Assessment of the potential to adopt biogas plants in Hokkaido and the environmental and economic benefits based on dairy farmers' willingness

酪農家の意思を踏まえた北海道における バイオガスプラントの導入可能性 及び環境的・経済的便益の評価

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Contents

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In addition, for three years from 2018 to the present, I have been working as a consultant at Biomass Research Co., Ltd., which has been conducting a biogas plant dissemination and feasibility study as a method for treatment of livestock manure, a serious issue in dairy farming and livestock. One of the solutions is expected to adopt biogas plants, and the plants are also expected as effective means of utilizing biogas as renewable energy and digestate available for organic fertilizer. From this point, this dissertation aimed to summarize the importance of adoption of biogas plants, such as a tool to maintain the core industries for sustainable Hokkaido and to approach the energy policy for a carbon-free society, which link to achievement of Sustainable Development Goals (SDGs). Through the entire progress in this research, I received a great deal of advice from President Dr. Sadao Kikuchi and all staff members of Biomass Research Co., Ltd. I am deeply grateful here. In addition, Professor Dr. Kazutaka Umetsu of Obihiro University of Agriculture and Veterinary Medicine gave me useful advices and examined my doctoral dissertation. Dr. Mohamed Farghali provided a lot of information and advices on how to approach for my research. I deeply appreciate their supports.

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Abstract

Intensification of the livestock industry has become environmentally problematic due to the uncontrolled treatment of large amounts of watery manure. One solution is the anaerobic digestion (AD) in biogas plants (BGPs). Many studies have already stated that BGPs offer environmental and economic benefits. Hokkaido, Japan, has significant potential for BGP adoption, however, BGP adoption has also been influenced by national policies such as subsidy and energy policy, and the large financial investments and lack of grid space for selling electricity are barriers.

To enhance BGPs, it is important to realize efficient supports from the national government. And the accurate potential to adopt BGP and the expected benefits of BGPs are needed to be assessed. Thus, this study aimed to investigate the farmers' willingness and farming planning to estimate the more realistic potential. Also, I clarified the current farming situation and the issues expected to be resolved by BGPs, and assessed the environmental benefits such as reduction of GHG emission and economic benefits by adopting BGPs.

Concerning the BGP adoption potential, there have been several studies investigating the potential by using statistical data. However, there was no study that confirmed the farmers' willingness and reflected it to estimate the potential in the world. To clarify the potential based on the farmers' willingness, this study conducted a questionnaire and an interview surveys of 268 dairy farmers who did not adopt BGPs in nine municipalities in Hokkaido. The result indicated that 2,484 dairy farmers having 385,856 to 461,342 dairy cows might adopt BGPs in Hokkaido, and 25,081 to 29,987 tons of manure would be treated in one day in the future.

This study investigated the farmers' current farming situation such as the farm scale, future plans and existence of issues to treat dairy manure. The result indicated that 119 dairy farmers (41.6% of total households) have willingness to adopt BGPs, and the average number of mature cows per household was 127 cows, which is 1.9 times as many as that of unwilling farmers. Also, large-scale farmers, particularly those with more than 100 mature cows, were clearly willing to adopt BGPs and expand their businesses in the future, while farmers who planned to downsize their businesses did not exhibit strong willingness to adopt BGPs was found. This result also showed that the farmers who were willing to adopt BGPs thought BGPs would help solving problems with manure treatment.

This study indicated that BGPs was expected to reduce GHG emission by replacing fossil fuels to produce energy and chemical fertilizer, and by changing from the manure treatments that emit GHGs. In addition, this study also estimated economic benefits by the GHG reduction. The expected 25,081 to 29,987 tons of manure per day could produce electricity in BGPs up to 3,673 MWh per day, which would be supplied to 314,866 households, covering 11.3%

of the total in Hokkaido. Additionally, BGPs simultaneously generated heat energy, which would cover 0.58% of the heat energy consumed annually in Hokkaido. Assuming that currently all the heat energy was produced by kerosene, BGPs could reduce annual imports of kerosene by 151 ML from overseas, saving 12.1 billion JPY in value. Regarding the GHG emission in the process of manure treatment (piling and forced composting that many dairy farmers currently implemented), the emission of methane (CH_4) and nitrous oxide (N_2O) was estimated, and the change due to adoption of BGPs were compared to assess the impact of BGPs. Ultimately, the leakage of 2% of produced biogas from BGPs was also estimated. The result showed that BGPs could replace energy from fossil fuels, resulting in the maximum annual reduction of 1,006,305 t CO_2-eq. Also, GHGs emitted annually from piling and forced composting were estimated to be 585,095 t CO_2-eq and 1,153,765 t CO_2-eq at maximum, respectively. Thus, the shift of manure treatment method could reduce up to 2,186,422 t CO_2-eq of annual GHGs emission, which was equivalent to 3.1% of GHG emission of Hokkaido at the level of 2016, required to stop the emission until 2050.

This study assessed the potential to adopt BGPs in Hokkaido with farmers' perspective and expected both environmental and economic benefits on the viewpoint of GHG reduction. As a result, 2,484 dairy farmers would continue farming with the improved farming environment by BGPs, and the farmers are expected to play an important role in enhancing local industries in each region of Hokkaido. From these points, BGPs would also be a tool to achieve sustainable development goals (SDGs), especially SDG Goals 7, 8, 12, and 13. And to enhance BGPs, it is also expected to obtain financial mechanism such as Environmental, Social, and Governance (ESG) investment and Japan Credit (J-Credit) system certifying GHG emission reduction.

Chapter 1: General Introduction

1.1. Issues on dairy manure treatment

Intensification of the livestock industry has led to serious environmental problems. Chief among these problems is untreated manure resulting from the increased number of livestock per household and changes in farming style. The amount of industrial waste generated in Hokkaido, Japan, in 2015 was recorded to be about 40 million tons, of which the proportion of livestock manure accounted for about 50% (Miyake et al., 2016). Problems caused by improper manure treatment include nitrate from undecomposed compost polluting the soil and water, poor feed (grass) produced without compost, the presence of weed seeds, the occurrence of pathogenic bacteria, and odor emissions resulting from insufficient aerobic fermentation, which reduce the quality of life in neighboring communities and impacts human health (e.g., headaches and eye and nose irritation) (DeLuca and DeLuca, 1997; Schiffman, 1998; Ward et al., 2008; Westerman and Gerowitt, 2013; Yoshida et al., 2014; Sahoo et al., 2016; Qi et al., 2018)

Therefore, the treatment of livestock manure is a critical issue, and appropriate treatment measures for concentrated dairy and livestock farming are urgently needed. One way to reduce these impacts is through the adoption of anaerobic digestion (AD). AD is normally carried out in biogas plants (BGPs) and has several benefits. For example, it reduces biomass, alleviates adverse effects by microorganisms, and reduces undesirable odors (Ward et al., 2008; Costa et al., 2017; Burg et al., 2018; Qi et al., 2018). In addition, it produces digestate that can be used as organic fertilizer and reduce the need for chemical fertilizers (Wilkie, 2005). Finally, it produces methane (CH_4), providing a source of renewable energy that can be used for heating, electricity, and in place of diesel or gasoline to operate equipment (Holm-Nielsen et al., 2009).

In addition to environmental benefits, BGPs can also improve overall business operations of farmers by reducing chemical fertilizer expenses, which can be replaced by digestate, increasing revenue from agricultural products by organic farm branding, and reducing the need for labor. This can allow for an increase in the number of cows, which enhances milk production. There is also a benefit of securing employment for BGP management in local areas (Yoshida et al., 2014; Miyake et al., 2016; Anabuki et al., 2016; Kitajima et al., 2017). Most of the dairy farmers have dealt with manure by making composts. However, Babalola (2020) pointed out that BGPs are preferably introduced to treat organic wastes in Japan because of the higher benefits, efficiency and safety, compared to composting, incineration and landfill. In addition, the utilization of biomass energy has become a global trend as a measure to mitigate climate change and relevant issues, and AD in BGPs has further been enhanced over composting from the viewpoint of energy production, which would be additional sources of income for dairy farmers

(Lantz et al., 2007; Shah et al., 2020; Babalola, 2020). Therefore, the dairy farmers might be motivated to adopt BGPs.

1.2. Dairy farming in Hokkaido

Hokkaido is a northern island of Japan with an area of 83,424 km^2, accounting for 22% of the total land area of Japan and containing the most intensive dairy farms in the industry (Geospatial Information Authority of Japan, 2020). As of 2019, Hokkaido had around 801,000 dairy cows, representing 60% of the total dairy cows in Japan. Figure 1.1 presents the change of farming situation in Hokkaido and in Japan. In Hokkaido, there are more than 50% of dairy cows nationwide. The number of dairy cows is decreasing not only in Hokkaido but throughout the country. On the other hand, the average number of dairy cows per household is increasing. In Hokkaido, the average number of dairy cows per household has increased by 24.8% from 108 dairy cows in 2010 to 134 dairy cows in 2019. The average number of dairy cows per household in Japan has increased by 31.0% from 68 dairy cows in 2010 to 89 dairy cows in 2019, which is smaller than that of Hokkaido. Revenue from the dairy industry in Hokkaido was 652.9 billion JPY, accounting for 40% of total agricultural revenue in Hokkaido in 2018 (Ministry of Agriculture, Forestry and Fisheries, Japan (MAFF) (MAFF, 2009, 2010, 2011, 2012, 2013, 2014, 2015, 2016, 2017, 2018a, 2018b, 2019)

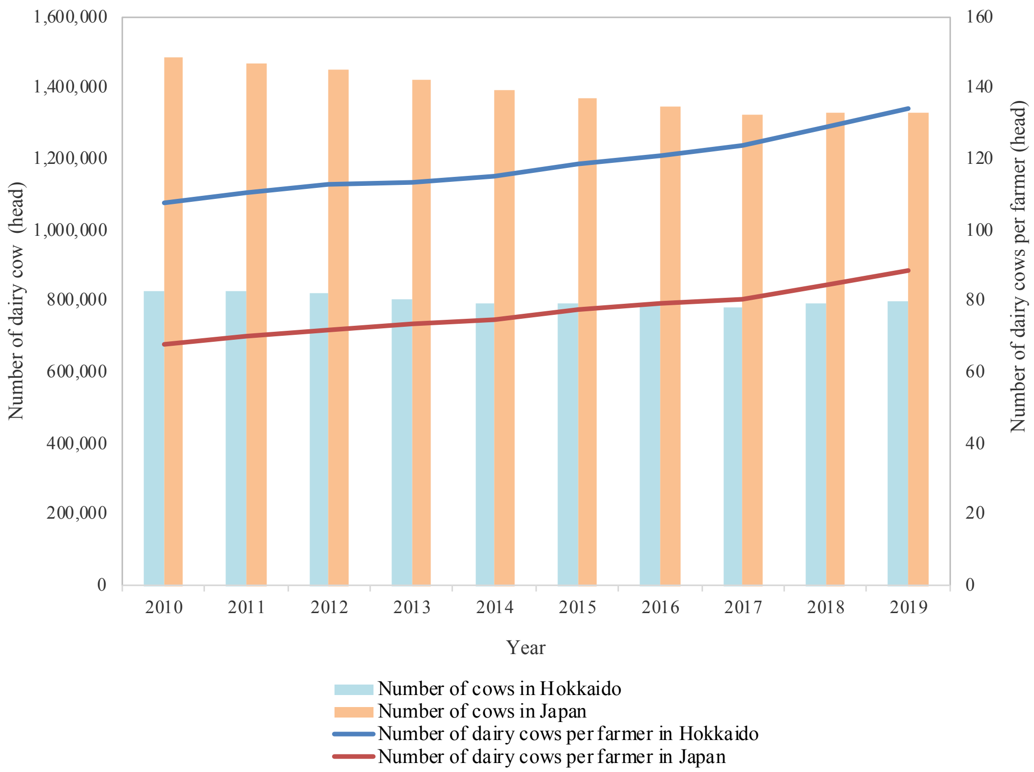

Figure 1.1. Change of farming situation in Hokkaido and Japan (MAFF, 2010, 2011, 2012, 2013, 2014, 2015, 2016, 2017, 2018b, 2019)

1.3. BGP in Hokkaido

The construction of BGPs over the former two decades has led to more appropriate treatment of manure as well as diminished greenhouse gas (GHG) emissions. The Fukushima Daiichi Nuclear power plant accident in 2011 led to renewed public interest in renewable energy. The Japanese government offered a Feed-in Tariff (FIT) that donates 39 JPY kWh^{-1} (tax exclusive) for the purchase price of biogas generated electricity over the next 20 years (Ministry of Economy, Trade and Industry, Japan (METI) (METI, 2020a). The system incentivizes various actors to establish new biogas power plants. As of 2020, there were 117 BGPs in Hokkaido with a total power capacity of 18.7 MW. Seventy-one percent of these plants primarily use cattle manure as substrate for biogas generation (METI, 2020b). Despite the progress, the construction of BGPs entails large investments and often relies on the assistance of the national government. Lack of grid availability to connect and sell electricity is also an obstacle to BGP expansion.

1.4. Promotion of BGPs in Hokkaido

Asai et al. (2019) indicated that farmers are likely to select BGPs because of their environmental benefits, and the general acceptance of digestate. Investment for new grid requires enormous money and time. Considering anticipated decreasing trend in population in Hokkaido in future, it is essential to consider whether such a large infrastructure investment is necessary or not. Also, there is a further discussion that renewable energy would be replaced from existing large-scale power plant using fossil fuels, especially biomass would be enhanced from a viewpoint of environmental and economic benefits to local communities (Anabuki et al., 2016).

BGPs are expected to be adopted in local regions where dairy farming is vigorous, and the local people in Hokkaido are expected to accept the new technology to improve the situation of the industry which is familiar in their daily lives (Capodaglio et al., 2016). Additionally, BGPs are expected to function as distributed power plants by generating and providing energy locally. In Hokkaido, which experienced a blackout caused by the 2018 Hokkaido Eastern Iburi Earthquake, it is considered essential to assess the possibility of distributed power systems in terms of energy security (Anabuki et al., 2016). Finally, effective utilization of the digestate produced in BGPs needs fields that are wide enough for spreading (Yuyama et al., 2007). From the above points, Hokkaido is regarded as the most suitable area to install BGPs in Japan.

