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Simulation of livestock biomass resource recycling and energy utilization model based on dry type methane fermentation system

Yoshiaki Kimura[1], Takeshi Suzuki[2], Seiichi Yaasui[3], Kota Ishii[1], Tsutomu Kaziyama[1], Kazato Oishi[4], Akifumi Ogino[5], Takahisa Hinata[6], Hiroyuki Hirooka[4], Takashi Osada[5], Haruhiro Fujita[7]

[1] Central Agricultural Experiment Station, Hokkaido Research Organization, Japan
[2] Tokachi Agricultural Experiment Station, Hokkaido Research Organization, Japan
[3] Hokkaido Air Water INC, Japan
[4] Graduate School of Agriculture, Kyoto University, Japan
[5] Institute of Livestock and Grassland Science, National Agriculture and Food Research Organization, Japan
[6] Rakuno Gakuen University, Japan
[7] Niigata University of International and Information Studies, Japan

Abstract. This study was aimed at investigating the local livestock biomass volume for dairy farms in Town A, located in eastern Hokkaido, Japan, and at presenting a model of a biogas plant that enables maximizing the use of the available livestock biomass. Using a dairy farm with 250 animals in Town A as a model for a biogas plant based on dry-type methane fermentation system (dry-type biogas plant), we set the operational conditions to an average hydraulic retention time of 20 days, digestion temperature of 55°C, and methane gas yield of 0.12 Nm^3 CH_4/kg VSA. We compared the biogas production of our presented model with that of a wet-type biogas plant with the same number of animals. The results showed that the dry-type biogas plant produced biogas at 859 Nm^3/day, while the wet-type biogas plant produced biogas at 666 Nm^3/day. These results indicate that introducing dry-type biogas plants in all dairy farms in Town A would potentially enable semi-solid livestock manure to be processed, which is not amenable to ordinary composting, in addition to the conventional processes being carried out through biogas plants, as well as lead to an increase in the amount of biogas production.

1. Introduction

Livestock is a major industry in Hokkaido, located in northern Japan. The animal manure produced from the livestock industry serves as an organic resource and is useful in producing biogas, a combustible gas primarily composed of methane, through anaerobic fermentation in a biogas plant.

A biogas plant is a facility where livestock manure and other organic wastes are made to undergo methane fermentation through the activity of anaerobic microorganisms [1]. A major feature of biogas plants is their ability to generate power by using the generated biogas to fuel generators, aside from the processing of organic wastes from farms [2]. Moreover, using the digested sludge produced in the process as a fertilizer enables a higher fertilization efficiency compared with ordinary slurry fertilization and reduces foul odours [3]. The digested sludge produced as an effluent from the anaerobic fermentation is not only useful as a liquid fertilizer but the solid component from the digested sludge after solid-liquid separation may also be composted and reused as bedding material (recycled bedding materials) [4].

The use of biogas plants is also known to effectively reduce greenhouse gas (GHG) emissions; wherein it was reported that the introduction of a biogas plant enabled the reduction of GHG emissions from the storage of unprocessed slurry at 90.5 kg CO_2 eq.m^{-3} down to 46.7 kg CO_2 eq.m^{-3} during the summer season (140 days) [5]. In addition to the processing of organic waste, biogas plants enable the selling of electricity at 39 yen/kW (excluding tax) under the current Feed-in Tariff (FIT) system in Japan [6]. Currently, there are around 80 biogas plants operating in Hokkaido alone.

This study was aimed at investigating the local livestock biomass volume for dairy farms in Town A, located in eastern Hokkaido, Japan, and at presenting a model of a biogas plant that enables maximum use of the available livestock biomass in Town A.

2. Methods

2.1. Available agricultural biomass volume in Town A

Livestock animals included in this study were dairy cattle, beef cattle, and swine. The volume of livestock excrement was computed using Equation 1, and the standard unit used was based on that in the "Handbook of Animal Waste Management and Utilization in Hokkaido 2000" [7]. Crops included in the computation of farm residues were paddy rice, wheat, soybean, and sugar beet. Farm residue was computed using Equation 2, and the standard unit used was based on Ogawa's report [8]. Crop acreage values were based on those in the "Major Crop Acreage, Hokkaido Statistics (2017)" [9].

