Biofuel Trigeneration with Energy Storage for Heating, Cooling and Power on Farms

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Abstract— The drive towards net-zero carbon emissions has prompted many industries to alter the way they operate. The agriculture industry is responsible for a large proportion of the UK's greenhouse gas emissions. Thus, the feasibility of implementing an anaerobic digestion (AD) system supplying biogas to a trigeneration system with energy storage for the provision of heating, cooling and power has been investigated in the context of a medium-scale arable farm. Two configurations – one supplied with wheat straw only, and the other supplied with wheat straw, barley straw and manure – were identified to meet the energy demands of the farm. Technical feasibility was investigated via simulations run in ECLIPSE, with the two configurations returning overall system efficiencies of 66.8% and 67.1%, respectively. Economic analyses indicated simple payback periods of 9.4 and 11 years, which fall within the expected 20-year lifetime of the project. Furthermore, the potential reduction in CO_2 emissions for each scenario was determined to be 42,764 kg and 43,956 kg per year.

Key words—Trigeneration, energy storage, biofuel, arable farm, levelized cost of energy, payback period

1. INTRODUCTION

WITH the escalation of human-driven climate change, the issue of global warming remains a priority for governments around the world. The UK Committee on Climate Change has set a target for a 68% reduction in greenhouse gas (GHG) emissions by 2030, and a 100% reduction by 2050 [1], compared to 1990 levels. The introduction of new policies, regulations and incentives has given impetus to sustainable technology solutions promoting a net-zero future.

In 2018, the UK territorial greenhouse gas emissions came to a total of 451 Mt, including 366 Mt of carbon dioxide (CO_2) [2]. It is estimated that the agriculture industry contributed 10% of these emissions, with methane - which has a global warming potential (GWP) of 25 times that of carbon dioxide [3] - accounting for 56%. Thus, there is an enormous potential for the agriculture industry to reduce their GHG contribution. Friel et al. [4] identified that this can be achieved through technological improvements and innovations, focused on increasing efficiency and improved farm management. Furthermore, a study by Maturo et al. [5] found that energy schemes involving energy-efficient technologies and novel system layouts – such as anaerobic digestion, cogeneration and biogas upgrading – returned notable economic and environmental benefits in the context of an agricultural community in Italy.

The GHG emissions issue is further aggravated by a growing demand for electricity. Due to population increase, decarbonisation of heating and cooling, and electrification of the automotive industry – among other factors – electricity demand could increase by up to nearly 50% by 2050 [6]. The intermittency inherent in renewables also poses a reliability problem. One method of reducing grid-dependency is the implementation of distributed energy resources (DERs) [7].

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Anaerobic digestion (AD) is a biochemical process used to obtain biogas fuel from waste material. In addition to reducing the amount of waste material either going to landfill or left to decompose on open fields, a by-product of AD is an organic, nitrogen-rich digestate which can be used as a potent fertiliser [8], [9]. Animal waste and organic residential and industrial wastes are common feedstocks with a recognised potential for biogas production [10], [11].

Biogas can further be used to produce useful energy via combined heat and power generation (CHP) or combined cooling, heat, and power (CCHP)[12], [13]. A review of previous work by Lahoud et al. [14] indicates that the implementation of CHP and CCHP systems can achieve efficiencies in the range of 80-90%. CHP is a mature technology, and CCHP, also called trigeneration, is growing in popularity. Applications include the residential sector REF [15] and in industry, especially where variable cooling and heating demands exist. One such industry is agriculture.

Large quantities of agricultural by-products on arable farms, such as cereal straws and maize stalks, are often directed to landfills or abandoned on fields after harvest. The addition of crop straw to soil can improve soil properties as it is rich in organic material and soil nutrients [16],[17]. However, the presence of residual herbicides and pesticides in straw and CO_2 emissions from straw-amended soil can pose significant problems [18] and highlights the importance for farmers to limit straw left in fields. The biogas potential of crop straws is much lower than other agricultural waste due to lignocellulosic compounds, however, the sheer quantity generally produced on an arable farm suggests there is significant potential for meeting energy demands [19],[20]. The energy potential of crop residues could be further exploited via co-digestion with animal wastes [21],[22], which is viable for a mixed arable farm, or if animal waste from neighbouring farms is available. Additionally, continued research into commercially viable pre-treatment options is increasing the level of interest in crop straw AD, which is crucial for countries where burning straw is the only way to clear land [23].

In the UK, the drive towards sustainable growth has resulted in economic incentives for implementing combined AD and CHP or CCHP systems [24]. Such incentives include the Business Rating Exemption, the Renewable Heat Incentive (RHI), and Feed-in Tariffs (FIT). Although it should be noted that applications for the FIT scheme closed in March 2019 [25]; instead, it is set to be replaced by the Smart Export Guarantee (SEG) [26]. Therefore, implementation of a CHP or trigeneration system has the potential to generate additional revenue streams for a farm.

Ultimately, by reducing waste straw left to openly decompose, powering process energy demands through biogas instead of red diesel or the grid, and redirecting waste straw which might have gone to landfill, a farm may contribute to climate protection. A research gap exists due to limited research in using biogas from straw – in particular, wheat and barley – with trigeneration for a sustainable energy supply to an arable farm, which demonstrates the novelty of the study. Thus, the aim of this research project was to investigate the technical and economic feasibility of meeting the heating, cooling and power demands of an arable or mixed farm via a novel biogas-fuelled trigeneration system. The use of energy storage within the system will also be considered due to positive results reported by Shao et al. [27] when investigating a CCHP system with energy storage. The main contributions are to develop a net-zero energy supply system to be used as a mitigation option towards sustainable farming, and demonstrate the energy potential of waste straw.

2. Methodology

The feasibility study was carried out using data from an arable farm located in England. The farm spans 485 ha, of which 25 ha are used for 200 ewes. Crop distribution across the remaining land varies from year-to-year, with an average distribution as shown in Table 1.

Table 1 Crop distribution on an average year

Crops	Land occupied / ha

Oilseed rape	50
Barley	180
Wheat	140
Dry peas	20

Approaches adopted in this study include surveys and virtual meetings to obtain data for the electricity, heating and cooling demands of the farm, in addition to simulations of various systems on ECLIPSE (the personal computer-based process simulation package). Energy demand fluctuates throughout the year as grain drying and grain cooling are not continuously carried out. The yearly demands are displayed in Figure 1 and summarised in Table 2.

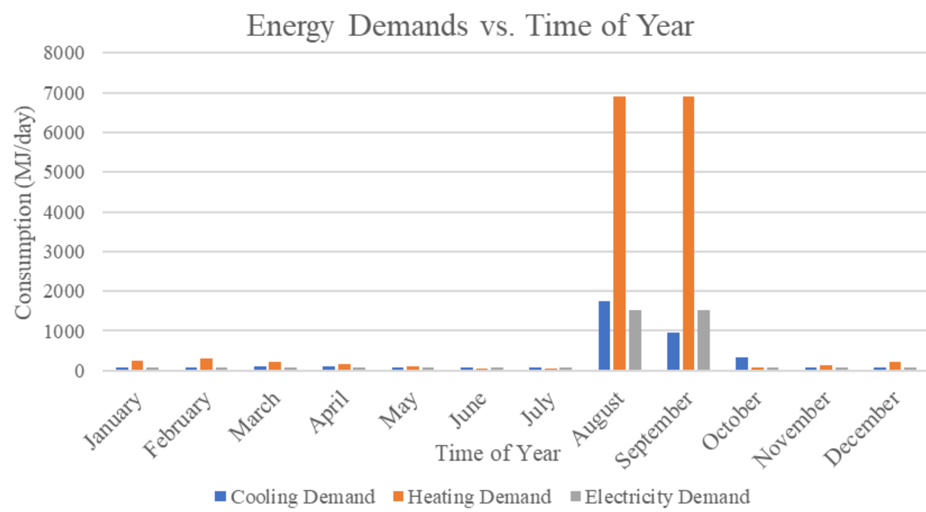


Figure 1 Electricity, heating and cooling demand throughout the year

Table 2 Summary of total yearly demand, and maximum and minimum demands per day

	Yearly Demand (kWh)	Maximum ($kWh \cdot day^{-1}$)	Minimum ($kWh \cdot day^{-1}$)
Electricity	31200	420	20
Heating	127915	1920	12
Cooling	32283	486	24

The energy demand due to farming operations and domestic use is currently supplied by electricity from the grid and red diesel fuel (see Figure 2).

To determine biowaste availability, data from 2018 was provided by the farm, where wheat straw production totalled 684 tonnes, and barley straw totalled 110 tonnes. This indicated feedstock flow rates of 0.0217 kg/s and 0.0035 kg/s for wheat and barley straws, respectively. The available waste from livestock was also estimated to be 0.0044 kg/s.