In the assessment of the potential to adopt BGPs in Hokkaido, Yabe (2013) estimated the potential based on the current number of dairy farmers and number of cows from the statistical data in Hokkaido. However, the farmers' agreement is important for the implementation and maintenance of BGP project, thus the potential should be estimated based on farmers' willingness. In addition, it is important to design the scale of BGPs considering the farming plan of individual dairy farmers, assuming that the BGP project will be operated. Also, the adoption of BGPs depends on the farming plan in the future. Thus, it is important to evaluate the potential to adopt BGPs from more realistic and a long-term view when considering future investment for BGPs.

In addition, it has been shown that it is difficult to maintain the construction and operation of BGPs worldwide without the assistance of the government, implying that the finance is important (Ward et al., 2008; Cucchiella et al., 2019). The biogas business is often affected by policy-making and needs to reconsider to avoid relying solely on subsidies. There are some global schemes such as Environmental, Social, and Governance (ESG) investment and 100% renewable energy (RE100) movement (Tajima and Okada, 2019). To apply them in Japan, there is a scheme for a certificate to show the reduction of greenhouse gases (GHGs) emission such as Japan Credit (J-Credit) (Ogawa, 2018). This would be another financial scheme to attract citizens who are seriously think about environmental problems. In order that the limited grid availability can be used efficiently and that the investor of ESG investment understand the advantages of BGPs projects in Hokkaido, it is important to assess the potential of the expected BGPs projects in the future, which is closer to reality.

1.5. Objective and outline of this study

This study is designed to achieve the following objectives:

- To investigate the willingness of dairy farmers to adopt BGPs in Hokkaido.
- To determine the amounts of dairy manure produced from dairy cattle in Hokkaido and for next coming 10 years.
- To estimate the environmental impact of established BGPs in Hokkaido based on contributors who were willing to adopt BGPs.

Chapter 2 focused on estimation of the relationship between farmers' current situations and their willingness to adopt BGPs. The study included three steps. First, I performed a questionnaire survey to understand farmers' current situations (the number of cows, the existence of successors, and the existence of issues surrounding manure treatment) and willingness to adopt BGPs. Second, I analyzed this relationship and identified factors contributing to willingness to adopt BGPs using multivariate analyses. Third, I discussed the expected effects of, and possibilities for enhancing, BGP installation as a means to achieving sustainable agriculture in Hokkaido.

Chapter 3 assessed the environmental and economic benefits on GHG emission reduction with BGPs adopted with the assumed amount of dairy manure in Hokkaido. First, based on the adoption potential of BGPs in Hokkaido presented in Chapter 2, I estimated the expected GHG emission reduction if the electricity and heat produced by biogas replace with the those produced by fossil fuels. Next, I estimated GHG emission by using digestate as a fertilizer. I also estimated GHG emissions such as CH_4 and N_2O released from piling and forced composting as reference manure treatment methods that many farmers currently perform, and assessed the GHG emission reduction due to the BGP adoption. Finally, I also evaluated the economic benefits such as profit from selling electricity with FIT scheme, and saved costs to purchase kerosene producing heat energy if the energy would be replaced with that derived from BGPs. The profits from J-credit would also be evaluated.

In Chapter 4, I discussed the potential of BGP adoption and following environmental and economic benefits, and the relationship with Sustainable Development Goals (SDGs). Ultimately, Chapter 5 concluded this study, expecting that the results would helpful to enhance BGPs in Hokkaido.

Chapter 2: Factors influencing the willingness of dairy farmers to adopt biogas plants

2.1 Introduction

Chapter 1 presented that it is necessary to understand the farmers' willingness to adopt BGPs to clarify the potential close to real situation to promote BGPs scheme in Hokkaido.

There are problems to be solved for promoting adoption of BGPs. For instance, there are voices of opposition from residents over the construction of BGPs. This is considered to be primarily resulting from concerns that the BGPs would disturb the view of landscape and will enhance traffics to transport dairy manure in surrounding areas every day ("Not in my back yard" (NIMBY) syndrome) (Capodaglio et al., 2016; Asai and Takai, 2017). The second possible reason is that, while the construction of BGPs requires a large financial investment, the profitability of electricity generated by BGPs is nowadays uncertain due to the lack of grid availability to transfer and sell the electricity, and the difficulty of using the other energy sources generated by BGPs, such as gas and heat (Tranter et al., 2011; Hachimura et al., 2015). These concerns are critical obstacles for dairy farmers' willingness to adopt BGPs, resulting in reluctance of farmers. Besides, Rupf et al. (2015) reported that the lack of experience to operate BGPs and insufficient follow-up services of BGPs were the chief hinders (Rupf et al., 2015).

Considering social backgrounds, this study of this chapter included three steps. First, I conducted a questionnaire survey to understand farmers' willingness and their current situations (the number of cows, the existence of successors, and the existence of issues surrounding manure treatment). Second, I analyzed this relationship and identified factors contributing to willingness to adopt BGPs using multivariate analyses. Third, I discussed the expected effects of, and possibilities for enhancing, BGP installation as a means to achieve sustainable agriculture in Hokkaido.

2.2. Conceptual framework for adoption of BGPs

Technology adoption in the agricultural field has been a central topic of agricultural research and has been widely considered by scientists and economists for decades (Feder and Umali, 1993). Various previous studies have explained and expected key factors of adoption and diffusion of technologies by evolving essential sets of conceptual frameworks (Adnan et al., 2019). Among them, the diffusion of innovation model has been extensively recognized. This model suggests the compatibility and complexity of the new technology, the prospective end user's characteristics, the person's perception and knowledge regarding the technology, and the communication channels to determine the diffusion and the adoption of innovative new technologies (Rogers, 2003; Adnan et al., 2019).

Operation of BGPs needs local acceptance and cooperation with farmers, which indicates that it is important to understand farmers' perceptions and characteristics. Much of the research on the diffusion of innovation has analyzed socio-personal and socioeconomic variables (Peshin et al., 2019). The socioeconomic variables include education, gender, age, social status, income, labor, and so on. Tranter et al. (2011) reported that the survey questioned farm size (the number of cattle and the area of field), labor, age, and income, and that expected adopters of BGPs tended to have a large farm size. Knowler and Bradshaw (2007) also showed that farm size positively influences the decision of adopting BGPs, indicating that owners of larger facilities are more willing to accept new technologies. Lansink et al. (2003) found that the existence of successors is a key factor for determining the expansion of a farm and improvement of the quality of the production process. The results were based on data analyses including the age, existence of successors, and farming plans. Additionally, in most countries, creation of local employment and the subsequent vitalization of the local economy are probably the two most important issues regarding the use of local biomass for energy production (Domac et al., 2005).

Based on the previous criteria, I selected several questions, i.e., willingness to adopt BGPs, number of dairy cows, existence of successors, and existence of issues on manure treatment (Table 2.1). I hypothesized that in the case of Hokkaido there was also a possibility to distinguish the farmers who were willing to adopt BGPs from those who were not, through the factors of the number of dairy cows (as farm size), the existence of successors (as labor force), and the existence of issues on manure treatment (as farming quality). In addition, the future plan of the business (change of the number of dairy cows in the future) would be a certain criterion as an indicator of investment and income gain. Finally, I added the existence of BGPs as a possible factor which could be a communication channel for farmers to get knowledge about BGPs.

2.3. Methods

2.3.1. Data collection from dairy farmers

The questionnaire survey was carried out from 2017 to 2018. The research targets were 601 dairy farmers across nine municipalities of Hokkaido (Wakkanai, Hamatonbetsu, Nakatonbetsu, Oumu, Yubetsu, Shikaoi, Hiroo, Toyokoro, and Yakumo) that did not operate BGPs (Figure 2.1). The research sites were one city and eight towns whose main industries are agriculture and related businesses. In some of the municipalities, private sectors already owned BGPs. The survey was conducted in cooperation with the local administration and the Japan Agricultural Cooperatives (JA) within each community. The questionnaire contained closed- and open-ended questions about willingness to adopt biogas projects, the number of dairy cows, the existence of successors, and issues with manure treatment (Table 2.1). Answer sheets from 422 participants were collected, from which 286 (47.6%) were chosen for data analyses. Answer sheets that were completely filled out and whose respondents owned dairy cows were used for the analyses. The answer sheets from respondents with beef cattle were not used because the number of respondents was not statistically sufficient.

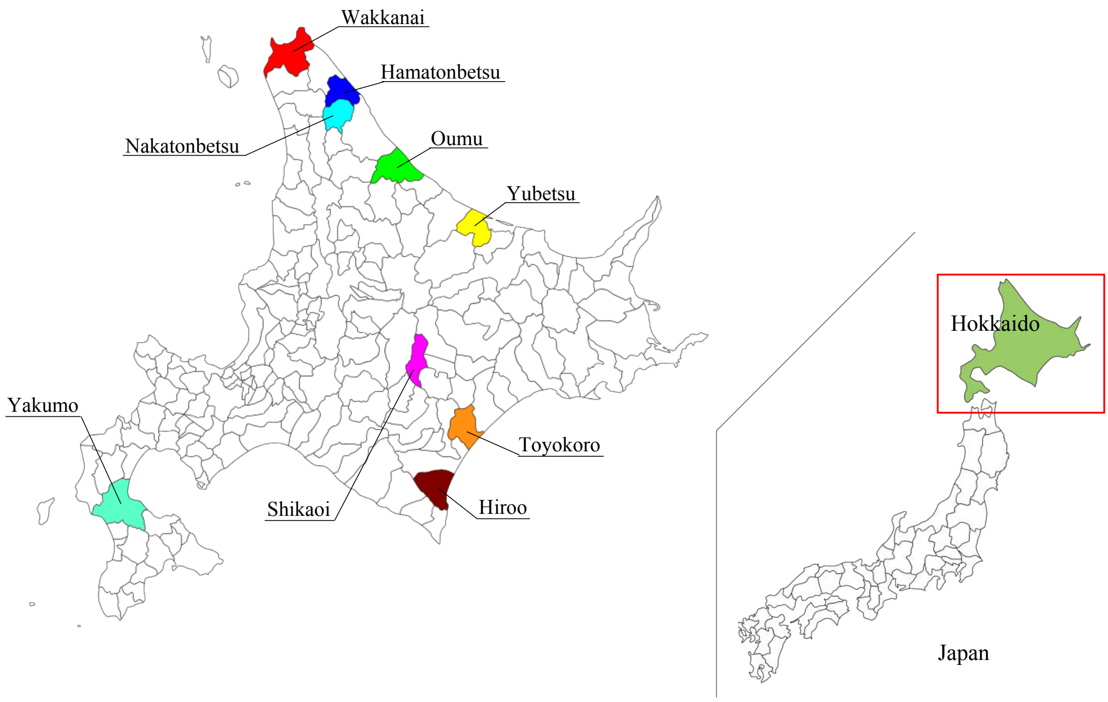

Figure 2.1. Map of Hokkaido island, Japan, and the nine municipality research sites (Wakkanai, Hamatonbetsu, Nakatonbetsu, Oumu, Yubetsu, Shikaoi, Toyokoro, Hiroo, and Yakumo).

Table 2.1. Questionnaire summary.

Element	Expression	Purpose
Willingness to adopt BGP	"Yes" or "No"	Willingness to adopt BGP is questioned.
Number of dairy cows	Current and future numbers (in the next 10 years) of milking cows, dry cows, heifers, and calves, respectively	Number of dairy cows needed to decide the scale of BGP. The extent of the change indicated the farmer's future plans, i.e., to increase, decrease, maintain, or abandon farming.
Existence of successors	"Already determined", "Not decided but have a candidate", "No candidate", or "No successors required"	Existence of a post-retirement successor would influence the decision whether to adopt BGPs.
Existence of issues on manure treatment	"Yes", "No", or "No, but it may occur in the future"	Optional answers for specific issues on manure treatment: "Bad odor is emitted from the manure", "Space to make compost pile is insufficient", "Weeds in the field increase due to weed seeds remaining in the compost", "Compost is less effective as a fertilizer", "Time to spread the compost is not enough", "Field to spread compost is too far from farm", "Field area to spread compost is insufficient", "Too much labor time is needed to treat manure"

2.3.2. Sociodemographic characteristics of surveyed farmers and mature cows

From the questionnaire results, I assessed farmers' willingness to adopt BGPs, and their current and estimated future numbers of mature cows (MCs) (Kabir et al., 2013; Kelebe et al., 2017). MCs include both milking and dry cows, and the number is an indicator of farm size for milk production (Miyake, 2018). In addition, I estimated the ratio of change as future farming planning and assessed the difference in farmers' willingness to adopt BGPs (Oude Lansink et al., 2003).

2.3.3. Analyses of current situations

The results of the questionnaires were classified into "existence of successors" and "existence of issues surrounding manure treatment" based on willingness to adopt BGPs. In addition, I divided the number of MCs into five categories, following Miyake's (2018) approach that described farmers with 100 MCs or more as large-scale (Table 2.2). In addition, future business planning was divided into four categories: retirement, decrease, maintain, and increase. Zero future MCs were categorized as retirement. Decrease, maintain, and increase were based on future projected changes in the number of MCs. I added "existence of BGPs" as a factor because it is easier for farmers to obtain information and feedback on BGPs if there are already some in the area. I automatically categorized answers into either "yes" or "no" based on the list of power generation equipment allowed to sell generated electricity with FIT prices by the Ministry of Economy, Trade and Industry, Japan. The choice of "yes" was selected for Wakkanai, Yubetsu, Shikaoi, Hiroo, and Yakumo, and "no" was selected for Hamatonbetsu, Nakatonbetsu, Oumu, and Toyokoro. There was one BGP in Oumu at the time, but it was excluded because it was not in operation when the survey was conducted (METI, 2020b).

Table 2.2. Categories of farmers according to number of mature cows (MCs).

