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Techno-economic Analysis of a Cogeneration System in a Norwegian Farm

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ABSTRACT

This paper contains a techno-economic feasibility study of implementing an anaerobic digester to supply biogas to a cogeneration system, meeting the electricity and heating demand on a small-scale Norwegian livestock farm. Three configurations, using the same model with different compositions of biowaste, were identified to meet the energy demand on the farm while being financially feasible. Running simulations in ECLIPSE found overall system efficiencies of 86.25%, 90.12% and 87.83% for a combined heat and power (CHP) unit. Annual emissions can be reduced from self-produced energy, carbon sequestration and replacing mineral fertilisers with digestate by up to 2,605, 153,096, and 10,958 kg of CO_{2eq}, respectively. Economic analysis proved that with external funding, the payback period of the project would be between 10 and 19 years for the different options, which is within the 20-year lifetime of the system. Additionally, yearly savings of up to £1,406 and £2,761 could come from avoiding paying a potential carbon tax and using digestate.

Keywords: anaerobic digestion, biogas, CHP system, net-zero energy system, sustainable farming, and techno-economic analysis

NONMENCLATURE

Abbreviations	
AD	Anaerobic Digestion
CHP	Combined Heat and Power
GHG	Greenhouse Gas
NOK	Norwegian Krone

1. INTRODUCTION

The climate crisis and the means to reduce the effects of global warming continue to be a top priority in policy-making globally. Norway is at the forefront of utilising renewable energy, with renewable electricity accounting for 98% of the electricity production and having one the most electric vehicles on the road per capita [1].

In 2021, the Norwegian territorial GHG emissions reached 48.9 Mt of carbon dioxide (CO_2) equivalent (CO_{2eq}). Agriculture contributed to 9.4% of these emissions, accounting for 55% and 64% of the methane (CH_4) and nitrous oxide (N_2O) emissions. Mainly caused by livestock and crop production and using fertilisers [2]. Thus, the government has signed a letter of intent with the agricultural organisation to reduce emissions and enhance carbon uptake by 5 Mt CO_{2eq} [3]. Agriculture can reduce GHG emissions by improving waste management, replacing mineral fertilisers, and using energy-efficient technologies such as anaerobic digestion (AD). In AD, microorganisms break down organic matter without oxygen to produce biogas [4]. Waste such as animal manure and agricultural waste is common feedstock. Large amounts of animal manure on livestock farms are left to decompose openly in fields, emitting CH_4 and N_2O. Therefore, the Norwegian government outlined an ambition in 2009 to use 30% of the livestock manure to produce biogas from AD by 2020 [5].

The biogas produced from AD can be used as fuel in a combined heat and power (CHP) unit, typically used in district heating power plants. Industries with coincident power and thermal loads are suited for CHP, such as the agricultural sector [6]. Additionally, digestate, a by-product of AD, can be used as fertiliser as it contains necessary nutrients for the soil, such as nitrogen, phosphorus, and potassium [7].

A farm can become more sustainable by reducing the manure left to decompose openly, generating energy through biogas instead of diesel or the grid, and substituting mineral fertiliser with digestate. A research gap exists due to limited research regarding using deep bedding as a substrate in AD, utilising CHP systems in livestock farms, quantifying the reduction in emissions and costs from using digestate as fertiliser, and implementing CHP systems in farms in Norway. All demonstrating the novelty of this study.

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K. Fjørtoft et al. reported that the comparatively small size of Norwegian farms and the cold climate present challenges for implementing farm-scale biogas plants in Norway [8]. According to K-A. Lyng et al., there have been few drivers to produce electricity from waste in Norway due to the large share of renewable electricity, mainly from hydropower, and low electricity prices [9]. However, Norway experienced record-high electricity prices in 2022 due to the global energy crises [10]. The cost of mineral fertilisers in Norway has more than doubled from 2021 to 2022 due to limited access to necessary raw materials. Both putting generating electricity from AD and using digestate to replace mineral fertilisers on the agenda in Norwegian agriculture [11]. Thus, this paper aimed to perform a techno-economic feasibility study of meeting the electricity and heating demand on a livestock farm in Norway through biogas-fuelled cogeneration.

2. METHODOLOGY

2.1 Introduction of Case Study

The case study used data from a livestock farm in Vang in Valdres, Norway. According to the Norwegian scale, the farm is small to medium with 1.2 man-years. It consists of a 345 m^2 domestic property, a 605 m^2 barn that holds livestock, and 172 acres of unused land. The land is not used for cultivating crops as the high altitude of the farm gives nonarable soil. Currently, the farm has approximately 15 suckling cows and 130 ewes, which reproduce 15 calves and 220 lambs yearly. Arable land from nearby abandoned farms is used to cultivate grass for fodder.

2.2 Energy Consumption on farm

The energy consumption due to farming operations and domestic use is currently all supplied by electricity from the grid. Electricity drives an air source heat pump and other electrical applications. Statistics Norway found that 73% of Norwegian households use electricity as the primary source of heating [12].