Equation 1: Available livestock excrement volume = Standard unit of livestock excrement volume × number of animals

Equation 2: Farm residue volume = Farm residue standard unit × crop acreage

2.2. Biogas production volume from dry-type biogas plants

The settings for the operational conditions of the dry-type & wet-type biogas plant used in this study were based on the results of studies conducted by the authors from 2013 to 2014 on dry methane fermentation [10],[11],[12]. Simulations were based on 250 head of dairy cattle to compare biogas production volumes from dry-type biogas plants and wet-type biogas plants.

3. Results and Discussion

3.1. Available agricultural biomass volume in Town A

The agricultural biomass volume in Town A was computed to be 4000 t/year for wheat straw, 4000 t/year for bean husks and other crop residues, and 40,000 t/year for forest products biomass (unused), or approximately 12% of the total biomass resources of Town A. Livestock biomass was computed to be 161,000 t/year for dairy cattle manure (of which 52,000 t/year were processed as slurry) and 134,000 t/year for beef cattle manure, or approximately 85% of the total biomass resources of Town A. It was found that manure slurry (dairy cattle manure), which can be directly processed through a wet-type biogas plant, totalled 52,000 t/year, while semi-solid and solid livestock manure, which requires hydration, solid-liquid separation, and other preliminary treatments before processing in wet-type biogas plants, totalled 243,000 t/year for both dairy and beef cattle manure.

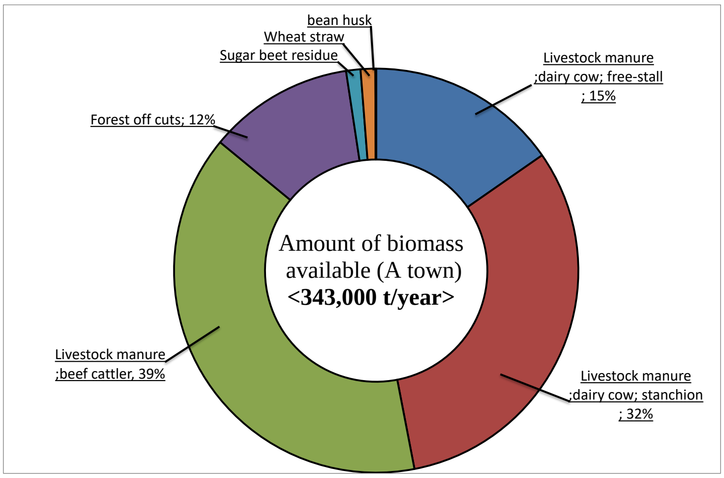

Figure 1. Composition of agriculture biomass resources in Town A.

3.2. Biogas plant settings
The basic premise for the wet-type and dry-type biogas plants was to sell all the electricity produced from biogas power generation using the FIT system, to use commercial electricity for farm and plant operations, and to utilize the dried solid component of digested sludge as recycled bedding material.
Figures 2 and 3 show the system configurations of the wet-type and dry-type biogas plants, respectively. The wet-type biogas plant was an individual-type plant for a 250-head farm, and the raw material used was dairy cattle manure slurry produced from free-stall barns. Operational conditions of the wet-type methane fermentation tank were set to an average hydraulic retention time of 20 days and a digestion temperature of 55°C. Similarly, the dry-type biogas plant was an individual-type plant for a 250-head farm, and the raw material used was semi-solid dairy cattle manure, which is the largest component of dairy cattle manure. The operating conditions were set the same as those in the wet-type biogas plant.