Category	Current number of MCs	Number of farmers
1	0–50 heads	99
2	50–100 heads	125
3	100–150 heads	27
4	150–200 heads	15
5	> 200 heads	20

2.3.4. Assessment of critical factors influencing willingness to adopt BGPs

I used multivariate analyses to measure the strong factors influencing willingness to adopt BGPs. I used Hayashi's quantification theory type II, which is a statistical method for predicting or discriminating qualitative criteria ("yes" or "no") in qualitative data (Li et al., 2005; Jiang et al., 2010). I evaluated the factors contributing to willingness to adopt BGPs and the total weight of each factor, such as current farming status, future plans, and existence of BGPs in the surrounding area, using Eq.1.1 (Table 2.3) (Koizumi et al., 2001; Kan, 2017):

$$y = \sum_{j=1}^{Q} \sum_{k=1}^{C_j} a_{jk} x_{jk} + \varepsilon \qquad \text{Eq.1.1}$$

where y is the sample score as an objective variable, Q is the item number of explanatory variables, C_j is the category number of the *j-th* explanatory variable, x_{jk} is a dummy variable that takes a value of 1 or 0 depending on whether the objective variable responded to the *k-th* category of the explanatory variable j, a_{jk} is the coefficient of the model formula and is known as the "category score", and ε is the error. I used Maruchi–Tahenryo (multivariate analysis) software developed by the Institute of Statistical Analyses Inc. (Tokyo, Japan) to solve Eq. 1.1 (Institute of Statistical Analyses Inc., 2020). Difference values between the maximum and minimum value of category scores of each explanatory variable were defined as the "range". Explanatory variables with a larger range have greater contributions to the objective variable, which is a stronger category affecting the perspective of farmers (Kan, 2017). Positive y values denote that farmers are willing to adopt BGPs, while negative y values denote they are not.

Table 2.3. Summary of items and categories used in quantification theory type II. a_{jk} denotes the category score related to Eq. 1.1 in the text.

Item	Category	a_{jk}
Existence of successors	Already determined	a_{11}
	Not determined, but have a candidate	a_{12}
	No candidate	a_{13}
	No successors required	a_{14}
Existence of issues on manure treatment	Yes	a_{21}
	No, but it may occur in the future	a_{22}
	No	a_{23}
Current number of MCs	0–50 heads	a_{31}
	50–100 heads	a_{32}
	100–150 heads	a_{33}
	150–200 heads	a_{34}
	> 200 heads	a_{35}
Future plan of business (change of number of MCs)	Retirement	a_{41}
	Decrease	a_{42}
	Maintain	a_{43}
	Increase	a_{44}
Existence of BGPs	Yes	a_{51}
	No	a_{52}

2.4. Results

2.4.1. Sociodemographic characteristics of surveyed farmers and MCs

The current and expected future numbers of MCs, and the corresponding average of MCs per household, are illustrated in Table 2.4. At the time of the survey, there were 26,415 MCs with an average of 92 MCs per farmer. The number of MCs per household differed among municipalities, with a maximum of 182 in Toyokoro and a minimum of 41 in Yakumo. In the future, most farmers anticipate expanding their businesses, with the total number of MCs expected to increase by 21.4%, from 92 to 112. Farmers in Shikaoi, Toyokoro, and Yubetsu expect to increase their number of MCs by 33.4%, 33.0%, and 33.0%, respectively. It is predicted that the number of MCs in Yakumo and Nakatonbetsu will decrease by 18.9% and 3.4%, respectively.

Tables 2.5 and 2.6 show the number of dairy farmers who were and were not willing to adopt BGPs along with the number of MCs they own. I defined farmers who were willing to adopt BGPs as “Group 1” and farmers who were not as “Group 2.” Group 1 was estimated to include 119 households (41.6% of the 286 surveyed) with 15,116 MCs (57.2% of the 26,415 total), averaging 127 MCs per household. Group 2 consisted of 167 households (58.4% of the total) with 11,299 MCs (42.8% of the total), averaging 68 MCs per household, nearly half that of Group 1. The expected future number of MCs per household in Group 1 was estimated to be 174, an increase of 36.9%. There was a robust desire to increase operation size in most municipalities in Group 1, with farmers in Oumu expecting the highest increase of 66.6%. On the other hand, there were virtually no anticipated increases in MCs in Group 2, with farmers in Wakkanai and Shikaoi expecting to increase the scale of their operations and those in Hamatonbetsu and Yakumo expecting to decrease theirs.

Table 2.4. Current and future numbers of MCs among municipalities, and the ratio of expected change from the present to the future. "#" denotes the number.

Municipality	# of farmers	Current # of MCs		Future # of MCs		Ratio of change (%)
		# of MCs	# of MCs /farmer	# of MCs	# of MCs /farmer	
Wakkanai	53	3,096	58	4,005	76	29.4
Hamatonbetsu	42	4,195	100	4,305	103	2.6
Nakatonbetsu	22	1,220	56	1,178	54	−3.4
Oumu	35	3,339	95	3,750	107	12.3
Yubetsu	46	3,691	80	4,910	107	33.0
Shikaoi	24	2,904	121	3,873	161	33.4
Toyokoro	31	5,634	182	7,495	242	33.0
Hiroo	20	1,808	90	2,116	106	17.0
Yakumo	13	528	41	428	33	−18.9
Total	286	26,415	92	32,060	112	21.4

Table 2.5. Number of farmers in Group 1, their current and estimated future numbers of MCs, and the ratio of expected change from the present to the future. "#" denotes the number.

Municipality	# of farmers	Current # of MCs		Future # of MCs		Ratio of change (%)
		# of MCs	# of MCs /farmer	# of MCs	# of MCs /farmer	
Wakkanai	17	1,074	63	1,592	94	48.2
Hamatonbetsu	19	2,974	157	3,457	182	16.2
Nakatonbetsu	5	336	67	351	70	4.5
Oumu	8	1,088	136	1,813	227	66.6
Yubetsu	16	1,789	112	2,844	178	59.0
Shikaoi	17	2,124	125	2,891	170	36.1
Toyokoro	18	4,383	244	6,102	339	39.2
Hiroo	14	1,123	80	1,413	101	25.8
Yakumo	5	225	45	231	46	2.7
Total	119	15,116	127	20,694	174	36.9

Table 2.6. Number of farmers in Group 2, their current and estimated future numbers of MCs, and the ratio of expected change from the present to the future. "#" denotes the number.

Municipality	# of farmers	Current # of MCs		Future # of MCs		Ratio of change (%)
		# of MCs	# of MCs /farmer	# of MCs	# of MCs /farmer	
Wakkanai	36	2,022	56	2,413	67	19.3
Hamatonbetsu	23	1,221	53	848	37	−30.5
Nakatonbetsu	17	884	52	827	49	−6.4
Oumu	27	2,251	83	1,937	72	−13.9
Yubetsu	30	1,902	63	2,066	69	8.6
Shikaoi	7	780	111	982	140	25.9
Toyokoro	13	1,251	96	1,393	107	11.4
Hiroo	6	685	114	703	117	2.6
Yakumo	8	303	38	197	25	−35.0
Total	167	11,299	68	11,366	68	0.6

2.4.2. Analyses of farmers' current situations

Differences in the responses from Groups 1 and 2 are compared in Table 2.7. Statistical analyses using the chi-square test indicated significant differences in the responses to questions about the existence of successors, issues with manure treatment, current number of MCs, and future plans. Of those in Group 1, 37.8% indicated they had chosen successors, compared to 24.0% of farmers who were not willing to adopt BGPs (those in Group 2). In addition, farmers who had not chosen successors but had candidates comprised 28.6% of Group 1 and 23.4% of Group 2. The existence of a successor may influence a farmer's perspective on BGPs. The analyses showed that 58.8% of Group 1 experienced problems with manure treatment, while 32.8% did not currently but might in the future. In Group 2, 22.8% had issues with manure treatment and 25.1% did not currently but might in the future. These results indicate that 91.6% of respondents in Group 1 were worried about issues with manure treatment while 52.1% of those in Group 2 were not.

Most respondents in both groups had less than 100 MCs. Of those in Group 2, 41.3% were small-scale with 0–50 livestock, while 14.3% of Group 1 were large-scale farmers with 200 MCs or more. This implies that farm size affects willingness to adopt BGPs. Concerning the future plans, 56.3% of those in Group 1 planned to expand the size of their farms and were willing to increase BGPs, while 40.1% of Group 2 planned to maintain the same farm size and 18.0%

planned to abandon their businesses. This indicates that business planning affects motivation to adopt BGPs. Finally, there was no significant relationship between willingness to adopt BGPs and the existence of BGPs in the area ($p = 0.3142 > 0.01$), inferring that the condition affecting farmers' willingness to adopt BGPs could not be verified.

Table 2.7. Category distribution according to willingness to adopt biogas plants (BGPs).

Categories		Number of farmers (ratio)		p-value
		Group 1	Group 2	
Existence of successors	Already determined	45 (37.8%)	40 (24.0%)	0.0044 *
	Not determined, but have a candidate	34 (28.6%)	39 (23.4%)	
	No candidate	36 (30.3%)	69 (41.3%)	
	No successors required	4 (3.4%)	19 (11.4%)	
Existence of issues on manure treatment	Yes	70 (58.8%)	38 (22.8%)	0.0000 *
	No but it may occur in the future	39 (32.8%)	42 (25.1%)	
	No	10 (8.4%)	87 (52.1%)	
Current number of MCs	0–50 heads	30 (25.2%)	69 (41.3%)	0.0004 *
	50–100 heads	48 (40.3%)	77 (46.1%)	
	100–150 heads	15 (12.6%)	12 (7.2%)	
	150–200 heads	9 (7.6%)	6 (3.6%)	
	> 200 heads	17 (14.3%)	3 (1.8%)	
Future plan of business (change of number of MCs)	Retirement	4 (3.4%)	30 (18.0%)	0.0003 *
	Decrease	3 (2.5%)	13 (7.8%)	
	Maintain	45 (37.8%)	67 (40.1%)	
	Increase	67 (56.3%)	57 (34.1%)	
Existence of BGPs	Yes	70 (58.8%)	87 (52.1%)	0.3142
	No	49 (41.2%)	80 (47.9%)	

Note: The p-values with "*" denote those that are statistically significant ($p < 0.01$).

2.4.3. Assessment of critical factors influencing willingness to adopt BGPs

Table 2.8 shows the results of our analysis using the quantification theory type II. “Category scores” for each item are presented in Figure 2.2. This analysis is also a discriminant analysis, so if other farmers were asked the same questions, I could predict what they would think about BGPs. The analyses evaluated the rate of correct answers of predictions compared to actual answers (whether they were willing to adopt BGPs) and the predicted value by sample score y, as calculated in Eq.1.1. In total, 212 out of 286 farmers were correctly predicted, a rate of 74.1%. All comparison results are shown in detail in the Supplementary Materials. Among the items and categories, it was found that issues with manure treatment and future business plans have a significant, strong influence on the willingness to adopt BGPs. This is due to the category ranges, which are 1.796 (0.770 minus -1.026, based on the difference between maximum and minimum category scores for issues with manure treatment) and 1.204 (0.328 minus -0.876 for future business plan) (p-values of 0.0000 [<0.01] and 0.0011 [<0.01], respectively) (Table 2.8).

In terms of influence on each category, the higher the positive value of the category score, the more the factor makes the farmers who were willing to adopt BGPs. For issues with manure treatment, the value was positive for farmers who had issues, and those who did not have any issues at present but may in the future were inclined to have a positive attitude towards adopting BGPs. Meanwhile, the value for farmers who did not have issues with manure treatment was strongly negative, thus they were not expected to adopt BGPs. Table 2.9 details the specific issues that were part of the optional answers. In Group 1, 286 answers (62.9% of the 455 total) were collected, compared to 169 (37.1%) in Group 2. Among the detailed problems seen individually, “Field area to spread compost is insufficient” was selected by 100 farmers, representing the highest percentage (35.0%) of the 286 total farmers, followed by “Too much labor time is needed to treat manure” by 96 farmers (33.6% of the total). Focusing on the 119 farmers in Group 1, 63 farmers (52.9%) selected “Space to make compost pile is insufficient” and 53 farmers (44.5%) selected “Too much labor time is needed to treat manure”. For future business plans, the value of increase was positive, indicating that farmers who will expand their farms in the future were motivated to adopt BGPs. On the other hand, the category score of retirement and decrease was strongly negative, indicating that farmers planning to retire or shrink their businesses did not require BGPs or could not adopt them. This may be due to the significant investment needed to construct BGPs and the long-term planning required to operate them. There were no significant relationships in the items for existence of successors, current number of MCs, or existence of BGPs.

Table 2.8. Summary of the results of quantification theory type II.

Items	Category	Number of farmers	Category score	Range	p-value
Existence of successors	Already determined	85	0.142	0.232	0.7839
	Not determined, but have a candidate	73	−0.023		
	No candidate	105	−0.090		
	No successors required	23	−0.038		
Existence of issues on manure treatment	Yes	108	0.770	1.796	0.0000 *
	No but it may occur in the future	81	0.202		
	No	97	−1.026		
Current number of MCs	0–50 heads	99	0.010	0.935	0.0861
	50–100 heads	125	−0.218		
	100–150 heads	27	0.223		
	150–200 heads	15	0.399		
	> 200 heads	20	0.716		
Future plan of business (change of number of MCs)	Retirement	34	−0.876	1.204	0.0011 *
	Decrease	16	−0.695		
	Maintain	112	0.002		
	Increase	124	0.328		
Existence of BGPs	Yes	157	0.123	0.273	0.1320
	No	129	−0.150		

Note: The p-values with "*" denote those that are statistically significant ($p < 0.01$).

