Net-Zero Farming: Trigeneration with Carbon Capture and Storage

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Abstract – Aiming to achieve net-zero farming, this study explores the potential of anaerobic digestion of various biowastes to produce biogas for meeting the energy demands of a dairy farm, including electricity, heating, and cooling. Two options were investigated: Option 1 focuses solely on meeting the farm's energy demand, while Option 2 focuses on a big system that utilizes all available biowastes to produce biogas, with surplus electricity sold back to grid. These options were modelled using ECLIPSE software and evaluated in terms of practicality, environmental impact, and economic viability.
Option 2, employing trigeneration, achieved an overall efficiency of 80.0%, significantly higher than Option 1's 48.4%. However, the efficiencies of the combined heat and power (CHP) system for Option 1 and 2 were 62.2% and 81.1%, respectively, both higher than their corresponding trigeneration. Option 2 also produced a greater annual carbon dioxide offset of 4,206Ton CO2-eq compared to 299Ton CO2-eq for Option 1 by leveraging digestive fertilizers and carbon capture and storage technology (CCS). Finally, it was found that the payback period for Option 1 was projected at 11 years while Option 2 would require 12 years, with anticipated profits of £124,900 and £891,900 for Options 1 and 2, respectively.

Key words: Anaerobic Digestion, Biogas, Carbon Capture, ECLIPSE, Trigeneration.

1. Introduction

The COP28 UN Climate Change Conference in Dubai, called for transitioning away from fossil fuels; the scaling-up of carbon capture, utilisation, and storage (CCUS); tripling renewable energy capacity by 2030; doubling energy efficiency by 2030 [1], with transitioning towards sustainable agriculture being a significant hurdle to overcome. In 2023, the UK agriculture made up 12% of total greenhouse gas (GHG) emissions, approximating 46.1 million tonnes of carbon dioxide (CO_2) equivalent, with methane (CH_4) emissions contributing 49% [2]. CH_4 has a global warming potential of 28-34 times that of CO_2 over 100 years, creating a vast opportunity to reduce emissions in agriculture [3]. Manure waste is the second-largest source of GHG emissions on dairy farms [4]. Purdy demonstrated that manure left uncovered for four months resulted in a 16.92% reduction in biogas production and a 3-fold increase in CH_4 emission rate, therefore necessitating proper manure management [5]. Studies recognised that CH_4 emissions from dairy farms could be reduced through the anaerobic digestion (AD) of manure waste to generate biogas, producing power that would otherwise come from fossil fuel-based power plants [6].

AD decomposes organic matter in the absence of oxygen to form biogas and digestate. Studies found that AD is enhanced through co-digestion of manure and straw waste resulting in a higher synergetic effect [7]. Biogas and digestate provide environmental benefits in greener energy production and organic fertilisers [8, 9]. Furthermore, digestate can replace artificial fertilisers, which are energy-intensive and expensive to manufacture. Although digestate can be used directly as a fertiliser, it can also be processed using nutrient recovery technologies, upgrading its quality [10]. Aggressive agriculture has left soils eroded with reduced organic matter and soil fertility. However, digestate is rich in nitrogen and phosphorus, enabling increased microbial biomass and enzyme productivity [11], which increases crop yield and the chemical properties of the soil, restoring soil quality [12].

Despite the clear environmental benefits of AD, CO_2 is still released during the combustion process. This creates a huge opportunity to integrate carbon capture and storage (CCS) technology into existing AD plants to reduce CO_2 emissions and generate additional revenue for the farm [13]. Hence biomass with CO_2 capture and storage (Bio-CCS) has become increasingly popular in the global movement to become net-zero and eliminate 20% of global emissions by 2050, and potentially the technologies of bioenergy with carbon capture and utilisation or storage may remove some CO2 from atmosphere and produce negative emissions [14 – 17]. One study indicated that globally, this could result in the removal of 3 $GtCO_2eq$ by 2050 [18].

Hamzehkolaei et al. [18] validated the feasibility of meeting an animal farm's heating and electricity demand using biogas through a combined heating and power system (CHP). It was found that using biogas as fuel provided a more substantial economic and environmental benefit. Further developments have shown biogas to meet the power, heating, and cooling requirements through a combined cooling, heating, and power plant (CCHP) whilst providing a 28% increase in power and 40% reduced CO_2 emission than a CHP plant [19]. A CCHP plant is achieved with an absorption chiller that utilises the waste heat from the generator to provide cooling. Many different absorbents can be used in absorption chillers. Although lithium bromide absorption chillers have a high coefficient of performance (COP), they risk the refrigerant crystallising at temperatures below 5ºC causing pipe blockages [20]. Therefore, for lower temperature applications, such as milk cooling, an ammonia absorption (NH_3-H_2O) chiller is more suitable to maintain high condensation pressures and temperatures [21].

However, even with the existence of CHP and CCHP plants, there has only been a recent increase in AD plants on farms. Previously, farmers lacked resources, money, and motivation to implement these systems. There are now schemes such as the Smart Export Guarantee (SEG), launched in 2021 [22], that pay for excess low-carbon electricity to be exported back to the grid. Other schemes, such as the Green Gas Support Scheme (GGSS), also launched in 2021, provide quarterly payments over 15 years for installing AD plants [23]. Therefore, incorporating CHP or CCHP systems into farms has become more accessible and provides a supplement income for farmers. [24] recently demonstrated that a CCHP system for a medium scale arable farm can be achieved, providing both environmental and financial benefits.

Farmer's insufficient resources, funding, and time to investigate such systems has resulted in a vast research gap that can reduce reliance on the national grid whilst eliminating thousands of tonnes of CO_2 and generating additional revenue for the farm. Therefore, it is necessary to carry out a study on assessing the technical and economic practicality of a cogeneration and trigeneration system for a dairy farm using biogas from AD of the manure whilst considering the added benefits of CCS technology and digestate fertiliser potential. Thus, the objective of this study is to demonstrate the viability of a net-zero CHP and CCHP trigeneration system for this dairy farm, and evaluate the feasibility of using the method to achieve sustainable and net-zero agriculture by 2050.

2. Methods and materials

A dairy farm located in North England was selected as the case study used in this investigation, where data was collected through a series of online communication and site visits. The farm is approximately 533 acres of rented land and is split across several sites. The farm grows one arable wheat crop, making up 50 acres of land, but is cut early to make whole crop silage so it will not be considered bio-waste. However, 600 tonnes of straw are brought in each year, used in a 60:40 ratio on bedding to feeding. Bedding is mucked out frequently for animal hygiene and left to rot in the field, releasing considerable amounts of CH_4 into the atmosphere. The dairy farm's bio-waste availability is detailed in Table 1.

Table 1: Bio-Waste Availability.

Type of Bio-Waste	Quantity	Total Daily Waste Production (kg)	Mass Flow Rate (kg/s)
Holstein Cow	280	2,044	0.0237
Youngstock	340	2,482	0.0287
Sheep	720	1,306	0.0151
Lamb	1,300	2,359	0.0273
Straw	50 ha	986	0.0114
		8,191	0.1062

2.1 Current Energy System

The farm's current energy system consists of electricity from the grid to meet the electricity and cooling demand and an oil-fired central heating system to meet the heating demand, as illustrated in Figure 1.

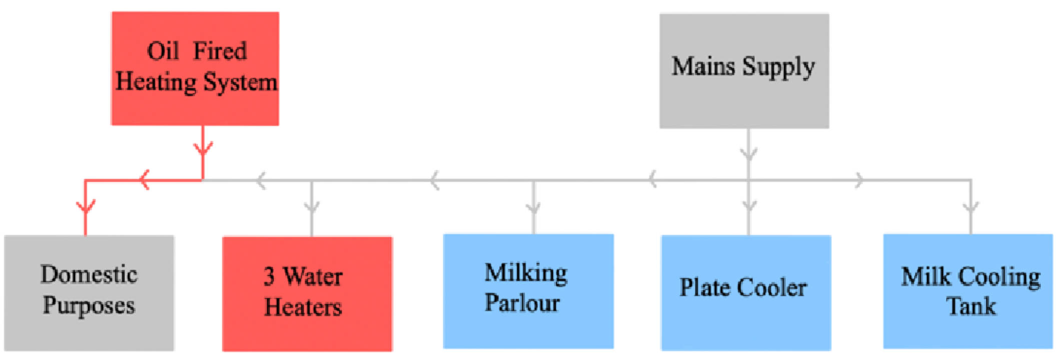


Figure 1: Current Energy System.