3.3. Energy evaluation and biomass utilization rate
The biogas production and consumption volumes for each biogas plant system model were summarized separately (Figures 4 and 5). Since the dry-type biogas plant can process semi-solid livestock manure, which includes a large amount of straw and other bedding materials, it has a higher volume of organic matter input material, resulting in a larger biogas production volume compared with the wet-type plant. The biogas volumes computed for each type of plant for a 250-head farm were 1666Nm^3/day for the dry-type plant and 859 Nm^3/day for the wet-type plant.
These results indicate that introducing dry-type biogas plants to all dairy farms in Town A would potentially enable semi-solid livestock manure to be processed, which is not amenable to ordinary composting, in addition to the conventional processes being carried out through biogas plants, as well as lead to an increase the amount of biogas production. Assuming that the heat recovered during generation of power by the gas-powered generators is used as a heat source for heating the anaerobic fermentation tanks for each model, the amount of electricity generated by the power generators using biogas from these plants was computed to be 1,000 kWh/day for the wet-type plant and 2,443 kWh/day for the dry-type plant. Kusch et al. [13] reported that both laboratory and full-scale achieved biogas yields were comparable to the yield obtained in liquid-phase digestion, if process conditions were optimal. However, under sub-optimal conditions, it is necessary to assume that result in an inhomogeneous and incomplete degradation at farm-scale.

Table 1 shows a comparison of energy output and consumption for the two types of biogas plant fermentation processes. Assuming that the electricity generated through the dry-type biogas plant is able to supply the power used for the milking equipment, bulk milk cooler, barn cleaner, and other barn equipment, the power for operating the biogas plant, and the power used in the household, the surplus power based on the total power consumption of 957 kWh/day is 1,486 kWh/day.

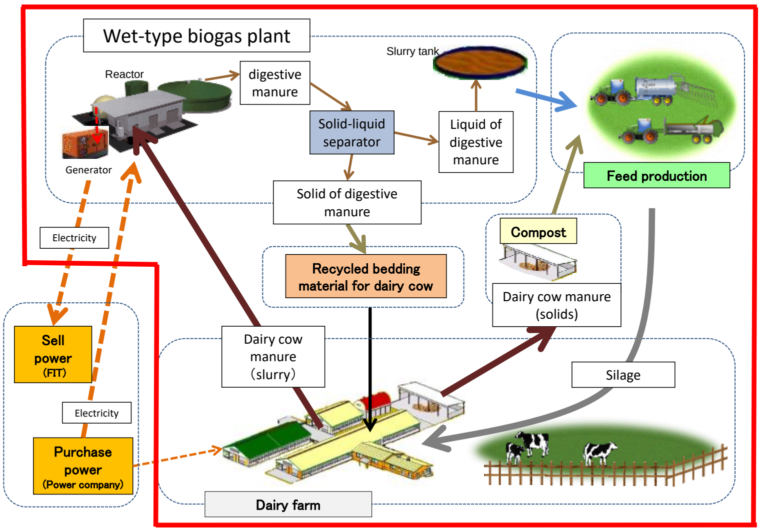

Figure 2. Wet-type biogas plant (250-head farm) (Area enclosed in red line is the scope included in energy evaluation)

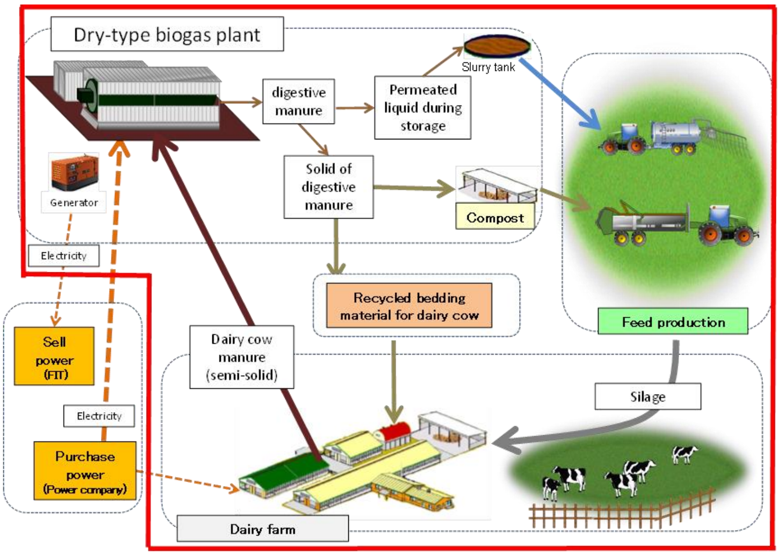

Figure 3. Dry-type biogas plant (250-head farm) (Area enclosed in red line is the scope included in energy evaluation)