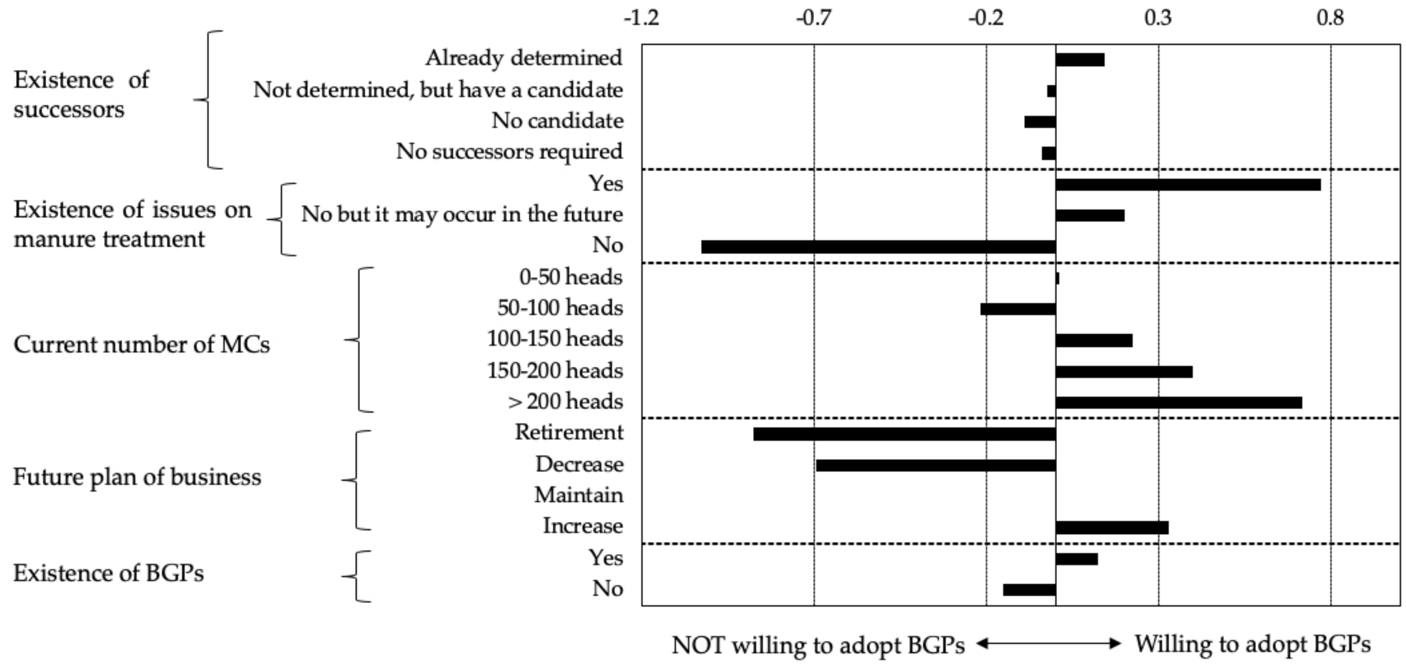

Figure 2.2. Category score analyses of different items. Bar chart shows the category score of each category for the items “existence of successors”, “existence of issues on manure treatment”, “current number of MCs”, “future plan of business”, and “existence of BGPs”.

Table 2.9. Details of issues experienced with manure treatment selected by both Groups, i.e., the number of farmers and percentage of each group.

	# in Group 1 (119 farmers)			# in Group 2 (167 farmers)			Total
	Yes (%)	No, but it may occur in the future (%)	Total (%)	Yes (%)	No, but it may occur in the future (%)	Total (%)	
Bad odor is emitted from the manure.	19 (16.0%)	11 (9.2%)	30 (25.2%)	6 (3.6%)	8 (4.8%)	14 (8.4%)	44
Space to make compost pile is insufficient.	44 (37.0%)	19 (16.0%)	63 (52.9%)	18 (10.8%)	19 (11.4%)	37 (22.2%)	100
Weeds in the field increase due to weed seeds remaining in the compost.	24 (20.2%)	7 (5.9%)	31 (26.1%)	9 (5.4%)	10 (6.0%)	19 (11.4%)	50
Compost is less effective as a fertilizer.	8 (6.7%)	2 (1.7%)	10 (8.4%)	2 (1.2%)	1 (0.6%)	3 (1.8%)	13
Time to spread the compost is not enough.	25 (21.0%)	8 (6.7%)	33 (27.7%)	7 (4.2%)	9 (5.4%)	16 (9.6%)	49
Field to spread compost is too far from farm.	27 (22.7%)	9 (7.6%)	36 (30.3%)	14 (8.4%)	14 (8.4%)	28 (16.8%)	64
Field area to spread compost is insufficient.	20 (16.8%)	10 (8.4%)	30 (25.2%)	4 (2.4%)	5 (3.0%)	9 (5.4%)	39
Too much labor time is needed to treat manure.	36 (30.3%)	17 (14.3%)	53 (44.5%)	19 (11.4%)	24 (14.4%)	43 (25.7%)	96
Total	203	83	286	79	90	169	455

2.5. Discussion

Our survey showed that 41.6% of dairy farmers could be categorized as "willing to adopt BGPs", with a corresponding number of 57.2% of the MCs. The expected number of MCs per household is an increase of 36.9%. Meanwhile, farmers who do not adopt BGPs will remain the farm size. This finding is in agreement with Tranter et al. (2011) and Aruba (2019), explaining that the larger the business, the more likely farmers are to introduce new equipment and technologies (Tranter et al., 2011; Aruba et al., 2019). In this study, the size of a farm and future plans were significant factors contributing to the willingness of farmers to adopt BGPs. Large-scale farmers produced 36.1% of Hokkaido's milk in 2010 (Miyake, 2018). In the 10 years from 2009 to 2019, the number of dairy farmers in Hokkaido decreased by 1,720 (22.4%) (MAFF, 2009, 2019). As a result, farmers with large farms who are motivated to adopt BGPs account for an even greater proportion of the number of MCs, and they will play more important roles in the dairy industry in Hokkaido. This study revealed the importance of BGP installation by farmers who are most responsible for, and contribute the most to, the development of the local industry in the future.

This study also revealed that issues with manure treatment are significant factors influencing BGP adoption. Of the farmers who were willing to adopt BGPs, 52.9% selected "space to make compost pile is insufficient" and 44.5% chose "too much labor time is needed to treat manure". Since the enactment of the Act on Proper Management and Promotion of Use of Livestock Manure (hereafter, the "Livestock Manure Act") in 2004, many farmers have built compost houses with a concrete floor for the composting space, but due to the increase in the number of MCs, the composting space has been insufficient and has taken more and more time to treat the manure. In addition, many farmers changed their feeding style to a stall barn, which does not require much bedding. However, it becomes difficult to make compost because the manure has a lot of water that can easily flow out of the compost house (Nishimura, 2014; Miyake et al., 2016).

Furthermore, I found that farmers faced the problems with application of the compost to the field. 30.3% of the farmers chose "field to spread compost is too far from farm" and 25.2% selected "field area to spread compost is insufficient". This may be explained by the tendency of farmers to have large fields, and in order to increase the number of MCs, they add farmland abandoned by retired farmers. "Time to spread the compost is not enough" was selected by 27.7% of respondents and relates to the excessive amounts of manure and compost that need to be spread across large fields. Selected by 26.1% of respondents, "weeds in the field increase due to weed seeds remaining in the compost" refers to compost and manure slurry that is contaminated by weed seeds that are not deactivated by the high aerobic composting temperature (Kimura et al., 1994; Serizawa et al., 2008). Referring to difficulties in making fully ripe compost because of the large amount of manure and its high water content, 25.2% mentioned “bad odor is emitted from the manure” and 8.4% indicated that “compost is less effective as a fertilizer” (Nishimura, 2014).

For these issues, BGPs can be expected to treat manure effectively. BGPs operate continuously, so treatment space for composting is not required. Because manure is collected regularly or is automatically carried into a BGP, the labor time required to treat manure is reduced. The liquid digestate can be used as an organic fertilizer, which adds nitrogen, phosphorus, and potassium, which are particularly important for agricultural products. In Hokkaido, it is common for operators of BGPs to spread digestate, which may reduce the labor time of farmers and enable the spreading of digestate to distant fields. BGPs could therefore solve the aforementioned issues, a view held by the dairy farmers in this study. Yet, the amount of digestate to be spread is controlled by the fertilization standard, which determines the upper limits of nitrogen, phosphoric acid, and potassium that can be spread (Fujikawa and Nakamura, 2010). The fertilization standard varies depending on the type of land. Thus, if the amount of digestate is too large and farmers cannot spread all of it on their own fields, they must cooperate with neighboring farmers to use all of it.

As mentioned above, in this survey, it was confirmed that the existence of issues on manure treatment and the future plans of a business strongly influenced the willingness to adopt BGPs, which was consistent with my original hypothesis. On the other hand, the current number of MCs, the existence of successors, and the existence of BGPs did not show a clear relationship with the farmers' willingness, which contradicts my original hypothesis.

The existence of successors is a major factor determining whether dairy farmers continue to farm. According to Araki (2017), the most frequent reason for farming abandonment is the absence of a successor (by 42%), following debts (by 24%), labor shortages (by 12%), and anxiety about the future (by 11%) (Araki et al., 2017). As shown in Table 2.7, 66.4% of farmers motivated to adopt BGPs had identified successors or successor candidates, compared to only 47.4% of farmers who were not willing to adopt BGPs. This result infers that farmers may choose to install BGPs when they are likely to continue farming, which may align with the conclusions of Kurihara et al. (2019) that larger farms tend to have successors. However, through the quantification theory type II, I did not find a significant correlation between willingness to adopt BGPs and the existence of successors. A possible reason is that our questionnaire did not ask about farmer age and thus could not identify differences by age structure. Kurihara et al. (2019) mentioned that farmers involved in large-scale farming who plan to expand the scale of their operations are relatively young (Aruba et al., 2019). Thus, it may be too early for the young farmers to consider successors, and they might have answered that they did not a have successor even if they were interested in BGPs. According to Araki (2017), successor shortages are due to a lack of consideration of working conditions (such as working hours) and sustainable farm management (Araki et al., 2017). In recent years, the number of MCs per household has increased, and the expansion of farm sizes has led to an increase in the number of hours worked per person (Kamata, 2011; Aruba et al., 2019). Miyake (2018) reported that owners tend to spend less time with their own MCs at farms that are poorly managed (Miyake, 2018). In other words, BGPs could reduce the time spent on manure treatment, increase the amount of time spent with MCs, increase production efficiency, stabilize business operations, improve working conditions, and allow more time to identify successors.

The biogas produced from BGPs is also important. AD in BGPs use organic waste effectively to produce renewable energy that is distributed and can increase self-sufficiency and mitigate climate change (Yabe, 2013; Anabuki et al., 2016; Babalola, 2020). Distributed, self-sufficient energy is important in Japan given its history of large earthquakes (e.g., the 2011 Great East Japan Earthquake and the 2018 Hokkaido Eastern Iburi Earthquake) that have cut off the supply of large-scale, centralized power plants (Hager and Hamagami, 2020). Electricity from the FIT policy generates the majority of BGP revenue, however, the constraint of grid interconnection remains a serious problem (Yoshida et al., 2014). There are some discussions about revising the grid system, such as developing a Japanese "Connect and Manage" rule, but in Japan the energy is required to be used not only for electricity but also heating, gas, and hydrogen (Hikino and Kurumi, 2018). In Hokkaido, combined heat and power (CHP) systems in BGPs have been used to cultivate vegetables and fruits in greenhouses and aquaculture, however, heat can currently only be used in the surrounding area (Hachimura et al., 2015). In Germany and Denmark, the gas grid is widespread across the country and the FIT system for gas supply is also institutionalized (Hoo et al., 2018). Because Hokkaido is a particularly cold region and energy demand per household is the highest in Japan, promoting biogas as a heat source makes sense (Takita et al., 2016).

Sufficient investment for construction is necessary to install more BGPs. There should also be subsidies for their operation, such as FIT schemes (despite the difficult situation for power grid use). The effects of BGPs on the environment and dairy farming have already been explained in previous studies, as mentioned above. Therefore, it should be emphasized that BGPs are different from other power sources that require policy design, such as preferential grid use and support of continuous FIT schemes. FIT schemes for gas supply should be institutionalized in Japan. Zheng et al. (2020) showed the importance of subsidizing the production of BGPs. It may be possible to consider support in the form of ESG investments from the viewpoint of improving environmental problems and regional economies, for which the dairy farmers who are willing to adopt BGPs would be responsible.

2.6. Conclusion

To achieve sustainable farming with BGPs, this study investigated the relationship between farmers' willingness to adopt BGPs and their current farming situations. I found that farmers who were willing to adopt BGPs were likely to have large farms and to expand the size of their farms in the future. As the number of dairy farmers has recently decreased, farmers motivated to adopt BGPs would play an important role in the dairy industry in Hokkaido. BGPs would support effective manure treatment to improve farming conditions and revitalize local economies.

In this study, I could not identify a clear relationship between the existence of successors and willingness to adopt BGPs, because I did not collect data on the age of the farmers. It seems that some of the farmers were relatively young and had not yet identified their successors. To identify successors is a major issue for sustainable dairy farming, and therefore, further research might be necessary to promote dairy farming, particularly in local scales.

There has been much discussion about barriers to the use of electricity produced by biogas (such as restriction of grid connection), but BGPs could be accepted as a means of agricultural promotion. Therefore, it is important to understand the effects of BGPs on farming. This study may be valuable for decision-making regarding efficient allocation of subsidies and efficient development of other energy systems that could reduce the cost of fossil fuels.

Chapter 3: Potential of biogas plant adoption in reducing greenhouse gases emissions in Hokkaido, Japan

3.1. Introduction

The result of Chapter 2 indicated that 41.6% of the 286 dairy farmers have willingness to adopt BGPs. The farmers, in particular those that had large-scale farms with 100 or more cows, planned to expand the scale in the future, and were concerned about the treatment of manure. Thus, the BGPs were expected to sustain the dairy industry in Hokkaido as a tool for reducing the labor force and solving problems related to manure treatment. Around 11.9% of 286 dairy farmers are considering abandonment of farming in the future (10 years later), which resulted from the aging and the lack of labor such as with no successors. Furthermore, 56.3% of dairy farmers who were willing to adopt BGPs plan to increase dairy cows in the future.