The electricity, heating, and cooling demand are investigated using the model in Figure 1 and are calculated in the following three sections to compile the farm's energy profile.

2.2 Electricity Consumption

Electricity consumption on the farm can be divided into domestic demand, electric water heaters, vacuum pumps used in the milking parlour, and borehole water pumps used for the plate cooler. Their usages are summarised in Table 2.

Table 2: Electricity Usages.

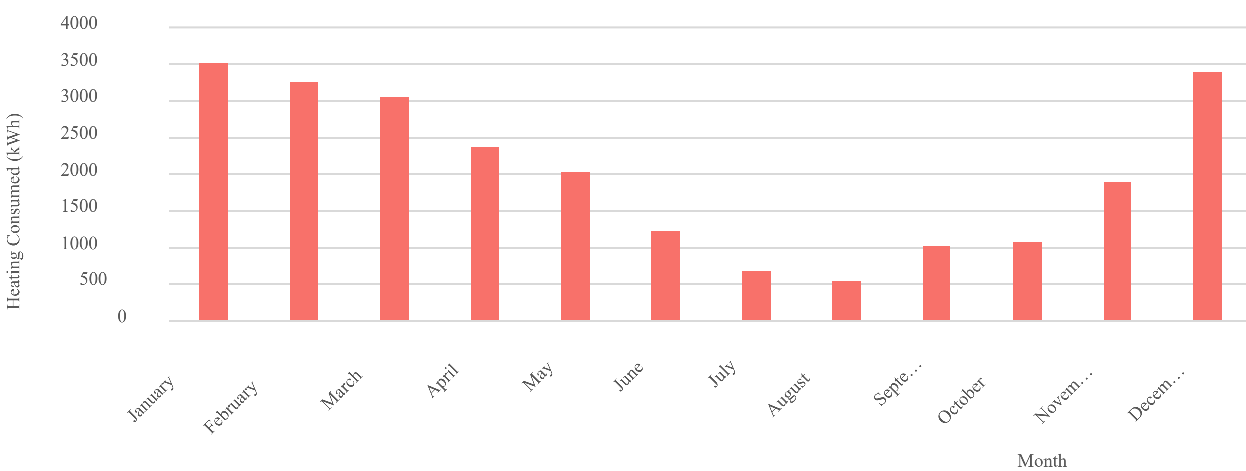
Parameters	Vacuum Pump	Water Heater	Borehole Water Pump

Power Capacity (kW)	3	3	1.1
Period of Operation (h)	3	7	2
Quantity	2	3	1
Daily Usage (kWh/day)	18	63	2.2
Annual Usage (kWh/year)	6,570	22,995	803

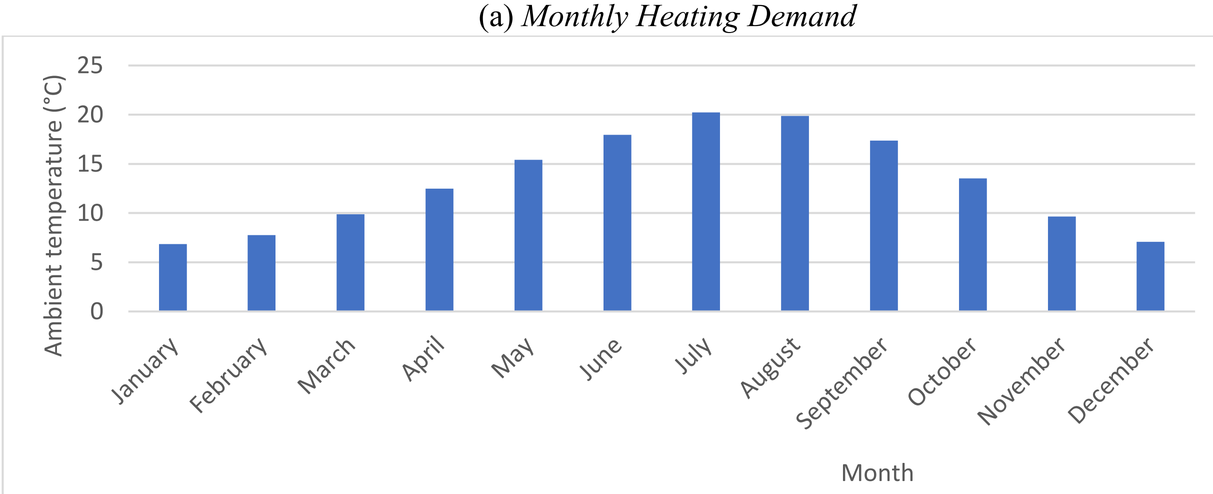
The vacuum pump, water heater and borehole water pump annually use 6,570 kWh, 22,995 kWh and 803 kWh, totalling 30,368 kWh. Given that the farms annual electricity usage is 54,317 kWh a year, the remaining 23,949 kWh can be estimated to be the annual domestic demand.

2.3 Heating Consumption

The farm's only heating demand is domestic space heating via an oil-fired central heating system fuelled using kerosene. Given that the farm spent £1,136 on kerosene each year, using these conversion rates [25], approximately 24,017kWh is required for heating each year. However, heating demand fluctuates during the year; therefore, the farm's heating demand is determined comparatively using a household's typical heating profile throughout the year, as seen in Figure 2 [26].



(a) *Monthly Heating Demand*



(b) *Mean Outside Temperature* [27]

Figure 2: Monthly Heating Demand and Mean Outside Temperature

2.4 Cooling Consumption

The most significant energy consumption on the farm is cooling 7200 litres of milk per day. Milk is cooled through a two-stage process, first through a PCA1-130-15 Fabdec Plate Cooler [28], then stored in a Mueller S-20000 Silo Tank comprised of 3 Mueller HiPerform AC51 E-Star condensing units [29], each with a power rating of 4.19 kW totalling 12.57 kW. Milk is collected every other day in the evening so an average operating period of 20 hours per day can be assumed. The other parameters in Table 3 are used to calculate the cooling demand.

Table 3: Milk Cooling Conditions.

Parameters	Value
Operating period (h)	20
Initial temperature of milk (°C)	35
Temperature After Plate Cooler (°C)	19
Final temperature of milk (°C)	3.8
Cp of milk (kJ/kgK)	3.93

Cooling demand Q (kWh) can be calculated using (1) and the parameters in Table 3 [30].

$$Q = m\, c_p\, (t_2 - t_1) \qquad (1)$$

Where m is the mass of the substance in kg, c_p is the specific heat capacity in $Jkg^{-1}K^{-1}$ and t_2 and t_1 is the final and initial temperature in K. Therefore, utilising this equation provides a cooling demand of 45,351.57 kWh a year.

2.5 Summary

A summary of the farm's energy demand throughout the year is shown in Figure 3 and quantified in Table 4.