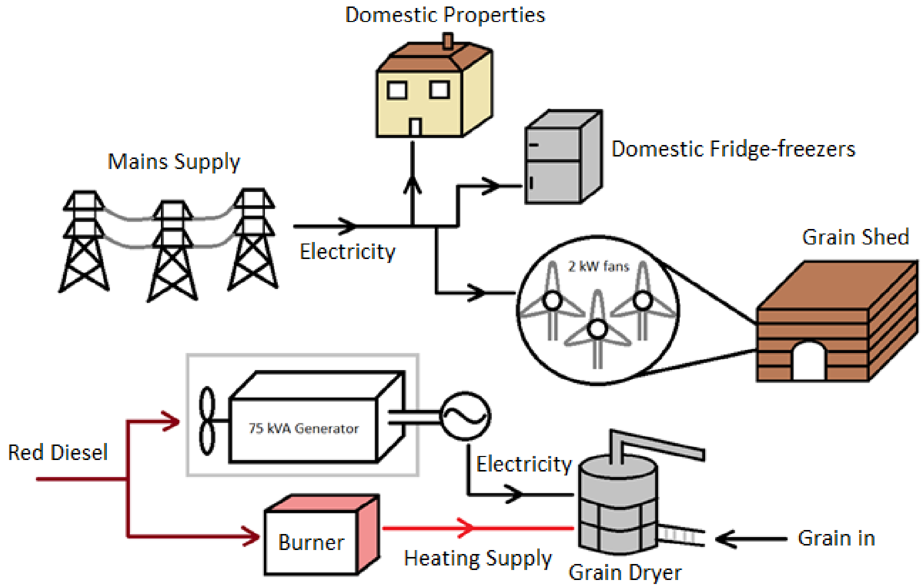


Figure 2 Current energy supply system

2.1. Electricity Demand

2.1.1. Domestic consumption

Currently, the cost of electricity is around £180 per month on average in a year. This value covers the cost of electricity consumed across domestic properties and electricity used to power three 2 kW cooling fans in the grain shed; it has been estimated that consumption is split equally between domestic use and grain cooling.

The energy supplier operates with time-of-use rates, where the day-time (peak) price is £0.16 / kWh and the night-time (off-peak) price is £0.12 / kWh. The farm further estimates that 80% of electricity is consumed in peak hours, suggesting a yearly consumption of 14400 kWh. Eliminating the cooling demand results in 7200 kWh being supplied by the grid per year.

2.1.2. Grain Drying

An additional demand stems from operation of a 60 kW / 75 kVA diesel generator used to power the grain dryer. This generator consumes 1500 litres of red diesel across the 2-month harvest period, where the grain dryer operates for 400 hours, resulting in a power requirement of 24,000 kWh.

2.2. Heating Demand

2.2.1. Grain Drying Heat

For an arable farm, the most energy intensive process is grain drying during the harvest season. In one year, the farm can expect to start drying grain in late July or early August and complete the drying process at any point in September – the period and intensity of drying is heavily dependent upon climate. For the purpose of this study, it is assumed that the grain dryer operates for two months of the year (August – September).

During the drying period, 10,000 litres of red diesel is burned to generate heat, which equates to 9600 kg. The quantity of supplied heat was calculated using the higher heating value of red diesel, which is given as $C_v = 42{,}893\ kJ/kg$, and the mass of red diesel, m_{fuel} :

$$Q_{drying} = C_v \times m_{fuel} \tag{1}$$

The heat energy required for grain drying was calculated to be 114415 kWh per year.

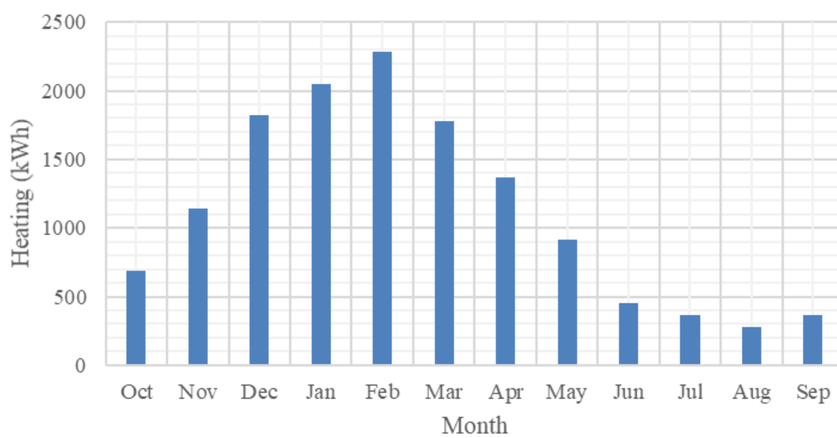
With the knowledge that 400 hours of drying is completed in an average year (approximately 6.7 hours per day across two months), this indicates a heating requirement of 1030 MJ/hour or 286 kW. A standard thermal efficiency of 33% is applied, while 60% of losses are assumed to be from heat (exhaust gases and coolant), with the remaining energy lost due to friction, pumping, and so on. Since 286 kW of heat energy is required for grain drying, the heat losses from the engine are equated to this value. Thus, the size of the engine is calculated from (2), where the thermal efficiency $\eta_{th} = 33\%$, the heat loss percentage $\eta_{heat} = 60\%$, $P_{drying} = 286\ kW$, and P_{engine} is the required engine size.

$$P_{engine} = \frac{P_{drying}}{\eta_{heat}} \times \eta_{th}$$

In order to meet the heating demand, the engine should be approximately 160 kW.

2.2.2. Domestic Heat

An additional heat demand stems from space heating and domestic hot water. The mean average gas consumption for a household in the North East is estimated to be 13,500 kWh [28]. Combining this with data on monthly variation of natural gas consumption in the UK [29] allowed domestic heating demand to be calculated proportionally for each month (Figure 3).



2.3. Cooling Demand

2.3.1. Grain Cooling

On arable farms, cooling is employed for the purpose of maintaining grain quality, which is crucial for minimising the probability of grain rejection and extending the maximum storage period.

Currently, grain cooling is achieved via three 2 kW fans installed in the grain shed, consuming an average of 750 kWh of electricity per month across 9 months, as provided by the case study. Fans are manually turned on and the grain temperature is checked periodically by hand.

The cooling demand was calculated using data from Table 1. For each crop, the 5-year average yield value in tonnes per hectare was obtained from DEFRA [30]. The mass of each crop stored immediately after harvest is given in Table 3.

Table 3 Annual crop production and yield

Crop	Yield ($T \cdot ha^{-1}$)	Production (T)
OSR	3.3	165

Barley	6.2	1116
Wheat	8.3	1162
Dry peas	3.5	70

To calculate cooling demand, the following assumptions were made:

- Oilseed rape (OSR), barley, wheat, and dry peas are the crops to be stored.
- Harvested crops are kept in a grain shed for a maximum of 9 months.
- Crops are sold linearly from August – April, such that the grain store is full in August and empty by May.
- Proportion of each stored crop remains constant, i.e. 7% OSR, 44% barley, 46% wheat, and 3% dry peas.
- Grain should be stored at a temperature of 10 °C or lower, as indicated by the farmer.
- An absorption chiller and fan coil unit are used for cold storage.

The required cooling demand Q_{cold} was calculated using (2).

$$Q_{cold} = M_w C_{pw}(T_{ambient} - T_{ideal}) + M_c C_{pc}(T_{ambient} - T_{ideal}) \quad (2)$$

where M_w is the mass of water calculated from moisture content during storage, M_c is the dry mass of each crop, C_{pw} is the specific heat capacity of water, taken as a constant of 4.2 kJ·kg^{-1}·°C^{-1}, C_{pc} is the specific heat capacity corresponding to each stored crop, $T_{ambient}$ is the ambient air temperature, and T_{ideal} is the ideal storage temperature.

The specific heat capacity of each crop [31]-[33], along with moisture content (MC) immediately post-harvest and during storage is given in Table 4.

Table 4 Specific heat capacity and moisture content post-harvest and during storage for each crop

Crop	C_p (kJ·kg^{-1}·°C^{-1})	MC Post-harvest (%)	MC in Storage (%)
OSR	1.84	12	14.5-15
Barley	1.63	21	14.5-15
Wheat	1.55	21	7.5-8
Dry peas	3.39	25	14-15

$T_{ambient}$ varies throughout the year and average monthly temperatures were obtained from the Meteorological Office, while the ideal storage temperature T_{ideal} was set to 10°C.

The cooling demand in a given month was calculated for each crop and summed (see Table 5). Results indicated that cooling would be required for 5 months of the year, as ambient temperature would be sufficiently low in the winter months to not necessitate cooling.

Table 5 Cooling demand

Month	Q_{cold} (kWh)
August	13864
September	7293
October	1981
March	228
April	126

An investigation into thermal conductivity suggested that it would be sufficient to pass a cooling front through the stored mass once per month. However, if this proves to be practically insufficient, the 2 kW fans currently installed may be utilised to make up any deficit in supply.

2.3.2. Domestic Cooling

There are 2 fridge-freezers present in domestic properties on the farm, rated at 272 W. On average, the refrigeration unit is maintained at a temperature of 5°C, while the freezer unit is maintained at a temperature of -20 °C. To estimate the cooling energy utilised, the Carnot coefficient of performance (COP) for a vapour compression refrigeration cycle (3) was calculated for each unit.

$$\eta = \frac{T_C}{T_H - T_C} = \frac{Q_{out}}{W_{in}} \quad (3)$$

where $T_C = 5^oC$ for the fridge, $T_C = -20^oC$ for the freezer, $W_{in} = 272W$ split between the two stores, and $T_H = 21^oC$ to represent room temperature. The average fridge operates with 120 W, while the average freezer operates with 150 W, therefore these values were used as W_{in} for each case. Using the Carnot COP allowed maximum demand to be estimated, to represent a worst-case scenario. A final domestic cooling value of 8791 kWh was calculated.

2.4 Trigeneration Schematic

Figure 4 displays the preliminary schematic for the trigeneration system. Biowaste is input into the AD system, which produces biogas for the generator. The generator produces electricity for domestic properties and to run the grain dryer. Simultaneously, heat from the generator exhaust is supplied to the absorption cooler for domestic refrigeration and grain cooling, and either stored or immediately used for grain drying and domestic heating.