The biogas business is often affected by policy-making and needs to reconsider to avoid relying solely on subsidies and is difficult to maintain the construction and operation of BGPs worldwide without the assistance of the government, implying that the finance is important (Ward et al., 2008; Cucchiella et al., 2019). Regarding securing of project finance, there are some global schemes such as Environmental, Social and Governance (ESG) investment and 100% renewable energy (RE100) movement (Tajima and Okada, 2019).

The GHG emissions in Japan in 2018 were 1.24 billion tons CO_2-eq, with the agricultural sector emitting 33 million tons CO_2-eq (2.7% of total). Manure treatment must be managed carefully in terms of the emissions of CH_4 and N_2O with strong global warming effects. The GHG emission from manure treatment were 2.3 million tons CO_2-eq for CH_4 and 4.0 million tons CO_2-eq for N_2O, accounting for 0.2% and 0.3% of the total GHG emissions in Japan, respectively (MOE, 2020). To approach ESG investment and RE100 in Japan, there is a scheme for a certificate to show the reduction of GHGs such as Japan Credit (J-Credit) (Tajima and Okada, 2019). This would also attract citizens who seriously think about environmental problems. In order that the investor of ESG investment understand the advantages of BGPs projects in Hokkaido, it is important to assess the potential of positive impact from the expected BGPs in the future which is closer to reality.

Chapter 3 aimed to evaluate the environmental impact by adopting BGPs in Hokkaido by applying results obtained in Chapter 2, such as the proportion of dairy farmers who were willing to adopt BGPs and the expected number of dairy farmers in the future. In particular, GHG emission reduction from replacing energy source to biogas and preventing release from reference manure treatment methods were evaluated. Finally, the environmental benefit from GHG emission reduction and economic benefit from expected energy usage and application of J-Credit for GHG reduction were discussed.

3.2. Methods

3.2.1. Evaluation of BGP adoption potential in Hokkaido

3.2.1.1. Evaluation of manure processing amount by questionnaire and interview survey

The results of questionnaire survey for study of Chapter 2 was also applied in this chapter. In addition, I did supplemental survey with interview in Oumu, Yubetsu, Shikaoi, Toyokoro, and Hiroo in 2018, 2019 and 2020. The interview survey was carried out with 60 dairy farmers who answered the questionnaire survey and who were willing to adopt BGPs. The interview involved questions on the current and future number of cows and the expected proportion of manure to be treated in the BGPs. The amount of manure processed in the BGPs was calculated using the proportion. The farmers were chosen by the local governments and Japan Agricultural Cooperative (JA). Table 3.1 summarized the question items interview survey.

Table 3.1. Contents of the interview survey

Element	Expression
1. Number of dairy cows	Current and future numbers (in the next 10 years) of milking cows, dry cows, heifers, and calves.
2. Ratio of manure emitted from dairy farms to be treated in BGPs	Comparison between the number of dairy cows and expected number of cows, whose manure to be treated in BGPs

3.2.1.2. Estimation of number of cows and amount of manure based on farmers' willingness to adopt BGPs

The dairy cows were divided into four categories of milking cows, dry cows, heifers, and calves and their corresponding amount of manure excreted is different. Expected scales of BGPs depends on the total amount of manures excreted by all the cow categories. In this study, the number of dairy cows was reconsidered as a milking cows equivalent to estimate the expected changes of farm size in the future (Iwasaki et al., 2017).

The total amount of manures was calculated by converting the cow number into that of milking cow equivalent, by referring to the amount of dairy manure of each type of livestock (Table 3.2) and by applying Eq. 3.1 (Japan Livestock Industry, 2000):

$$N_{milk\_eq} = \frac{N_{milk} \times M_{milk} + N_{dry} \times M_{dry} + N_{heifer} \times M_{heifer} + N_{calf} \times M_{calf}}{M_{milk}} \quad \text{Eq. 3.1}$$

where N_{milk_eq} is the converted number population to milking cow equivalent in head; N_{milk} is the number of milking cows in head; N_{dry} is the number of dry cows in head; N_{heifer} is the number of heifers in head; N_{calf} is the number of breeding cows in head; M_{milk} is the amount of manure excreted by milking cow in kg day^{-1}. The value is 65; M_{dry} is the amount of manure excreted by dry cow in kg day^{-1}. The value is 27; M_{heifer} is the amount of manure excreted by heifer in kg day^{-1}. The value is 23; M_{calf} is the amount of manure excreted by calf in kg day^{-1}. The value is 23. The values of M_{milk}, M_{dry}, M_{heifer} and M_{calf} were based on the manure production illustrated in Table 3.2.

Table 3.2. Manure production (feces and urine) per dairy cows (Japan Livestock Industry, 2000)

	Feces (kg day^{-1})	Urine (kg day^{-1})	Total (kg day^{-1})
Milking cow	50	15	65
Dry cow	21	6	27
Heifer / Calf	16	7	23

The expected growth rate of each farmer who were willing to adopt BGPs was calculated from the current and future number of milking cow equivalent by using Eq. 3.2.

$$R_{change\_N\_will} = \frac{(N_{fut\_will} - N_{cur\_will})}{N_{cur\_will}} \times 100 \quad \text{Eq. 3.2}$$

where $R_{chage\_N\_will}$ is the rate of change of number of cows by individual farmer who were willing to adopt BGPs (%); N_{cur_will} is the current number of milking cow equivalent in head; N_{fut_will} is the future number of milking cow equivalent in head.

Shimahata et al. (2020) reported that adopting BGPs was not significantly affected by the existing of BGPs located in the areas (Shimahata et al., 2020). Therefore, in this study, the proportion of farmers who were willing to adopt BGPs in the nine municipalities surveyed and the rate of farm size growth were applied to evaluate the number of farmers and raised cow in whole area in Hokkaido in order to assess the potential to adopt BGPs in Hokkaido. Based on statistical data of Hokkaido in 2018, the number of dairy farmers is 5,970 and the number of dairy cows is 801,000. Here, the number of cows was converted to that of milking cow equivalent as 548,758 (MAFF, 2019) (Table 3.3).

Table 3.3. Number of dairy farmers and dairy cow raised in Hokkaido in 2018 (MAFF, 2019)

Number of dairy farmers	(household)	5,970
Number of cows		
Milking cow	(head)	399,500
Dry cow	(head)	103,100
Heifer/Calf	(head)	298,400
Total	(head)	801,000
Milking cow equivalent	(head)	548,758

The rate of farmers who were willing to adopt BGPs was calculated by Eq. 3.3:

$$R_{F\_will} = \frac{N_{F\_will}}{N_{F\_Surveyed}} \times 100 \qquad \text{Eq. 3.3}$$

where R_{F_will} is the rate of farmers who were willing to adopt BGPs (%); $N_{F\_Surveyed}$ is the number of targeted farmers in the questionnaire survey in household (286 households); N_{F_will} is the number of farmers who were willing to adopt BGPs in the questionnaire survey in household.

The total number of farmers expected to have willingness to adopt BGPs in the whole area of Hokkaido was estimated by Eq. 3.4:

$$N_{F\_will\_H} = N_{F\_H} \times R_{F\_will} \qquad \text{Eq. 3.4}$$

where $N_{F\_will\_H}$ the number of farmers expected to have willingness to adopt BGPs in whole area of Hokkaido in household; N_{F_H} is the number of dairy farm household in Hokkaido in household; R_{F_will} is the rate of farmers who were willing to adopt BGPs in head.

The expected current number of dairy cows raised by farmers who were willing to adopt BGP was calculated by Eq. 3.5:

$$N_{cur\_will\_H} = N_{F\_will\_H} \times N_{ave\_will} \qquad \text{Eq. 3.5}$$

where $N_{cur\_will\_H}$ is the expected current number of dairy cows raised by farmers who were willing to adopt BGP in Hokkaido in head; $N_{F\_will\_H}$ is the number of farmers expected to have willingness to adopt BGPs in Hokkaido in head; N_{ave_will} is the average number of dairy cows raised by farmers who were willing to adopt BGPs in head.

The expected future number of dairy cows raised by farmers who were willing to adopt BGP in Hokkaido was calculated by Eq. 3.6:

$$N_{fut\_will\_H} = N_{cur\_will\_will} \times R_{change\_N\_will} \qquad \text{Eq. 3.6}$$

where $N_{fut\_will\_H}$ is the expected future number of dairy cows raised by farmers who were willing to adopt BGP in Hokkaido in head; $N_{cur\_will\_H}$ is the expected current number of dairy cows raised by farmers who were willing to adopt BGP in Hokkaido in head; $R_{chage\_N\_will}$ is the rate of change of cows by individual farmer who were willing to adopt BGP (%).

The expected number of dairy cows whose manure to be treated by BGPs in Hokkaido was calculated by Eq. 3.7:

$$N_{treated\_H} = N_{fut\_will\_H} \times R_{treated} \qquad \text{Eq. 3.7}$$

where $N_{treated\_H}$ is the expected number of dairy cows whose manure to be treated by BGPs in Hokkaido in head; $N_{fut\_will\_H}$ is the expected future number of dairy cows raised by farmers who were willing to adopt BGP in Hokkaido in head; $R_{treated}$ is the rate of dairy cows whose manure to be treated (%). The expected amount of manure to be treated by BGPs was calculated by Eq. 3.8:

$$A_{m\_treated\_H} = N_{treated\_H} \times M_{milk} \qquad \text{Eq. 3.8}$$

where $A_{m\_treated\_H}$ is the expected amount of manure to be treated by BGPs in Hokkaido in head. $N_{treated\_H}$ is the expected number of dairy cows whose manure to be treated by BGPs in Hokkaido in head; M_{milk} is the amount of manure excreted by milking cow in kg day^{-1}. The value in a milking cow equivalent was set to be 65.

3.2.2. Estimation of environmental impact of adoption of BGPs

3.2.2.1. Adopted biogas system

The BGPs are expected to be run under mesophilic conditions (38 °C) with an entirely stirred digester tank. The produced biogas is transformed into energy (electrical) in a combined heat and power unit (CHP) and fed into the grid. Thermal energy as a side product of the combustion process is used to heat the digester in order to maintain the anaerobic process and used for agriculture in greenhouse or aqua-culture in the facility close to BGPs (Meyer-Aurich et al., 2012; Hachimura et al., 2015).

The process of anaerobic digestion in BGP is shown in Figure 3.2. This is a reaction in which carbohydrates, proteins, and lipids in organic matter such as manure are transformed by microorganisms. They are decomposed into sugars, amino acids, and fatty acids through hydrolysis, respectively. After that, they are also converted to volatile fatty acid such as propionic acid and acetic acid as intermediate substances, and are finally converted to biogas (CH_4 and CO_2) by methanogenesis (Rashed Al Mamun, 2015; Fukumoto et al., 2015). In addition, about 60% of the biogas produced in anaerobic fermentation is CH_4. Since all CH_4 is used as fuel for energy production, the emission of CH_4 was assumed to be zero in this study. On the other hand, N_2O emissions were also calculated, assuming that a small amount of N_2O is emitted from the digestate stored in the storage tank (Intergovernmental Panel on Climate Change (IPCC), 2019; Vergote et al., 2020).

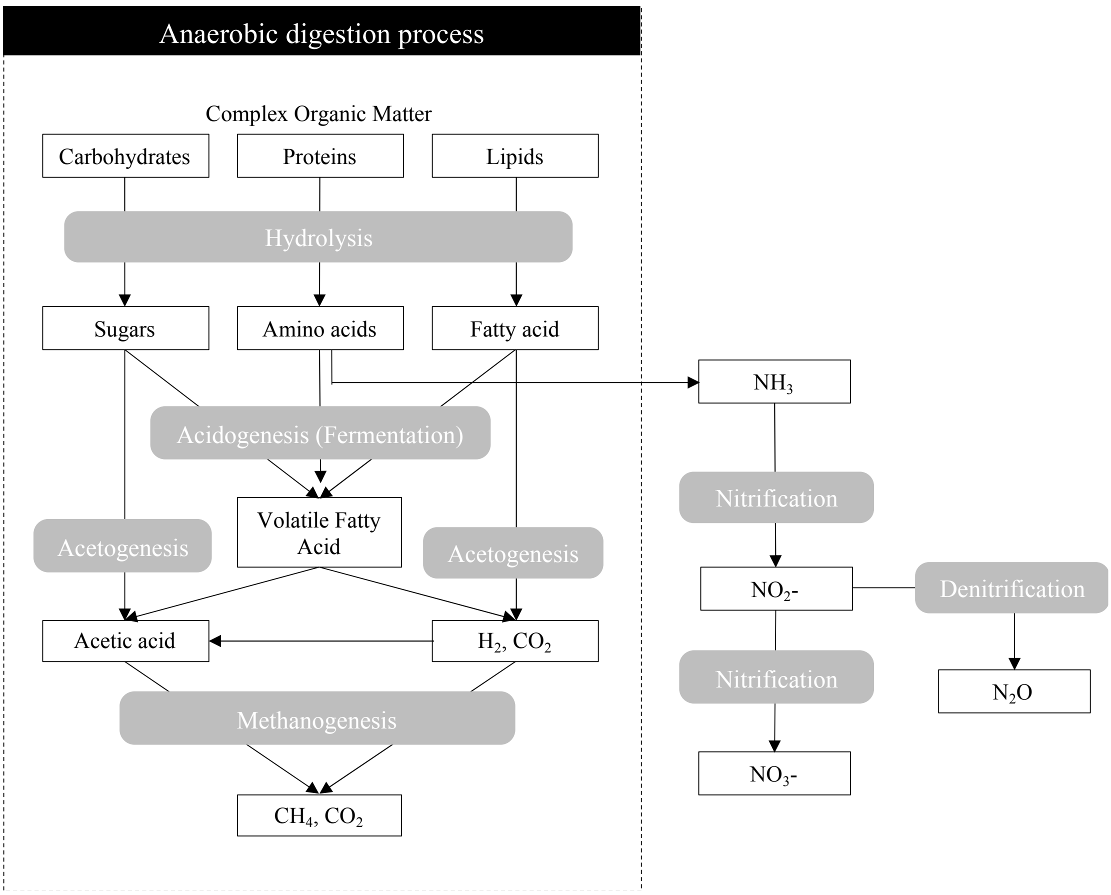

Figure 3.2 Process of anaerobic digestion and production of N_2O

3.2.2.2. Estimation of GHG emissions

GHG reduction potential was calculated for the expected BGP model dealing with typical dairy farm in Hokkaido. To estimate the impact of adopting BGPs, the GHG emissions of reference management system were compared. Since the manure is directly injected into the digester of BGPs, GHG emissions from the manure storage were presumed to be avoided, which would reduce the gaseous emissions.