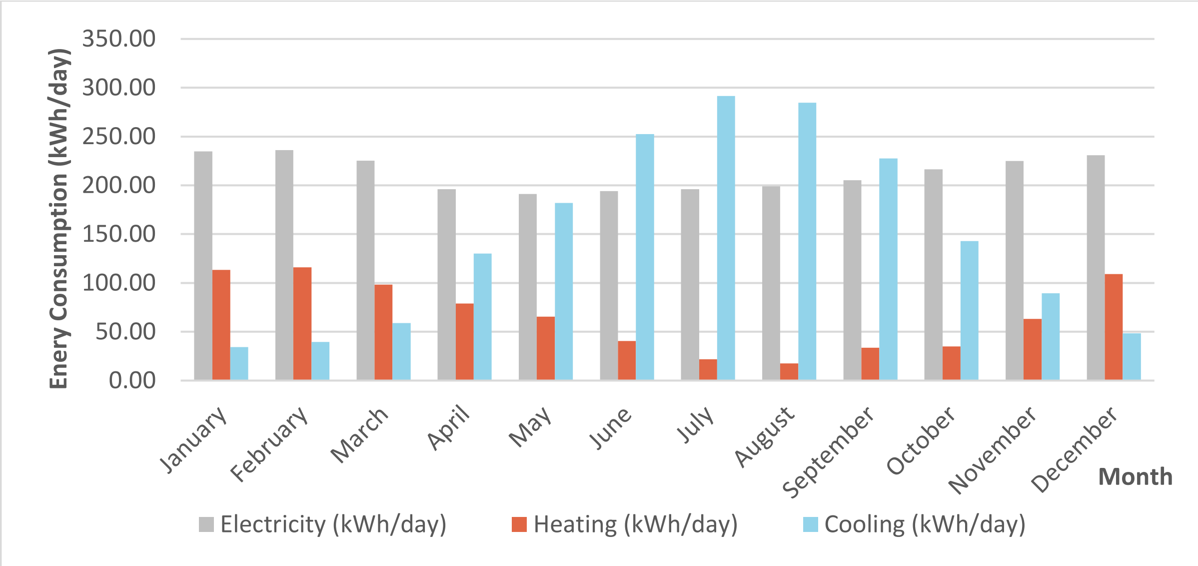


Figure 3: Energy Demand Throughout the Year.

Table 4: Daily Average, Maximum and Minimum Energy Demand.

Energy	Yearly demand (kWh)	Average Daily Demand (kWh/day)	Maximum Daily Demand (kWh/day)	Minimum Daily Demand (kWh/day)
Electricity	54,317	149	236	191
Heating	24,017	66	116	17
Cooling	45,352	124	292	34

Figure 3 shows farm's electricity consumptions remain constant through the year. It also coincides with predicted trends where heating requirements peak in winter, where heating is required for space heating. In contrast, cooling reaches a maximum in summer, particularly the July and August months, as more energy is required to cool and store milk from higher temperatures. By utilising the benefits of a CCHP system, a new proposed energy system is shown in Figure 4.

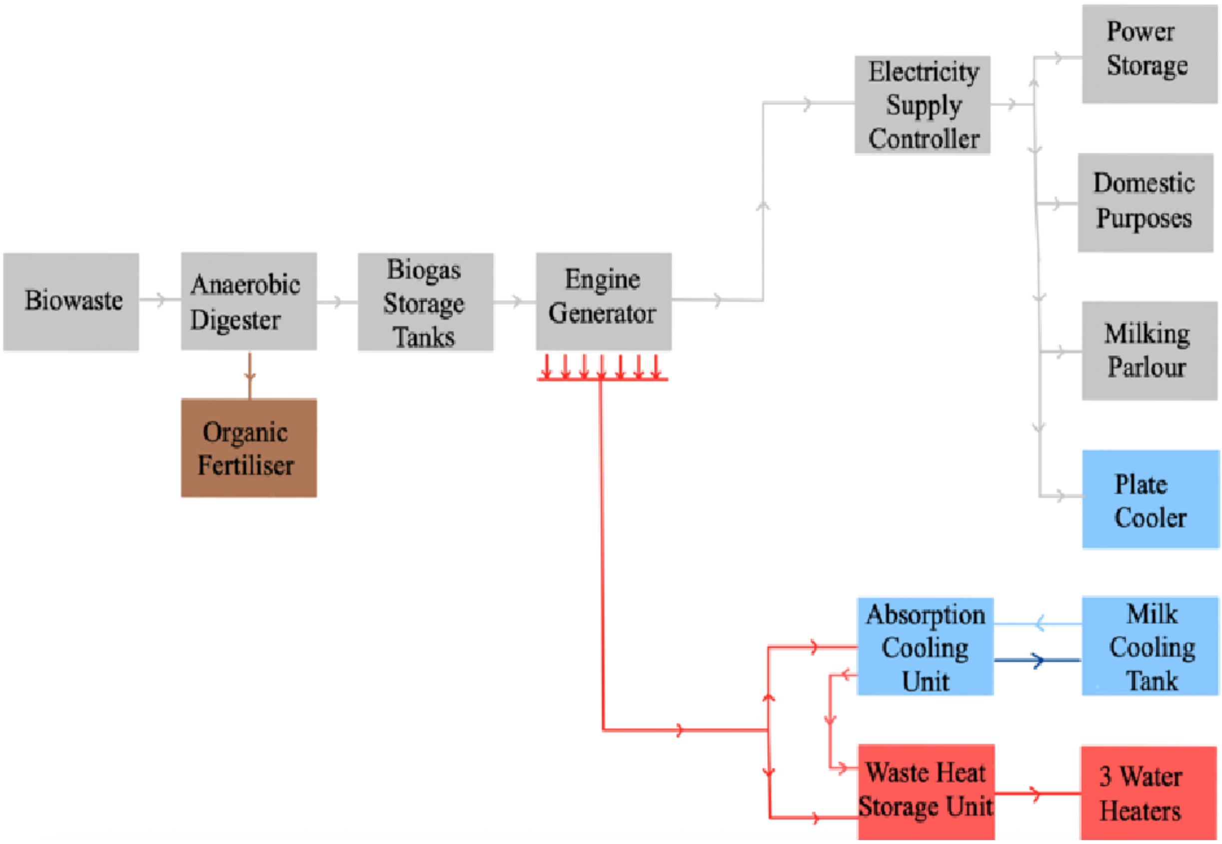


Figure 4: New Proposed System.

The new system features an anaerobic digestor that transforms the available biowaste into biogas that can fuel the biogas generator, producing electricity. Waste heat from the generator is partially used to meet the heating demand but is also used in a Robur GA ACF 60-00 NH_3-H_2O absorption chiller to meet the cooling demand [31]. The absorption chiller properties are shown below in Table 5 [32]. Additional power can then be stored, if necessary, in months where demand is low or sold back to the grid for profit.

Table 5: Absorption Chiller Parameters.

Parameters	Value
Chiller Heat Consumption (kW)	30.85
Cooling Output (kW)	17.50
COP	0.567

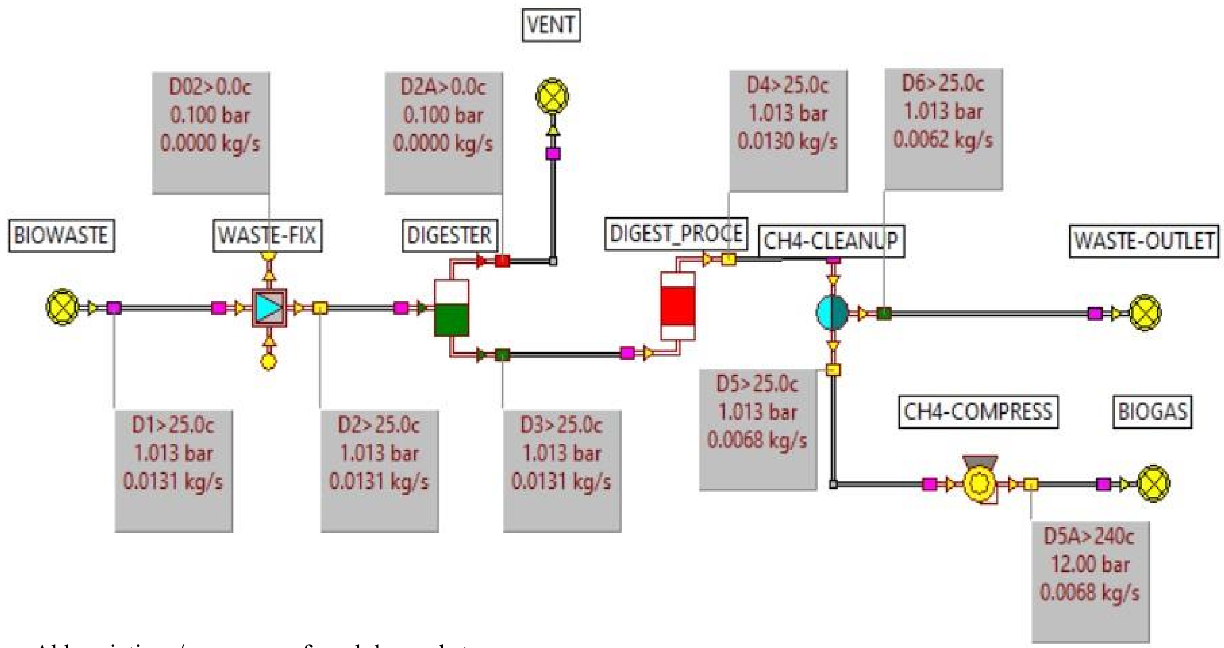
2.6 Software used for modelling and simulations

