

AGRICULTURAL BIOGAS PLANTS – ENERGY BALANCE

John MORKEN¹, Kristian FJØRTOFT², Tormod BRISEID³

¹Norwegian University of Life Sciences, Department of Mathematical Sciences and Technology

Drobakveien 31, 1432 Aas, Norway

²Aalesund University College, Faculty of Engineering and Natural Sciences

Larsgaardsveien 2, 6009, Aalesund, Norway

³Bioforsk, Divisjon Miljø,

Fredrik A. Dahls vei 20, 1430 Aas, Norway

Email: johnmo@nmbu.no, krfj@hials.no, tormod.briseid@bioforsk.no

Abstract. Greenhouse gas (GHG) emissions from agriculture could be reduced by producing biogas from animal manure. Biogas production would reduce methane emissions from stored manure and provide climate-neutral methane gas, which could be used for energy purposes, improving the GHG balance. One problem for farmers could be the investment costs for biogas plants, which are currently high. This study compared energy production in two dairy manure-based, farm-scale biogas plants in Norway and the energy consumption in producing this energy. The results for the plants, which had no heat exchanger and minimal insulation on the biogas reactor, clearly demonstrated the necessity of using a co-substrate with dairy manure. Using only manure during January at the Åna plant, SW Norway, resulted in only 10% net energy production. The best result obtained when using co-substrate was 73% (fish ensilage; October). Maximum biogas yield of 0.355 m³ CH₄/kg VS was recorded by having 31% of total VS provided by fish ensilage with 31 days retention time. Using food waste to supply 29% of total VS gave maximum biogas yield of 0.268 m³ CH₄/kg VS with 23 days retention time. There were also differences between the plants, which were of different designs. The lowest heat consumption was observed for the Åna plant with its one reactor (in October) and the highest heat consumption for the Tomb plant with its two reactors running in parallel (in January/February). Reactor design probably resulted in higher heat consumption for all periods in the Tomb plant, as biogas storage capacity can be too small when only the headspace of the reactor(s) is used for storage. External biogas storage capacity is recommended.

Key words: Agriculture, manure, biogas, energy balance.

INTRODUCTION

Emissions of CH₄ and N₂O are regulated as part of the Kyoto Protocol under the United Nations Framework Convention on Climate Change (UNFCCC). The greenhouse gas (GHG) reduction target for the European Union (EU) is 9% by 2008-2012 compared with 1990, and the EU has approved a further reduction target of 40% by 2030 [1]. Biogas production has been introduced by the Norwegian government as a contribution to reducing GHG emissions from the agriculture sector, in a white paper which specifies that 30% of the livestock manure on Norwegian farms should be used for biogas production by 2020 [2]. Furthermore, the EU 2030 target has been adopted in Norway [3]. Production of biogas through anaerobic digestion (AD) of manure is regarded as a viable method to reduce emissions from agricultural activities [4].

Anaerobic digestion of manure provides the potential for production of renewable energy, but the process also requires thermal energy to heat new substrates and to cover heat losses from reactor/s and pipes. The amount of energy required depends on the temperature in the digester, the ambient temperature, the temperature of new substrates and the amount of insulation used on the reactor/s and pipes [5]. Energy recovery devices such as heat exchangers can reduce the demand for thermal energy [6]. Using a heat exchanger to enable the digestate to heat new substrates improves the energy efficiency of the process. However, the high investment costs limit the use of this type of equipment on smaller farm-scale biogas plants. Agriculture in Norway is characterised by relatively small farms [7], and biogas plants thus have to be relatively small to fit the farm structure. Moreover, small biogas reactors have a large surface area per unit volume compared with larger reactors, which can reduce the energy efficiency. In addition, mean annual temperature in Norway is below 10°C [8], and during the winter the temperature in many areas is below 0°C for several months. This requires insulation to keep the heat losses at an acceptable level.

It has been shown that the total reduction in GHG emissions from manure management depends not only on reducing GHG losses from manure during storage and field application, but also on the substitution effect of biogas compared with fossil fuel. Therefore, reduced internal use of energy is positive, as it leads to increased substitution of fossil fuel. It has been concluded that substitution of fossil fuel has the greatest potential to reduce GHG emissions [9].