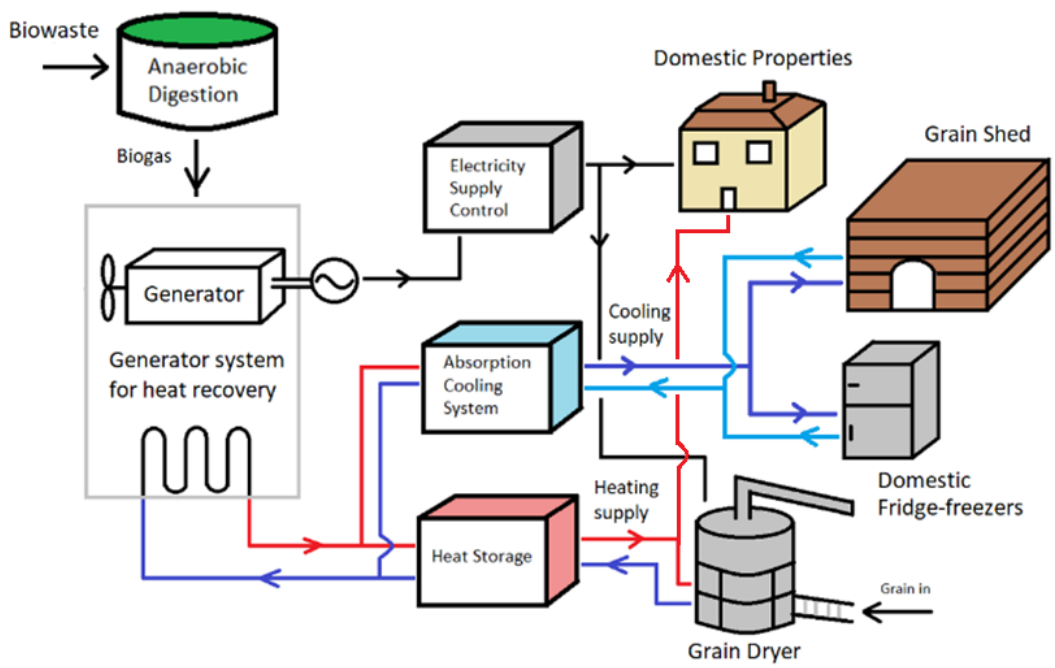


Figure 4 Preliminary trigeneration schematic detailing electricity, heat and cooling flows

2.5. Modelling and Simulation

Three systems were modelled in ECLIPSE: an AD system, a CHP system, and a trigeneration system. Simulations were run to first obtain quantities of produced biogas from available biowaste, then to determine energy potential from the biogas, heat transfers throughout the system, and the electrical power generated.

ECLIPSE is a chemical process simulation package. There are 4 programs within ECLIPSE in which models are created and simulations are run to evaluate the technical feasibility of a process. The first step involves creating a process flow diagram (PFD) and inputting essential technical data (efficiencies, temperatures, pressures, etc.). Relevant data for compounds used within the PFD must be added to the compound database (CD), including the C, H, O, N and S compositions. Simulations can then be run on the defined system to generate a mass and energy balance (MEB), which provides data regarding flows and composition, heat transfer, and energy usage. The utilities usages can be calculated after completion of the MEB, which computes the system electricity demand and power surplus.

The ECLIPSE models for components of the trigeneration system, including the engine and the absorption chiller, were validated against commercially available units [34],[35] to ensure technical feasibility. Figure 5 and Figure 6 present the ECLIPSE models used for validation.

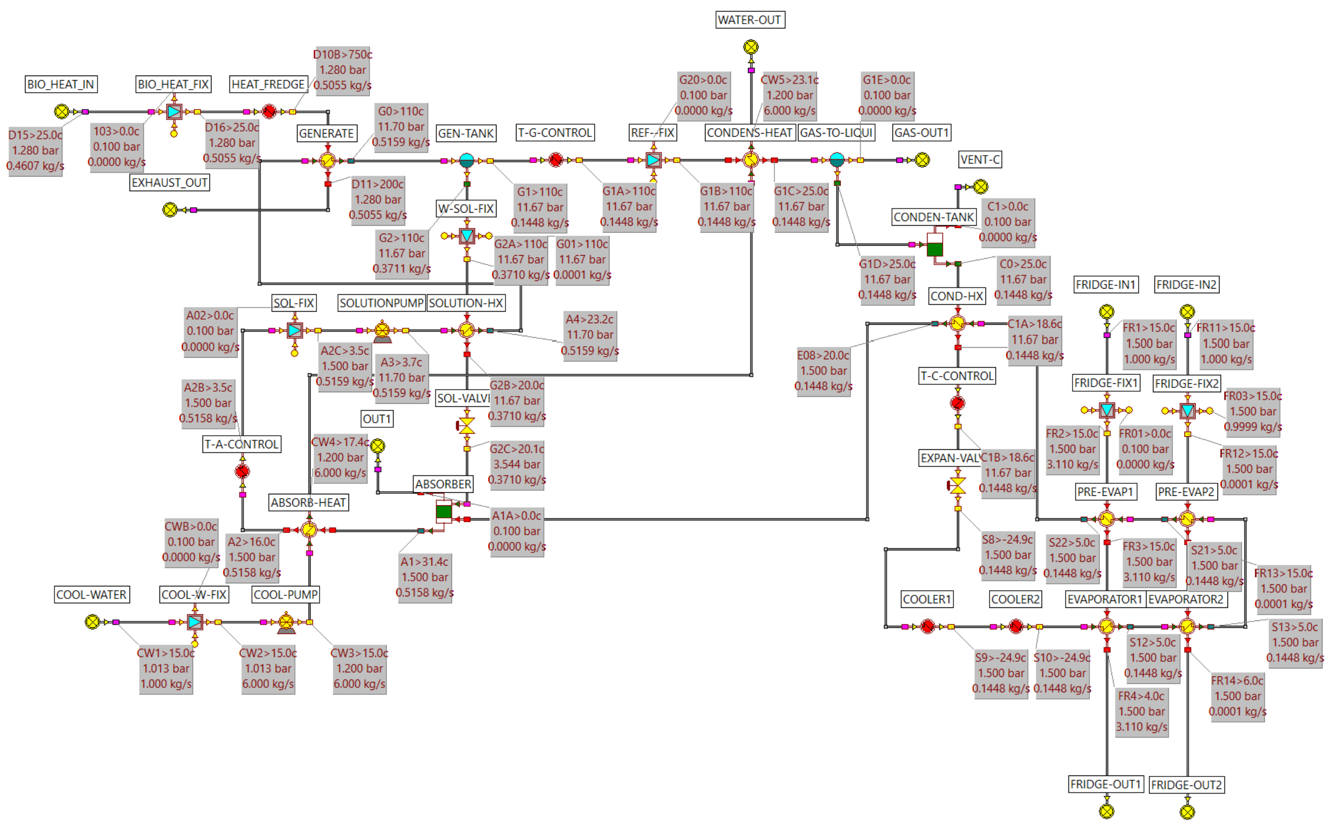


Figure 5 Model Validation: Mass energy balance model for the 17.6 kW Robur absorption chiller

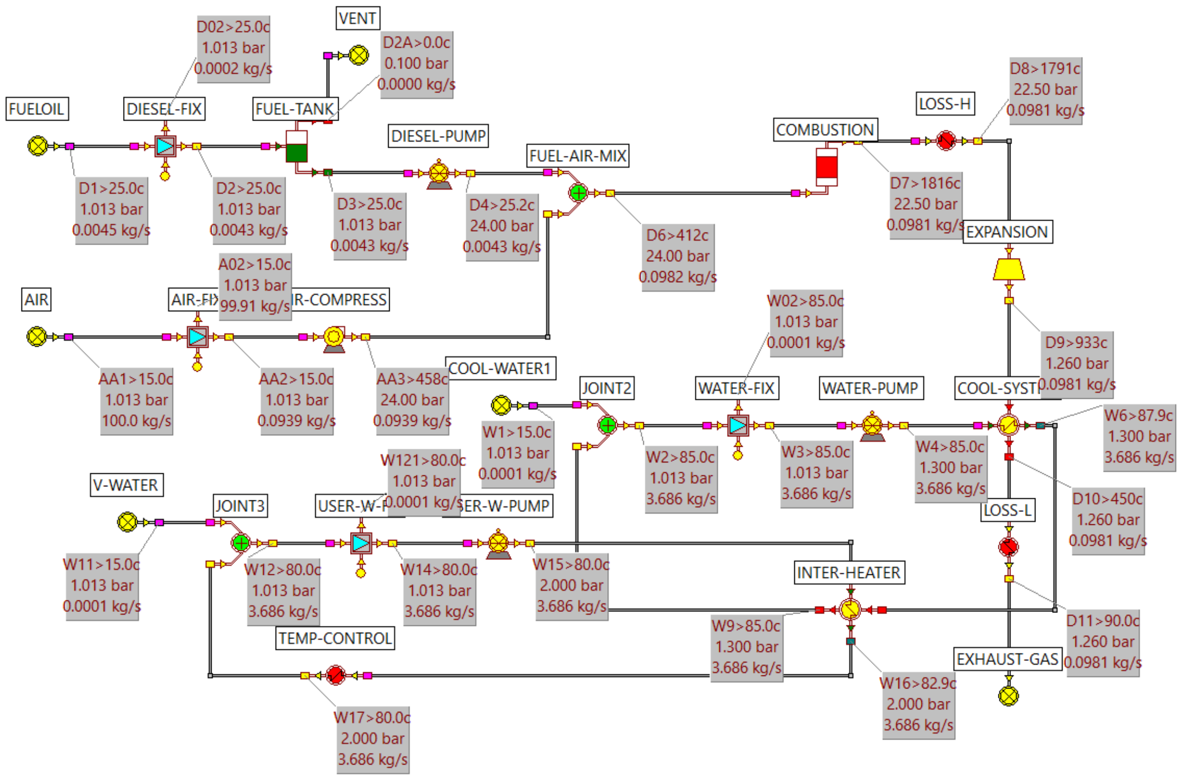


Figure 6 Model Validation: Mass energy balance model for the 60 kW Engine

3. Results and Discussion

3.1. Simulations for Anaerobic Digestion

Initially, AD simulations were run for 12 scenarios to compare the effect of 2 independent variables. A mass energy balance model was created and modified for each AD scenario. The 2 variables were feedstock input and the period of operation. The available feedstock options are wheat straw (W), wheat and barley straws (W, B) and wheat straw, barley straw and sheep manure (W, B, M), where the straws are chopped prior to loading. The periods of operation are 12, 9, 6 and 3 months.