The software used for this study is ECLPSE. It is called "European Coal Liquefaction Process Simulation and Evaluation (ECLIPSE)", which is a chemical process simulator developed at the Ulster University [33]. Two key evaluations are carried out using data obtained from ECLIPSE simulations. The first is a technical evaluation to determine the process feasibility by creating process flow diagrams and generating a mass and energy balance, and the second is an economic evaluation. This software will be used to model and simulate biogas production, a biogas CHP system, and a CCHP system, where results will be compared and analysed. Lastly, ECLIPSE will be used to provide cost evaluations for the different processes and options.

3. Results and discussion

3.1 Biogas Production

The amount of biogas available was determined using the model in Figure 5. To produce this, the ultimate analysis was completed for the different types of biowaste available, shown in Table 6 [34] and inputted into the compound database in ECLIPSE. A process flow diagram was then be assembled, and relevant technical data inputted to compute a mass and energy balance. All feed streams were fully defined, including the biowaste mass flow rates determined previously in Table 1.



Abbreviations/acronyms of modules and streams:
BIOWASTE – Input of the biowastes WASTE-FIX – Flowrate control DIGESTER – AD
DIGEST_PROCE – Biomass to biogas VENT – Ventilation CH4-CLENUP – Separate biogas from wastes
WASTE-OUTLET –Waste outlet CH4-COMRESS –Compress biogas to store BIOGAS – Biogas outlet
Streams: D1, D2, … D6, are the digestion process flowing from 1 – 6.

Figure 5: Biogas Production Model and Simulation.

A water mass flow rate was added in a 60:40 feedstock to water ratio that provides maximum biogas production [35].

Table 6: Ultimate Analysis (wt%).

Type of Bio-Waste	Dry Ash Free Weight Percentage (daf wt%)				
	C	H	O	N	S
Cow	49.04	6.43	41.94	2.25	0.34
Sheep	51.33	6.45	38.81	2.65	0.76
Straw	47.92	6.54	44.8	0.53	0.09

This model runs at mesophilic conditions at 25 ºC and an atmospheric pressure of 1.013 bar due to higher heat surpluses at mesophilic over thermophilic conditions [36]. The digestion process occurs under isothermal conditions with a methane conversion efficiency of 60%, given commercially viable anaerobic digestors with this efficiency [37].

Two different options were modelled. Option 1 was to only meet the farm's demand, and Option 2 was to convert all the possible biowaste into biogas and sell the remainder back to the grid. For Option 1, this simulation was run, and a converged solution of 0.0065 kg/s was achieved, as shown in Figure 5. For Option 2, 0.0784 kg/s of biogas was produced. All ECLIPSE simulation figures correspond to results obtained for Option 1.

3.2. Biogas CHP system

Both options are now compared in a CHP system to determine whether they sufficiently meet the heat and electricity demand of the farm using the model in Figure 6. This model has been validated using biogas generators available in the market running at 50% and 100% load capacity [38][39].

The electricity demand includes the electricity required to also meet the cooling demand. The result from the simulation is shown in Tables 7 and 8.

Table 7: Electricity and Heat Produced from CHP System.

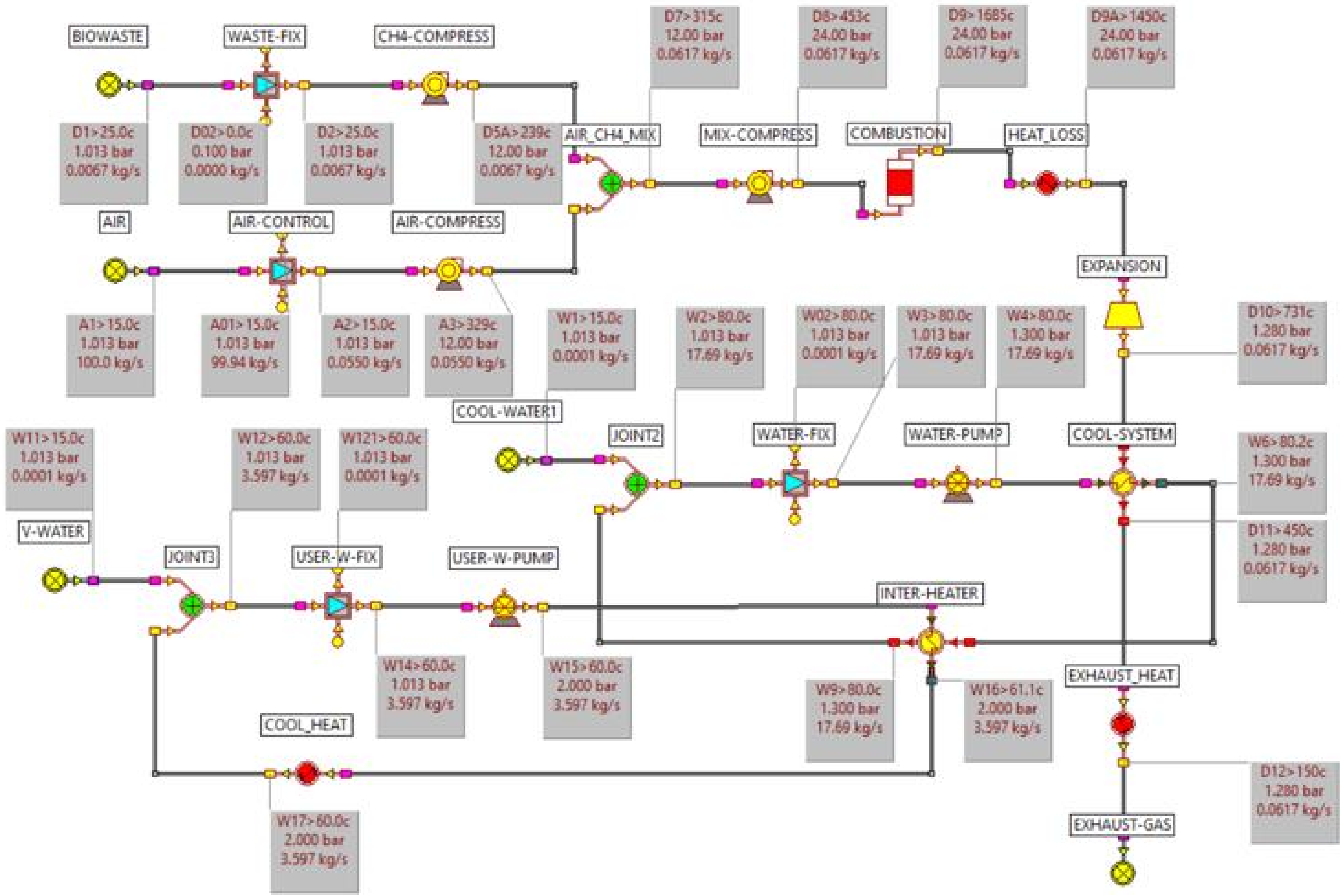
Option	Electricity (kW)	Heating (kW)	Electricity (kWh/day)	Heating (kWh/day)
1	23.5	43	564	1,032
2	376	670	9,024	16,080

Table 8: Efficiencies and Heat to Electricity Ratio.