Farm-scale biogas production is anticipated to be one of the future suppliers of renewable energy in Norway. Despite the large areas of non-productive mountain in the country, the total potential of agricultural biogas from straw and manure is estimated to be 3055 GWh year⁻¹ [10]. By including energy crops and food waste as co-substrates, this figure could be increased. However, due to high investment costs for biogas production, there are currently fewer than five operative farm-scale biogas plants in Norway [11].

The small farm size and the scattered pattern of farming areas caused by mountains and fjords do not favour large-scale biogas systems in Norway. The relatively large heat losses from small reactors, combined with the harsh climate and limited experience of building biogas plants for cold climate areas, indicate a need for improving the energy efficiency of biogas plants. The present analysis, which is based on data from two Norwegian biogas plants, sought to identify crucial characteristics in plant design and in choice of substrates.

MATERIALS AND METHODS

The two farm-scale biogas plants Åna in Rogaland on the SW coast [12] and Tomb in Østfold in SE Norway [13] were investigated in terms of their energy balance, the energy contribution from the different substrates they use and the possibility of optimising energy production. Both plants use dairy cow slurry as the main substrate, while the co-substrate at the Åna plant is fish ensilage and at the Tomb plant it is food waste.

The Åna biogas plant consists of one circular 314 m³ reactor made from 4 m high concrete elements, insulated on the inside by 100 mm thick insulating foam plates. The biogas is transported from the reactor via a fan to a gas boiler. The biogas is used to heat water for the heating system in a prison located near the farm. The hot water boiler can use oil as an alternative fuel and is only switched to biogas when the gas pressure in the headspace of the reactor is high enough to feed the boiler to 100%. The temperature in the reactor is set to 37°C and the reactor is run semi-continuously and fed 5 times per day. An electrical propeller stirs the reactor contents continually. The following parameters were recorded during the test period (July 2009-June 2011): Gas production, energy consumption (electrical and thermal), daily volume of substrates used, and chemical composition of substrates and digestate (occasionally). The gas storage unit consists of the headspace of the reactor.

The Tomb biogas plant is of a different design. It consists of two reactors, each 175 m³, running in parallel. The reactors are made of insulated plastic material and most of the body is below the soil surface. Inside the reactors there is a fibreglass reinforced plastic sheet. A positive displacement pump (lobe type pump) is used as a metering device when pumping substrate (food waste and manure) in and digestate out. Each reactor has a propeller-type stirrer. The temperature in the reactors is set to 37°C, but due to problems with the heating system in the reactors, the actual reactor temperature was several degrees lower for most of the study period. The biogas is combusted in a boiler located close to the reactors and the hot water is pumped to nearby (500 m) school buildings and dormitories, where it is used for heating. The heat losses in this pipe were included in the heat losses from the plant. The following parameters were recorded during the monitoring period (April 2012-June 2013): Energy production, energy transfer to school buildings, daily volume of substrates used, and chemical composition of substrates and digestate (occasionally).

RESULTS AND DISCUSSION

From the long series of monitoring data for the two plants, data for short periods with a stable supply of substrate were selected. Three such periods were selected for the Åna plant, while 21 short periods were used for further analyses of the Tomb plant and from these 21 periods, four longer periods were created according to ambient temperature; April/May 2012, November/December 2013, January/February 2013, and March/April 2013.

The average values in each of the periods were calculated separately for the Åna plant (Table 1) and the Tomb plant (Table 2). The retention time varied in the study period, mainly due to varying volumes of substrate

treated per day in the reactors. This was due in turn to varying numbers of animals and variations in the volume of fish ensilage available. Although fish ensilage only contributed 8-10% of total volume, it had a higher dry matter (DM) content and higher proportion of volatile solids (VS, % of DM), so its contribution to total VS was around 40%. In period 3 for the Åna plant (Table 1), methane production was low when only manure was used as substrate and also low compared with the production rate observed for Åna substrate in the laboratory [14]. Using fish ensilage as co-substrate contributed to high specific methane production, which also resulted in increased energy production. The variation in retention time resulted in variation in the amount of energy produced in a pattern which did not follow that of specific methane production. Consumption of electricity represented almost 50% of the heat consumed, with colder periods clearly resulting in higher heat consumption (Table 1). The energy was used both for heating new substrate and to compensate for heat losses. The reactor had no insulation on the top cover sheet and this was probably the main reason for the high heat consumption.

