Economic Analysis of Introducing Biogas Plants to Japanese Dairy Households

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1 Introduction

Recently, the Japanese government has been promoting the introduction of renewable energy to replace fossil fuels and to reduce CO_2 emissions. Biomass is one such source for renewable energy. Among the various available biomasses, this study focuses on livestock excreta generated by Japanese dairy farming. Biogas plant (BGP) has been developed to dispose of livestock excreta emitted by dairy farming. It makes biogas from animal excreta by methane fermentation. Biogas is mainly composed of methane and can be utilized as a fuel for electric power generation. This process of generation is recognized as "Carbon Neutral." However, according to Matsuda (2009), BGP is still uncommon in Japan when compared to European countries such as Germany.

This study focuses on a dairy farming household in the Hokkaido region in Northern Japan because this region dominates the dairy farming industry. Hokkaido has half of Japan's total number of dairy cows. A dairy cow is known to emit about 70 kg of manure per day, which means that a good deal of manure is emitted on dairy lands. Therefore, deterioration of the water quality in local rivers and lakes has become a concern in Hokkaido. To address this issue, the "Act on the Appropriate Treatment and Promotion of Utilization of Livestock Manure" was enacted in 1999. Dairy farmers are obliged to build a concrete-covered compost depot and to use it to store livestock manure. Beyond fuel production, BGP operation can have an additional positive effect on this issue because it converts livestock manure into digested slurry that scarcely smells. According to Matsuda (2009), only a few hundred BGP have been introduced in Japan, while Germany has more than 4,000. He insists that the popularity of BGP in Germany depends on the feed-in tariff for the power generated by BGP. In Germany, electlic power generated in BGP with less than 150kW generater, can be sold at 28.2 ¥/ kWh. Moreover, the price is guaranteed for 20 years, though the level is decreasing by 1 % per year. Therefore, it is quite obvious that the diffusion of the BGP depends on the price level of generated power and the resulting profitability. This study investigates the possibility of BGP diffusion in Japan by considering economic conditions such as the price level of the generated power.

In Japan, a feed-in tariff has been adopted for household solar power generation since last year. The possibility of the introduction of a feed-in tariff for electricity generation via BGP could be also considered. Thus far, many studies focusing on BGP profitability have been done in Japan. Some of them investigate the break-even calculation pertaining to the rate of electricity generated in a BGP. Ishikawa et al. (2005) investigated the relationship between power selling price and redemption period of a BGP. They showed that even if 90 % of the initial cost is subsided, the power selling price must be more than 100 ¥/kWh for 30 years to pay off for the construction of a BGP. However, they also indicated that if the revenue from receiving supplementary materials can be assured, a BGP could be paid off in 20 years at 37 ¥/kWh and a subsidy of 75% of the initial cost. Ono and Ugawa (2005) compared the profitability between different specifications of dairy farming operation. They showed that a BGP becomes profitable when it deals with liquid cattle manure only and its scale of operation is doubled. These existing studies are based on the close observation of the actual management of BGP.

Generally, such studies are based on the simple comparison between cost and revenue. These studies do not account for changes in dairy production induced by a change in the price of power generated by BGP. It is very possible that depending on the price, a dairy farming household could change the amount of inputs such as labor and cows, which could affect the resulting quantity of output.

Meanwhile, the “ household model ” was developed by the fields of development and agricultural economics in order to investigate the behavior of farmers (see Sadoulet and de Janvry (1995) and Kurosaki (2002)). This model provides a microeconomic foundation for the analysis of farming households and assumes that they are not only profit maximizing agents but also consumers who maximize their own utility. In literature related to this model concerning Japanese agriculture, Sonoda and Maruyama (1999) applied the model to a study of Japanese rice farmers. The application of the household model to a dairy household seems appropriate because most dairy farm operations in Japan still rely on family labor. However, there are few existing studies that investigate Japanese dairy farming using the household model. Accordingly, this study applies the household model to investigate the technology of dairy farming and the preferences of the households engaged in it. Using the household model, the structural parameters of production and the utility function are estimated. Furthermore, BGP production functions that represent the relationship between the amount of generated biogas and its required input are estimated in the current study.

