Output (kW)			LHV Efficiency (%)	
Option	Electrical	Thermal	Cooling	Electrical	Overall
1	41.12	47.00	17.72	33.63	86.78
2	41.02	47.00	17.72	33.85	87.48
3	40.64	46.00	17.72	33.60	86.52

Table 7
Surplus biogas availability.

Option	Surplus BG (kg/s)	CH4 (%)	Surplus BG (m3/wk)	Value (£/wk)
1	0.0046	47.45	2156.67	521.91
2	0.0095	47.15	4478.22	1083.73
3	0.0126	47.08	5923.20	1433.41

over winter periods. Refrigeration requirements are met through generated electricity in this case, requiring no alteration to existing business infrastructure or appliances.

Table 6 shows results from the trigeneration system simulation incorporating the CHP system and the absorption chiller. Biogas input values were unchanged from CHP parameters, and a small reduction in electrical and thermal outputs were observed, due to losses as a result of the heat and electricity consumption to run the chiller. Reduced outputs are still sufficient however to meet baseline electrical and thermal energy demands. Cooling energy supplied through chiller output exceeds the actual cooling demand of refrigeration appliances at the farm shop, therefore surplus cooling capacity can be utilised by WF at their discretion, for example, supplying farm shop enterprise expansion requiring additional cold storage. Cooling was delivered at 4.02°C, exceeding the current 5.00°C standard at WF (Owners and employees, 2023). The coefficient of performance (COP) was 0.75, within expected ranges for absorption chillers (OFGEM, 2019).

Table 7 shows the maximum quantities of biogas able to be stored assuming a maximum fuel intake for the CHP generator. As expected, option 3 with the largest feedstock input provides the largest quantity of excess biogas, and therefore the greatest financial benefit from sale. Furthermore, the use of feedstock option 1, with no consumption of surplus wheat straw bales, results in an increased reserve of straw quantity available for emergency cattle bedding or for sale at the end of the farming year (Owners and employees, 2023).

3.2. Results of environmental analysis

From the simulation, it is found that CO_2 emission values of 0.01541 kg/s for option 3, and 0.01545 kg/s for options 1 and 2. Table 8 displays results for the increased potential emissions reduction through PCCC processes, with 90 % CO2 recovery rate.

3.3. Results of financial analysis

Initially, the financial position of the existing electricity and heating supply infrastructure was quantified in OPEX, with fixed costs of electricity, heating oil supply and servicing totalling £ 31,446 per annum (Owners and employees, 2023). This cost will provide the basis for the annual saving in the event of a renewable generation system installation. The provision of loan-based financing was assumed given the high expected CAPEX costs, with an approximate rate of 8 % (Owners and employees, 2023). Annual OPEX reduction from the sale of generated electricity to the grid via the SEG was calculated for each case, under WF operational hours at a conservative 75 % power generation capacity. The proposed systems are also eligible under the SEG scheme, comprising AD derived biogas and a micro-CHP capacity of $\leq$ 50 kW electricity (Octopus Energy, 2024). The SEG tariff offered by Octopus Energy was selected, paying £ 0.04/kWh (Octopus Energy, 2024). Profit from biogas sale was calculated according to the volumetric weekly availability shown in Table 7, multiplied by a conservative cost-to-produce price as detailed previously.

The CAPEX cost of the required equipment varied between cases. Initially, price estimates of the different anaerobic digester configurations were calculated based on quotes obtained from a commercially available provider (Biogas Products Ltd, 2024). Digester component cost was unchanged for each size requirement, with only the tank material and construction cost being scaled appropriately as per the manufacturer recommendation (Biogas Products Ltd, 2024). The cost of the CHP generator unit across all generation configurations was £ 80,000 (2G Energy UK, 2024), including equipment to run synchronous to the grid for SEG export. For the trigeneration system, a fixed cost of the modified Robur chiller was added, with installation and service costs considered (Robur SpA, 2024). The final CAPEX component was the low-pressure BG storage container. Cost varied with volume for each container, calculated from the surplus biogas available on a weekly basis, as shown in Table 7, corrected for the pressure increase of 5.5 mBar gauge by Boyle's Law. The required volume was then compared with published prices for commercially available storage sizes, varying between £ 43, 500 and £ 80,500 (Zorg Biogas, 2024).

Table 9 displays the results for CHP system implementation, and Table 10 displays the Trigeneration system results. The configuration with the lowest initial CAPEX cost is the CHP system powered by feedstock option 1, due to the relatively small biogas storage container and anaerobic digester sizes required, and the baseline generation hardware needed. Low CAPEX cost is a significant requirement of any farming enterprise project, increasing the chances of securing loan financing, minimising the impact on existing WF operations, and minimising the quantity of interest payable if the project is loan financed. If loan financing was not utilised, it would serve to reduce the payback period from the calculated values, making the financial analysis in this study conservative. Despite this, the CHP system with feedstock option 3 offered the shortest payback time of 5 years.