The data also indicated that it would be wrong to use a set percentage of energy produced for calculating the internal energy usage, since consumption is dependent on the losses of energy, and not on the energy input. Compared with results from Germany [5], the energy consumption in the Åna plant as a percentage of energy produced was much higher, but the specific energy consumption was more similar to results reported for farm-scale plants in Sweden [6],[11].

Table 1

Energy production and consumption (average per period) in the one-reactor Åna plant in SW Norway in periods 1-3

			Period 1 (week 36-39, 2009)	Period 2 (week 49-53, 2009)	Period 3 (week 49-52, 2010 and week 1-2, 2011)
Hydraulic retention time		Days	31	26	28
Volatile solids (VS) from fish ensilage		% of total VS	46	35	0
Specific methane production		m ³ /kg VS	0.355	0.223	0.122
Energy production		kWh/week	11,900	14,800	5,600
Energy consumption	Electricity	kWh/week and m ³ reactor	4.1	4.4	3.6
		% of methane produced	8.5	8.4	18.1
	Heat	kWh/week	2,095	5,350	3,892
		kWh/week and m ³ reactor	8.4	19.1	13.9
		% of methane produced	30	42	70
	Total	kWh/week and m ³ reactor	13	24	17
% of methane produced		27	45	88	

Compared with Åna, the hydraulic retention time in the Tomb plant was shorter in all periods and especially in period 4 (Table 2), where it was only approximately half the retention time at Åna. The food waste substrate contained less VS than the fish ensilage and, although the input ratio based on mass was higher, the percentage of VS was lower for all periods. This is attributable to the higher concentrations of protein and fat components in fish ensilage than in the food waste used in the Tomb plant. The shorter retention time in the Tomb plant combined with moderately high specific methane production resulted in higher energy production than in the Åna plant. The electricity consumption was low for all periods but the heat consumption was higher in colder periods, which was expected since the heat losses were higher in these periods. There were problems during the recording periods, which can be summarised as:

- Too small capacity of the burner, which caused loss of biogas from the reactors if the production became very high.

- Too little biogas storage capacity. This meant that the burner had to run when the gas was available and not only when there was demand for energy.
- The plant had seven different heating pipes and these all interacted with each other. Controlling the heating of the reactors was therefore difficult.

Table 2

Energy production and consumption (average per period) in the twin-reactor Tomb plant in SE Norway in periods 1-3

			Period 1 (week 16-20, 2012)	Period 2 (week 45-50, 2012)	Period 3 (week 5-10, 2013)	Period 4 (week 11-18, 2013)
Hydraulic retention time		Days	18	23	21	15
Volatile solids (VS) from food waste		% of total VS	22	31	30	30
Specific methane production		m ³ /kg VS	0.186	0.268	0.263	0.261
Energy production		kWh/week	14,871	12,932	12,565	17,056
Energy consumption	Electricity	kWh/week and m ³ reactor	1,6	1.8	2.0	1.9
		% of methane produced	3.2	4.2	4,7	3.3
	Heat	kWh/week	6,000	7,125	7,822	6,678
		kWh/week and m ³ reactor	20	24	26	22
		% of methane produced	41	55	62	39
	Total	kWh/week and m ³ reactor	6,469	8,864	9,681	8,444
% of methane produced		45	59	67	42	

Overall, these results show that increased retention time in small-scale reactors also increases the specific methane production, as shown here for the Åna plant. This could also lead to lower emissions from final storage of the bioresidues. On the other hand, it also resulted in much lower total energy production per week, which is a critical shortcoming.

CONCLUSIONS

The conclusions from analysis of the data from these two farm-scale biogas plants were that:

- Heat consumption in anaerobic digestion plants is high in the Norwegian climate. Net energy production could be increased by using co-substrate/s. This is probably essential for the economic viability of farm-scale plants.
- A large proportion of the energy produced is used to heat new substrate. A heat exchanger would reduce the energy demand substantially.
- Some of the energy produced is used to compensate for heat losses in the reactor. In both plants studied there was no insulation on the top cover. Investment in a well-insulated cover is strongly recommended.
- Comparing energy consumption in the two plants, the Tomb plant had the highest heat consumption per m³ reactor. Good design of the reactor is essential for minimising heat consumption and maximising net production of GHG-neutral energy.
- Increasing the hydraulic retention time resulted in higher specific methane production, but decreased energy production. There was a tendency for this to result also in decreased net energy production.