This study provides a simulation analysis related to the feed-in tariff for generated power from BGP using the parameters estimated in the household model. The analysis shows that a BGP is seldom introduced under the current feasible power selling price. Therefore, in addition to a feed-in tariff policy, some other profit from BGP such as thermal usage, and utilization of digested slurry seem necessary for the widespread introduction of BGP in Japan.

This study is comprised of four sections. The next section details the specifications of the economic model used to represent dairy farming households. The third section describes the details of the employed data and the econometric model utilized in this study. The fourth section presents policy implications that can be derived from the simulation analysis. The last section concludes the study and discusses the remaining issues that should be addressed in future research.

2 Model

In this study, the household model developed in agricultural and development economics (see Sadoulet and de Janvry (1995) is applied to investigate the technology used in dairy farming and the preferences of the households engaged in it. In this model, a farming household is regarded as not only a consumer maximizing its own utility but also as a producer that maximizes profit. Furthermore, Kurosaki (2002) showed that the household model can be broken down into a separable model and a non-separable model. If markets for all inputs and outputs appear to exist, a farm's production is independent from its consumption behavior. This case corresponds to the separable model. However if a market for one or more of the inputs (such as labor) is absent, the farm households must provide it by themselves. Kurosaki (2002) refer to this case as belonging to the non-separable model.

Many studies have applied the non-separable household model for the analysis of subsistence farming households in developing countries. In addition, Sonoda and Maruyama (1999) adopted this model to analyze Japanese rice farming households, because they appear to face constrained off-farm employment. They implemented a structural estimation of the utility and production functions and used comparative static analysis. They showed that an increase in the price of rice induces a reduction of labor input and the resulting rice production due to an internal wage rate change. Thus far, few studies have applied the non-separable household model to Japanese farms.

In general, raw milk production must occur constantly, because dairy cows provide raw milk every day. Most dairy farming households in Hokkaido rely only on their own family labor [1] These facts imply that the Hokkaido dairy farming households are not only managers or employers of raw milk production, but also employees of the industry. In this case, the optimal labor force input for dairy production is no longer separable from their preferences as consumers. For this reason, this study applies the non-separable household model to analyze the dairy households in Hokkaido. The utility maximization problem for a non-separable dairy household with BGP is described as follows.

2.1 The Household Model

Considering the dual nature of dairy households, the non-separable household model is adopted to represent their behavior. The following utility maximization problem is assumed for dairy households in the Hokkaido region.

$$\begin{gathered} \textbf{Max}\; U(C,Z) \qquad (1) \\ s.t.\; \pi_Y = P_Y Y - P_M M - P_S S - P_K K - P_F F, \;\; \pi_G = P_G G - P_B B \\ Y = f_Y(M,S,K,F,L),\; G = f_G(M,B), \\ P_C C = (\pi_Y + \pi_G)/\text{Lnum}, \\ L/\text{Lnum} + Z = T \end{gathered}$$

where U is the utility level of a dairy farmer, Lnum is the number of household members engaged in dairy production, C is the household consumption per Lnum, P_C is its price, Z is leisure time per *Lnum*, π_Y is the profit of dairy farming, π_G is the profit from a biogas plant, Y is the amount of milk production, P_Y is its price, $f_Y(\cdot)$ is the production function of milk, M is

[1] Dairy helpers have been introduced recently in order to give dairy households time for vacation. However, according to the Hokkaido government (2004), the average annual period of dairy helper use is only 14.9 days.

the number of dairy cows, S, K is the scale of plant for dairy production, F is input other than M, S, K, P_M, P_S, P_K, P_F are the respective prices of the inputs, L is labor hour, G is the amount of generated biogas, P_G is its price, $f_G(\cdot)$ is the production function of biogas, B is P_B is its price, and T is the initial endowment of time.