The ultimate compositions (CHONS) of both straw types and sheep manure were researched [36], as shown in Table 6. These values were used as inputs in the AD simulation process.

Table 6 Ultimate analyses for feedstocks [31]

	Composition by weight %		
Constituent	Wheat	Barley	Manure
Carbon	48.46	49.18	51.33
Hydrogen	5.79	5.81	6.45
Oxygen	43.64	44.08	38.81
Nitrogen	1.74	0.43	2.65
Sulphur	0.11	0.06	0.76
Chlorine	1.26	0.44	0.00

The model represents a mesophilic digestion process at 25°C, where the material conversion efficiency is 50% [37]. Due to lower temperatures, the operating cost of mesophilic digestion is lower than for thermophilic digestion (50 – 65°C), and the process is more stable [38].

Results from the ECLIPSE simulations revealed predictable trends. Running the system for fewer months throughout the year increased the amount of feedstock available during operational months, which increased biogas yield. Likewise, increasing feedstock input led to a rise in biogas output, and in particular the percentage of CH_4 within the produced biogas for the case of wheat, barley and manure.

In the interest of eliminating reliability on the grid and designing a completely self-sufficient system, consideration of 9, 6 and 3 month periods was rejected. The options in Table 7 were taken forward for further analysis. Additionally, a trigeneration system supplied with diesel fuel was analysed to evaluate the environmental impact of biogas adoption. This is Option 4.

Table 7 Description of options for further analysis

Option	Period (Months)	Feedstock	Fuel
1	12	W	Biogas
2	12	W, B	Biogas
3	12	W, B, M	Biogas
4	12	N/A	Diesel

3.2. Biogas CHP Analysis

Simulations were run to investigate whether combinations of the available feedstocks could meet the demands of the farm across the year when used in a continuously operated biogas CHP system. Mass energy balances for a biogas CHP system utilising Options 1 (see Figure 7), 2 and 3 were generated, in order to derive values for recovered heat and electricity generation capacity.

The reaction defined in the combustion chamber of the CHP model is described by (4).

$$CH_4 + 2O_2 = 2H_2O + CO_2 \tag{4}$$

Results are displayed in Table 8.

Table 8 Biogas CHP results

Option	Heat ($MJ \cdot s^{-1}$)	Heat ($MJ \cdot day^{-1}$)	Power (kW)	Electricity ($kWh \cdot day^{-1}$)
1	0.097	8381	57.6	1382.4
2	0.102	8813	59.9	1437.6
3	0.125	10800	74.2	1780.8

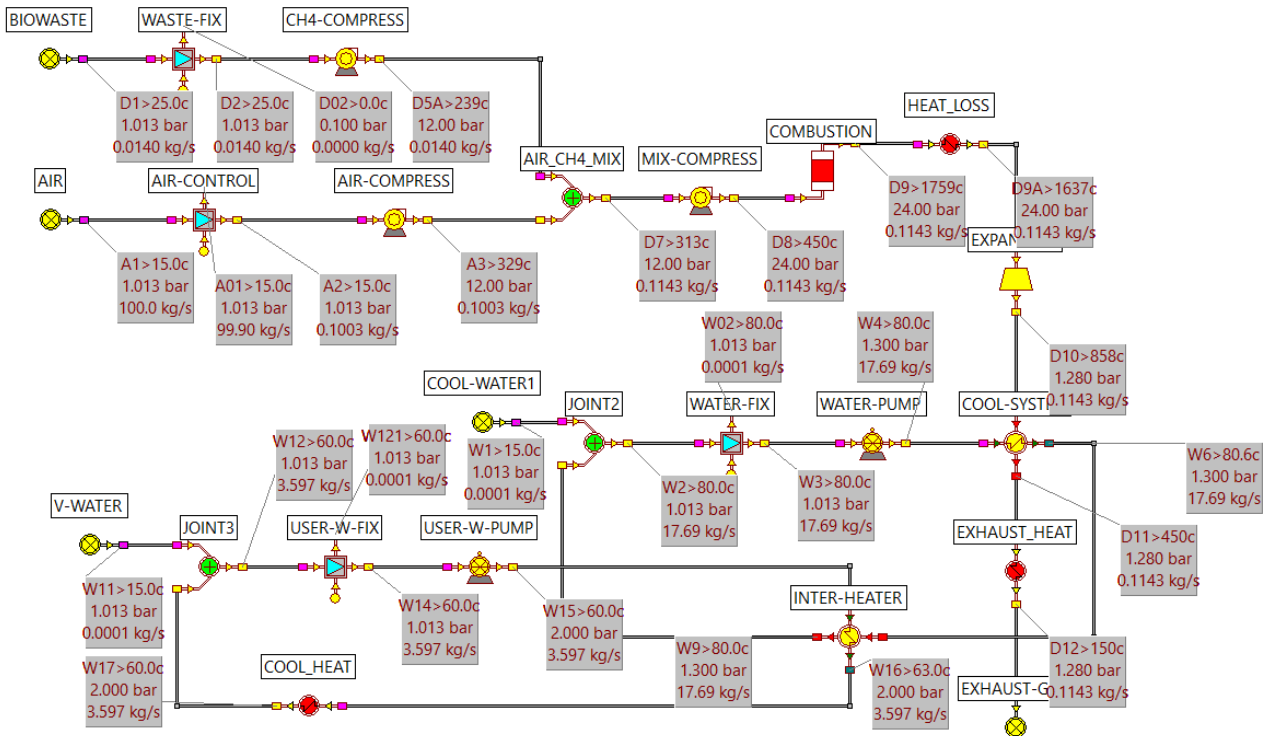


Figure 7 ECLIPSE mass energy balance to model CHP for Option 1

Comparing these values to the farm's energy consumption (Table 2) indicates that all options provide sufficient electrical power to meet demand throughout the year (maximum 420 kWh/day). Furthermore, all options are able to meet the maximum heating demand (6914 MJ/day). However, there is indication that electrical and thermal energy storage will be required.

Option 1 Power generated by Option 1 is not able to meet the 60 kW demand of the diesel generator used to operate the grain dryer, therefore an electrical storage unit must be integrated into the system to store electricity generated at night for use during the day. Batteries are the most commercially viable for small-scale generation (<100 kW), and integration with CHP systems has proved to be cost-effective and energy efficient [39]. Additionally, the rate of heat energy supplied (0.097 MJ/s) is lower than demand (0.286 MJ/s), consequently a short-term (daily) thermal energy storage (TES) unit must also be integrated.

Option 2 The system is able to meet the 60 kW demand, although there is no margin for domestic consumption, such that when the grain dryer is in operation, domestic properties will have no access to electricity. Therefore, an electrical storage unit should also be included in this system. As for Option 1, Option 2 will also require TES.

Option 3 The system will require a new generator to accommodate higher power consumption, but no electrical storage. As for the previous 2 cases, short-term TES is required.

The advantages of uncoupling electricity and thermal energy production by incorporating TES into CHP and therefore CCHP systems are abundant, and include improved energy efficiency and reduced CO_2 emissions [40],[41]. Sensible heat storage (SHS) with water is the simplest, most prevalent, and most cost-effective method of short-term TES [42]. The energy storage capacity can be calculated according to [42]. Hot water for thermal storage has a capacity of 10-50 kWh/tonne, an efficiency of 50-90%, and a cost of <1-180 £/kWh, dependent upon the size of the system.

Electrical energy storage maximises the advantages of flexible electricity tariffs, in addition to providing load shifting and contingency benefits.

System efficiencies and key technical results from the CHP system are displayed in Table 9.

Table 9 Key technical results for CHP system

	Electrical Efficiency (%)	Overall system efficiency (%)	Heat/electricity ratio
Option 1	27.0	73.7	1.69
Option 2	25.1	69.0	1.70
Option 3	26.7	72.3	1.67
Diesel	32.4	84.2	1.60

3.3. Biogas CCHP Analysis

The system was further extended to assess the feasibility of cooling provision, thus representing a trigeneration system. The model used is identical to the CHP system, except for the incorporation of an absorption chiller, which is supplied by an additional heat recovery stream from the combustion engine exhaust. The mass energy balance of the absorption chiller system, which is based on and validated according to a 17.6 kW ammonia-water chiller by Robur [35], is displayed in Figure 5.

The results for the trigeneration simulations are displayed in Table 10.

Table 10 Trigeneration results, where excess heat is calculated as CHP heat minus the absorption chiller heat consumption

Option	Absorption Chiller Cooling ($MJ\cdot day^{-1}$)	Available Heat ($MJ\cdot day^{-1}$)	Power (kW)	Electricity ($kWh\cdot day^{-1}$)
1	1521	5703	56.5	1356
2	1521	6135	58.8	1411
3	1521	8122	73.1	1754

The absorption chiller was modelled with the parameters in Table 11.

Table 11 Absorption chiller properties

Parameter	Value
COP	0.55
Heat Input (kW)	31.0
Refrigeration Capacity (kW)	17.6
Minimum Temperature (°C)	4
Type	Air-cooled

With the addition of the absorption chiller for refrigerated cooling, 0.031 MJ/s of heat is consumed, which equates to 2678 MJ/day. This results in reduced energy available for heating.

Option 1 Results from Option 1 indicate insufficient heat energy generation. In a 24-hour period, 5703 MJ of heat is generated, while the heat demand for drying and domestic usage is 6914 MJ, resulting in a deficit of 1211 MJ. In this case, short-term TES is not a viable solution, since this deficit occurs on a daily basis, therefore excess heat energy must be derived from an alternative source.