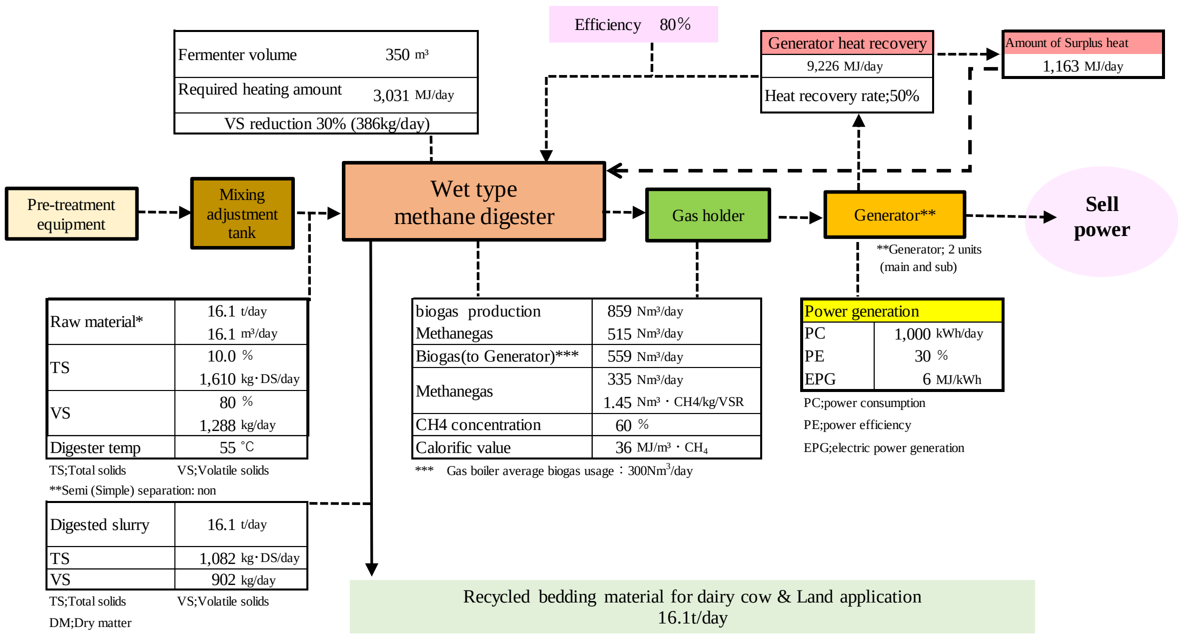

Figure 4. Wet-type biogas plant material flow (250-head farm)