ACKNOWLEDGEMENTS

We gratefully acknowledge the financial support of the Norwegian Research Council (Grant 188914) and the Norwegian Agricultural Authority (Grant 33 000 046). Additional financial support was provided by Follo Ren IKS, Biowaz AS, Green Gas AS, Innovasjon Norge and the Norwegian Farmers' Union. We would also like to acknowledge the owners of both plants, who made this work possible. We especially acknowledge Gaute Njå (Åna plant) and Knut Huseby for their assistance.

REFERENCES

1. European Council (2014). 2030 Climate and Energy Policy – Conclusions. pp. 16. Available at: http://www.consilium.europa.eu/uedocs/cms_data/docs/pressdata/en/ec/145397.pdf
2. The Norwegian Department of Agriculture and Food (2009). St.meld. Nr. 39. (2008–2009) Klimautfordringene – landbruket en del av løsningen. (Norwegian White Paper) Available at: <https://www.regjeringen.no/nb/dokumenter/stmeld-nr-39-2008-2009-/id563671/>
3. <https://www.regjeringen.no/nb/dokumenter/stmeld-nr-39-2008-2009-/id563671/>
4. Det Kongelige Klima- og Miljødepartementet (2015). Ny utslippsforpliktelse for 2030 – en felles løsning med EU. Stortingsmelding 13 (2014/15). pp. 29. Available at: <https://www.regjeringen.no/contentassets/07eab77cc38f4085abb594a87aa19f10/no/pdfs/stm201420150013000dddpdfs.pdf>
5. Lyng, K.-A., Saur Modahl, I., Møller, H., Morken, J., Briseid, T. and Hanssen, O.J. (2015). The BioValueChain model: a Norwegian model for calculating environmental impacts of biogas value chains. *The International Journal of Life Cycle Assessment* XX, 1-13. Available from DOI 10.1007/s11367-015-0851-5.
6. Deublein, D. & Steinhauser, A. (2008). *Biogas from waste and renewable resources: an introduction*. Wiley-VCH Verlag. Weinheim, Germany, 443 pp.
7. Berglund, M. & Börjesson, P. (2006). Assessment of energy performance in the life-cycle of biogas production. *Biomass and Bioenergy* 30 (3), 254-266.
8. SSB, 2014. *Structure of agriculture, 2014. Agriculture, forestry, hunting and fishing*. Available from <https://www.ssb.no/statistikkbanken/selecttable/hovedtabellHjem.asp?KortNavnWeb=stjord&CMSSubjectArea=jord-skog-jakt-og-fiskeri&checked=true>.
9. Statistisk Sentralbyrå, 2012. *Statistisk årbok 2012*. Oslo/Kongsvinger, Norway, 400 pp.
10. Morken, J. & Sapci, Z. (2013). Evaluating biogas in Norway - bioenergy and greenhouse gas reduction potentials. *Agric Eng Int: CIGR Journal* 15 (2), 13.
11. Raadal, H., Schakenda, V. & Morken, J. (2008). *Potensialstudie for biogass i Norge*. Oppdragsrapport. 21/08 Fredrikstad, Norway. 55 pp.
12. Klima- og forurensningsdirektoratet (2013). *Underlagsmateriale til tverrsektoriell biogass-strategi*. TA 3020. Norwegian Environment Agency, Oslo, Norway. 246 pp.
13. Fjørtoft, K., Morken, J., Hanssen, J.F. and Briseid, T. 2014. Methane production and energy evaluation of a farm scaled biogas plant in cold climate area. *Bioresource Technology* 169, 72-79.
14. Fjørtoft, K., Morken, J., and Gjetmundsen, M. 2014. *Dokumentasjon av biogassanlegget på Tomb VGS*. IMT Rapport 54, NMBU, Ås, Norway 2014, 43 pp.
15. Solli, L., Bergersen, O., Sørheim, R. and Briseid T. (2014). Effects of a gradually increased load of fish waste ensilage in co-digestion with cow manure on methane production. *Waste Management* 34, 1553-1559.