This model means that 1) the utility of a dairy household depends on its consumption and leisure, 2) their consumption is financed only by dairy farming and BGP, 3) the labor force for dairy farming is employed only from their own household, and 4) the output of BGP only depends on the number of dairy cows and the scale of the fermenter. Moreover, the possibility of a corner solution for BGP operation is also considered. The utility maximization problem of a dairy household provides following Lagrangian.

$$L = U(C, Z) \tag{2}$$
$$+\lambda\{(P_Y f_Y(M, S, K, F, L) - P_M M - P_S S - P_K K - P_F F) + (P_G f_G(M, B) - P_B B) - PcC \cdot \text{Lnum}\}$$
$$+\mu(T * \text{Lnum} - L - Z * \text{Lnum})$$

Differentiating the (2) with respect to the choice variable of the dairy household, the following first order conditions are derived.

$$\frac{\partial L}{\partial C} = \frac{\partial U}{\partial C} - P_C\lambda = 0$$
$$\frac{\partial L}{\partial Z} = \frac{\partial U}{\partial Z} - \mu * \text{Lnum} = 0 \tag{3}$$
$$\frac{\partial L}{\partial M} = \lambda\left(P_Y\frac{\partial f_Y}{\partial M} - P_M + P_G\frac{\partial f_G}{\partial M}\right) = 0$$
$$\frac{\partial L}{\partial S} = \lambda(P_Y\frac{\partial f_Y}{\partial S} - P_S) = 0$$
$$\frac{\partial L}{\partial K} = \lambda(P_Y\frac{\partial f_Y}{\partial K} - P_F) = 0$$
$$\frac{\partial L}{\partial F} = \lambda(P_Y\frac{\partial f_Y}{\partial F} - P_F) = 0$$
$$\frac{\partial L}{\partial L} = \lambda(P_Y\frac{\partial f_Y}{\partial L}) - \mu = 0 \tag{4}$$
$$\frac{\partial L}{\partial B} = \lambda(P_G\frac{\partial f_G}{\partial B} - P_B) = 0$$
$$\frac{\partial L}{\partial \lambda} = (P_Y f_Y(M,S,K,F,L) - P_M M - P_S S - P_K K - P_F F) + (P_G f_G(B,M) - P_B B) - P_c C * \text{Lnum} = 0$$
$$\frac{\partial L}{\partial \mu} = T * \text{Lnum} - L - Z * \text{Lnum} = 0$$

(5)

3 Estimation of the Household Model

The household model analysis specifies the utility and production functions of a farming household. Next, by using actual data for a farming household, it estimates the parameters of both functions under the assumption of utility maximization. Furthermore, based on the economic model and estimated parameters, the analysis of policy such as intervention price could be implemented.

3.1 Data

In this study, the Production Cost of Farm and Livestock Products (PCFLP) (1997-2010) published by Japan's Ministry of Agriculture, Forestry and Fisheries is employed for econometric analysis. These statistics contain data related to the production and consumption of a dairy farming household. They provide data for the whole of Japan, but this study only uses data for the Hokkaido region. The Price Indices of Commodities in Rural Areas(2009) (PICRA) and the Annual Report on the Consumer Price Index(2009)(ARCP) are utilized to determine the price levels of dairy inputs and the consumption of a dairy household. The data gathered from these statistics are arranged to make them suitable for application in the econometric analysis. Table 1 presents the variables used in this study and their source. Table 2 describes the means and standard deviations of the variables.

3.2 Econometric Model

Because BGP operation is still uncommon, PCFLP does not include data on BGP operation. Therefore, BGP operation in the utility maximization problem (1) is ignored with regard to the procedure for parameter estimations. Eventually, the following economic model is considered in the estimation process.

$$\mathbf{Max}\, U(C,Z)$$
$$s.t\ \ P_C C = \pi_y/\text{Lnum},\ \pi_y = P_Y Y - P_M M - P_S S - P_k K - P_F F$$
$$Y = f(M,S,K,F,L),\ L/\text{Lnum} + Z = T$$

3.2.1 Estimation of the Dairy Farming Production Function

So far, the production functions that represent dairy production have been developed by other studies. Egaitsu(2002) presented the BC-M procedure for dairy production. He divided dairy production into a biology-chemistry (BC) procedure, in which labor and artificial are the inputs, and a mechanics (M) procedure, in which dairy cows and feedstuffs are employed. In this model, both procedures are assumed to be complementary to each other. While this procedure is very suitable for actual dairy production, the assumption of perfect complementarity is very restrictive and complicates parameter estimation. Therefore, in accordance with Sonoda (1999), this study employs the Cobb-Douglas production function, [2] which has flexibility in

[2]Toki et al. (2008) investigated the cost structure of dairy production in Hokkaido using the translog cost function. However, they did not consider the utility maximization of dairy households, as is the case in this study.