One solution considered was long-term (interseason) TES, which would involve storing heat energy in June and July to meet any deficits occurring throughout August and September. It is currently unfeasible to employ hot water for long-term TES in small-scale applications, such as the case study. Latent heat storage (LHS) is more common, and advances in phase-change materials (PCM) [43] has led to a rise in applications. However, barriers to implementing this include high cost (10-50 € / kWh) [42], as well as instability issues. Therefore, at present this solution is suboptimal.

Alternatively, the deficit could be met by supplying the existing burner with biogas stored from low-consumption months. To determine the quantity of biogas required to meet the deficit of 1211 MJ per day, the burner was modelled in ECLIPSE.

In the months May, June and July, consumption for electricity, heating and cooling is extremely low due to the absence of drying and cooling processes. The only load during this period is assumed to be domestic. Therefore, reducing biogas supply to the generator during this time in order to build up a store for the burner in harvest months is a viable solution. There will be an economic impact due to reduced electricity available for selling back to the grid (see 3.4.3), in line with Feed-in Tariff considerations.

As was the case for Option 1 in the CHP system, sufficient electricity is generated for daily consumption, but a battery is required for load balancing.

Option 2 For Option 2, results indicate the same outcomes as in Option 1. Insufficient heat energy generation necessitates the use of the burner supplied with biogas to meet the deficit. The deficit is smaller for Option 2, therefore the biogas demand is lower. Deficit and biogas demand values are displayed in Table 12.

Table 12 Biogas and heat energy data for the burner in Options 1 and 2

Option	Deficit ($MJ\cdot day^{-1}$)	Deficit ($MJ\cdot s^{-1}$)	CV ($MJ\cdot kg^{-1}$)	Biogas Demand ($kg\cdot s^{-1}$)
1	1212	0.01402	15.643	0.000896
2	780	0.00902	15.132	0.000596

Assuming that the system's biogas input is reduced in June and July, such that enough biogas is stored for burning in August and September, then the quantities of heat and electricity output by the trigeneration system are given in Table 13.

Option 3 Results indicate that heat energy production (8122 MJ/day) is sufficient, therefore there is no need to consider additional components to meet deficits. Electricity generation (1754 kWh/day) is also sufficient, as is the rate of generation (73.1 kW), which can comfortably meet the 60 kW demand for the grain dryer, in addition to domestic loads in real-time.

Table 13 Electricity and heat energy outputs in June and July when biogas is reduced for later use

Option	Biogas input ($kg\cdot s^{-1}$)	Heat Out ($MJ\cdot day^{-1}$)	Electricity (kW)	Electricity ($kWh\cdot day^{-1}$)
1	0.0125	4579	50.9	1222
2	0.0149	6048	52.8	1266

Cooling Since the same absorption chiller is modelled in all cases, the cooling supply is consistent. Per day, the absorption chiller provides 1521 MJ of cooling. The cooling load varies throughout the year, with the peak occurring in August, where 49910 MJ is required. This equates to 1664 MJ per day, exceeding the supply of the chiller.

One solution is to utilise an absorption chiller with a greater refrigeration capacity, however this would exacerbate the heat energy deficit already present in Options 1 and 2. Therefore, since the cold energy deficit only occurs in one month, a feasible solution is to simply operate the existing 2 kW fans to achieve the desired storage temperature. This solution would reduce the electricity available for selling back to grid, which is accounted for the economic analysis (3.4).

Diesel The baseline diesel engine, which is available on the farm, was modelled using specification data from a 60 kW Cat XQ60 Generator Set.

The system efficiencies for the 3 biogas options in the trigeneration case were lower than for the CHP case. The overall efficiencies were 66.8% for Option 1, 62.9% for Option 2, and 67.1% for Option 3. The diesel system saw an efficiency decrease to 77.6%, when operating with the same absorption chiller. The efficiency decrease arises due to the fact that less cold energy is produced by the absorption chiller than heat energy consumed, with the chiller having a COP of 0.55.

Ultimately, the technical analysis has highlighted Options 1 and 3, with some modifications, as better potential solutions than Option 2 due to higher overall system efficiencies. The same trigeneration schematic applies to Options 1 and 2 (Figure 8). The schematic for Option 3 (Figure 9) is identical, except for a 75 kW generator instead of a 60 kW generator, and no burner for additional heat supply in August and September.

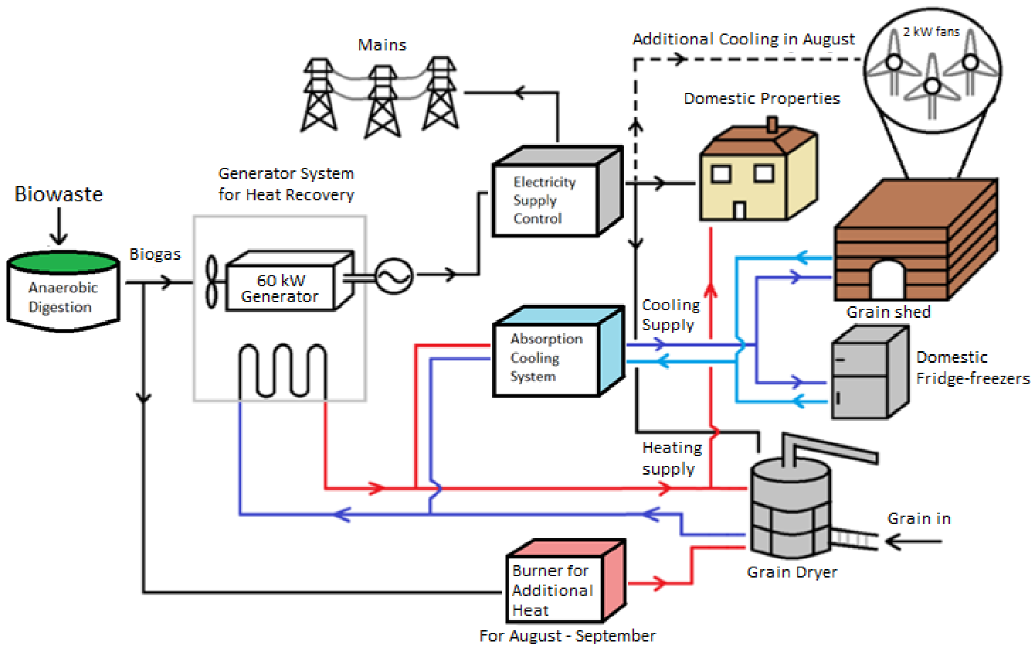


Figure 8 Trigeneration schematic for Options 1 & 2

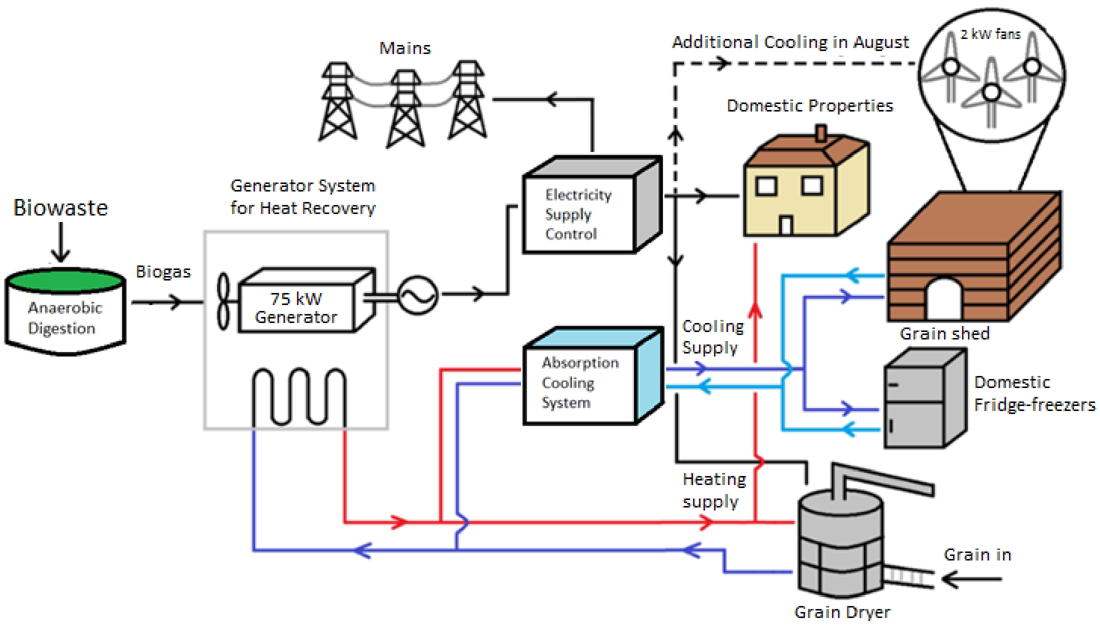


Figure 9 Trigeneration schematic for Option 3

3.4. Economic Analyses of Trigeneration Systems

3.4.1. Costs of Options

The essential components for a trigeneration system include a fuel source, a generator, a heat recovery unit, any energy storage solutions, and an absorption chiller. The fuel and capital costs associated with each option, along with specific investment, are given in Table 14.

Table 14 Associated costs and specific investment

		Option			
Parameter	Unit	Diesel	1	2	3
Annual Fuel Cost	£	74,461	0	0	0
Energy storage, extra parts	£	19,181	23,120	24,153	28,694
Power generation & electric storage	£	5300	170,040	211,225	218,265
Total Process CAPEX	£	25,118	186,762	228,979	240,560
Specific Investment	£/kW$_e$	421	3306	3893	3289

To determine the capital expenditure (CAPEX) for Options 1, 2 and 3, the cost of the anaerobic digestion system was adjusted according to the amount feedstock available. The capital cost for the diesel system is much lower than for the biogas systems, however annual fuel costs drive up the overall system cost. As observed in Table 14, the specific investment cost of the diesel system is also much lower than for the biogas systems, due to the comparatively high cost of AD units.