This is attributed to the large OPEX saving created by the profits of

Table 8
Additional emissions reduction with PCCC.

Option	Captured CO_2 (kg/s)	PCCC total reduction (kg CO_2/year)
1	0.01390	459200
2	0.01390	459200
3	0.01387	458300

Table 9
CHP system financial performance.

Option (CHP)	CAPEX (£)	OPEX Saving (£)	Payback Period (year)
1	331,055.39	39,055.54	8.48
2	376,771.01	64,558.89	5.84
3	402,742.40	80,562.41	5.00

Table 10
TG system financial performance.

Option (TG)	CAPEX (£)	OPEX Saving (£)	Payback Period (yrs)
1	340,341.45	37,731.84	9.02
2	386,057.07	63,262.13	6.10
3	412,028.46	79,265.65	5.20

Table 11
LCOE of electricity for CHP and TG cases.

Option	CHP LCOE (£/kWh)	TG LCOE (£/kWh)
1	0.54	0.57
2	0.31	0.35
3	0.17	0.20

increased biogas sale volumes. It should be noted however, that in spite of the attractive payback and saved revenue performance, the increased biogas storage size requirements are impractical for adoption at WF, varying between 38 and 40 + metres in diameter for options 2 & 3, in comparison with the 30 m maximum diameter required for option 1 (Zorg Biogas, 2024). Furthermore, the usage of FYM without additional WS input leaves surplus bales available for further use or sale by WF owners, minimising disruption to the existing operational chain. Finally, it is seen that the Trigeneration system offers payback periods and total CAPEX costs in excess of all configurations of CHP system. While this difference is not extensive, alongside the complexity and further cost of a significant modification of existing refrigeration systems at WF to utilise the trigeneration cooling output, the case for adoption is weakened due to the lack of financial or maintenance upsides.

Table 11 also displays the results for the LCOE of electricity generated for each configuration, and it shows that the trigeneration system yields greater energy costs versus a CHP system. It also shows that option 3 yields the lowest LCOE against options 1 & 2, for the same reasons as previously stated. It is noted however that the majority of LCOE values for the proposed renewable generation system are lower than that of the current grid electricity supply of 0.36 (£/kWh), highlighting the benefit of adoption. This reduction and the overall low LCOE values are due to swift payback periods from BG and grid electricity sale. As a result of all of these economic factors, and in the context of the farming business as a whole, that the adoption of a CHP generation system powered by feedstock option 3 is the most viable for WF.

4. Conclusions

In conclusion, this study has investigated and confirmed the feasibility of operating an AD powered combined generation system at a mixed-model farm. The economic and environmental importance of an improved energy generation infrastructure was explored, with key objectives established. The case study farm produced a baseline biowaste output of 2000 tonnes/year of FYM, taken to be the primary feedstock for the AD process. Computational models developed in the ECLIPSE software and validated against commercially available hardware were utilised to evaluate the quantitative performance of a variety of generation system configurations, including varied feedstocks powering a CHP or trigeneration system. Feedstock chemical compositions, mass flow rates, and biochemical process assumptions were specified in each model.

All configurations modelled met the maximum electricity, heating and cooling energy demand of 38.4 kW, 26 kW and 4.6 kW respectively, with maximum instantaneous electricity outputs of circa 41 kW. The environmental impact of implementation was found to be significant, with a baseline CO_2 emissions reduction of 20,866 kg CO_2/year not including additional reduction through PCCC. Excess biogas production provided scope for a storage strategy providing further income to the farm through theorised biogas sale. Financial analysis was then conducted, confirming the financial feasibility of the systems evaluated, most of them providing payback periods of < 10 years and LCOE electricity figures less than the 0.36 £ /kWh of the status quo grid supply, providing attractive financial performance through the service lifetime. In an overall context, the CHP system operating with FYM only feedstock proved to be the most viable, meeting WF requirements with the lowest space, CAPEX outlay and maintenance requirements. Further development of this work would be enabled by increased industry research into PCCC commercial availability and cost, laboratory analysis to optimise AD performance for BG yield and quality, and increased commercialisation of biogas sale opportunities.

CRediT authorship contribution statement

Ye Huang: Software. **William Shorrocks:** Writing – review & editing, Writing – original draft, Visualization, Investigation, Formal analysis, Data curation. **Yaodong Wang:** Writing – review & editing, Supervision, Funding acquisition, Conceptualization.