The energy end-use was broken down into electricity, heating, and cooling applications to assess the feasibility of implementing a cogeneration (CHP) or trigeneration system (CCHP). Cooling was only used for one fridge and freezer in the domestic property, with minimal consumption, discarding a trigeneration system. The electricity supplier provided the yearly consumption, displayed in Fig. 1. According to estimates by the farmer, the demand is split equally between the domestic property and the barn, giving a domestic consumption of 26,833 kWh. Statistics Norway reported an average energy consumption per household of 26,301 kWh, supporting this estimate [13]. Throughout the report, the 2021 data was used.

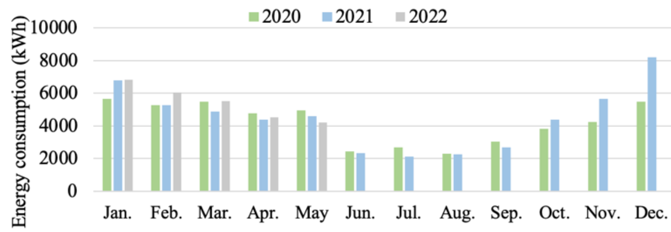

Fig. 1. Monthly energy consumption throughout the year

The farmer estimated the electricity usage to have a split of 40% and 60% for electricity and heating applications, respectively. In comparison, the standard Norwegian domestic property energy end-use constitutes of 22% and 78% electricity and heating, respectively [14]. The barn does not require any space heating, as the animals are kept warm from warm up in the bedding, which explains the lower share of heating usage on the farm compared to standards.

2.3 Biowaste Availability on the Farm

The biowaste available on the farm is cow manure (CM), sheep bedding (SB), and fodder residues (F). The sheep bedding consists of an equal amount of barley (B) and sheep manure (SM), and the fodder residues consist of timothy grass (T). The available amounts, the dry matter (DM) contents, and mass flow rates are presented in Table 1.

Type of biowaste	Amount (kg/year)	DM content (%)	Mass flow (DM kg/s)
CM	93,750	20 [1]	0.000594
SM	59,054	20 [2]	0.000373
B	59,054	89 [3]	0.001658
T	78,400	88 [3]	0.002188

Table.1. Biowaste availability, DM content, and mass flow

2.4 Cogeneration Schematic

A biogas CHP system was designed to replace the original energy system on the farm. The system was modelled and simulated to investigate whether the available biowaste generated sufficient biogas through AD to meet the energy demand of the farm. Fig. 2 displays the preliminary schematic for the cogeneration system. Biowaste is used as feedstock in the AD system to produce biogas for fuelling the CHP generator. Simultaneously, electricity from the generator is supplied to the domestic property and barn, while waste heat from the exhaust is either stored or immediately used for domestic heating and warming water in the barn. Additionally, the waste heat is used to cover the heat demand of the anaerobic digester itself.

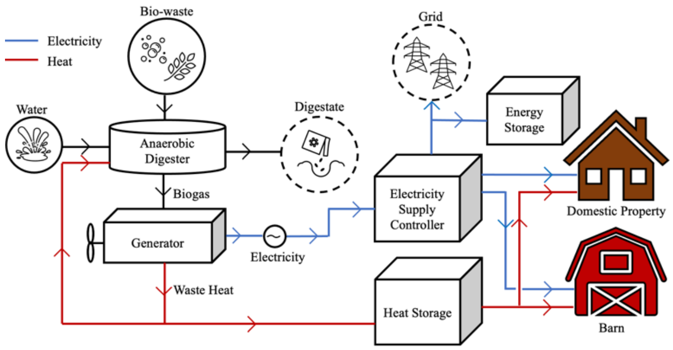

Fig.2. Preliminary cogeneration energy supply system

The minimum capacity of the CHP engine was found to be 4.92 kW_e, meeting the maximum hourly energy consumption of 12.30 kW. A commercially available CHP biogas engine of 5 kW from Seven Power was chosen, removing the need for electrical storage [15]. The domestic property will directly use the electricity, and any excess will go to the grid.

2.5 Software for Modelling

Two different systems were modelled in ECLIPSE: an AD system and a CHP system. Simulations were run to determine the biogas yield for the available biowaste through AD and the amount of electricity and heat generated by the CHP system. ECLIPSE is a chemical process software developed by the Energy Research Centre at the University of Ulster in 1992. It carries out the simulations by using (1) and (2) to model the combustion of diesel and biogas, as reported by B. Sturm et al. [16].

$$C_{12}H_{26} + 18.5(O_2 + 3.76N_2) \rightarrow 12CO_2 + 13H_2O + 69.56N_2 \quad (1)$$

$$CH_4 + 2(O_2 + 3.76N_2) \rightarrow CO_2 + 2H_2O + 6.52N_2 \quad (2)$$

3. RESULTS & DISCUSSION: TECHNICAL ANALYSIS

3.1 Anaerobic Digestion (AD) Simulations

The models of AD and CHP, created in ECLIPSE, were run to simulate the system presented earlier in Fig. 4. The C, H, N, O, and S composition of the biowastes was used as inputs in the AD process (Table 2). The AD simulations modelled a mesophilic digestion (MD) process with operating temperature of 25°C and a material conversion efficiency of 50%, as found by Gao et al. [17].