The annual operational and maintenance costs (OPEX) were set equal to 7% of the CAPEX, based on estimations for an AD system [44] and a CHP system [45].

3.4.2. Levelised Cost of Energy

A common economic indicator used to evaluate a renewable energy project is the levelised cost of energy (LCOE), which represents the discounted life cost of energy production. It is the net present value (NPV) at which energy should be sold for the project to breakeven over the system lifetime and can be calculated according to (5) [46].

$$LCOE = \frac{\sum_{n=0}^{N} \frac{(I_n + O_n + M_n + F_n)}{(1+d)^n}}{\sum_{n=0}^{N} \frac{E_n}{(1+d)^n}} \quad (5)$$

where I_n is the initial investment cost, O_n and M_n are the operation and maintenance costs, d is the interest rate from borrowing, F_n is the fuel cost, and E_n is the electricity produced in a particular year, n. The analysis assumed a discount rate of 6% based on other studies concerning AD and CHP systems [47] and the fuel cost for biogas systems was set to zero, due to feedstock availability.

The lifetime of a CHP system, which encompasses the generator and heat recovery units, is estimated by Huang et al. [48] to be 20 years, while absorption chillers, which are low maintenance and durable [49], can operate for 20-30 years. Based on manufacturers' specifications, the anaerobic digester can operate for upwards of 20 years. Therefore, an estimated lifetime of 20 years was adopted for the analysis. LCOE values considering electricity on its own, and then with energy generated for cooling and heating, are displayed in Table 15.

Despite low capital costs, the baseline diesel system exhibits the highest LCOE due to very high fuel costs. The price of red diesel in 2020 was approximately 52.47 ppl. With a fuel input of 0.00432 kg/s for the diesel generator, 141912 litres of diesel is required annually.

Table 15 LCOE values, for electricity and total energy

Option	LCOE (£ · MWh^{-1})	
	Electricity	Electricity, heat and cooling
1	57.45	38.83
2	67.66	44.92
3	57.17	37.80
Diesel	149.69	106.39

In terms of the biogas systems, Options 1 and 3 performed the best, with LCOEs of 57.45 £/MWh and 57.17 £/MWh, for electricity only. The LCOE of Option 2 is relatively high due to the increased cost of the AD system, accompanied by a small increase in biogas production from the addition of barley straw. Options 1 and 3 perform on similar scales. The composition of manure indicates a higher biogas yield, resulting in a greater electrical output for a smaller increase in AD system size. From Option 1 to Option 2, the feedstock input increases by 16% while the electrical power output increases by 4%. From Option 2 to Option 3, the addition of manure results in a feedstock increase of 17%, while the electrical power output increases by 24%. The difference in output is expected, as straw is known to be a less effective feedstock due to its lignocellulosic properties. Furthermore, the method of cost estimation for the AD system was based on the quantity of feedstock input per day. The AD system used for analysis has a loading capacity of 500 kg of feedstock per day, therefore 4 units are required for Option 1 (1875 kg/day) and 5 units are required for Options 2 and 3 (2177 kg/day and 2557 kg/day). This method of cost estimation is conservative. In reality, a system with a loading capacity of 1000 kg/day is less expensive than 2 systems with a capacity of 500 kg/day. Therefore, the LCOE for Option 2 is likely to be an overestimation.

3.4.3. Economic Incentives

Non-domestic RHI and tariff schemes provide additional sources of income, reducing the payback period of a project. Estimations of revenue from the RHI scheme are derived from rates available online. The new SEG scheme, established to transfer responsibility to individual energy suppliers, provides consumers with more flexible tariff rates for electricity export during peak periods. Rates vary between energy companies, therefore an average of 4.6 p/kWh, based on FIT payments from previous years, was used.

The annual income generated by tariff schemes was calculated with the following assumptions:

- For Options 1 and 2 in the trigeneration configuration, electricity generation is reduced in June and July to accommodate biogas storage for August and September.
- Cooling is reinforced by the 2 kW fans in August, with the estimation that 25 kWh is required per day based on the data provided by the farm.
- Tariff rates remain constant across the 20-year lifetime.

After deducting energy consumption across the farm, Options 1, 2 and 3 yield £26,680, £27,553 and £33,646 per year in payments via the trigeneration configuration.

3.4.4. Simple Payback Period

The simple payback period (SPB) describes the number of years required to recover the project cost for an investment. The SPB is calculated by taking into account the CAPEX, OPEX, savings from foregone energy bills due to project implementation, and any tariff payments. Figure 10 displays the project net income against time after installation. The payback period is identified as the point at which net income is positive and the project becomes profitable.

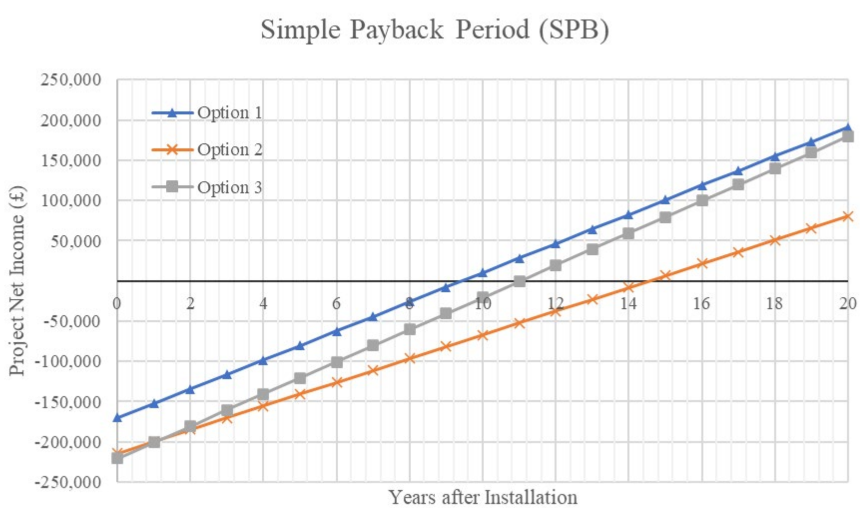


Figure 10 Cumulative cash flow in each year after installation

Figure 10 indicates an SPB of 9.4 years for Option 1, 14.5 years for Option 2, and 11 years for Option 3. As indicated by the LCOE, the longer payback period for Option 2 arises due to the higher cost of a larger AD system, accompanied by a comparatively small increase in biogas production.

The payback periods of AD and CHP systems vary from project to project, depending upon project scale and other technical conditions. Carlini et al. [47] reported payback periods of 9 years for a 100 kW AD-CHP plant, in addition to payback periods of 5 and 4 years for a 500 kW and 1000 kW plant, respectively. Achinas [50] also reported a payback period of 11 years for a 49 kW AD-CHP system. Thus, larger scale projects are able to recover investment costs sooner, as the cost per unit of electricity is reduced. Therefore, the SPB values determined for Options 1, 2 and 3 align with the results of this study, since the proposed systems are smaller in scale, driving up the cost per unit of electricity.

The SPBs indicate economic feasibility for all 3 options, as profitability is achieved before the projected lifetime of 20 years.

The calculation assumes that the project is internally funded, such that no interest is accrued from borrowing. If the project is instead entirely financed from debt, the lifecycle cost and payback periods will be greater. Assuming an interest rate of 6%, over a 20-year borrowing period, the SPBs for Options 1, 2 and 3 are 18, 26 and 19 years. With a shorter borrowing period, e.g. 15 years, where monthly repayments could still be covered by tariff payments, the SPBs are then reduced to 16, 23 and 17 years. Most likely, a combination of internal and external sources of finance would be utilized, offering true SPBs between the values discussed and those indicated in Figure 10.

The SPB metric does not take into account the time value of money, i.e. a discount rate, which justifies the need to consider multiple metrics in order to determine economic feasibility.

3.4.5 District Heating & Heat Energy Surplus

The growing interest in renewable energy technology is likely to increase incentives designed to reduce project costs.

During months where grain drying is not carried out, there is a significant heat energy surplus. As with electricity trading, it is possible that with the growing demand for decarbonisation of heating and cooling systems, there will be a considerable increase in district heating networks operating with buy-back schemes. The concept of two-way district heating has been explored by Sitra and Finnish Energy [51], although lack of infrastructure and high economic competitiveness have acted as barriers. However, in the future, if heat energy can be sold to networks, economic feasibility would be greatly increased.

A brief analysis can be conducted, assuming that unused heat can be bought at the same price per unit as the mains gas standard rate of £0.036 / kWh [52]. Additional revenue streams could amount to £57504, £64409, and £87559 per year for Options 1, 2, and 3. This would reduce payback time dramatically. For total internal funding, SPB across all options would fall between 1-2 years, while for total debt funding, SPB would fall between 2-4 years, making investments incredibly attractive from an economic standpoint.

The impact of trading heat is therefore significant, and with the government's decision in 2020 to invest £270 million into Green Heat Networks, such a scheme could be available in the near future.

3.5. Carbon Impact

The CO_2 emissions for each option were determined via analysis of components present in mass flow streams before and after the combustion process in ECLIPSE. The diesel engine generates 424.3 tonnes of CO_2 per year, while Options 1, 2 and 3 generate 346.9 tonnes, 378.3 tonnes and 442.5 tonnes per year, respectively. However, biogas is assumed to be a carbon neutral fuel as the CO_2 released during combustion is captured from the atmosphere by the feedstock, thus CO_2 from biogas is regarded as part of the natural carbon balance and therefore not a contributor to atmospheric CO_2.