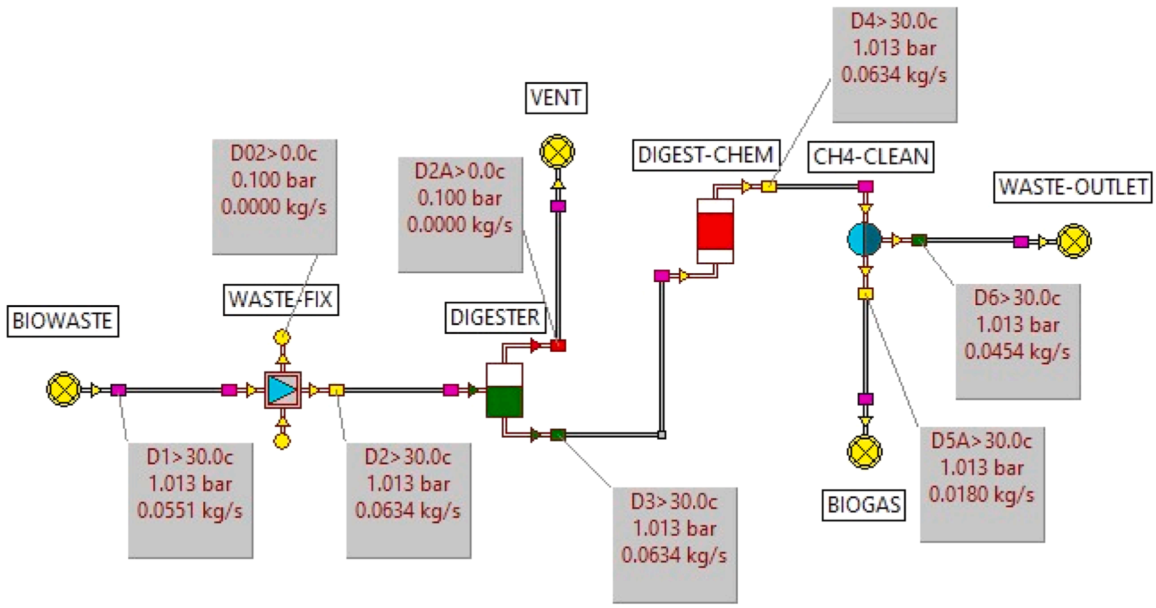
Declaration of Competing Interest

As Dr. Yaodong Wang, a co-author on this paper, is an Editor of Energy Reports, he was blinded to this paper during review, and the paper was independently handled by Editor-in-Chief Dr. Nelson Fumo.

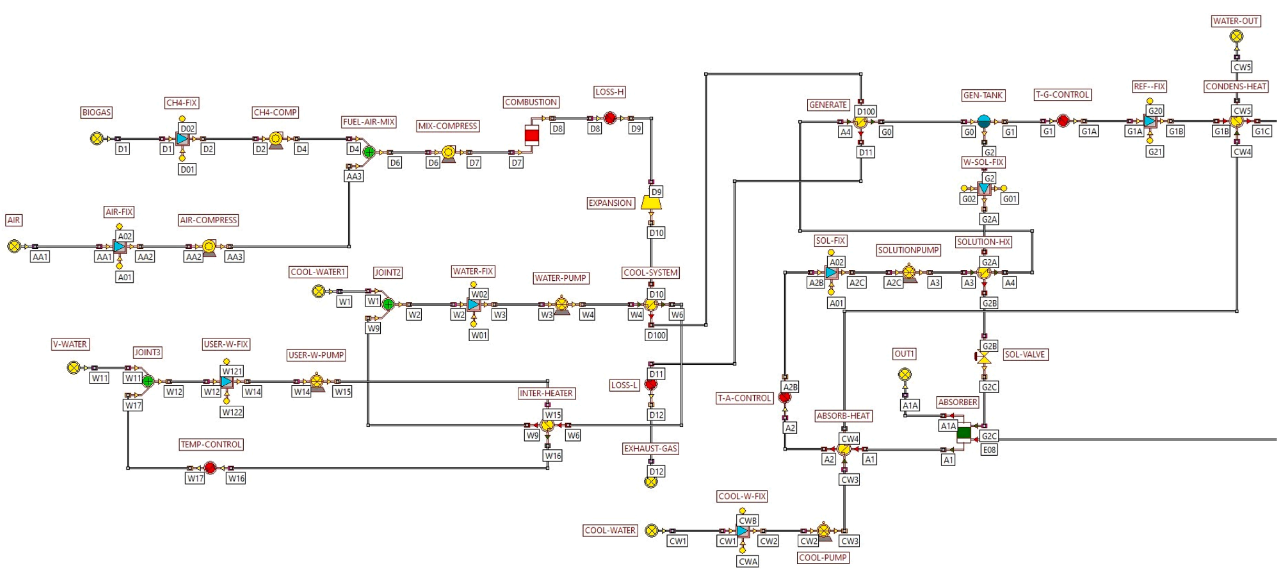
Acknowledgment

This research is partly supported by the Innovate UK funded project 'Energy Catalyst Round 9—GAS-SCRIPt (10046865)'. The author would like to thank the Innovate UK; and the owners of the farm for their research contributions and support.