Element	Compositions by weight (%)			
	CM	SM	B	T
Carbon	42.33	51.33	49.18	49.38
Hydrogen	6.000	6.45	5.810	7.080
Oxygen	49.12	38.81	44.52	41.98
Nitrogen	2.550	2.65	0.430	1.460
Sulphur	0	0	0.060	0.100

Table. 2. CHONS composition of biowaste

The digestion of CM gave a biogas yield of 0.039 m^3/DM kg of CM and a methane content (CH_4 %) of 46.60% (Table 3). The biogas yield is within the researched range of 0.035 to 0.072 m^3/DM kg of CM [18] [19] [20]. A study by R. Alvarez found the methane content to be between 40% to 60% for manure [21]. Due to a lower operating temperature, the biogas yield and methane content were at the lower end of the ranges. Supported by K.J. Chae et al., who calculated a 17.4% reduction in methane yield for digestion at 25°C compared to 35°C [22]. The chosen CHP engine requires a CH_4 concentration of $\geqslant$55%, and the options viable for the engine are highlighted in bold in Table 3.

Option	Composition	Biogas (kg/s)	CH_4 (%)
1	CM	0.00012	46.70
2	SB	0.00142	37.32
3	F	0.00141	45.00
4	**CM + SB**	**0.00143**	**59.97**
5	**CM + F**	**0.00155**	**57.03**
6	SB+ F	0.00270	46.40
7	CM + SB + F	0.00284	53.08
8	**CM + SB + F/2**	**0.00213**	**55.58**
9	**CM + SB + F/4**	**0.00160**	**58.67**

Table. 3. Biogas yield for biowaste compositions

3.2 CHP Simulations

To confirm that the biogas CHP system accurately represented the Seven Power engine, model validation (MV) was performed. Running the MV gave errors below 5% for all the technical specifications of the engine, considered negligible, and the model was accepted.

Options 4, 5, 8, and 9 were used as feedstocks to evaluate the electricity and heat generation from the CHP system. A baseline case giving an electrical output of 5kW from MV, referred to as option 0, was included for comparison with the current system. The simulations proved that all the feedstock combinations could produce sufficient biogas to fuel the 5kW engine at maximum capacity (Table 4). Engines with greater capacities were considered such that excess electricity and heat could be sold to the grid or neighbouring farms. The efficiency increased with the capacity of the engine, as seen in Table 4. An expected trend as CHP systems of larger scale has greater efficiencies [23]. All options exceeded the electricity and heating demand on the farm of 4.92 kW and 7.38 kW.

	Energy outputs (kW)		Efficiencies (%)			Engine size
Option	Electricity	Thermal	Electrical	Thermal	Overall CHP	(kW)
0	5.160	13.0	24.23	61.03	85.26	5
4	6.185	15.3	25.04	61.94	86.98	7
5	6.154	15.4	24.91	62.35	87.26	7
8	8.500	20.7	26.33	63.89	90.12	9
9	6.750	16.7	25.28	62.55	87.83	7

Table. 4. Electricity and heat production from the biowastes

3.3 Heat Demand of Anaerobic Digester

For the 5kW baseline case, a 100 m^3 biogas PUXIN anaerobic digester will be used to produce the expected biogas to option 0, which is 94.5 m^3 [24]. The supplier informed that the anaerobic digester could be constructed for both less and greater biogas amounts. Therefore, the size of the anaerobic digester was scaled according to the amount of biogas needed for the various options. The energy demand of the anaerobic digester was examined to ensure a self-sufficient energy system. The heat demand of the digester is mainly composed of the heating required to raise the temperature of the incoming biowaste to the operating temperature, (3), and to account for the heat losses through the anaerobic digester (4).

$$Q_{req} = \dot{m}C_p(t_{ad} - t_b) \quad (3)$$

$$Q_{loss} = UA(t_{ad} - t_o) \quad (4)$$

Where Q is the heat, $\dot{m}$ is the mass flow of biowaste, t_{ad} is the operating temperature of the biowaste (25°C), t_b is the biowaste temperature, U is the U-value of the digester, and t_o is the outdoor temperature. The U-value for the different digester surfaces was found from the Building Acts and Regulations, called TEK17, regarding energy efficiency in Norwegian houses [25]. For t_b and t_o, the minimum outdoor temperature of -25°C, collected from a nearby weather station, was used as a conservative estimate. All systems proved to have adequate heat to meet the demand of the farm, Q_{farm}, and supply the anaerobic digester, Q_{ad}, with remaining excess heat between 3.79 to 9.73 kW (Table 5).

Option	Total heat demand of digester (kW)	Excess heat after considering Q_{farm} (kW)	Excess heat after considering Q_{farm} and Q_{ad} (kW)
0	1.828	5.62	3.79
4	2.697	7.92	5.22
5	2.543	8.02	5.47
8	3.590	13.32	9.73
9	2.923	9.32	6.39

Table. 5. Excess heat after considering heat needed for anaerobic digester

3.4 Thermal Storage

A thermal energy storage (TES), in form of a water tank, was integrated to meet the fluctuating heating demand and change the temperature of the waste heat to the appropriate range for the heating application. [26]. The water tank size was calculated by rearranging (3) to find the required mass of water. The temperature difference is between the temperature of the water tank, 70°C, and the main water supply, ~10°C, set by the Norwegian Institute of Public Health [27]. All the excess waste heat from the CHP engine was assumed to be stored for two hours. The required mass of the water for the options is displayed in Table 6. The farm already has two installed hot water tanks, each with a capacity of 200 litre of water, which can sufficiently store the heat.