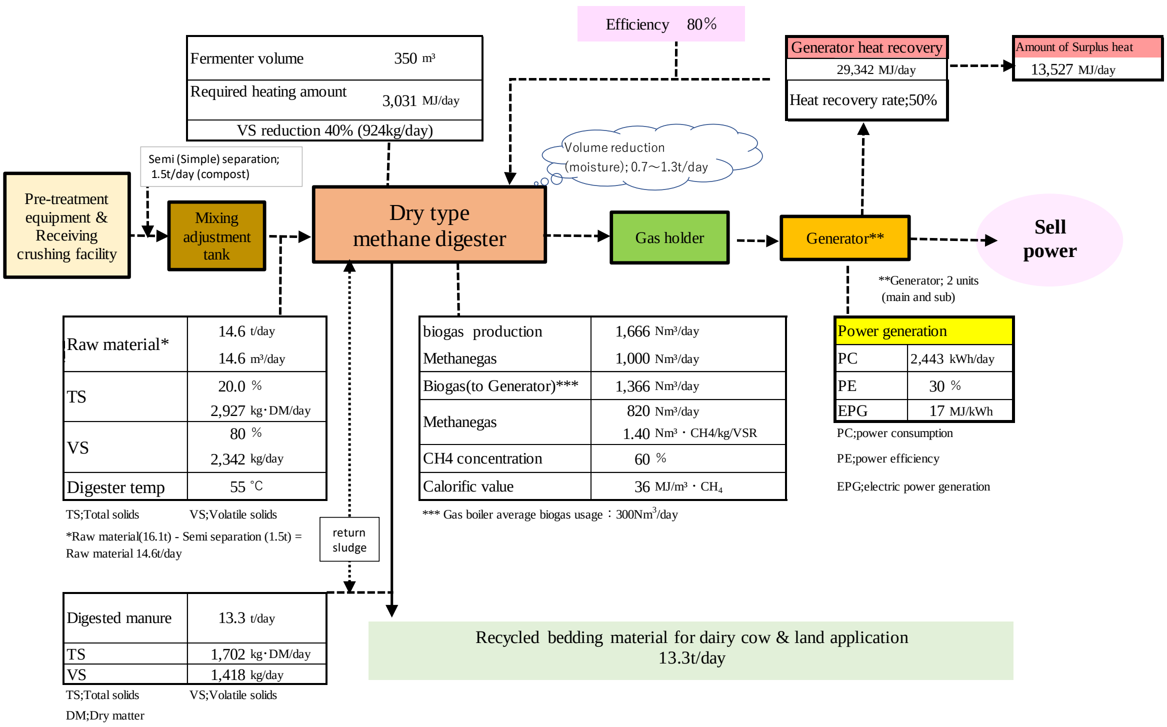

Figure 5. Dry-type biogas plant material flow (250-head farm)

Table 1. Comparison of energy output and consumption for the two types of biogas plant fermentation processes (heat conversion, 250-head farm)

<Methane fermentation type>		Wet	Dry	
(1) Number of breeding animals	head	250	250	Grassland area; 75 ha
<Energy production>				
(2) Methane gas production	Nm^3/day	559	1,000	Methane concentration; 60%
* Methane gas yield	Nm^3/CH_4/kg VS	0.10	0.12	
(3) *(Calorific value conversion value)*	MJ/day	20,007	35,791	(2)×35.79 MJ/$m^3 \cdot CH_4$
(A) Total amount of energy production (calorific value conversion value)				
(4) Biogas plant	MJ/day	20,007	35,791	Converted amount of methane gas into heat
<Energy consumption>				
(5) Electricity consumption of biogas plant	kWh/day	31	281	Commercial power
(6) Fossil fuel consumption of biogas plant	L /day	0	0	Use biogas during steady operation
(7) Electricity consumption in dairy cow stalls and milking facilities	kWh/day	582	582	
(8) Fossil fuel consumption in dairy cow stalls and milking facilities	L/day	35	35	
(9) Biogas consumption by biogas boiler*	m^3/day	0	0	Electricity consumption is included in (5), Biogas boiler; 200 KW
(10) Electricity consumption required to dry the solid content of digested dairy cow manure	kWh/day	94	94	Electricity consumption in solid-liquid separator; 16.5 kWh/day
(11) Spray of digestive dairy cow manure	L/day	3.3	3.3	Slurry injector/Manure spreader
(12) Transfer of raw material slurry	L/day	0	0	Scraper and pump
(13) Feed production	L/day	1.3	1.3	High moisture silage system; twice a year
<Biogas plant; Total>				
(14) Total Electricity consumption of biogas plant	kWh/day	707	957	(5)+(7)+(10)
(15) *(Calorific value conversion value)*	MJ/day	6,900	9,340	1 kWh = 9.76 MJ
(16) Total Fossil fuel consumption of biogas plant	L/day	0	0	Heating energy of biogas plant : Biogas
(17) *(Calorific value conversion value)*	MJ/day	0	0	1 L = 38.2 MJ
<Dairy farm; Total >				
(18) Electricity consumption of dairy farm	kWh/day	707	957	
(19) *(Calorific value conversion value)*	MJ/day	6,900	9,340	1 kWh = 9.76 MJ
(20) Fossil fuel consumption of dairy farm	kWh/day	39.6	39.6	(6)+(8)+(11)+(12)+(13)
(21) *(Calorific value conversion value)*	MJ/day	1,513	1,513	1 L = 38.2 MJ
(B) Total energy consumption (calorific value conversion value)				
(22) Biogas plant	MJ/day	6,900	9,340	(15)+(17)
(23) Dairy farm	MJ/day	8,413	10,853	(19)+(23)
< Energy balance>				
(C) Amount of surplus energy (calorific value conversion value)				
(24) Biogas plant	MJ/day	13,107	26,451	C = A-(22)
(25) Dairy farm	MJ/day	11,594	24,938	C = A-(23)