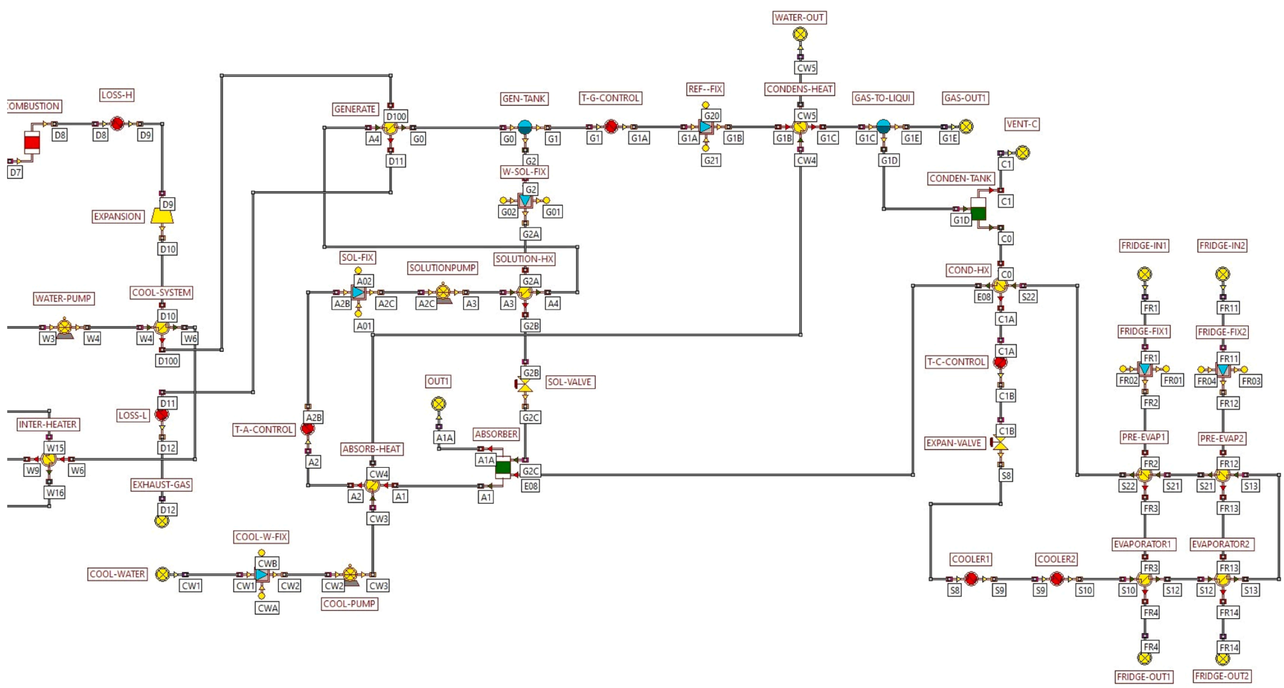
Appendix A. - ECLIPSE AD mass-energy balance model