Option	Excess waste heat from CHP (kW)	Required mass of water (kg/2 hours)
0	5.62	161.5
4	7.92	227.6
5	8.02	230.5
8	13.32	382.7
9	9.32	267.8

Table 6 – Required mass of water for thermal storage

4. RESULTS & DISCUSSION: ENVIRONMENTAL ANALYSIS

4.1 Emission Reduction from Energy Production

The CO_{2eq} emissions for all options were calculated by comparing the CO_2 component of the mass flow before and after combustion in ECLIPSE. A similar-sized diesel Excalibur engine was simulated for comparison purposes, as diesel is one of the most common fuels for generators used in farms [28] [29]. The diesel engine generated 37,528 tonnes of CO_{2eq} per year compared to 37,212 tonnes per year for biogas option 0 with the same power rating. However, biogas is classified as carbon neutral as the carbon combusted is initially removed from the atmosphere by the feedstock. Hence, the CO_2 emitted from biogas does not contribute to greenhouse emissions.

In 2019, the Norwegian Water Resources and Energy Directorate found that the electricity from the grid contributes to 17 g/kWh of CO2eq [30]. Significantly lower than the EU, with a reported value of 300 g/kWh of CO_{2eq}, due to the high share of renewable electricity in Norway [30]. The total electricity consumption on the farm implies a reduction in annual emissions of 912 kg of CO_{2eq}. Additionally, any electricity sold back to the grid or nearby farms would be net-zero and supply some of the demand met by non-renewable electricity, reducing the amount of emitted CO_{2eq}. Excess heat could be redirected to nearby farms and assuming that all their energy demand is supplied by electricity, the amount of displaced CO_{2eq} was calculated. Table 7 compares the carbon impact of the diesel and biogas systems.

	Amount of CO_{2eq} (kg/year)					
Emission type	0	4	5	8	9	Diesel
From combustion	0	0	0	0	0	+37,528
Displaced (current use)	-912	-912	-912	-912	-912	-
Displayed (electricity)	-	-100	-177	-473	-207	-
Displayed (heating)	-	-259	-457	-1,220	-533	-
Net CO_{2eq} contribution	-912	-1,272	-1,547	-2,605	-1,652	+37,528

Table. 7. Comparison of annual CO_{2eq} emission from biogas and diesel systems (negative values indicate CO_{2eq} prevented and positive indicate CO_{2eq} emitted)

4.2 Emission reduction from Digestate Use

An environmental benefit of digestate is the reduction of CO_2 emissions from carbon sequestration. The amount of digestate produced for each option was calculated as 50% of the dry biomass mass flow based on the 50% material conversion efficiency. The preliminary carbon content was found by taking the weighted average of the carbon content, from the CHNOS analysis, of the biowaste composition. The percentage of ash content (ash%) was used to find the actual carbon content by multiplying the weighted average by (1-ash%). In the short term, the amount of carbon sequestrated for a one-year period was reported to be between 26% to 81% [31] [32]. In the long-term, defined as a period of 100 years, a range between 4 to 14% of carbon sequestered was found by J. Møller et al. [33]. Performing an upper and lower estimate gave the potential amount of carbon stored in the soil and the reduction of CO_{2e} emissions, displayed in Table 8. The value before and after the hyphen is the lower and upper estimate, respectively.

	Long-term (l-t) storage (100 years)		Short-term (s-t) storage (1 year)	
Option	C sequestered (kg/year)	Prevented emissions (kg CO_{2eq}/year)	C sequestered (kg/year)	Prevented emissions (kg CO_{2eq}/year)
0	130 - 453	475 - 1,664	844 -2,623	3,091 - 9,629
4	705 - 2,467	2,587 - 9,055	4,582 -14,275	16,816 - 52,390
5	775 - 2,711	2,843 - 9,951	5,035 -15,689	18,482 - 57,578
8	2,060 - 7,210	7,560 - 26,461	13,339 - 41,715	49,142 - 153,096
9	786 - 2,751	2,885 - 10,098	5,110 - 15,920	18,754 - 58,427

Table. 8. Prevented emissions from long- and short-term carbon storage

To assess the overall environmental impact of using digestate, the emissions related to material sourcing, production, transportation, application to field, and field use must be compared with mineral fertilisers. It is challenging to individually estimate each of these emissions due to variability in factors such as the type of biowaste used, digestate composition, soil characteristics and weather conditions. A study by K. Timonen et al. performed an LCA analysis on anaerobic digestion, with a part dedicated to emissions related to digestate use [34]. The overall emissions for mineral fertiliser and digestate were calculated as 11.7 and 8.2 kg $CO2_{eq}$/kg N, respectively. Using this estimate and finding the amount of nitrogen content available from digestate by the same procedure described for the carbon content, the emissions saved using digestate were calculated (Table 9).