System	Option 1	Option 2
Electrical Efficiency (%)	22.0	29.2
Heat to Electricity Ratio	1.83	1.78
Overall Efficiency (%)	62.2	81.1

Results were calculated using a lower heating value (LHV) of 16,449 kJ/kg obtained from the simulation. Electricity available was found through the utility usages function in ECLIPSE, giving 23.5 kW for Option 1 and 376 kW for Option 2. Heat energy available was calculated as a combination of the exhaust and cooling heat providing 43 kW for Option 1 and 670 kW for Option 2. From Table 7, both options meet the maximum electricity/cooling of 528 kWh/day and the farm's heating demand of 116 kWh/day, hence no need for energy storage on the farm. However, Table 8 shows that Option 2 provides a 32.7% increase in electrical efficiency and a 30.4% increase in overall efficiency than Option 1. Therefore, Option 2's excess electricity and heating production can be used in energy storage and can be exploited for economic and environmental benefit.

Figure 7(a) shows Option 1 produces enough electricity, heating, and cooling to meet maximum demand most days. However, it is crucial to consider a battery energy storage system (BESS) to compensate for random fluctuations throughout the day and potential blackout, improving energy efficiency and resilience of the system. Hybrid energy storage systems using biogas and batteries have been proven to increase project lifetime and maximise efficiency [40, 41].



Abbreviations/acronyms of modules and streams:
BIOWASTE – Input of biogas WASTE-FIX – Biogas flowrate control CH4-COMRESS –Compress biogas to mix with air at 'AIR_CH4_MIX' AIR – Air input AIR-FIX – Air flowrate control AIR-COMRESS –Compress air to mix with biogas at 'AIR_CH4_MIX' AIR_CH4_MIX – Mix air with biogas MIX-COMPRESS – Compression of the mixture of air/biogas COMBUSTION – Combustion of air/biogas HEAT_LOSS – Heat loss during the expansion process of engine EXPENSION – Expansion process of engine for power output COOL-SYSTEM – Engine cooling system EXHAUST HEAT – A heater to identify the heat energy available in engine exhaust COOL-WATER1 – Cooling water supply when needed JOINT2 – Cooling water of the engine starting point WATER-FIX – Water flowrate control WATER-PUMP – Water pump INTER-HEATER – Heat exchanger to output/collect the heat from the cooling system V-WATER – Heating water supply when needed JOINT3 – Starting point of heating water to user USER-W-FIX - Water flowrate control USER-W-PUMP – User water pump COOL_HEAT – Heat user
Streams: D1, D2, … D12, are processes of the biogas to generate heat and electrical power from combustion to exhaust, flowing from D1 – D12; "W1 – W9; W11 – W17" are cooling water flow from Stream W1 – W9; and W11 – W17, respectively.

Figure 6: Biogas CHP system Model and Simulation.

The farm requires a maximum of 236 kWh of electricity per day. To account for blackouts which typically last from minutes to a couple of days, the farm requires a 250-kWh battery [42]. For a CHP system, the farm requires 538 kWh/day to meet the electricity and cooling demand; therefore, Option 2 can sell back 8486 kWh/day and generate revenue via the smart export guarantee (SEG) scheme by exporting renewable electricity to the grid.

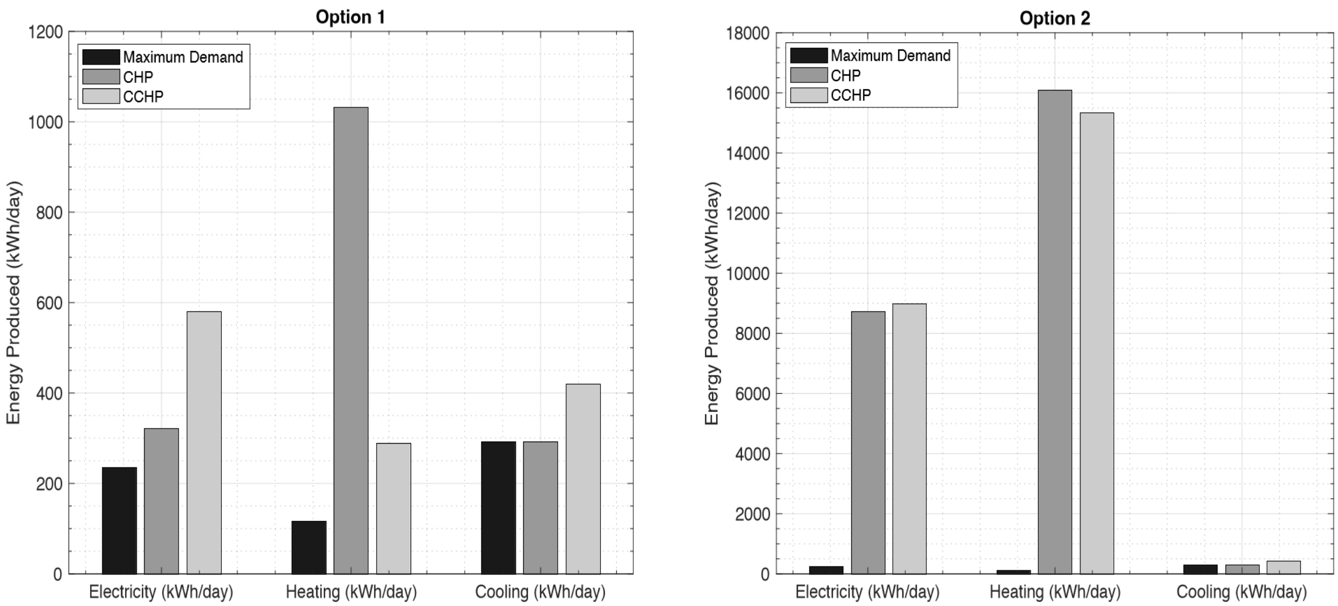
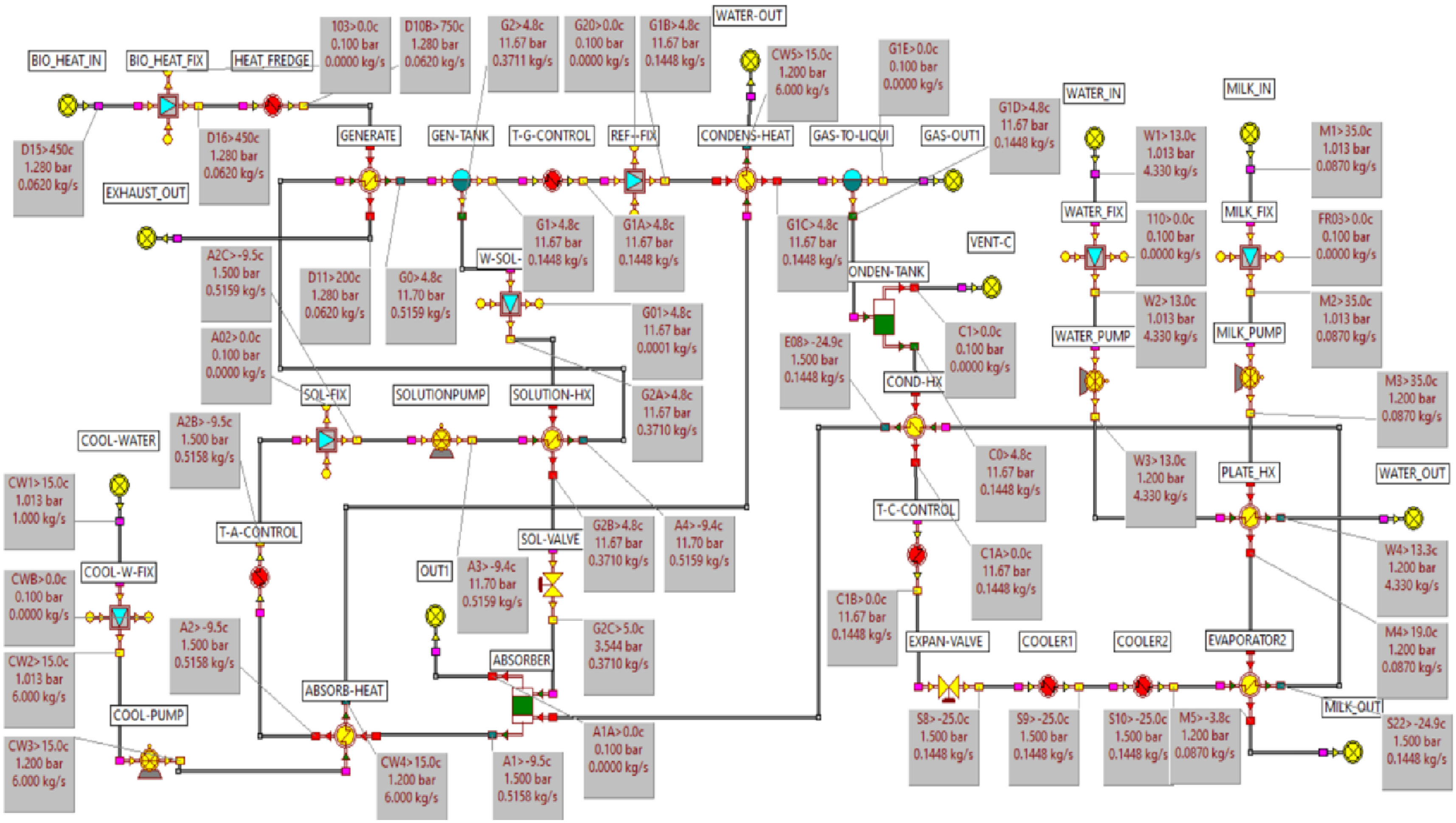