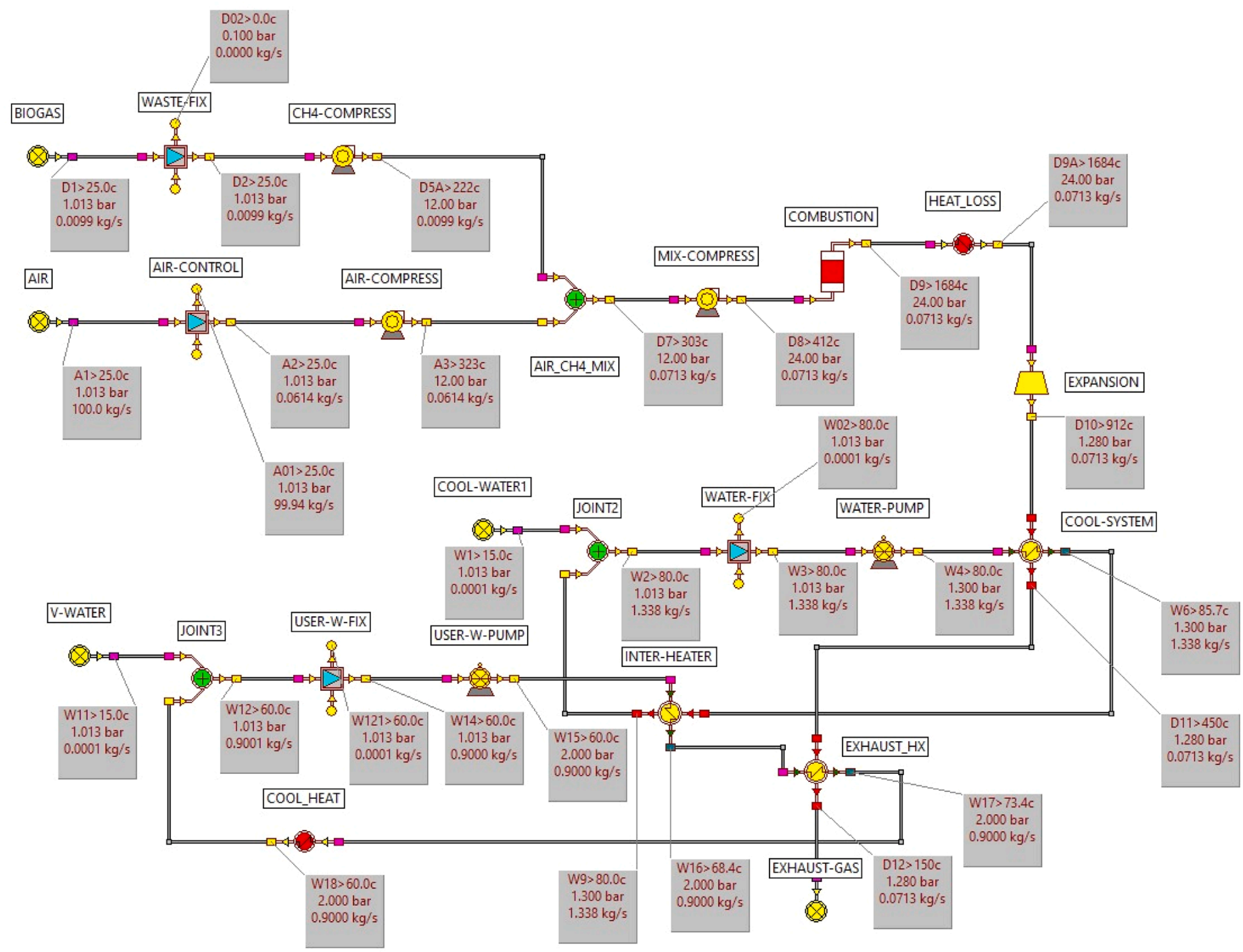
Appendix B1. - ECLIPSE TG process flow diagram model (LHS)



Appendix B2. - ECLIPSE TG process flow diagram (RHS)



Appendix C. - ECLIPSE CHP mass-energy balance model



Appendix B3. – Validation of Biogas CHP system

	Energy input (kJ/s)	Electrical power (kW)	Biogas generator efficiency (%)	Heat recovered (kW)	CHP efficiency (%)
From the manufacturer's manual	132	45	34.1	75	90.9
From simulation:	131	45.001	34.4	72	89.3
Deviation (%)	−0.758	0.002	0.766	−4.00	−1.75

Appendix D. - CHP payback period tables

OPTION 1

Opex (Annual)	Current	New (CHP)	Delta (CHP)	
Oil cost	£ 520	£ -	£ 520	
Electricity cost	£ 30,826	£ -	£ 30,826	
Misc costs	£ 100	£ 500	-£ 400	
Loan Cost	£ -	£ 22,486	-£ 22,486	
Electricity Sale	£ -	-£ 7,454	£ 7,454	
Biogas Sale	£ -	-£ 27,139	£ 27,139	
Total costs	**£ 31,446**	**-£ 11,608**	**£ 43,054**	**Annual Saving**

Capex	Current	New (CHP)	Delta (CHP)
Anaerobic Digester	£ -	£ 157,490	-£ 157,490
CHP Generator	£ -	£ 80,000	-£ 80,000
Biogas Storage	£ -	£ 43,565	-£ 43,565
Installation	£ -	£ 15	-£ 15
Total costs	**£ -**	**£ 281,070**	**-£ 281,070**

Payback	**-£ 6.53**	**Years**

OPTION 2

Opex (Annual)	Current	New (CHP)	Delta (CHP)	
Oil cost	£ 520	£ -	£ 520	
Electricity cost	£ 30,826	£ -	£ 30,826	
Misc costs	£ 100	£ 500	-£ 400	
Loan Cost	£ -	£ 30,142	-£ 30,142	
Electricity Sale	£ -	-£ 7,400	£ 7,400	
Biogas Sale	£ -	-£ 56,354	£ 56,354	
Total costs	**£ 31,446**	**-£ 33,113**	**£ 64,559**	**Annual Saving**