	Composition by weight (%)					
Option	N	Ash	Updated N	N mass flow (kg/s)	Annual N (kg/year)	Prevented emissions (kg CO_{2eq}/kg N year)
0	2.60	18.30	2.08	$6.19 \cdot 10^{-6}$	195	3,104
4	1.22	11.24	1.09	$1.43 \cdot 10^{-5}$	450	7,162
5	1.69	7.152	1.57	$2.17 \cdot 10^{-5}$	686	10,907
8	1.29	9.149	1.17	$2.18 \cdot 10^{-5}$	689	10,958
9	1.25	10.57	1.11	$1.61 \cdot 10^{-5}$	510	8,109

Table. 9. Prevented emissions from using digestate

5. RESULTS & DISCUSSION: ECONOMIC ANALYSIS

5.1 Emission Reduction from Energy Production

The capital expenditure (CAPEX) and operating expenditure (OPEX) of the cogeneration system was calculated. Innovation Norway offers a support scheme for bioenergy systems, covering up to 45% of the investment cost, which was adopted in the analysis [35]. Based on estimations for an AD plant by G. Oreggioni et al., the OPEX was set equal to 7% of the CAPEX [36]. The costs of the 5kW baseline case (option 0), the current electricity-driven air source heat pump system, and a diesel system was used for comparison purposes (Table 10). The costs of the biogas systems are displayed in the overall financial metric table at the end of the economic analysis (Table 12).

	Description	Current system	Diesel system
CAPEX (£)	Power unit	2,450	406
OPEX (£/year)	Maintenance	150	182
	Feedstock	6,386	21,401
	Potential carbon tax	7.70	317

Table. 10. Cost for current system and diesel system

5.2 Levelised Cost of Energy

An important economic metric used to compare different energy technologies (e.g., biogas and diesel) is the levelised cost of energy (LCOE). Defined as the average net present costs of generating one kWh of electricity over the lifetime of the energy system [37]. Calculated according to (6),

$$LCOE = \frac{\sum_{n=0}^{N} \frac{I_n + O_n + M_n + F_n}{(1+d)^n}}{\sum_{n=0}^{N} \frac{E_n}{(1+d)^n}} \quad (6)$$

where I_n is the investment cost, O_n is the operational cost, M_n is the maintenance cost, F_n is the fuel cost, d is the interest rate from borrowing, and E_n is the electricity produced in a particular year, n. The Central Bank of Norway set the policy rate to 2.75% from the 20th of January 2023, which was used as the interest rate [38]. The lifetime, N, of a CHP engine and AD unit was estimated to be 20 years by Y. Huang et al. and Y. Li et al., respectively [39] [40]. For an air source heat pump, A. Violante et al. specified a lifetime of 25 years [41]. Therefore, a lifetime of 20 years was adopted in the analysis. The LCOE values for solely electricity production and combined electricity and heat generation are displayed in Table 11.

	LCOE (£/MWh)			
	Without scheme		With scheme	
Option	Electricity	Electricity and heat	Electricity	Electricity and heat
0	85.9	24.0	67.01	18.87
4	99.6	28.7	78.17	22.51
5	100.1	28.6	78.58	22.43
8	93.1	27.1	73.14	21.29
9	91.2	26.3	71.63	20.62
Current	152.8	42.7	-	-
Diesel	493.2	141.9	-	-

Table. 11. LCOE for electricity and total energy with and without support scheme

All biogas options have lower LCOEs than the current and diesel system, mainly caused by the high fuel and electricity price in Norway of 17.89 NOK (£1.51) per litre and 1.415 NOK/kWh (0.119 £/kWh), respectively. All options had a similar biogas yield for the feedstocks, so the difference in cost efficiency is mainly related to the ratio of electricity produced to the electrical capacity of the engine.

5.3 Economic Incentives for Biogas Production

Multiple economic incentives are put in place by the Norwegian government to increase biogas production and ensure financial viability. Additional sources of revenue can be generated from using manure and selling electricity. There is a scheme by the Department of Agriculture where farmers can receive payment for delivering or using animal manure for biogas production [42]. For documenting the use of manure as substrate, 1583 NOK/suckling cow, 950 NOK/heifer, and 311 NOK/sheep (above one-years old) are granted annually. By selling excess electricity to the grid, an average rate of 0.085 NOK/kWh (0.0072 £/kWh) was estimated based on information from Norwegian energy companies.

There are saving opportunities with implementing the biogas options from using digestate as fertiliser and preventing carbon tax. Digestate can replace some of the currently used 22-2-12 NPK fertiliser. The amount of available digestate that could substitute mineral fertilisers was calculated by assuming that the amount of available nitrogen equalled 22% of the total weight of fertiliser. Then the value of digestate, was found using the current price of NPK fertiliser, 10.45 NOK/kg, reported by the farmer. Agriculture is currently exempt from carbon tax, but in November 2022, the second largest party in the Norwegian parliament proposed imposing a tax of 100 NOK/CO_{2eq} per tonne on agriculture [43]. The carbon tax savings were calculated based on the emissions prevented by implementing a biogas system.

Combining the cost and additional revenues highlighted the most financially viable options, displayed in bold in Table 12. A negative net annual cash flow indicated that option 5 was unviable. This is mainly due to missing out on revenue from the manure scheme as the sheep manure is not utilised.