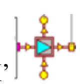
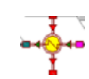
Figure 7(a) and (b): Option 1 and 2's Electricity, Heating and Cooling Produced in a CHP and CCHP system.

Overall, for the co-generation of electricity and heating for this farm, it is more efficient to go with Option 2, as shown in Table 8. However, the only potential disadvantage of Option 2 is the significant capital and operating expenditures of running a larger plant.

3.3. Biogas CCHP System

Both options are now compared in a CCHP system to see whether the waste heat can be used further to meet the cooling requirements of the farm using an NH_3-H_2O absorption chiller. The CCHP system model combines the CHP system shown in Figure 6 and the absorption chiller system shown in Figure 8, where the exhaust gas in the CHP system is the input to the absorption chiller system. The NH_3-H_2O absorption chiller model was developed using the following schematic in Figure 9 [42] and validated against [32]. The results obtained from the simulation are shown in Tables 9 and 10. The results of both options are displayed graphically in Figures 7(a) and 7(b) for direct comparison.



Abbreviations/acronyms of modules and streams: Summary of the modules: '…FIX'  – are used to control the flowrates of fluids (liquids/gases);  - are heat exchangers. All modules are explained in Appendix 1.

Streams: D15, … D11, are exhaust heat flow to the 'GENERATE (Generator)' in the absorption machine. A1 – A4 are the strong solution pumped from 'Absorber' to 'Generator'. G2 – G2C are weak solution flowing from generator back to the 'Absorber'. G0, G1, …G1E are the refrigerant ammonia (NH3) flowing from generator to 'Condenser' (CONDENS-HEAT, GAS-TO-LIQUI). C0, C1A, C1B, S8, …S22, E05 are ammonia (NH3) flowing from Condenser to Evaporator (EVAPORATOR2) to generate refrigeration effect, and returned back to the Absorber – completing the refrigeration cycle. CW1, …, CW5 are the cooling water flow to provide cooling to Absorber and Condenser.

Figure 8: NH_3-H_2O Absorption Chiller Model and Simulation.

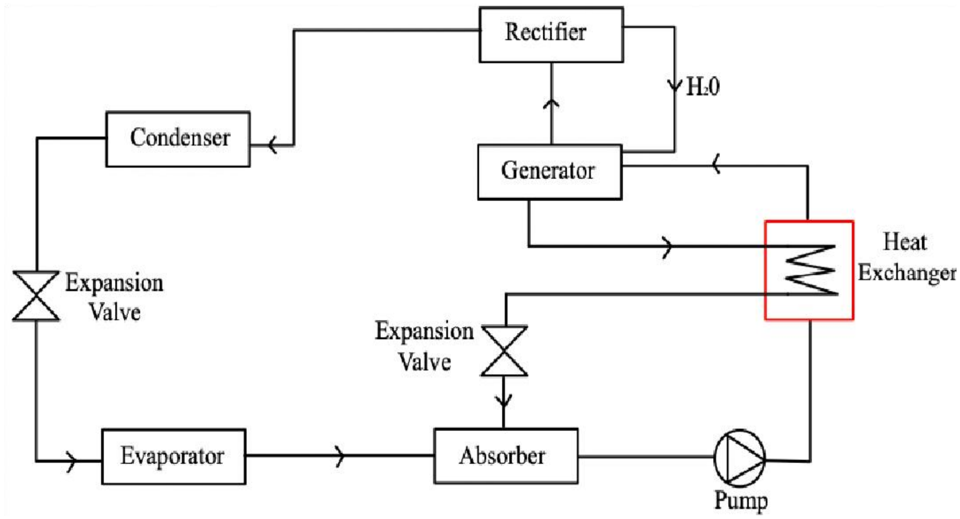


Figure 9: NH_3-H_2O Refrigerator schematic illustration.

Table 9: Outputs from Biogas CCHP System Model and Simulation.

Options	Electricity (kWh/day)	Heating (kWh/day)	Cooling (kWh/day)
1	534	292	420
2	8,992	15,336	420

Table 10: Efficiencies of Option 1 and 2.

Options	Overall CHP Efficiency (%)	Overall CCHP Efficiency (%)
1	62.2	48.6
2	81.1	80.0

Table 9, compared to the energy demand in Table 4, confirms that both options can sufficiently meet the electricity, heating, and cooling demand. As predicted in both cases, the heating output decreases by 31 kW due to the absorption chiller using some of that waste heat to meet the cooling demand. As seen in Table 10, for Option 1, the overall efficiency for a CHP system was 62.2% but 48.4% for a CCHP system due to the losses associated with the addition of the absorption chiller. For a smaller system, the thermal losses of the absorption chiller have a much more significant effect on the overall efficiency of the system. This suggests it is much better to implement a CHP system for Option 1 in terms of efficiency and financially from the costs avoided from buying an absorption chiller. Option 1 is just about meeting demand; there is little opportunity to benefit from exchanging additional energy financially or environmentally, unlike Option 2.

As expected, Option 2 meets the electricity, heating, and cooling demand, seen in Figure 7(b). However, unlike Option 1, Option 2 had similar overall efficiencies for a CHP and CCHP system of 81.1% and 80.0%, respectively. This is due to the impact of the absorption chiller losses being a smaller percentage of the total energy output of the system and therefore having a lesser impact on the overall efficiency. Both Option 2 efficiencies were significantly higher than the efficiencies for Option 1, given the higher feedstock input. Like the CHP system, the CCHP system of Option 2 produces similar amounts of excess electricity and heat that can be utilised in the same way mentioned previously for the CHP system.

3.4. Environmental Benefits

3.4.1 Organic Fertiliser

Anaerobic digestion of bio-wastes produces biogas as well as a by-product digestate. The biogas production simulation uses a 60% conversion efficiency during the anaerobic digestion process. Using this and the ultimate analysis in Table 6, the percentage of CO_2 stored in the digestate can be estimated using carbon and carbon dioxide's molar mass, 12g/mol and 44g/mol, respectively. Results are shown below in Table 11 which is divided into the carbon stored in cow, sheep, and straw waste to display CO_2 prevented from entering the atmosphere.

Table 11: Carbon Stored in Digestate for Option 1 and 2.