There are several reference methods for managing dairy manure in Japan. And piling and forced composting are the most major manure management practice in Japan (Osada, 2005). Piling system (solid storage) is a method of composting, in which a pile of about 1.5-2.0 m height at compost bed or in compost house to ferment the contents for several months with occasional turning. The forced composting is a fermentation method for a couple of weeks with forced aeration and agitation in covered or closed tanks (Ministry of the Environment, Japan (MOE), 2020). Composting is a method of decomposing easily degradable organic matter by microorganisms under aerobic conditions, but the many piles of manure of dairy cows easily becomes anaerobic condition due to high watery content, which caused the emission of CH_4 and N_2O. In particular, forced composting maintains aerobic conditions at high concentrations through aeration, which not only speeds up composting but also reduces the generation of CH_4 and N_2O (Shiraishi et al., 2004; MOE, 2020). CH_4 and N_2O emissions were considered according to their corresponding global warming potential (GWP) (Meyer-Aurich et al., 2012). The GWP is presented in CO_2 equivalents (CO_2-eq) value. Details of the methodologies for the estimation of GHGs mitigation by adopting BGP in Hokkaido was estimated by using Eq. 3.9:

$$Gm = Mt + Mf + Ms + Ml + Mc \qquad \text{Eq. 3.9}$$

where *Gm* is the GHG emission reduction by the adopted BGP in kg CO_2-eq; *Mt* is the GHG emission reduction by energy production in kg CO_2-eq; *Mf* is the CO_2 emission from electricity consumption in ton CO_2-eq; *Ms* is the GHG emission reduction of manure treatment in kg CO_2-eq; *Ml* is the GHG emission from BGP in kg CO_2-eq; *Mc* is the CO_2 reduction from replacement of chemical fertilizer by applying digestate in kg CO_2-eq.

3.2.2.2.1. GHG emission reduction by energy production (*Mt*)

The biogas can generate electricity and heat to be used as renewable energy source, expected to replace fossil fuels. Most BGPs in Japan have applied CHP to generate both electricity and heat (Lybæk and Asai, 2017). The GHG reduction to generate electricity and heat by replacing fossil fuels was calculated by using Eq. 3.10. Prior to this, the GHG reductions were calculated by using Eq. 3.11 for electricity and Eq. 3.12 for heat, respectively. This study calculated the electricity and heat from the CHP whose electrical efficiency was 35% and heat efficiency was 40%, and the biogas yield was assumed to be 61.2 m^3 ton^{-1} of fresh manure (Achinas et al., 2017). Meyer-Aurich et al. (2012) reported that the biogas losses were supposed to vary from 0% to 2% of the total produced biogas, including leakage and CHP slip (Meyer-Aurich et al., 2012). Therefore, the worst scenario of losses of 2% was applied, resulting in 60.0 m^3 ton^{-1} for estimation of generated energy:

$$Mt = Me + Mh \quad \text{Eq. 3.10}$$

$$Me = M \times Eb \times EFe \quad \text{Eq. 3.11}$$

$$Mh = M \times B \times EFh \times Hf \times \frac{1}{Ck} \times Ek \quad \text{Eq. 3.12}$$

where *Mt* is the GHG emission reduction by adopted BGPs to generate electricity and heat in kg CO_2-eq; *Me* is the GHG emission reduction by adopted BGPs to generate electricity in kg CO_2-eq; *Mh* is the GHG emission reduction by adopted BGPs to generate heat in kg CO_2-eq; *M* is the amount of fresh dairy manure in ton; *Eb* is the electricity generated by the amount of manure in 60.0 m^3 ton^{-1} and was set to be 122.5 kWh ton^{-1}; *EFe* is the CO_2 emission factor of the major power company in Hokkaido in 2019 (0.000643 tons kWh^{-1}); *B* is the biogas yield (60.0 m^3 ton^{-1}); *EFh* is the conversion factor which biogas generates energy (21MJ m^{-3}); *Hf* is the heat efficiency of CHP for this study (40%); *Ck* is the standard calorific value of kerosene (36.5 MJ L^{-1}); *Ek* is the emission factor of kerosene (2.49 kg CO_2 L^{-1}) (MOE, 2016, 2017, 2020; Achinas et al., 2017; METI, 2020c).

3.2.2.2.2. GHG emission from energy consumption for manure treatment (*Mf*)

The GHG emissions resulting from electricity consumption by piling, forced composting, and AD in BGPs were calculated. In this study, it was assumed that electricity was not consumed in the process of piling, because it was an occasional turning, which was not automatically operated. Forced composting consumed electricity due to the aeration process. AD consumed electricity but it was generated in the process of AD and can be used for self-consumption. Thus, the electricity consumption of AD was zero. The electricity consumption by aeration of forced composting was reported to be 133-160 kWh ton^{-1} of the raw material (Erasmo et al., 2009). In this study, the 160 kWh ton^{-1} as the maximum value was used to calculate the electricity consumption and emission of GHGs for forced composting by the following equation:

$$M_f = M \times EF_e \times CF_a \quad \text{Eq. 3.13}$$

where *Mf* is the CO_2 emission from electricity consumption in tons CO_2 day^{-1}; *M* is the amount of dairy manure in tons day^{-1}; *EFe* is the CO_2 emission factor of the major power company in Hokkaido in 2019 (0.000643 tons kWh^{-1}); *CFa* is the emission factor of electricity consumption in tons CO_2 kWh^{-1} of which value is 160 (Erasmo et al., 2009).

3.2.2.2.3. GHG emissions from manure treatment (*Ms*)

CH_4 and N_2O emissions in the process of manure treatment are significant factors of global warming. In this study, the emissions from piling, forced composting and AD in BGPs were calculated by following equations, respectively. This study was conducted using equations and coefficients from the previous studies based on the guidelines of IPCC and MOE in Japan (IPCC, 2006, 2019; MOE, 2020). According to the IPCC guidelines, GHG emissions can be calculated using three types of methods (Tier 1 to Tier 3) depending on the type and the amount of obtained data. The guideline of MOE published in 2020 indicates the method based on Tier 2 to estimate the emission of CH_4 and N_2O during the manure treatment process, because more detailed data are available in Japan. Thus, this study also followed the method of MOE (MOE, 2020). Furthermore, the equations such as Eqs. 3.14, 3.15 and 3.16 in this study were modified to calculate with the obtained data from the survey such as the number of dairy cows, the amount of manure, and the amount of nitrogen contained in manure, and the coefficient such as GWP (Meyer-Aurich et al., 2012).

a. CH_4 emissions

CH_4 emissions during the manure storage were estimated by using Eq. 3.14, based on Greenhouse Gas Inventory Office of Japan (GIO) (MOE, 2020):

$$E_{CH4} = EF_{CH4} \times M \times Org \times Mix_n \times MS_n \quad \text{Eq. 3.14}$$

where E_{CH4} is the CH_4 emission of manure storage system in kg-CH_4; EF_{CH4} is the emission factor of CH_4 in g-CH_4 (g-organic $matter)^{-1}$; *M* is the fresh manure quantity injected into BGPs in kg day^{-1}; *Org* is the organic matter content in manure (feces and urine) (%). The value of feces and urine were 16% and 0.50%, respectively; Mix_n is the proportion of feces and urine separated (%), of which value was 54.5% for dairy cows; MS_n is the share of each treating method (%). The values were set with each category for manure treating method, 50.9% for piling and 22.9% for forced composting, respectively.

b. N_2O_x emissions

Nitrogen released to air in the forms of N_2O and NH_3, or losses to water bodies as NO_3^- during manure storage, therefore, it has direct and indirect contribution to GHG emissions. The latter-so called indirect N_2O_x, can finally convert to N_2O through series of process (i.e., leaching, ammonia volatilization and nitrogen deposition).

Direct N_2O emission ($E_{N2O\text{-}D}$) and indirect N_2O ($E_{N2O\text{-}i}$) from NH_3 and NO_3^- were calculated by using Eqs. 3.15 and 3.16, respectively (MOE, 2016):

$$E_{N2O-D} = [EF_{N2O} \times Cp \times Nex \times Mix_n \times MS_n] \times CF_N \qquad \text{Eq. 3.15}$$

where $E_{N2O\text{-}D}$ is the direct N_2O emission in kg-N_2O; EF_{N2O} is the emission factor of N_2O in g-N_2O-N (g-N)$^{-1}$; Cp is the number of dairy cows (milking cow equivalent) in head; Nex is the nitrogen content of manure (0.43 kg-N head^{-1} day^{-1} for milking cow) (National Agriculture and Food Research Organizatioin, 2006); Mix_n is the proportion of feces and urine separated (54.5 % for dairy cows (MOE, 2020)); MS_n is the share of each treating method (50.9 % for piling, 22.9 % for forced composting, and 1.7 % for AD, respectively (MOE, 2020)); CF_N is the conversion factor of N_2O-N emissions to N_2O emissions, which was 44/28 (IPCC, 2019; MOE, 2020).

$$E_{N2O-i} = [Cp \times Nex \times (Frac_{GASM1i} + Frac_{GASM2i}) \times EF_N] \times CF_N \qquad \text{Eq. 3.16}$$

where $E_{N2O\text{-}i}$ is the indirect N_2O emission in a manure management system in kg-N_2O; $Frac_{GASM1i}$ is the volatilization rate of NH_3 and NO_x in cow barn for management system in kg-NH_3-N+NO_x-N (kg-N)$^{-1}$. The values are 0.045, 0.045 and 0.103 for piling, forced composting and AD, respectively; $Frac_{GASM2i}$ is the volatilization rate as NH_3 and NO_x in process of manure treatment in kg-NH_3-N+NO_x-N (kg-N)$^{-1}$. The values are 0.137, 0.137 and 0.108 for piling, forced composting and AD, respectively.

To estimate GHG emissions from the above three processes, GHG emissions of manure storage systems were obtained by using Eq. 3.17.

$$Ms = E_{CH4} \times GWP_{CH4} \times (E_{N2O-D} + E_{N2O-i}) \times GWP_{N2O} \qquad \text{Eq. 3.17}$$

where Ms is GHG emissions of manure storage systems in kg CO_2-eq; E_{CH4} is the CH_4 emission of manure storage system in kg-CH_4; $E_{N2O\text{-}D}$ is the direct N_2O emission in kg-N_2O; E_{N2Oi} is the indirect N_2O emission in a manure management system in kg-N_2O; GWP_{CH4} is the GWP for CH_4 which was set to 25; GWP_{N2O} is the GWP for N_2O which was set to 298 (IPCC, 2019).

3.2.2.2.4. GHG emission from BGP (*Ml*)

According to Meyer-Aurich et al. (2012), the BGP may lose the 0 to 2% of produced biogas due to leakage and CHP slip. This study estimated the impact of GHG emission by using Eq. 3.18 (IPCC, 2019).

$$Ml = (M \times Bp \times Bl \times Gd) \times (C_{CH4} \times GWP_{CH4} + C_{CO2}) \quad \text{Eq. 3.18}$$

where Ml is the total biogas loss (kg CO_2-eq); M is the amount of manure used in ton; Bp is the biogas yield and the value was set to 61.2 m^3 ton^{-1} of manure in this study; Bl is the proportion of biogas loss, and the value was set to 2% (Meyer-Aurich et al., 2012); C_{CH4} is a content of CH_4 in biogas and the value was set to 55%; C_{CO2} is a content of CO_2 in biogas and the value was set 45%; Gd is gas density and the value was set to 1.221, in kg m^{-3} (25°C and 1 atm) (Hou et al., 2017); GWP_{CH4} is the GWP for CH_4 which was set to 25.

3.2.2.2.5. GHG reduction from replacement of chemical fertilizer by digestate (*Mc*)

According to Mishima et al. (2008), the amount of nitrogen lost in the composting process of dairy manure was 72.2% of the raw material. On the other hand, the digestate by BGPs contains almost the same amount of nitrogen as the raw material (Matsunaka et al., 2002). Dairy farmers apply both compost and chemical fertilizers as required by the soil according to the fertilizer application standards (Fujikawa et al., 2010). In other words, chemical fertilizers are used to supplement the components that compost alone does not provide. By using digestate instead of compost, it is expected that chemical fertilizers can be reduced. This study focused on the amount of nitrogen among the basic components of nitrogen, phosphate, and potassium, and assumed that the same amount of nitrogen would be lost in both piling and forced composting. Therefore, the use of digestate would provide 100% of the nitrogen in the raw material and reduce the use of chemical fertilizers that supplement the same amount of nitrogen lost in composting, which is 72.2% of raw material. Urea and ammonium sulfate are the most common nitrogenous fertilizers widely used in Japan (Association of Agriculture & Forestry Statistics, 2009). Kobayashi et al. (2001) show that the CO_2 emissions in manufacturing urea and ammonium sulfate are 1.59 kg-CO_2 kg^{-1} (0.74 kg-CO_2 $(kg\text{-}N)^{-1}$) and 1.25 kg-CO_2 kg^{-1} (0.26 kg-CO_2 $(kg\text{-}N)^{-1}$), respectively. From the consumption of each fertilizer, the average value was obtained as 1.43 kg-CO_2 kg^{-1} (0.51 kg-CO_2 $(kg\text{-}N)^{-1}$) (Table 3.4). The reduction of CO_2 emission by shifting from composting to AD was estimated by using the following equation:

$$M_C = Cp \times Nex \times Day \times R_C \times EF_C \times \frac{1}{1{,}000} \qquad \text{Eq. 3.19}$$

where *Mc* is the CO_2 reduction from replacement of chemical fertilizer by application of digestate in kg-CO_2 $year^{-1}$; *Cp* is the number of dairy cows (milking cow equivalent in head); *Nex* is the nitrogen content of manure (0.43 kg-N $head^{-1}$ day^{-1} for milking cow) (National Agriculture and Food Research Organizatioin, 2006); Day is 365 days; *Rc* is the reduction of chemical fertilizer (%) of which value is 27.8; *EFc* is the emission factor of CO_2 (0.51 kg-CO_2 $(kg\text{-}N)^{-1}$).