		Options			
	Description	**4**	5	**8**	**9**
CAPEX (£)	AD system	21,854	21,854	28,099	21,854
	CHP system	18,428	18,428	23,693	18,428
	Total investment cost	40,282	40,282	51,791	40,282
	Investment cost with 45% coverage	22,155	22,155	28,485	22,155
OPEX (£/year)	Maintenance	2,820	2,820	3,625	2,820
	Feedstock	0	0	0	0
Revenue (£/year)	Using manure	5,416	2,004	5,416	5,416
	Selling electricity	74	72	220	110
	Selling heating				
Savings (£/year)	Potential CO_2 tax	512	592	1,403	574
	Using digestate	1,799	2,752	2,755	2,038
Annual account (£/year)	Net annual cash flow (excl. CAPEX)	**2,670**	-743	**2,010**	**2,706**

Table. 12. Overall financial metrics for biogas options

5.4 Payback Period

The payback period (PP) indicates the years required to cover the initial investment cost, making the project profitable. The interest rate of 2.75% was applied, assuming the project is financed from a loan. This metric does not consider the devaluation of money due to inflation. The PP was calculated iteratively in Excel. The compound interest formula, (7), was used to calculate the debt after the first year.

$$D_N = I_0(1+i)^N \quad (7)$$

Where D_N is the debt after N years, I_o is the initial investment costs, i is the interest rate and N is the number of years. Then the net annual cash flow was subtracted from the debt after year one, I_1. This value was used as the initial investment cost for year two to calculate the debt after year two. Repeating this procedure until the debt equalled zero or turned negative, gave the year profitability was achieved. Fig. 3 displays the profitability of the systems against years after installation of the system.

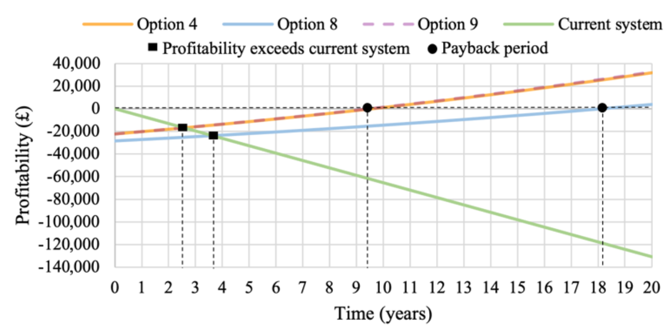

Fig. 3. Net financial status with

The annual payments were covered mainly by the revenue generated from the manure scheme, giving PPs of 10, 19 and 10 years for options 4, 8, and 9, respectively. All options proved financial feasibility as profitability is attained within the project lifetime of 20 years. Ignoring the PP, the profitability of biogas options 4, 8, and 9 exceeds the current energy system after 3, 4, and 3 years, respectively. This is because the biogas options avoid paying the high electricity price, saving £6,386 yearly, and generate up to £5,416 annually from the manure scheme. This emphasises that even for a greater PP, adopting a biogas system is more financially viable than keeping the current one.

The key results related to reduction in emissions, savings, and payback period is summarised in Table 13.

	Option	4	8	9
Reduced emissions (kg of CO_{2eq}/year)	Energy use and sale	1,272	2,605	1,652
	Carbon seq. (s-t)	16,816-52,390	49,142-153,096	18,754-58,427
	Carbon seq. (l-t)	2,587-9,055	7,560-26,461	2,885-10,098
	Digestate use	7,162	10,958	8,109
Profitability	Payback period (y)	10	10	19
Savings (£/y)	Carbon tax	513	1,406	575
	Digestate use	1,805	2,761	2,043

Table. 13. Key results from environmental and economic analysis

6. CONCLUSION

This techno-economic analysis proved that the available biowaste could provide sufficient biogas to meet the energy demand on the farm, ensuring a sustainable energy system. The financially viable biogas systems were options 4, 8 and 9.

The system considered is small-scale, which is why the reduction of CO_{2eq} seems small, and it can be questioned whether it is worth implementing a biogas CHP system in small-scale systems. However, Norwegian agriculture mainly consists of many small-scale farms [44]. Meaning that if the 9.4% contribution from agriculture to GHG emissions is to be reduced, it is essential that small-scale farms implement sustainable energy systems. CHP technology has not been applied to many farms in Norway and it is necessary to provide the farmers with knowledge to design, evaluate and implement such emission reducing solutions.

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REFERENCE

[1] Norwegian Government. (2016, May 11). *Renewable energy production in Norway*. Retrieved from https://www.regjeringen.no/en/topics/energy/renewable-energy/renewable-energy-production-in-norway/id2343462/

[2] Statistics Norway. (2022, November 3*). Emissions to air.* Retrieved from https://www.ssb.no/en/natur-og-miljo/forurensning-og-klima/statistikk/utslipp-til-luft

[3] Norwegian Ministry of Climate and Environment. (2020). *Norway’s Climate Action Plan for 2021-2030 Norwegian Ministry of Climate and Environment.* Retrieved from https://www.regjeringen.no/contentassets/a78ecf5ad2344fa5ae4a394412ef8975/en-gb/pdfs/stm202020210013000engpdfs.pdf

[4] United States Environmental Protection Agency. (2019, March 18). *How does anaerobic digestion work?* Retrieved from https://www.epa.gov/agstar/how-does-anaerobic-digestion-work