Option 1	Carbon (%)	Digestate Output (kg/s)	CO_2 in Digestate (kg/s)	Annual CO_2 (TonnesCO_2eq/year)
Cow	49.04	0.0024	0.0044	137.70
Sheep	51.33	0.0020	0.0037	116.56
Straw	47.92	0.0005	0.0009	29.25
Total		0.0049	0.0090	283.51

Option 2	Carbon (%)	Digestate Output (kg/s)	CO_2 in Digestate (kg/s)	Annual CO_2 (TonnesCO_2eq/year)
Cow	49.04	0.029	0.052	1,650.77
Sheep	51.33	0.024	0.044	1,398.11
Straw	47.92	0.0063	0.011	350.94
Total		0.0590	0.1078	3,399.82

A waste mass flow rate of approximately 0.0049 kg/s is produced annually for Option 1 and 0.059 kg/s for Option 2. This digestate can be used to replace carbon-intensive mineral fertilisers and be utilised for carbon capture and storage, as shown in Table 11. In addition, research by [43] shows that approximately 13 kgCO_2eq/tonne of digestate can be saved by replacing mineral fertilisers, suggesting a total of 283.51 TonnesCO_2eq/year for Option 1, and 3,399.82 TonnesCO_2eq/year for Option 2, can be prevented from entering the atmosphere and contributing to climate change. Furthermore, as well as enjoying environmental benefits, the farm can sell the digestate providing an economic incentive for sustainable manure management.

3.4.2 Carbon Capture and Storage

Power generation inevitably produces CO_2 due to the combustion of fuels. Carbon capture and storage allows this CO_2 to be captured and prevents it from entering the atmosphere. Therefore, the farm could retrofit a post-combustion CCS system in which CO_2 can be captured from biogas through a chemical absorption process in which 90% of CO_2 can be captured [44]. There are alternative methods such as adsorption or membrane separation, but absorption is the most mature post-combustion capture method available [45]. The cost of CO_2 separation increases with decreasing CO_2 concentration in the gas stream due to more energy being required to overcome the mixing entropy. Therefore, carbon enrichment of anaerobic digestors has been known to reduce CO_2 emissions and increase methane production [46]. Once captured, this carbon needs to be transported then stored. Typically, CO_2 is stored deep underground in geological formations such as depleted oil and gas reservoirs and brine aquifers. Brine aquifers are more abundant and have become more prevalent in the CCS industry, especially in the UK, where brine production could save the UK £2 billion at a minimum [47].

3.4.3 Net Carbon Dioxide Emissions

From the simulations developed in ECLIPSE, CO_2 emissions for both options were determined and are shown in Table 12.

Table 12: Annual CO2 Emissions.

CO_2 Emission (kgCO_2e)	Option 1	Option 2
CO_2 from Combustion	173,448	1,989,922
CO_2 Displaced from CCS	-156,103	-1,790,929
CO_2 Displaced due to Net-Zero Usage	-37,058	-3,7058
CO_2 Displaced due to Grid	0	-968,292
CO_2 Displaced due to Digestate	-285,527	-3,423,940
CO_2 Displaced due to Residue Biowastes	4,302	0
Net CO_2	-298,921	-4,206,179

From the simulation, the proportion of CO_2 increased from 0.0058 kg/s to 0.0113 kg/s and 0.0578 kg/s to 0.1209 kg/s post-combustion, generating 173 tCO_2 and 1,990 tCO_2 each year for Option 1 and 2 respectively. However, assuming 90% of the post combusted CO_2 is captured using CCS, for Option 1, only 173,448 kgCO_2e is released into the atmosphere and 1,989,922 kgCO_2e for Option 2.

The farm's electricity and cooling consumption supplied by the grid is 99,669 kWh, where the national grid's CO_2 emission factor is 0.3 kgCO_2e/kWh [48], releasing 29,901 kgCO_2e. The farm uses a kerosene central heating system where each kWh produced releases 0.298 kgCO_2e. The farm's heating consumption is 24.017 kWh which comes to 7,157 kgCO_2e.

As calculated previously, 285,527 kgCO_2e and 3,423,940 kgCO_2e is displaced per year, respectively, due to the replacement of artificial fertilisers using digestate.

In addition, Option 1 does not use all the available biowastes and leaves residue biowastes that must be accounted for. Residue biowastes for Option 1 left to decompose in landfill sires account for 4,302 kgCO_2e.

For Option 2, the CCHP system produces 3.28 MWh of electricity a year. However, it only requires a total of 54,317 kWh of electricity a year, providing a surplus of 3.23 MWh which can be sold back to the grid as a net-zero alternative to fossil fuel-based power production. This means a total of 968,292 $kgCO_2$ can be displaced due to the grid, giving a net CO_2 total of 4,206,179 $kgCO_2e$ for Option 2 that can be eliminated.

3.5 Economic Analysis

3.5.1 Levelized Cost of Energy

The costs associated with Option 1 and 2 can be divided into capital (CapEx) and operational (OpEx) expenditures, shown in Table 13.

Table 13: CapEx and OpEx Costs.

CapEx (£*)	Option 1	Option 2
Anaerobic Digestor	110,000	1,125,000
Power and Heating Generation	12,664	66,000
Absorption Chiller	10,346	10,346
Energy Storage	31,152	0
Total	£164,142	£1,201,346
OpEx (£)	Option 1	Option 2
Anaerobic Digestor	7,700	78,750
Power, Heating and Cooling Generation	885	4,620
Absorption Chiller	724	724
Energy Storage	2,181	0
Carbon Capture and Storage	1,376	32,238
Total	£12,866	£116,332

* The UK GBP(£) to US$ exchange rate is: 1.00 GBP = 1.3134903 US$ [on 31 August 2024]

The anaerobic digester and generator costs, including construction and electrical generation costs, were estimated using various case studies [49]. Operational and maintenance costs associated with the anaerobic digester and electrical generator can be estimated using 7% of capital costs for a mixed dairy manure farm. The transport and carbon storage cost are approximately 8.82 £/tonne of CO_2 stored, totalling £1376 for Option 1 and £32,238 for Option 2 [50].

For Option 1, the total CapEx is £164,142 only occurring in the first year and an annual OpEx of £12,866. Similarly, for Option 2, a total CapEx of £1,201,346 and an annual OpEx of £116,332 due to the increased cost of a more extensive system.

The Levelized Cost of Energy (LCOE) can be used to compare different methods of energy production and evaluate its economic feasibility. It can be calculated using the following formula.

$$LCOE=\frac{\sum \frac{I_n+M_n+F_n}{(1+r)^n}}{\sum \frac{E_n}{(1+r)^n}} \qquad (2)$$

Where I_n is the initial cost of investment expenditures, M_n is the maintenance and operations expenditures, F_n is the fuel expenditures, E_n is the electricity generated, r is the discount rate, and n is the system's lifetime in years [51]. This calculation utilised a discount rate of 5% [52], typical for investments in the UK market and a project lifetime of 20 years based on the useful lifetime of an AD plant [53]. Results for the LCOE for both options can be seen in Table 14, calculated using Equation 2.

Table 14: LCOE.

	Average UK Price of Electricity	Option 1	Option 2
LCOE (£/kWh)	0.184	0.0551	0.0228

From Table 14, both Option's LCOE fall below the price of electricity in Northern England of 0.184 £/kWh. However, Option 2 has a 58.6% lower price per kWh than Option 1 despite a CapEx 7 times larger. This is due to Option 2 producing energy proportionate to almost 20 times that of Option 1 with only a relatively small increase in cost. Therefore, the advantage of a more extensive system is that for every increase in unit capital cost, there is a much bigger increase in electricity production and, therefore, revenue. Option 2 has a significantly higher CapEx than Option 1, and most farmers alone do not have the resources or money to implement this complex system. However, several schemes can help overcome this substantial initial investment cost. First, farmers can apply for loans from the government up to £400,000 or 50% of the overall cost [54]. However, this scheme would only be appropriate for Option 1, as Option 2 costs upwards of £1 million. The Rural Community Energy Fund (RCEF) offers £140,000 of funding for feasibility and preplanning development work to encourage renewable energy projects [55]. The Green Investment Bank (GIB) has set aside £3 billion to invest in sustainable projects, focusing on anaerobic digestion plants, which can help farmers with the initial capital costs [56]. Finally, the Green Gas Support Scheme (GGSS) is a government support scheme offering quarterly payments up to 15 years to encourage new AD plants. Both options would fall into the Tier 1 tariff offering 5.51p/kWh up to 60,000 MWh [57].