Capex	Current	New (CHP)	Delta (CHP)
Anaerobic Digester	£ -	£ 172,584	-£ 172,584
CHP Generator	£ -	£ 80,000	-£ 80,000
Biogas Storage	£ -	£ 69,187	-£ 69,187
Installation	£ -	£ 55,000	-£ 55,000
Total costs	**£ -**	**£ 376,771**	**-£ 376,771**

Payback	**-£ 5.84**	**Years**

OPTION 3

Opex (Annual)	Current	New (CHP)	Delta (CHP)	
Oil cost	£ 520	£ -	£ 520	
Electricity cost	£ 30,826	£ -	£ 30,826	
Misc costs	£ 100	£ 500	-£ 400	
Loan Cost	£ -	£ 32,219	-£ 32,219	
Electricity Sale	£ -	-£ 7,298	£ 7,298	
Biogas Sale	£ -	-£ 74,538	£ 74,538	
Total costs	**£ 31,446**	**-£ 49,116**	**£ 80,562**	**Annual Saving**

Capex	Current	New (CHP)	Delta (CHP)
Anaerobic Digester	£ -	£ 182,168	-£ 182,168
CHP Generator	£ -	£ 80,000	-£ 80,000
Biogas Storage	£ -	£ 80,574	-£ 80,574
Installation	£ -	£ 60,000	-£ 60,000
Total costs	**£ -**	**£ 402,742**	**-£ 402,742**

Payback	**-£ 5.00**	**Years**

Appendix E. - TG payback period tables

OPTION 1

Opex (Annual)	Current	New (TG)	Delta (TG)	
Oil cost	£ 520	£ -	£ 520	
Electricity cost	£ 30,826	£ -	£ 30,826	
Misc costs	£ 100	£ 1,000	-£ 900	
Loan Cost	£ -	£ 27,227	-£ 27,227	
Electricity Sale	£ -	-£ 7,374	£ 7,374	
Biogas Sale	£ -	-£ 27,139	£ 27,139	
Total costs	**£ 31,446**	**-£ 6,286**	**£ 37,732**	**Annual Saving**

Capex	Current	New (TG)	Delta (TG)
Anaerobic Digester	£ -	£ 157,490	-£ 157,490
CHP Generator	£ -	£ 80,000	-£ 80,000
Absorption Chiller	£ -	£ 8,086	-£ 8,086
Biogas Storage	£ -	£ 43,565	-£ 43,565
Installation	£ -	£ 51,200	-£ 51,200
Total costs	**£ -**	**£ 340,341**	**-£ 340,341**

Payback	**-£ 9.02**	**Years**

OPTION 2

Opex (Annual)	Current	New (TG)	Delta (TG)	
Oil cost	£ 520	£ -	£ 520	
Electricity cost	£ 30,826	£ -	£ 30,826	
Misc costs	£ 100	£ 1,000	-£ 900	
Loan Cost	£ -	£ 30,885	-£ 30,885	
Electricity Sale	£ -	-£ 7,347	£ 7,347	
Biogas Sale	£ -	-£ 56,354	£ 56,354	
Total costs	**£ 31,446**	**-£ 31,816**	**£ 63,262**	**Annual Saving**

Capex	Current	New (TG)	Delta (TG)
Anaerobic Digester	£ -	£ 172,584	-£ 172,584
CHP Generator	£ -	£ 80,000	-£ 80,000
Absorption Chiller	£ -	£ 8,086	-£ 8,086
Biogas Storage	£ -	£ 69,187	-£ 69,187
Installation	£ -	£ 56,200	-£ 56,200
Total costs	**£ -**	**£ 386,057**	**-£ 386,057**

Payback	**-£ 6.10**	**Years**

OPTION 3

Opex (Annual)	Current	New (TG)	Delta (TG)	
Oil cost	£ 520	£ -	£ 520	
Electricity cost	£ 30,826	£ -	£ 30,826	
Misc costs	£ 100	£ 1,000	-£ 900	
Loan Cost	£ -	£ 32,962	-£ 32,962	
Electricity Sale	£ -	-£ 7,244	£ 7,244	
Biogas Sale	£ -	-£ 74,538	£ 74,538	
Total costs	**£ 31,446**	**-£ 47,820**	**£ 79,266**	**Annual Saving**

Capex	Current	New (TG)	Delta (TG)
Anaerobic Digester	£ -	£ 182,168	-£ 182,168
CHP Generator	£ -	£ 80,000	-£ 80,000
Absorption Chiller	£ -	£ 8,086	-£ 8,086
Biogas Storage	£ -	£ 80,574	-£ 80,574
Installation	£ -	£ 61,200	-£ 61,200
Total costs	**£ -**	**£ 412,028**	**-£ 412,028**

Payback	**-£ 5.20**	**Years**

Data availability

Data will be made available on request.