[5] Lyng, K.-A. (2019). *Country Report for Norway 2019 (draft*). Retrieved from https://task37.ieabioenergy.com/wp-content/uploads/sites/32/2022/02/Norway_-_Country_Report_september_2020.pdf

[6] United States Environmental Protection Agency. (2021, December 28). *CHP Applications*. Retrieved from https://www.epa.gov/chp/chp-applications

[7] Kalnina, I., Rugele, K., & Rubulis, J. (2018). *Digestate management practices in Latvia from nitrogen perspective.* Energy Procedia, 147, 368–373. https://doi.org/10.1016/j.egypro.2018.07.105

[8] Fjørtoft, K., Morken, J., Hanssen, J. F., & Briseid, T. (2014). *Methane production and energy evaluation of a farm scaled biogas plant in cold climate area*. Bioresource Technology, 169, 72–79. https://doi.org/10.1016/j.biortech.2014.06.077

[9] Lyng, K.-A., Skovsgaard, L., Jacobsen, H. K., & Hanssen, O. J. (2019). The implications of economic instruments on biogas value chains: a case study comparison between Norway and Denmark. Environment, Development and Sustainability, 22(8), 7125–7152.

[10] Statistics Norway. (n.d.-d). *Rekordhøy strømpris i 2022 – dempet av strømstøtte.* Retrieved from https://www.ssb.no/energi-og-industri/energi/statistikk/elektrisitetspriser/artikler/rekordhoy-strompris-i-2022--dempet-av-stromstotte

[11] Norwegian Broadcasting Corporation. (2022*). Mener Yaras gjødselpriser kan gi mindre mat til Norges befolkning. In NRK.* Retrieved from https://www.nrk.no/nordland/mener-yaras-gjodselpriser-truer-norges-selvforsyning-1.16047354

[12] Statistics Norway. (2022). *Energy consumption in households. Statbank Norway.* Retrieved from https://www.ssb.no/en/statbank/list/husenergi

[13] Statistics Norway. (2022). *Produksjon og forbruk av energi, energibalanse og energiregnskap.* Retrieved from https://www.ssb.no/statbank/table/11563/

[14] Energy Facts Norway. (2020). *Energy use by sector. In Energifakta Norge*. Retrieved from https://energifaktanorge.no/en/norsk-energibruk/energibruken-i-ulike-sektorer/

[15] Seven Power. (n.d.). *220V 380V 50Hz 5KW Biogas Cogeneration Systems.* Retrieved from https://www.gas-chp.com/sale-12973321-220v-380v-50hz-5kw-biogas-cogeneration-systems.html