3.5.2 Payback Period

The payback period indicates the economic achievability by determining the period for a project to reach its break-even point. The payback period can be expressed by Equation (3) [58]:

$$\text{Payback Period} = \frac{Initial\ Investment}{Net\ annual\ earnings} \tag{3}$$

Each year, the total revenue was based on the money saved from importing electricity and heating, profit made from selling electricity back to the grid via the GGSS scheme for 5.51p/kWh, and profits made from the digestate sold at £12/tonne [59]. This was calculated over a 20-year period where the annual payback after the first year was £13,765, and £99,679 and the annual revenue was £26,630 and £216,011 for Options 1 and 2. This can be seen graphically in Figure 10.

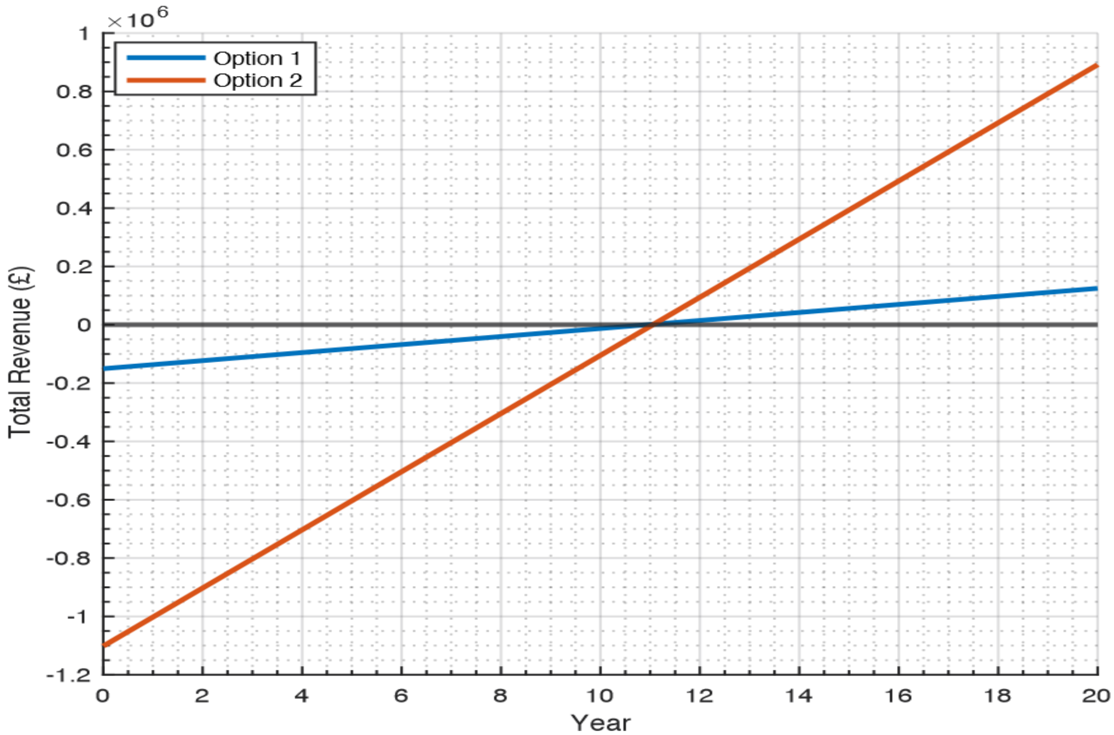


Figure 10: Payback Period for Options 1 and 2.

Option 1 can achieve a payback period of 11 years, whereas Option 2 achieves a longer payback period of 12 years due to the increased initial CapEx. However, both options can profit within the 20-year project lifetime, with Option 2 profiting £891,906 and Option 1 profiting £124,915. Option 2 produces almost seven times the revenue of Option 1 after the 20 years at the cost of a 1-year increase in the payback period. These profits are likely to be an underestimation as the price of electricity and heating are continuously increasing, resulting in higher revenue and shorter payback periods. In addition, this analysis does not consider the time value of money and assumes a constant rate; hence an NPV can be calculated for more detailed financial analysis, but in this case, the payback period can sufficiently indicate the economic feasibility of both systems.

4. Conclusions

This project demonstrates that utilizing farm bio-wastes with a CHP and CCHP system can achieve efficiencies of 48.4% for Option 1 and 80.0% for Option 2. Both options produced more electricity and heat than the farm's maximum demand of 236 kW/day and 116 kW/day. Environmentally, the systems, with CCS and digestate, offer carbon savings of 299 Ton CO2e for Option 1 and 4,206 Ton CO2e for Option 2. Economically, the systems provide attractive LCOEs of 0.0551 £/kWh and 0.0228 £/kWh, well below the market price of energy. Payback periods are 11 and 12 years for Options 1 and 2, respectively. Although the payback time is long, considering that agriculture is a very difficult sector to reduce CO2e, and within the 20-year project lifetime, we can still have the end profits of £124,900 and £891,900. Further study could focus on how to increase financial gains and refine economic analysis for more precise payback periods.

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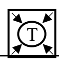
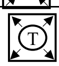
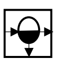
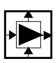
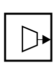
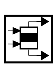
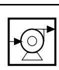
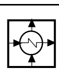
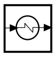
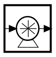
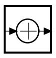
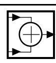
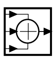
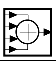
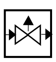
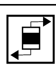
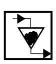
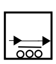
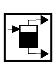
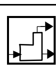
Appendix 1

Table A1. Module Types of ECLIPSE software

Icon	Module Name	Function
	Terminal (End)	This module must be added to all streams exiting the PFD
	Terminal (Start)	This module must be added to all streams entering the PFD
	Compound Separation	This module represents the separation of specified compounds from a stream. There is one inlet stream and two outlet streams.
	Fixed Flow	This module represents the control system required to maintain a fixed flow in a particular stream. It is particularly useful for maintaining a constant flow in a recycle loop or a closed loop. It comprises the following streams: main inlet stream, main outlet stream, flow make-up inlet stream, surplus flow outlet stream, No module may be connected to the flow make-up inlet stream.
	Gas/Liquid Expansion	This module represents polytropic gas or liquid expansion. There is one inlet stream and one outlet stream.
	Gas Absorption	This module represents the removal of specified compounds by gas absorption. There are both liquid and gas inlet streams and outlet streams.
	Gas Compression	This module represents polytropic gas compression. There is one inlet stream and one outlet stream.
	Heat Exchanger	This module represents the transfer of heat between two process streams. There are two inlet streams and two outlet streams. When positioning heat exchangers into the PFD be aware of where the hot

		side and cold side streams should be and carefully place the heat exchanger the right way round. The red arrows indicate the hot-side streams; the zigzag line represents the cold stream.
	Heater/Cooler	This module represents the heating or cooling of a process stream by a utility. There is one inlet stream and one outlet stream.
	Liquid Pump	This module represents liquid pumping. There is one inlet stream and one outlet stream.
	Pipe Connection (1)	This module represents the pipework used to combine streams. There are up to four inlet streams and one outlet stream.
	Pipe Connection (2)	
	Pipe Connection (3)	
Icon	**Module Name**	**Function**
	Pipe Connection (4)	
	Pressure reduction	This module represents the adiabatic pressure reduction of a process stream. There is one inlet stream and one outlet stream.
	Chemical Reaction	This module represents a chemical reactor. There is one inlet stream and one outlet stream.
	Size Reduction of a Solid	This module represents the size reduction of a solid. There can be up to four inlet streams and one outlet stream.
	Solid Feeder/Conveyor	This module represents the mechanical conveying or feeding of a solid. There can be up to four inlet streams and one outlet stream.
	Storage Tank or Vessel	This module represents a storage tank or process vessel. There can be up to four inlet streams, one solid/liquid outlet stream and one vapour outlet stream.
	Flow Splitter	This module represents the pipework used for splitting one process stream into two process streams.