Table 3.4. Emission factor of CO_2 in production of urea and ammonium sulfate as chemical fertilizer

	CO_2 emission (kg-CO_2 kg^{-1})	CO_2 emission kg-CO_2 $(kg\text{-}N)^{-1}$ *	Amount of Consumption (ton $year^{-1}$)	Average of CO_2 emission (kg-CO_2 $(kg\text{-}N)^{-1}$)
Urea	1.59	0.74	129,575 (52.4%)	0.51
Ammonium sulfate	1.25	0.26	117,879 (47.6%)	

*Urea (CH_4N_2O) was converted with 28/60, Ammonium sulfate ($(NH_4)_2SO_4$) was converted with 28/136

3.3. Results

3.3.1. Evaluation of BGP adoption potential in Hokkaido

Table 3.5 shows the number of farmers and dairy cows (milking cow equivalent) for farmers who were willing to adopt BGPs and those who were not in each municipality. The results showed that 119 dairy farmers (41.6% of total surveyed farmers) were willing to adopt BGPs, while 187 dairy farmers (58.4% of total) were not. Hereafter, the farmers who were willing to adopt BGPs and those who were not are presented as Groups 1 and 2, respectively. The total number of dairy cows was 17,427 for Group 1 and 12,790 for Group 2. The number of dairy cows per farmer was 146.3 for Group 1 and 76.6 for Group 2, which was 1.9 times higher for Group 1 than for Group 2.

Table 3.6 indicates the summary of the current and expected future number of dairy cows and average increase rate of dairy cows of each group in each municipality. In Groups 1 and 2, the current number of dairy cows was 17,427 and 12,790, and was expected to be 23,548 and 12,841, respectively, representing an increase of 35.1% and 0.4%, respectively, in the next 10 years. Referring to the farmer's plans per household individually, the average increase rate for 119 dairy farmers in Group 1 was 34.3% (95% confidence interval was 22.3% to 46.3%). In Group 2, on the other hand, the average increase rate of 186 dairy farmers was −7.4% (95% confidence interval was −15.5% to 0.7%), indicating that many dairy farmers who did not have willingness to adopt BGPs planned to maintain or reduce their farming scale.

Table 3.7 shows the summary of the expected rate of cows whose manure were treated in BGPs. Among the 60 dairy farmers who were willing to adopt BGPs in five municipalities, 86.8% of the total dairy cows would apply their manure to be treated by BGPs. Based on the interview, this is primarily because some farmers would like to treat the manure of dry cows and heifers by composting, which requires a low water content and then they use the compost products by themselves. Second, farmers were likely to exchange their composts with the wheat straws of upland farmers so that the straws were used for bedding in cow barn. Finally, some farmers have newly established manure treatment facilities such as composting houses and slurry stores, and therefore, planned to use BGPs for only manure excreted from cows installed in the future.

The potential to adopt BGPs in Hokkaido was assessed by using statistical data on livestock and the results from the survey in 9 municipalities (Table 3.8). In the future, 2,484 farmers would adopt BGPs to treat manure of 385,856 to 461,342 dairy cows, with 25,081 to 29,987 tons of manure in Hokkaido every day. This amount of manure was used to estimate its potential to adopt BGPs and expected GHG reduction under the assumption that the manure is totally treated in BGPs.

Table 3.5. Result of questionnaire for each municipality. The number of cows was milking cow equivalent based on the amount of cow manure.

Municipality	# of farmers	Current # of cows	Group 1				Group 2			
			# of farmers	Ratio of # of famers by total	Current # of cows	Current # of cows per farmer	# of farmers	Ratio of # of famers by total	Current # of cows	Current # of cows per farmer
Wakkanai	53	3,488	17	32.1%	1,240	73.0	36	67.9%	2,248	62.4
Hamatonbetsu	42	4,859	19	45.2%	3,464	182.3	23	54.8%	1,394	60.6
Nakatonbetsu	22	1,347	5	22.7%	380	76.0	17	77.3%	967	56.9
Oumu	35	3,729	8	22.9%	1,179	147.4	27	77.1%	2,550	94.4
Yubetsu	46	4,343	16	34.8%	2,135	133.4	30	65.2%	2,208	73.6
Shikaoi	24	3,384	17	70.8%	2,490	146.5	7	29.2%	894	127.7
Toyokoro	31	6,470	18	58.1%	5,046	280.3	13	41.9%	1,424	109.5
Hiroo	20	2,005	14	70.0%	1,240	88.6	6	30.0%	765	127.5
Yakumo	13	593	5	38.5%	252	50.5	8	61.5%	341	42.6
Total	286	30,217	119	41.6%	17,427	146.4	167	58.4%	12,790	76.6

Table 3.6. Comparison of the number of cows and rate of change in the number in the future between Groups 1 and 2 in each municipality

Municipality	Group 1 (119 farmers)					Group 2 (187 farmers)				
	Current # of cows	Future # of cows	Rate of change in # of cows	Average rate of change in # of cows per farmer*		Current # of cows	Future # of cows	Rate of change in # of cows	Average rate of change in # of cows per farmer*	
Wakkanai	1,240	1,742	40.5%	26.1%	(-15.1% - 67.3%)	2,248	2,665	18.6%	13.9%	(-5.1% - 32.9%)
Hamatonbetsu	3,464	4,007	15.7%	27.1%	(-7.3% - 61.5%)	1,394	953	-31.7%	-40.5%	(-64.4% - -16.6%)
Nakatonbetsu	380	395	3.9%	6.2%	(-5.9% - 18.3%)	967	917	-5.1%	-5.7%	(-30.5% - 19.1%)
Oumu	1,179	1,952	65.5%	37.7%	(-7.6% - 83.0%)	2,550	2,237	-12.3%	-17.8%	(-37.9% - 2.3%)
Yubetsu	2,135	3,304	54.8%	55.9%	(13.5% - 98.3%)	2,208	2,348	6.4%	-3.2%	(-22.8% - 16.4%)
Shikaoi	2,490	3,401	36.6%	43.5%	(5.1% - 81.9%)	894	1,126	26.0%	13.4%	(-7.8% - 34.6%)
Toyokoro	5,046	6,869	36.1%	43.5%	(22.8% - 64.2%)	1,424	1,553	9.0%	5.0%	(-19.0% - 29.0%)
Hiroo	1,240	1,621	30.7%	26.1%	(-13.1% - 65.3%)	765	819	7.1%	1.9%	(-13.9% - 17.7%)
Yakumo	252	256	1.4%	1.8%	(-19.1% - 22.7%)	341	222	-34.7%	-38.1%	(-81.5% - 5.3%)
Total	17,427	23,548	35.1%	34.3%	(22.3% - 46.3%)	12,790	12,841	0.4%	-7.4%	(-15.5% - 0.7%)

* the values in the parentheses represent values based on 95% confidential intervals.

Table 3.7. Summary of number and rate of cows whose manure will be treated in BGPs on the basis of future number of cows, based on the supplemental interview survey

Municipality	# of farmers	Future # of cows	Future # of cows whose manure will be treated in BGPs	Average rate of cows whose manure will be treated in BGPs
Oumu	5	900	852	92.5%
Yubetsu	13	4,324	3,986	91.7%
Shikaoi	16	3,994	2,635	79.4%
Toyokoro	17	6,571	5,510	82.8%
Hiroo	9	1,131	1,104	97.1%
Total	60	16,921	14,086	86.8%

Table 3.8. Summary of expected number of dairy cows and the amount of manure to be treated in Hokkaido

	Unit	value		Note
Expected # of farmers who were willing to adopt BGPs	household		2,484	41.6% of totally 5,970 farmers in Hokkaido
Expected current # of dairy cows	head		363,587	2,484 multiplied by 146.4 cows per farmer
Expected future # of dairy cows	head	488,261	(444,740 – 531,746)*	363,587 multiplied by 34.3% (23.0%-46.3%, 95% confidence interval) as rate of increase ($p = 0.00 < 0.01$)
Expected future # of dairy cows whose manure to be treated in BGPs	head	423,615	(385,856 – 461,342)*	488,261 multiplied by 86.8% as a proportion of cows whose manure to be treated in BGPs
Expected amount of manure to be treated in BGPs	ton day^{-1}	27,535	(25,081 – 29,987)*	423,615 multiplied by 0.065 ton day^{-1}

* 95% confidence interval is considered.

3.3.2. GHG emission reduction

3.3.2.1. GHG emission reduction by energy production

Table 3.9 shows the results of calculating the amount of power generation and heat generation from the manure expected to be treated by BGPs in the future in Hokkaido. The electricity and heat produced in BGPs would be self-consumed or sold and consumed at different places, but these are regarded as carbon-neutral, which does not contribute GHG emissions. Comparing with the assumption that this amount of power is purchased from an electric power company in Hokkaido or the kerosene is used to generate the same amount of heat, 2,838 to 3,393 ton CO_2-eq day^{-1} of GHG can totally be reduced.

Table 3.9. Results of energy production from BGPs and expected GHG emission reduction

	Unit	Min	Max
Energy production			
Electricity	MWh day^{-1}	3,072	3,673
Heat	GJ day^{-1}	12,641	15,114
Kerosene	kL day^{-1}	346	414
GHG emission reduction			
Electricity (*Me*)	ton CO_2-eq day^{-1}	1,976	2,362
Heat (*Mh*)	ton CO_2-eq day^{-1}	862	1,031
Total (*Mt*)	ton CO_2-eq day^{-1}	2,838	3,393

3.3.2.2. GHG emissions from manure treatment

Table 3.10 is the result showing the GHG emissions emitted by piling and forced composting, which are the manure treatment methods currently mainly used in Japan. Piling and forced composting are carried out under aerobic conditions, and CH_4 and N_2O are released into the air depending on the working method and efficiency. In both direct CH_4 emission, direct N_2O emission and indirect N_2O emission, piling and forced composting emitted larger amounts GHGs than AD, which were by 1,233 times and 58.5 times, respectively. In AD in BGPs, dairy manure is directly injected into BGPs and is treated under closed anaerobic conditions. CH_4 is also consumed for energy generation. Thus, CH_4 could be avoided from volatilizing into the air, resulting in zero emission of CH_4.

Table 3.10. Results of GHG emissions from manure treatment

		Piling		Forced composting		AD in BGPs	
		Min	Max	Min	Max	Min	Max
Direct CH_4 emissions (E_{CH4})	(t CO_2-eq day^{-1})	821	982	5	6	0	0
Direct N_2O emissions ($E_{N2O\text{-}D}$)	(t CO_2-eq day^{-1})	519	621	58	70	1.1	1.3
Indirect N_2O emissions ($E_{N2O\text{-}i}$)	(t CO_2-eq day^{-1})	0.039	0.047	0.018	0.021	0.0015	0.0018
Total (*Me*)	(t CO_2-eq day^{-1})	1,340	1,603	63	76	1.1	1.3

3.3.2.3. GHG reduction from replacement of chemical fertilizer by digestate (*Mc*)

Table 3.11 indicates the summary of reduction of chemical fertilizer and CO_2 emissions, when the manure treatment method is changed from composting to AD in BGPs. The use of digestate produced by AD was expected to reduce the use of chemical fertilizers, and CO_2 reduction was estimated to be between 43,898 and 52,485 t-N and between 22,437 and 26,827 t-CO_2 per year, respectively.

Table 3.11. Results of reduction of chemical fertilizer and CO_2 emissions

	Unit	Min	Max
Number of dairy cows	head	385,856	461,342
Amount of nitrogen content	t-N $year^{-1}$	60,800	72,694
Reduction of chemical fertilizer (Nitrogen)	t-N $year^{-1}$	43,898	52,485
Reduction of CO_2 emission	t-CO_2 $year^{-1}$	22,437	26,827

3.3.2.4. GHG reduction potential by adopting BGPs in Hokkaido

Table 3.12 summarizes the annual amount of *Mt*, *Mf*, *Ms*, *Ml* and *Mc* in each manure treatment method. *Mf* as GHG emission due to consumption of energy for manure treatment was estimated to be 941,700 to 1,126,025 ton CO_2-eq $year^{-1}$. *Ml* as GHG emission from BGPs due to leakage and CHP slip of biogas was estimated to be to 194,180 to 232,140 ton CO_2-eq $year^{-1}$.

Positive values indicated GHG emission reduction, and negative values indicated GHG emission. Piling and forced composting are the methods which emit GHGs. In particular, forced composting caused the largest impact of GHG emission. On the other hand, AD in BGPs significantly reduced GHG emissions through effective usage of biogas to produce energy by replacing energy source from fossil fuels, and digestate replacing chemical fertilizer.

According to Table 3.12, it was found that changing the manure treatment from piling to AD in BGPs in Hokkaido would have a GHG reduction effect between 1,352,825 (863,725 minus (- 489,100)) ton CO_2-eq year^{-1} and 1,617,752 (1,032,675 minus (- 585,095)) ton CO_2-eq year^{-1}. Also, shift from forced composing to AD in BGPs would have a GHG reduction effect between 1,828,420 (863,725 minus (- 964,695)) ton CO_2-eq year^{-1} and 2,186,422 (1,032,657 minus (- 1,153,765)) ton CO_2-eq year^{-1}. The huge GHG reduction potential was considered to provide great incentives for installing BGPs all over Hokkaido.

Table 3.12. Summary of annual amount of GHG emission reduction by replacing energy and manure treatment.