In 2018, the UK national grid produced 235 g/kWh of CO_2, and 0.0292 g/kWh of CH_4, totalling 236 gCO_{2eq} /kWh [53]. Electricity consumption data provided by the case study implies annual emissions of 3400 $kgCO_{2eq}$. Similarly, assuming an annual gas consumption of 13500 kWh, emissions of CO_2 amount to 2484 kg. The largest contributor from farming operations is the combustion of red diesel for grain drying. Annual consumption of 11500 litres results in 33350 kg of CO_2 emissions, bringing the total mass of CO_{2eq} emitted by the farm to 39234 kg. This is the annual CO_2 displacement achievable through implementation of a combined AD and trigeneration system.

Additionally, any electricity sold back to the grid is net-zero and would supply some amount of the electrical energy demand currently met by fossil fuels, further reducing emissions to the atmosphere. For Options 1, 2 and 3, considering the electricity available for selling, the amount of CO_2 displaced by utilising this electricity over fossil-fuel derived electricity is 3530 kg, 3680 kg and 4722 kg, respectively. At present, the UK ETS scheme, which facilitates the sale of carbon credits at £40/tonne [54], applies to installations with thermal inputs of 2MW, however if this were extended to smaller capacity systems in the future, savings could be considerable. Table 16 compares the carbon impact of the diesel-supplied trigeneration system and the biogas systems.

Table 16 Comparison of annual net CO_2 emissions, where negative values indicate CO_2 prevented from entering the atmosphere and positive values indicate emission

Option	Units	1	2	3	Diesel
CO_2 from Combustion	$kg \cdot yr^{-1}$	0	0	0	+424300
CO_2 Displaced (Current Use)	$kg \cdot yr^{-1}$	-39234	-39234	-39234	-39234
CO_2 Displaced (Grid)	$kg \cdot yr^{-1}$	-3530	-3680	-4722	-3829
Net CO_2 contribution	$kg \cdot yr^{-1}$	-42764	-42914	-43956	+381237

The environmental advantages of implementing any of the biogas systems is evident, and analysis of the diesel system puts into perspective how crucial it is to shift to carbon-neutral fuels. One further environmental advantage is the production of a nitrogen-rich digestate alongside the biogas, which can be used to recover soil fertility.

4. Conclusions

This feasibility study has verified that a trigeneration system powered by biogas from AD is able to meet the demands of a medium-scale arable farm. From the wastes available on the farm – wheat straw, barley straw and manure – enough energy can be extracted to meet heating and electricity demands throughout the year. The cooling demand can be met by a 17.6 kW Robur absorption chiller, with cooling reinforced by existing fans in particularly warm months. The use of fan cooling in one month reduces tariff payments by £34.50, which is a relatively small percentage of what is earned.

The feasibility study has identified two configurations for the trigeneration system which would allow the farm to be completely self-sufficient:

- System 1: An input of wheat straw generates 56.5 kW of electricity. An electric battery must be incorporated for daily use. Heat energy from this system is 5703 MJ/day, while the maximum demand is 6914 MJ/day, therefore the burner already installed at the farm will be utilised to meet the deficit by burning biogas stored from previous months, ensuring that the project is still net-zero.
- System 2: An input of wheat straw, barley straw and manure generates 73.1 kW of electricity, along with 8122 MJ/day of heat. In this case, all energy demands are met.

Some key figures from the analysis include:

- Overall efficiencies of 66.8% and 67.1% are achieved in the wheat straw system and the straw-manure system, respectively.
- Considering income from non-domestic RHI and FIT schemes, payback periods of 9.4 and 11 years are predicted, assuming an internally financed project.
- The annual CO_2 displacement achieved by replacing electricity and heat energy derived from fossil fuels was calculated to be 42,764 kg and 43,956 kg.

Thus, this study has demonstrated that installing an AD trigeneration system on a medium-scale arable farm to meet energy demand is a viable alternative to utilising fossil-fuel derived energy and can be considered a potential avenue towards more sustainable farming practices.

In terms of further work, constant technological advancements within the energy industry will influence how attractive the investment is in the future. Batteries will likely become cheaper, as production costs are predicted to decline in conjunction with rising demand, and DERs become increasingly widespread. PCMs and chemical reaction-based thermal storage solutions may become commercially viable for small-scale, long-term applications. Additionally, improved financial support for projects focused on clean growth could reduce payback periods to much more attractive figures.

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References

[1] UK Government, "UK sets ambitious new climate target ahead of UN summit," 2020. [Online]. Available: www.gov.uk/government/news/uk-sets-ambitious-new-climate-target-ahead-of-un-summit#:~:text=Today%27s%20target%20is%20the%20first,net%20zero%20emissions%20by%202050.

[2] UK. National Statistics 2020, 2018 UK Greenhouse Gas Emissions, Final Figures. London: BEIS. Available at: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/862887/2018_Final_greenhouse_gas_emissions_statistical_release.pdf. [Accessed: Dec. 15 2020].

[3] O. Boucher, P. Friedlingstein, B. Collins and K. Shine, "The indirect global warming potential and global temperature change potential due to methane oxidation," in *Environ. Res. Lett.*, vol. 4, no. 4, pp 1-5, October 2009. [Online]. Available: https://iopscience.iop.org. [Accessed: Dec. 10, 2020]

[4] S. Friel, A. Dangourm, T. Garnett, K. Lock, Z. Chalabi, I. Roberts, A. Butler, C. Butler, J. Waage, A. McMichael, and A. Haines, "Public Health Benefits of Strategies to Reduce Greenhouse-gas Emissions: Food and Agriculture," in *The Lancet*, vol 374, no. 9706, pp. 2016-2025, November 2009. [Online]. Available: https://www.tabledebates.org. [Accessed: Dec. 10, 2020].

[5] A. Maturo, A. Petrucci, C. Forzano, G.F. Giuzio, A. Buonomano, and A. Athienitis, "Design and environmental sustainability assessment of energy-dependent communities: The case study of a livestock farm in the North of Italy," in *Energy Rep*., Jul. 2021, doi: 10.1016/j.egyr.2021.05.080.

[6] U.S. Energy Information Administration (EIA), "International Energy Outlook 2019," *U.S. EIA*. [Online]. Available: https://www.eia.gov/outlooks/ieo/. [Accessed: Mar. 10 2021].

[7] . C. Burger, A. Froggatt, C. Mitchell, and J. Weinmann, *Decentralised Energy: A Global Game Changer*. London: Ubiquity Press Ltd, 2020.

[8] K. Moller and T. Muller, "Effects of anaerobic digestion on digestate nutrient availability and crop growth: A review,", in *Eng. Life Sci.*, vol. 12, no. 3, pp. 242-257, 2012.

[9] N. Voca, T. Kricka, T. Cosic, V. Rupic, Z. Jukic, and S. Kalambura, "Digested residue as a fertilizer after the mesophilic process of anaerobic digestion," in *Plant Soil Environ.*, vol. 51, no. 6, pp. 262-266, 2005.

[10] B. Singh, Z. Szamosi, Z. Simenfalvi, and M. Rosas-casals, "Decentralised biomass for biogas production. Evaluation and assessment in Pubjab (India)," in *Energy Rep*., vol. 6, Jun. 2020, doi: 10.1016/j.egyr.2020.06.009.

[11] T.H. Chowdhury, "Technical-economical analysis of anaerobic digestion process to produce clean energy," in *Energy Rep.*, vol. 7, Nov. 2021, doi: 10.1016/j.egyr.2020.12.024.
[12] M. Lantz, "The economic performance of combined heat and power from biogas produced from manure in Sweden," in *Appl. Energy*, vol. 98, pp. 502-511, Oct. 2012, doi: 10.1016/j.aoenergy.2012.04.015.
[13] G. Leonzio, "An innovative trigeneration system using biogas as renewable energy," in *Chin. J. of Chem. Eng.*, vol. 26, no. 5, pp. 1179-1191, May 2018, doi: 10.1016/j.cjche.2017.11.006.
[14] C. Lahoud, J. Asmar, and M. Brouche, "Review of cogeneration and trigeneration systems," in *Afr. J. of Eng. Res.*, vol. 6, no. 3, pp. 39-54, Oct. 2018, doi: 10.30918/AJER.63.18.016.
[15] S.H.T Karim, T.A. Tofiq, M. Shariati, H.N. Rad, and A. Ghasemi, "4E Analyses and multi-objective optimization of solar-based combined cooling, heating and power system for residential applications," in *Energy Rep.*, vol. 7, Mar. 2021, doi:10.1016/j.egyr.2021.03.020.
[16] D.S. Tan, J.Y. Jin, S.W. Huang, S.T. Li, and H.E. Ping, "Effect of long-term applications of K fertiliser and wheat straw to soil on crop yield and soil K under different planting systems," in *Agricultural Sci. in Chin.*, vol. 6, no. 2., pp. 200-207, Feb. 2007, doi: 10.1016/S1671-2927(07)60035-2.
[17] T. Wei, P. Zhang, K. Wang, R. Ding, B. Yang, J. Nie, Z. Jia, and Q. Han. "Effects of wheat straw incorporation on the availability of soil nutrients and enzyme activities in semiarid areas," in *PLoS One*, Apr. 2015. [Online]. Available: https://journals.plos.org/plosone/article?id=10.1371/journal.pone.0120994
[18] S. Chen, Y. Wang, Z. Hu, and H. Gao, "CO2 emissions from a forest soil as influences by amendments of different crop straws," in *Catena*, vol. 131, pp. 56-63, Apr. 2015, doi: 10.1016/j.catena.2015.03.016.
[19] S. Menardo, and P. Balsari, "An analysis of the energy potential of anaerobic digestion of agricultural by-products and organic waste," in *Bioenergy Res.* vol. 5, no. 1, pp. 759-767, Mar. 2012, doi: 10.1007/s12155-01209188-0.
[20] G. Nathia-Neves, M. Berni, G. Dragone, S.I. Mussatto, and T. Forster-Carneiro, "Anaerobic digestion process: technological aspects and recent developments," in *Int. J. of Environ. Sci. and Technol.*, vol.15, no. 9, pp. 2033-2046, 2018, doi: 10.1007/s13762-018-1682.2.
[21] L. Molnar, and I. Bartha, "High solids anaerobic fermentation for biogas and compost production," in *Biomass*, vol. 16, no. 3, pp. 173-182, May 1988, doi: 10.1016/0144-4565(88)90090-X.
[22] X. Wang, G. Yang, Y. Feng, G. Ren, and X. Han, "Optimising the feeding composition and carbon-nitrogen ratios for improved methane yield during anaerobic co-digestion of dairy, chicken manure and wheat straw," in *Bioresource Technol.*, vol. 120, pp. 78-83, Jun. 2012, doi: 10.1016/j.biortech.2012.06.058.
[23] S. Nhuvaneshwari, H. Hettiarachchi, and J.N. Meegoda, "Crop Residue Burning in India: Policy Challenges and Potential Solutions," in *Int J Environ. Res. Public Health*, vol. 16, no. 5, pp. 832, Mar. 2019, doi: 10.3390/ijerph16050832.
[24] BEIS, "Combined Heat and Power – Finance," Feb. 2021. [Online]. Available: https://www.gov.uk/government/collections/combined-heat-and-power-chp-developers-guides [Accessed: Mar. 1, 2021]
[25] OFGEM, "FAQ: FIT scheme closure," 2020. [Online]. Available: https://www.ofgem.gov.uk/publications-and-updates/faq-fit-scheme-closure [Accessed: Mar. 10, 2021].
[26] OFGEM, "About the Smart Export Guarantee (SEG)," 2021. [Online]. Available: https://www.ofgem.gov.uk/environmental-programmes/smart-export-guarantee-seg/about-smart-export-guarantee-seg [Accessed Mar. 10, 2021].