*(9), (17): Since the biogas used for heating the digester and drying the digested sludge is carbon neutral and offsets fossil fuel consumption, it is not included in the consumption and surplus energies.

Figure 6 shows the changes in biomass utilization rate resulting from the introduction of a dry-type biogas plant. The use of a dry-type biogas plant enables the processing of semi-solid dairy cattle manure and beef cattle manure, in addition to dairy cattle manure slurry, among the available livestock biomass resources in Town A. Our computations show that if all dairy and beef cattle farms in Town A introduce a dry-type biogas plant, Town A would be able to increase its livestock biomass utilization rate from 15% to approximately 85%.

Assuming that these plants were introduced to all dairy and beef cattle farmers in Town A, 103,793 MJ/day/wet-type biogas plant of energy would be generated in free-stall farming, where only wet biogas plants could be introduced. However, since it is possible to introduce both wet and dry processes, it was estimated that the amount of energy production that can be generated will increase to approximately three times (295,061 MJ/day/wet & dry-type biogas plant).

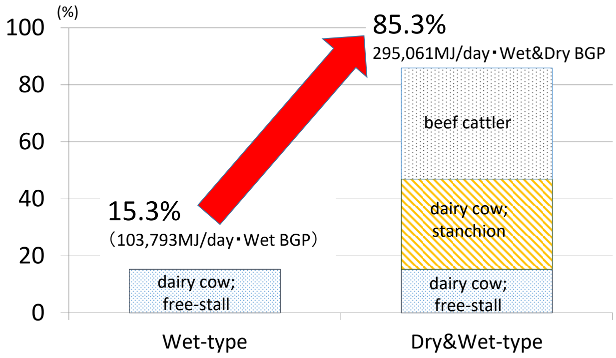

Figure 6. Changes in biomass utilization rate resulting from the introduction of a dry-type biogas plant

4. Conclusion

We used a dairy farm with 250 animals in Town A as a model for a dry-type biogas plant based on dry methane fermentation. We set the operational conditions to an average hydraulic retention time of 20 days and a digestion temperature of 55°C, and compared the biogas production with that of a wet-type biogas plant with the same number of animals. The results showed that the dry-type biogas plant produced biogas at 859 Nm3/day, while the wet-type biogas plant produced biogas at 666 Nm3/day. Assuming that these plants were introduced to all dairy and beef cattle farmers in Town A, since it is possible to introduce both wet and dry-type biogas plant, it was estimated that the amount of energy production that can be generated will increase to approximately three times.

These results indicate that introducing dry-type biogas plants to all dairy farms in Town A would enable semi-solid livestock manure to be processed, which is not amenable to ordinary composting, in addition to the conventional processes being carried out through biogas plants, as well as lead to an increase the amount of biogas production.

This study investigated the energy and biomass utilization specifically for livestock biomass, among the diverse biomass resources available in Town A. There is further need, however, to conduct modelling on the basis of the use of diverse renewable forms of energy, including solar and wind power, to determine the best combination of energy sources for effectively utilizing the locally available resources. Moreover, since the presented dry-type biogas plant is an individual-type plant, further studies need to be conducted to design a more efficient system, develop a vehicle exclusive for collection of semi-solid manure, and investigate methods to establish and implement a livestock manure collection system and to develop and deploy a concentrated manure spreader to propose a joint-use type plant.

5. References

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Acknowledgments

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