References

2G Energy AG, "Technical specification g-box 50 plus," pp. 2–9, 2023.

2G Energy UK, (2024) "Gbox 50plus bg - quote," personal communication.

Ahlberg-Eliasson, K., Westerholm, M., Isaksson, S., Schnürer, A., 2021. Anaerobic digestion of animal manure and influence of organic loading rate and temperature on process performance, microbiology, and methane emission from digestates. Front. Energy Res. 9. https://doi.org/10.3389/fenrg.2021.740314.

Aldersey-Williams, J., Rubert, T., 2019. Levelised cost of energy – a theoretical justification and critical assessment. Energy Policy 170. https://doi.org/10.1016/j.enpol.2018.10.004.

Alkhrissat, T., 2023. The impact of organic loading on the anaerobic digestion of cow manure: Methane production and kinetic analysis. Case Stud. Chem. Environ. Eng. 9, 2. https://doi.org/10.1016/j.cscee.2023.100589.

J. Barclay, "New UK grid emissions factors 2023," ITPEnergised, June 2023. [Online]. Available: ⟨https://www.itpenergised.com/new-uk-grid-emissions-factors-2023/#:~:text=The%20generation%20emissions%20factor%20for,year%20increase%20of%207%25⟩.

Biogas Products Ltd, (2024) "Digester quote," personal communication.

Boukhanouf, R., Godefroy, J., Riffat, S.B., Worall, M., 2008. Design and optimisation of a small-scale tri-generation system. Oxford University Press. ⟨https://scholar.google.co.uk/scholar?q=Design+and+optimisation+of+a+small-scale+tri-generation+system&hl=en&as_sdt= 0&as_vis= 1&oi=scholart⟩ ([Online]. Available:).