[27] Y. Shao, J. Sui, S. Huang, J. Chen, B. Hu, and F.G.F. Qin, "Active regulation for improving the off design conditions of distributed combined cooling, heat and power system," in *Energy Rep*., vol. 6, Nov. 2019, doi: 10.1016/j.egyr.2019.11.018.

[28] "Sub-national Electricity and Gas Consumption Statistics," BEIS, London, UK, pp. 21, Jan. 2018. [Online]. Available: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/678653/Sub-national_electricity_and_gas_ consumption_summary_report_2016.pdf Accessed: Dec. 20, 2020.

[29] S.D. Watson, K.J. Lomas, R.A. Buswell, "Decarbonising domestic heating: What is peak GB demand?" in *Energy Policy*, vol. 126, pp. 533-544, Mar. 2019, doi: 10.1016/j.enpol.2018.11.001.

[30] DEFRA, "Farming Statistics, Provisional crop areas, yields and livestock populations at June 2019," 2019. [Online]. Available: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/868943/structure-jun2019prov-UK-28feb20.pdf [Accessed: Dec. 4, 2020].

[31] American Society of Heating, Refrigerating and Air Conditioning Engineers, "Thermal Properties of Foods," in *2006 ASHRAE Handbook: Refrigeration (SI)*, Atlanta: ASHRAE, 2006.

[32] *Thermal Properties of Grain and Grain Products*, American Society of Agricultural and Biological Engineers, May 2003. [Online]. Available: http://citeseerx.ist.psu.edu/viewdoc/download?rep=rep1&type=pdf&doi=10.1.1.214.1870

[33] A.N. Jangi, S. Mortazavi, G.H. Haghayegh, "Comparison of mechanical and thermal properties of two varieties of barley grains," in *Aust. J. of Agricultural Eng.*, vol. 2, no. 5, pp. 132-139. Jan. 2011.

[34] Toromont Power Systems, "60 kW Diesel Generator," Accessed: Mar. 1, 2021. [Online]. Available: www.toromontpowersystems.com/rental/generators-power-products/60-kw-diesel-generator-rental

[35] A. N. de Carvalho, E. Bazzo, and M. C. Pierobom, Experimental Results and Performance Parameters for Assessment of a Natural Gas Small Scale Cogeneration Plant, in 20th *Int. Congr. of Mechanical Engineering*, Gramado, Brazil, 2009.

[36] Phyllis2, *Database for (treated) biomass, algae, feedstocks for biogas production and biochar*, TNO Biomass and Circular Technologies, 2020. [Online]. Available: https://phyllis.nl/ [Accessed: Dec. 1, 2020]

[37] J. Gao, J. Li, A.C. Wachemo, H. Yuan, X. Zuo, and X. Li, "Mass conversion pathway during the anaerobic digestion of wheat straw," in *RSC Advances,* vol. 10, pp.27720-27727, Jul. 2020, doi: 10.1039/D0RA02441D.

[38] V. Moset, M. Poulsen, R. Wahid, O. Hojberg, and H.B. Moller, "Mesophilic versus thermophilic anaerobic digestion of cattle manure: Methane productivity and microbial ecology," in *Microb. Biotechnol*, vol. 8, pp. 787-800, Sep. 2015, doi: 10.1111/1751-7915.12271.

[39] G. Coppez, S. Chowdhury, and S.P. Chowdhury, "Battery storage and testing protocols for CHP systems", in *2011 IEEE Power and Energy Society General Meeting*, Detroit, USA, 24-28 July 2011. [Online]. Available: https://ieeexplore.ieee.org/document/6039175 [Accessed: Mar. 3 2021].

[40] A.D. Smith, P.J. Mago, and N. Fumo, "Benefits of thermal energy storage option combined with CHP system for different commercial building types," in *Sustain. Energy Technol. and Assessments*, vol. 1, pp. 3-12, Mar. 2013, doi: 10.1016/j.seta.2012.11.001.

[41] O. Linkevics C. Aivars, S. Jaundalders, and P. Ivanova, "Possibility of thermal energy storage implementation at CHP plant," in 2015 12th Int. Conf. on the European Energy Market (EEM), Lisbon, Portugal, May 19-22 2015. [Online]. Available: https://ieeexplore.ieee.org/document/7216640/citations#citations

[42] I. Sarbu, and C. Sebarchievici, "A comprehensive review of thermal energy storage," in *Sustain.*, vol. 10, no.1, Jan. 2018, doi: 10.3390/su10010191.

[43] C.N. Elias, and V.N. Stathopoulos, "A comprehensive review of recent advances in material aspects of phase change materials in thermal storage," in *Energy Procedia*, vol. 161, pp. 385 – 394, Mar. 2019, doi: 10.1016/j.egypro.2019.02.101.

[44] G.D. Oreggioni, B.L. Gowreesunker, S.A. Tassou, G.Bianchi, M. Reilly, and M.E. Kirby, "Potential for energy production from farm wastes using anaerobic digestion in the UK: An economic comparison of different size plants," in *Energies*, vol. 10, no. 2396, Sep. 2017, doi: 10.3390/en10091396.

[45] *Advice Notes on Biomass CHP Technology Economics for NPA Region*, Generating Renewable Energy Business Enterprise, Sep. 2019, Accessed on: Mar. 7 2021. [Online]. Available: grebeproject.eu/wp-content/uploads/2018/04/GREBE-Advice-Notes-biomass-chp-2.pdf

[46] X. Ouyang, and B. Lin, "Levelised cost of electricity (LCOE) of renewable energies and required subsidies in China," in *Energy Policy*, vol. 40, pp. 64-73, Jul. 2014, doi: 10.1016/j.enpol.2014.03.030.

[47] M. Carlini, E. M. Mosconi, S. Castellucci, M. Villarini, and A. Colantoni, "An economical evaluation of anaerobic digestion plants fed with organic agro-industrial waste," in *Energies*, vol. 10, no. 1165, Aug. 2017, doi: 10.3390/en10081165.

[48] Y. Huang, Y.D. Wang, H. Chen, X. Zhang, J. Mondol, N. Shah, N.J. Hewitt, "Performance analysis of biofuel fired trigeneration systems with energy storage for remote," in *Appl. Energy*, vol. 186, no. 3, pp. 530-538, Jan. 2017, doi: 10.1016/j/apenergy.2016.03.028.

[49] R. Nikbakhti, X. Wang, A.K. Hussein, A. Iranmanesh, "Absorption cooling systems – review of various techniques for energy performance enhancement," in *Alexandria Eng. J.*, vol. 50, no. 2, pp. 707-738, Apr. 2020, doi: 10.1016/j.aej.2020.01.036.

[50] S. Achinas, G.J.W. Euverink, "Feasibility study of biogas production from hardly degradable material in co-inoculated bioreactor," in *Energies*, vol. 12, no. 1040, Mar. 2019, doi: doi:10.3390/en/12061040

[51] Sitra, "Two-way district heating creates a heat trading market for the customer." Sitra. https://www.sitra.fi/en/news/two-way-district-heating-creates-heat-trading-market-customer/ [Accessed: Feb. 28, 2021].

[52] BEIS, "Annual Domestic Energy Bills," 2020. [Online]. Available: https://www.gov.uk/government/statistical-data-sets/annual-domestic-energy-price-statistics [Accessed: Mar. 13, 2021].

[53] BEIS, "2020 Government greenhouse gas conversion factors for company reporting," 2020. [Online]. Available: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/901692/conversion-factors-2020-methodology.pdf [Accessed: Mar. 15, 2021]

[54] J. Burke, R. Byrnes, and S. Fankhauser, "Global lessons for the UK in carbon taxes," Centre for Climate Change Economics and Policy, Aug. 2019.