		Piling		Forced composting		AD in BGPs	
		Min	Max	Min	Max	Min	Max
Mt	(ton CO_2-eq year^{-1})	0	0	0	0	1,035,870	1,238,445
Mf	(ton CO_2-eq year^{-1})	0	0	-941,700	-1,126,025	0	0
Ms	(ton CO_2-eq year^{-1})	-489,100	-585,095	-22,995	-27,740	-402	-475
Ml	(ton CO_2-eq year^{-1})	0	0	0	0	-194,180	-232,140
Mc	(ton CO_2-eq year^{-1})	0	0	0	0	22,437	26,827
Total	(ton CO_2-eq year^{-1})	-489,100	-585,095	-964,695	-1,153,765	863,725	1,032,657

3.4. Discussion

In this chapter, different manure management systems were compared regarding GHG emission and the reduction effect, which are responsible for global warming potential. Piling and forced composting were methods that many farmers currently operate. In order to evaluate the impact of AD in BGPs, the GHG emission of three methods was compared. The result showed the adoption of BGPs made significant impacts on reducing GHG emission.

The highest GHG emission reduction was expected to be achieved by shifting from forced composting to AD in BGPs. In the process of forced composting, CH_4 was produced when the organic matter contained in the manure was rapidly decomposed more than piling. Besides N_2O production was also enhanced in the process of nitrification and denitrification by microorganisms under anaerobic condition (MOE, 2020). However, forced composting consumed a large amount of energy to maintain aeration. The annual value of the GHG emission reduction was estimated to be 2,186,422 ton CO_2-eq year^{-1}. Hokkaido government reported the GHG reduction of 70,170,000 ton CO_2-eq year^{-1} in 2016 (Hokkaido, 2020a). This study implies that the adopting BGPs would contribute maximum 3.1% of the GHG emission reduction, if all of the manure is utilized. The Japanese government has set a goal of reducing GHGs emissions to net-zero by 2050 (Prime Minister's Office of Japan, 2020). Several studies have also assessed the GHG emission of BGP construction (Yabe, 2013; Hou et al., 2017). Thus the impact of adopting BGPs against climate change would be enhanced more.

This study showed that the maximum amount of power generated by BGP was 1.3 GWh year^{-1}. Considering that the average monthly electricity consumption per household is around 350 kWh month^{-1} (Morita et al., 2016), the expected electricity could be supplied to 314,866 households, which could cover 11.3% of the total households in Hokkaido (Hokkaido, 2020b). Recently a distributed power system has been required after the great blackout caused by the 2018 Hokkaido Eastern Iburi Earthquake (Tajima and Okada, 2019). Considering that there was a potential to build 330 BGPs in whole area in Hokkaido (Yabe, 2013), BGPs could reasonably function as distributed power systems. The heat energy obtained by CHPs is normally used to maintain the temperature for biogas digesters, and the heat surplus is supplied for other purposes such as agriculture in green house or aquaculture (Yoshida et al., 2014). This study used CHP with 35 % of power efficiency and 40 % of heat efficiency. The assumed heat from the BGPs could cover maximum 0.58 % of heat demand in Hokkaido which is 951,634 TJ year^{-1} in 2017 (Hokkaido, 2020b). Especially, the thermal energy is more required in a cold regions such as Hokkaido, and boilers can also be used to produce only thermal energy with 80 % energy efficiency by burning biogas directly (Nakayama et al., 2011).

Economic valuation of BGPs is also important. BGPs have been adopted all over the world, but it is difficult for construction and maintenance without subsidies (Cucchiella et al., 2019; Xue et al., 2020). Currently, a major source of income is selling electricity with FIT scheme, which offer 39 JPY kWh^{-1} (excluding tax) as purchase price of electricity derived from biogas. The potential of Hokkaido was estimated to be 52.2 billion JPY year^{-1} (METI, 2020a; Yoshida et al., 2014). In addition, BGPs were also expected to produce thermal energy, which could save 151 ML of kerosene per year. Based on 80.1 JPY L^{-1} of the price in Hokkaido in October 2020, the economic effect would be 12.1 billion JPY (METI, 2020d). Those impacts from selling or saving energy were huge because kerosene products in Japan were normally imported from overseas. Furthermore, ESG investments and RE100 have been focused recently, and there is a mechanism to trade certificates indicating GHG reduction such as J-Credit (Tajima and Okada, 2019). Though J-Credit does not include the reduction from electricity which selling in FIT scheme, the assumed credits would be 1.8 billion JPY per day, based on the 947,677 (1,032,657 minus 1,238,445 minus (- 1,153,765)) ton CO_2-eq year^{-1} (Changing from forced composting to AD in BGPs, except for the effect for energy production in Table 3.12) and 1,887 JPY per ton CO_2-eq in June 2020 (METI, 2020e). The total economic benefits were estimated to be 66.1

billion JPY in maximum (Table 3.13). These mechanisms would enable BGP business without the limited subsidies. In Hokkaido, the annual sales of dairy industry in 2018 was 502.6 billion JPY, therefore the adopting BGPs would contribute economic benefits which accounts for 13% of the annual sale.

Table 3.13. Summary of maximum economic benefits by replacing energy and manure treatment.

	Unit	Value	Note
Selling electricity	billion JPY year^{-1}	52.2	39 JPY per kWh by FIT scheme
Saving kerosene	billion JPY year^{-1}	12.1	81.1 JPY per L (October 2020)
Selling J-Credit	billion JPY year^{-1}	1.8	1,887 JPY per ton CO_2-eq. (June 2020)
Total	billion JPY year^{-1}	66.1	

3.5. Conclusion

Promotion of BGP system would be an effective approach in combating environmental problems. Specifically, adoption of BGPs may initiate direct benefits such as GHG emissions reduction when fossil fuels are replaced, as well as indirect benefits by reducing GHG emissions in process of the manure treatment. This study focused on not only energy derived from biogas, but also differences between reference manure treatment methods and AD in BGPs. Currently, many dairy farmers perform piling and forced composting for manure treatment. However, this study clearly showed the benefit of AD in BGPs in the viewpoint of CH_4 and N_2O emissions produced in the process of manure treatment.

This study assessed the environmental and economic benefits based on the potential of adopting BGPs in all over Hokkaido. However, the construction of BGPs and the operation method such as transportation of manure and application of biogas digestate are different individually. The future research is expected to focus on a specific BGP to clarify the environmental and economic benefits individually.

Chapter 4: General Discussion

In this study, the potential for adopting BGPs in Hokkaido was evaluated based on the dairy farmers' willingness (Chapter 2). The result showed that 119 dairy farmers (41.6% of the surveyed farmers) were willing to adopt BGPs and had an average of 127 mature cows, which was 1.9 times more than the number of mature cows raised by unwilling farmers. This study revealed the significant factors influencing the farmers' willingness to adopt BGPs were the following two: 1) the farmers who were willing to adopt BGPs had several issues on manure treatment, 2) the farmers who were willing to adopt BGPs were planning to expand the farm scale in the future. This indicated that the farmers who were willing to adopt BGPs expected to solve the problems surrounding the their farming situation such as a lack of labor force due to the increase in the amount of dairy cows and manure, and the lack of composting space, resulting in a difficulty for proper manure treatment. When the manure treatment is not performed properly, bad odor and weed seeds that remain in composts also become their concerns.

In Chapter 3, this study evaluated the potential to adopt BGPs in whole area in Hokkaido based on the farmers' willingness discussed in Chapter 2. Yabe (2013) reported the potential to adopt BGPs based on the statistical data in 2013, such as 8,345 farmers and 847,100 dairy cows (733,372 milking cows equivalent). In this study, on the other hand, there were 2,484 dairy farmers who were willing to adopt BGPs, and the future number of cows was estimated to be 385,856 to 461,342. In other words, the number of farmers was estimated to be the 29.8% and the number of dairy cows were 52.6% to 62.9% of those used for estimation of Yabe (2013), respectively.

This study also assessed environmental and economic benefits as the impact of adopting BGPs. The manure produces a large amount of biogas, resulting in a huge potential to generate electricity and heat energy. The energy could offer economic benefits from selling or saving the energy (Yoshida et al., 2014). And the biogas-derived energy could contribute GHG emission reduction as a renewable energy. Furthermore, the impacts of BGPs was assessed, by comparing piling and forced composting that many farmers currently operate, because the process of manure treatment need to be managed carefully in terms of GHGs such as CH_4 and N_2O, which cause strong greenhouse effects (IPCC, 2015; MOE, 2020). Especially forced composting was the most significant method releasing GHGs. As reported by Babalola (2020), energy production was a factor for dairy farmers in selecting BGPs, but the environmental benefit by shifting from their current manure treatment to AD in BGPs would be another attractive factor in adopting BGPs.

Chapters 2 and 3 would present the benefits of adopting BGPs from three points of view: First, BGPs offer the benefits on their farming situation and local society as a means of manure treatment. Second, BGPs offer the environmental benefit as a tool to reduce GHG emissions.

Third, BGPs contribute the economic benefits from replacement of energy source. Those were summarized with the concepts of SDGs in Table 4.1, showing the benefits linked to SDG 7 (Ensure access to affordable, reliable, sustainable and modern energy for all), SDG 8 (Promote sustained, inclusive and sustainable economic growth, full and productive employment and decent work for all), SDG 12 (Ensure sustainable consumption and production patterns), and SDG 13 (Take urgent action to combat climate change and its impacts) (United Nations, 2015).

While the installed capacities of wind and solar power are 622 GW and 579 GW, in the world, that of BGPs is only 19 GW in 2019 (International Renewable Energy Agency (IRENA), 2020). BGPs need a large amount of finance and cannot be maintained without subsidies (Cucchiella et al., 2019; Xue et al., 2020). In recent years, ESG investment for achievement of SDGs has been accelerating internationally. Also companies with RE100 and certificates such as J-Credit have been increasing (Tajima and Okada, 2019).

The purpose of this study was to evaluate the potential for the adoption of BGPs in Hokkaido based on scientific evidence and to present data for society such as ESG investment. However, in this study, the construction and maintenance costs for the adoption of BGPs was not considered. However the costs are also important. In the past, there were many small-scale BGPs owned by individual farmers, but recently there has been an increase in the number of large-scale, aggregated BGPs, promoted by the FIT system. According to Yabe (2013), there was a potential for the adoption of 330 BGPs, with 2,223 milking cow equivalent in each BGP. Iwasaki et al. (2017) also reported that as of 2016, there were 86 BGPs adopted in Hokkaido, with the most common scale of BGPs treating the manure of 200 to 299 milking cow equivalent. Regarding construction costs, as the scale of the project increases, the construction cost per head of cows tends to decrease (Ono and Ukawa, 2005). On the other hand, regarding the running cost for integrated BGPs, it includes not only the maintenance cost of the BGP but also the cost of collecting/transporting the manure, and transporting or spreading the digestate (Yoshida et al., 2014; Anabuki et al., 2017). In most cases of integrated BGPs, dairy farmers are asked to pay for manure treatment. Basically, the construction and operation are carried out by local governments, Japan Agricultural Cooperative (JA), dairy farmers' associations, or private companies. Particularly, when local government provides subsidies, the farmers' payment tends to be smaller (Yoshida et al., 2014).

This study could offer the results assessing objective and quantitative valuation of benefits of BGPs so as to provide scientific guidelines for the society to promote further adoption of BGPs without subsidies.

Table 4.1. Summary of possible benefits by adopting BGPs and the relation with SDGs

	Benefits by adopting BGPs	Relation with SDGs
Farming (society) (Chapter 2)	**Issue on manure treatment surveyed in this study**	
	・ Space to make compost pile is insufficient.	
	・ Weeds in the field increase due to weed seeds remaining in the compost.	
	・ Compost is less effective as a fertilizer.	
	・ Time to spread the compost is not enough.	
	・ Field to spread compost is too far from farm.	
	・ Field area to spread compost is insufficient.	
	・ Too much labor time is needed to treat manure.	
	Solution of the issues by adopting BGPs	
	・ Manure is injected into BGP directly and no more space to making compost pile is needed.	12
	・ Weed seeds are deactivated by AD in BGP.	12
	・ Biogas digestate is produced and can be applied as an organic fertilizer.	12
	・ BGP business can support to spread biogas digestate.	12
	・ Labor time is reduced by manure treatment automatically operated in BGPs.	8
Environment (Chapter 3)	Biogas-derived energy is produced and replace energy from fossil fuels.	7
	N_2O and CH_4 emission from manure treatment (piling and forced composting) is reduced.	13
	CO_2 emission by using chemical fertilizer is reduced.	13
Economy (Chapter 3)	Income by selling electricity with FIT is obtained.	8
	Cost for buying kerosene is saved.	8
	Income by selling certificate of J-credit is obtained.	8

Chapter 5: General Conclusion

BGPs have so far played an important role as manure treatment facilities for dairy farmers, however since the start of the FIT system, BGPs have been categorized as power plants. In recent years, BGP construction costs have increased and income from selling electricity has become more important, but due to restrictions on grid availability the construction has been limited. As presented by Cucchiella et al. (2019) and Xue et al. (2019), the BGP business is affected by policy-making and is difficult to continue without subsidies. For dairy farmers and companies who wish to adopt BGPs, it is not easy to establish or continue the business if the income from selling electricity cannot be ensured.

However, it would say that BGPs become more attractive as manure treatment facilities with a policy of agriculture promotion. This study revealed that the dairy farmers who were willing to adopt BGPs especially expected BGPs for improving their farming situation such as too much labor time to treat manure and insufficient space to make compost pile. The results also found that 34.3% of the farmers having the willingness were large-scale farmers with 100 cows or more, and 56.3% of the farmers planned to expand the farm scale. Thus, in the future, the farmers with BGPs would play an important role in maintaining the core industry in each region.

BGPs are important not only for power plants, but also for climate change measures, dairy farming and local communities. This study aimed to investigate the more realistic potential based on farmers' willingness to adopt BGPs, and assess the environmental and economic benefits.

In the results, 2,484 dairy farmers having 385,856 to 461,342 dairy cows might adopt BGPs in Hokkaido, and 2,186,422 t CO_2-eq year^{-1} of GHG emission (3.1% of GHG emission in Hokkaido) was expected to be reduced by using energy produced in BGPs and by shifting manure treatment method to AD in BGPs. And the economic benefits were estimated to be 66.1 billion JPY year^{-1}. This study could help provide scientific insights to those who are interested in BGPs to enhance adoption of BGPs in business sector in Hokkaido.

Conflict of Interest

This study was conducted in a research project of Biomass Research Co., Ltd. and summarized with permission from the company to publish the results.

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