terms of substitution across input factors. The actual function is defined as follows,

$$\log Y = \beta_0 + \beta_1 \log M + \beta_2 \log S + \beta_3 \log K + \beta_4 \log F + \beta_5 \log L \tag{6}$$
$$+\beta_6 SD1 + \beta_7 SD2 + \beta_8 SD3 + \beta_9 TT + \varepsilon_1$$

Similar to Sonoda and Maruyama(1999), scale dummies and time trend dummies are also added into the production function. The first order conditions related to inputs, M, S, K, F are arranged by the following share equations.

$$\frac{P_M M}{P_Y Y} = \beta_1 + \varepsilon_2 \tag{7}$$
$$\frac{P_S S}{P_Y Y} = \beta_2 + \varepsilon_3 \tag{8}$$
$$\frac{P_K K}{P_Y Y} = \beta_3 + \varepsilon_4 \tag{9}$$
$$\frac{P_F F}{P_Y Y} = \beta_4 + \varepsilon_5 \tag{10}$$

In this model, we have to keep in mind that we cannot estimate the share equation of L. Although L is an input of dairy farming production, the wage rate is not observed because L is provided only in-household; consequently, the share equation of L is not formulated like other inputs. Error terms $\varepsilon = (\varepsilon_1, \varepsilon_2, \varepsilon_3, \varepsilon_4, \varepsilon_5)'$ are assumed to have zero mean and multivariate normal distribution. In this estimation process and $\log M$, $\log S$, $\log F$, $\log L$ are treated as endogenous variables. Employing $SD1, SD2, SD3, TT$, Hnum, Lnum, $P_c, P_y, P_m, P_s, P_k, P_f$ instruments, the parameters of the original production function (6), and the four share equations (7), (8), (9), (10) are estimated using the three stage least squares (3SLS) method. 3SLS command in TSP version 5.1 is employed for the actual estimation procedure. Table 4 presents the estimation result of the production function.

3.2.2 Estimation of the Utility Function

The Stone-Geary utility function is applied to represent the preference for the dairy household, just like Sonoda and Maruyama (1999).

$$U(C, Z) = b_1 \log(C - a_1) + b_2 \log(Z - a_2)$$

Imposing homogenous of degree one, $b_1 + b_2$ is set to one. According to Sonoda and Maruyama(1999), a_1, a_2 are assumed to depend on the number of households $Hnum$ as follows.

$$a_1 = a_{10} + a_{11}\text{Hnum}$$
$$a_2 = a_{20} + a_{21}\text{Hnum}$$

From first order condition (3) and (4), we obtain the following equation.

$$\frac{P_C \cdot \partial U/\partial Z}{\text{Lnum} \cdot \partial U/\partial C} = P_Y \cdot \frac{\partial f}{\partial L}$$

The left-hand side corresponds to the marginal benefits of leisure, whereas the right-hand side corresponds to the value of the marginal product of household labor. This equation precisely implies equilibrium of the internal labor market in a dairy household. In other words, dairy production corresponds with labor supply (leisure demand), which must coincide with labor demand for dairy production under the internal wage rate w^*. Invoking the estimation result of the production function, w^* is calculated as follows[3]

$$w^* = P_Y \cdot \frac{\partial f}{\partial L} = \frac{p_Y Y}{L}\hat{\beta}_5$$

Here, we consider the full income (FI) of a dairy household to be defined as,

$$FI = P_c C + w^* Z$$

where T is endowment of time. Using this w^* and FI, the Stone-Geary specification yields the following linear expenditure system (LES).

$$w^* Z = (a_{20} + a_{21}\text{Hnum})w^* + b_2(FI - (a_{10} + a_{11}\text{Hnum})P_C - (a_{20} + a_{21}\text{Hnum})\ w^*)$$

This regression equation is estimated using a two stage least squares method. In the estimation, w^* is treated as an endogenous variable. Instrumental variables that are identical to those in the estimation of production function are also employed here. The estimation is implemented by *LSQ* command of TSP version 5.1. The estimation result is shown in Table 5.

[3]This procedure was introduced in Sonoda and Maruyama(1999). Kurosaka(2002) showed that this approach does not employ information of household preference and consequently is not consistent with the original model.