[16] Sturm, B., Butcher, M., Wang, Y., Huang, Y., & Roskilly, T. (2012). The feasibility of the sustainable energy supply from bio wastes for a small scale brewery – A case study. Applied Thermal Engineering, 39, 45–52.
[17] Gao, J., Li, J., Wachemo, A. C., Yuan, H., Zuo, X., & Li, X. (2020). Mass conversion pathway during anaerobic digestion of wheat straw. RSC Advances, 10(46), 27720–27727.
[18] Kechrist, O., Mamphweli, N., Meyer, E., Makaka, G., & Nwokolo, N. (2020). Design and Fabrication of a Plastic Biogas Digester for the Production of Biogas from Cow Dung. Journal of Engineering, 8.
[19] Hidayati, S., Utomo, T. P., Suroso, E., & Maktub, Z. A. (2019). Technical and technology aspect assessment of biogas agroindustry from cow manure: case study on cattle livestock industry in South Lampung District. IOP Conference Series: Earth and Environmental Science, 230.
[20] IEA Bioenergy. (2021). Potential anutilizationon of manure to generate biogas in seven countries | Bioenergy. Retrieved from https://www.ieabioenergy.com/wp-content/uploads/2021/07/Potential-utilization_WEB_END_NEW.pdf
[21] Alvarez, R., Villca, S., & Lidén, G. (2006). Biogas production from llama and cow manure at high altitude. Biomass and Bioenergy, 30(1), 66–75.
[22] Chae, K. J., Jang, A., Yim, S. K., & Kim, I. S. (2008). The effects of digestion temperature and temperature shock on the biogas yields from the mesophilic anaerobic digestion of swine manure. Bioresource Technology, 99(1), 1–6.
[23] Chae, K. J., Jang, A., Yim, S. K., & Kim, I. S. (2008). The effects of digestion temperature and temperature shock on the biogas yields from the mesophilic anaerobic digestion of swine manure. Bioresource Technology, 99(1), 1–6.
[24] Alibaba.com. (n.d.-b). *Puxin 100 M3 Cbm Biogas Plant For Cow Farm Waste Treatment - Buy Biogas Plant,Cow Farm Waste Treatment Anaerobic Digester Biogas Machine,Puxin Biogas Plant Product on Alibaba.com*. Retrieved from https://puxinbiogas.en.alibaba.com/product/60323385838-803018487/PUXIN_100_m3_cbm_biogas_plant_for_cow_farm_waste_treatment.html
[25] Direktoratet for byggkvalitet. (2022, July 1). *§ 14-3. Minimumsnivå for energieffektivitet*. Retrieved from https://dibk.no/regelverk/byggteknisk-forskrift-tek17/14/14-3/
[26] Campos Celador, A., Odriozola, M., & Sala, J. M. (2011). Implications of the modelling of stratified hot water storage tanks in the simulation of CHP plants. Energy Conversion and Management, 52(8), 3018–3026.
[27] Norwegian Institute of Public Health. (2020, April 8). *Interne vannfordelingsnett som forsyner dusjer og andre aerosoldannende tappepunkter.* Retrieved from https://www.fhi.no/nettpub/legionellaveilederen/temakapitler/interne-vannfordelingsnett-som-forsyner-dusjer-og-andre-aerosoldannende-tappepunkter/
[28] Alibaba.com. (n.d.-a). *3kw 4.6kw 5kw 5.5kw 6kw 6.5kw 7kw 7.5kw 8kw 8.5kw Single And Three Phase Silent Diesel Generator 5kva Generador Diesel - Buy Silent Diesel Generator,Generador Diesel Silencioso,Diesel Generator 5kw Product on Alibaba.com*. Retrieved February 17, 2023, from ´ website: https://www.alibaba.com/product-detail/3kw-4-6kw-5kw-5-5kw_62108201083.html?spm=a2700.galleryofferlist.normal_offer.d_title.5e3162c5mV8Vny&s=p.
[29] Agricultural Applications for Generator Sets. (n.d.). *Information Sheet #77*. Retrieved from https://ps.buckeyepowersales.com/wp-content/uploads/2017/03/Agricultural-Applications-for-Generator-Sets_BPS_77.pdf
[30] Norwegian Water Resources and Energy Directorate. (n.d.-b). *Lavt klimagassutslipp knyttet til norsk strømforbruk i 2021*. Retrieved from https://www.nve.no/nytt-fra-nve/nyheter-energi/lavt-klimagassutslipp-knyttet-til-norsk-stroemforbruk-i-2021/
[31] Nyang'au, J. O., Møller, H. B., & Sørensen, P. (2022). Nitrogen dynamics and carbon sequestration in soil following application of digestates from one- and two-step anaerobic digestion. Science of the Total Environment, 851(158177).
[32] Reuland, G., Sigurnjak, I., Dekker, H., Sleutel, S., & Meers, E. (2022). Assessment of the Carbon and Nitrogen Mineralisation of Digestates Elaborated from Distinct Feedstock Profiles. Agronomy, 12(2), 456.
[33] Møller, J., Boldring, A., & Christensen, T. (2009). Anaerobic digestion and digestate use: accounting of greenhouse gases and global warming contribution. Waste Management & Research, 27, 813–824.
[34] Timonen, K., Sinkko, T., Luostarinen, S., Tampio, E., & Joensuu, K. (2019). LCA of anaerobic digestion: Emission allocation for energy and digestate. Journal of Cleaner Production, 235, 1567–1579.
[35] Innovasjon Norge. (2022). *Fornybar energi i landbruket.* Retrieved from https://www.innovasjonnorge.no/no/tjenester/landbruk/finansiering-for-landbruket/fornybar-energi-i-landbruket/
[36] Oreggioni, G. D., Gowreesunker, B. L., Tassou, S. A., Bianchi, G., Reilly, M., Kirby, M. E., … Theodorou, M. K. (2017). Potential for Energy Production from Farm Wastes Using Anaerobic Digestion in the UK: An Economic Comparison of Different Size Plants. Energies, 10(9), 1396.
[37] Violante, A. C., Donato, F., Guidi, G., & Proposito, M. (2022). Comparative life cycle assessment of the ground source heat pump vs air source heat pump. Renewable Energy, 188, 1029–1037
[38] Bank of Norway. (2023). *Rate decision January 2023.* Retrieved from https://www.norges-bank.no/en/topics/Monetary-policy/Monetary-policy-meetings/2023/january-2023/
[39] Huang, Y., & Wang, Y. (2017). Performance analysis of biofuel fired trigeneration systems with energy storage for remote households. Applied Energy, 186, 530-538
[40] Li, Y., Han, Y., Zhang, Y., Luo, W., & Li, G. (2020). Anaerobic digestion of different agricultural wastes: A techno-economic assessment. Bioresource Technology, 315(123836). https://doi.org/10.1016/j.biortech.2020.123836

[41] Violante, A. C., Donato, F., Guidi, G., & Proposito, M. (2022). Comparative life cycle assessment of the ground source heat pump vs air source heat pump. Renewable Energy, 188, 1029–1037.
[42] Norwegian Agriculture Agency. (n.d.). *§ 4. Beregning av tilskudd.* Retrieved from https://www.landbruksdirektoratet.no/nb/jordbruk/ordninger-for-jordbruk/tilskudd-for-a-levere-husdyrgjodsel-til-biogassanlegg/forskrift-om-tilskudd-for-levering-av-husdyrgjodsel-til-biogassanlegg-kommentarer-til-regelverk/-4.beregning-av-tilskudd
[43] Høyre. (n.d.). Høyres Alternative Budsjett 2023. Retrieved from https://hoyre.no/content/uploads/2022/11/Alternativt-statsbudsjett-DIGITAL2-.pdf
[44] Heie, K. (2003). Viable Small Scale Farming in Norway. Retrieved from https://www.researchgate.net/publication/23512498_Viable_Small_Scale_Farming_in_Norway