Chen, Y.R., 1983. Thermal properties of beef cattle manure. Agric. Wastes 6, 13. https://doi.org/10.1016/0141-4607(83)90003-3.
DEFRA, "Agriculture in the United Kingdom 2021, Chapter 11: Environment," October 2022. [Online]. Available: ⟨https://www.gov.uk/government/statistics/agriculture-in-the-united-kingdom-2021/chapter-11-environment⟩.
Department for Environment Food and Rural Affairs, "Agriculture in the United Kingdom 2021 - Chapter 7: Crops," National Statistics, 2022. [Online]. Available: ⟨https://www.gov.uk/government/statistics/agriculture-in-the-united-kingdom-2021/chapter-7-crops⟩.
Energy Research Centre Ulster University, "ECLIPSE Manual and Software Package," 1992.
Gao, J., Li, J., Wachemo, A.C., Yuan, H., Zuo, X., Li, X., 2020. Mass conversion pathway during anaerobic digestion of wheat straw. RSC Adv. 27723. https://doi.org/10.1039/D0RA02441D.
Grant Engineering Ltd, (2024) "Vortex oil boiler ranges," p. 26, Vortex External Pro. [Online]. Available: ⟨https://www.grantuk.com/products/oil-fired-boilers/vortex-pro-external-combi/⟩.
International Renewable Energy Agency, "Biogas cost reductions to boost sustainable transport," 2017. [Online]. Available: ⟨https://www.irena.org/News/articles/2017/Mar/Biogas-Cost-Reductions-to-Boost-Sustainable-Transport#:~:text=Typically%20the%20price%20of%20producing,industrial%20waste%2Dbased%20biogas%20production⟩.
Kadam, R., Jo, S., Lee, J., Khanthong, K., Jang, H., Park, J., 2024. A review on the anaerobic co-digestion of livestock manures in the context of sustainable waste management. Energies 17, 12. https://doi.org/10.3390/en17030546.
Kahr, H., Jäger, A., Lanzerstorfer, C., 2012. Bioethanol production from steam explosion pretreated straw. Bioethanol 160. ⟨https://www.researchgate.net/publication/221923566_Bioethanol_Production_from_Steam_Explosion_Pretreated_Straw⟩.
Karki, R., Chuenchart, W., Surendra, K., Shrestha, S., Raskin, L., Sung, S., Hashimoto, A., Khanal, S.K., 2021. Anaerobic co-digestion: Current status and perspectives. Bioresour. Technol. 330. https://doi.org/10.1016/j.biortech.2021.125001.
Lamidi, R.O., Wang, Y., Pathare, P.B., Roskilly, A., Aguilar, M.C., 2017. Biogas tri-generation for postharvest processing of agricultural products in a rural community: Techno-economic perspectives. Energy Procedia 142. https://doi.org/10.1016/j.egypro.2017.12.011.
Li, H., Tan, Y., Ditaranto, M., Yan, J., Yu, Z., 2017. Capturing CO2 from biogas plants. Energy Procedia 114. https://doi.org/10.1016/j.egypro.2017.03.1738.
Meegoda, J.N., Li, B., Patel, K., Wang, L.B., 2018. A review of the processes, parameters, and optimization of anaerobic digestion. Environ. Res. Public Health 15. https://doi.org/10.3390/ijerph15102224.
Mertins, A., Wawer, T., 2022. How to use biogas?: A systematic review of biogas utilization pathways and business models. Bioresour. Bioprocess. 9. https://doi.org/10.1186/s40643-022-00545-z.
T. de Mes, A. Stams, J. Reith, and G. Zeeman, "Methane production by anaerobic digestion of wastewater and solid wastes," Status and perspectives of biological methane and hydrogen production, pp. 60–65, 2003. [Online]. Available: ⟨https://www.researchgate.net/publication/40126148_Methane_production_by_anaerobic_digestion_of_wastewater_and_solid_wastes⟩.
O'Connor, S., Ehimen, E., Pillai, S., Black, A., Tormey, D., Bartlett, J., 2021. Biogas production from small-scale anaerobic digestion plants on European farms. Renew. Sustain. Energy Rev. 139. https://doi.org/10.1016/j.rser.2020.110580.
Octopus Energy, (2024) "Smart export guarantee (SEG) at Octopus." [Online]. Available: ⟨https://octopus.energy/smart/smart-export-guarantee/⟩.
OFGEM, "Smart Export Guarantee (SEG): Guidance for Generators," December 2019. [Online]. Available: ⟨https://www.ofgem.gov.uk/sites/default/files/docs/2020/02/seg_generator_guidance_-_final_for_publication.pdf⟩.
Owners and employees, "Farm visit and data collection exercise," in-person activity, December 2023.
Robur, "GA ACF - Technical specification," p. 48, Absorption Chiller, 2023.
Robur SpA, (2024) "ESS - single GA ACF quote," personal communication.
Rosa, M.D., 2020. Economic assessment of producing and selling biomethane into a regional market. Energy Environ. 31, 65–68. ⟨https://journals.sagepub.com/doi/pdf/10.1177/0958305X18762581⟩.
Rosenberg, L., Kornelius, G., 2017. Experimental investigation of biogas production from feedlot cattle manure. J. Energy South. Afr. 28. https://doi.org/10.17159/2413-3051/2017/v28i4a1753.
Tang, Z., Ly, S., Wang, Y., Huang, Y., Luo, J., Fu, C., 2021. Biofuel trigeneration with energy storage for heating, cooling and power on farms. Energy Rep. 7, 5394–5405. https://doi.org/10.1016/j.egyr.2021.08.129.
Tatarczuk, A., Szega, M., Zuwała, J., 2023. Thermodynamic analysis of a post-combustion carbon dioxide capture process in a pilot plant equipped with a heat integrated stripper. Energy 278. https://doi.org/10.1016/j.energy.2023.127907.
Tauseef, S., Premalatha, M., Abbasi, T., Abbasi, S., 2013. Methane capture from livestock manure. J. Environ. Manag. 117, 189–190. https://doi.org/10.1016/j.jenvman.2012.12.022.
Uddin, M.M., Wright, M.M., 2022. Anaerobic digestion fundamentals, challenges, and technological advances. Phys. Sci. Rev. 8. https://doi.org/10.1515/psr-2021-0068.
US Energy Information Administration, "Carbon dioxide emissions coefficients," 2023. [Online]. Available: ⟨https://www.eia.gov/environment/emissions/co2_vol_mass.php⟩.
Watson, S., Lomas, K., Buswell, R., 2019. Decarbonising domestic heating: What is the peak GB demand? Energy Policy 126, 533–544. https://doi.org/10.1016/j.enpol.2018.11.001.
Wresta, A., Saepudin, A., 2018. Analysis of product and temperature of biogas combustion in various air biogas equivalence ratio and methane content. Indones. J. Chem. 213. https://doi.org/10.22146/ijc.23923.
Zanco, S.E., Pérez-Calvo, J.-F., Gasós, A., Cordiano, B., Becattini, V., Mazzotti, M., 2021. Postcombustion CO2 capture: A comparative techno-economic assessment of three technologies using a solvent, an adsorbent, and a membrane. ACS Eng. 63. ⟨https://pubs.acs.org/doi/10.1021/acsengineeringau.1c00002⟩.
Zorg Biogas, (2024) "Double membrane gasholder," price list and specifications. [Online]. Available: ⟨https://zorg-biogas.com/equipment/biogas-gasholders/double-membrane-gasholder-dome-shape-1_4d⟩.
Zupančič, G., Ros, M., 2003. Heat and energy requirements in thermophilic anaerobic sludge digestion. Renew. Energy 28, 2259. https://doi.org/10.1016/S0960-1481(03)00134-4.