3.2.3 Estimation of the Biogas Production Function

The BGP production function is also estimated[4]. Nogyo Doboku Shinbunsya (2002) provided detailed information on 13 BGP in operation in Hokkaido. This information included the cubic capacity of the biogas fermenters, the number of dairy cows, the initial and annual running costs, the amount of generated power, the power conversion efficiency of the plant, methane concentration of biogas, and so on. Table 3 shows the descriptive statistics of the 13 BGP.[5] The dependent variable of the BGP production function is the generated amount of biogas. This study employs the number of dairy cows and the cubic capacity of biogas fermenter as explanatory variables. This production function is also specified as using the Cobb-Douglas form.

$$\log G = \gamma_0 + \gamma_1 \log B + \gamma_2 \log M + \varepsilon$$

Using the 13 sampled BGP in Hokkaido, the parameters of this equation are estimated by the ordinary least squares method using OLSQ command of TSP version 5.1. Table 6 shows the estimation results of the BGP production function.

3.3 The Estimation Results

The estimation results of the parameters of the dairy production function are presented in Table 4. The estimated parameters of the scale dummies show that a larger scale of dairy management results in more milk production. The parameter of the time trend is estimated as a positive value, which implies that dairy production technology is improving on a yearly basis. The estimation results of the utility and biogas production functions are shown in Table 5 and Table 6, respectively. Table 5 indicates that the minimum leisure level per capita deceases as the number of household members grows. Table 6 gives a result that is consistent with our natural intuition.

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[4]Umetsu et al. also implemented regression analysis concerning the relationship between generated power and plant scale.

[5]This study postulates that the in-service period of BGP is 15 years. Consequently, the annual expenditure on BGP consists of the sum of the annual running cost and the fifteenth initial cost.

4 Policy Simulation

In the previous section, the structural parameters were estimated by a system of regression equations. The results show the characteristics of dairy farming production technology in the Hokkaido region. Sonoda and Maruyama (1999) applied the non-separable household model to Japanese rice farming households. Their results had counter-intuitive implications, which indicated that an increase in price of rice may cause a reduction of the labor supply via an internal wage effect. In a similar manner, by employing the estimated parameters, this study investigates how dairy farming household responds to a change in the rate for generated electricity for a BGP.[6] This study also attempted to solve for the optimal level of each dairy farming input under the change in the rate. The simulation result will have some policy implications for a BGP feed-in tariff policy.

4.1 Feed-in Tariff

Recently, feed-in tariffs have been introduced to promote renewable energy use. The Japanese government also formulated the Renewable Portfolio Standard (RPS) in 2002. This standard obliges power companies to utilize a certain ratio of renewable energy in the total amount of electricity they sell. Furthermore, the photovoltaic power generated by general households has been purchased at 48¥(kWh) since 2009. The energy generated by BGP is also included in the list of renewable energies designated by the law. Therefore, it is important to consider a feed-in tariff for Japanese BGP power production and to predict the resulting outcome on dairy farming operations in the Hokkaido region.

4.2 Simulation

By solving the following simultaneous equations, we will obtain solutions for choice variables for optimal dairy production at different levels of P_G^*. In this equation, $C, Z, M, S, K, F, L, B, Y, G$ are defined as choice variables. By substituting the sample mean values into $P_C, P_M, P_S, P_K, P_F, P_B, P_Y$,

[6] Iwamoto et al. (1999) also implemented simulation analysis for a dairy farming operation. They investigated the change in income for a Hokkaido dairy household resulting from a regulation policy that tightened the stocking density of cattle.

they are set to exogenous.[7]

$$\log Y = \hat{\beta}_0 + \hat{\beta}_1 \log M + \hat{\beta}_2 \log S + \hat{\beta}_3 \log K + \hat{\beta}_4 \log F + \hat{\beta}_5 \log L + \hat{\beta}_{24} 2010$$

$$\log G = \hat{\gamma}_0 + \hat{\gamma}_1 \log B + \hat{\gamma}_2 \log M$$

$$P_M M = \hat{\beta}_1 P_Y Y + \hat{\gamma}_2 P_G^* G$$

$$P_S S = \hat{\beta}_2 P_Y Y$$

$$P_K K = \hat{\beta}_3 P_Y Y$$

$$P_F F = \hat{\beta}_4 P_Y Y$$

$$\frac{P_C \cdot \hat{b}_2 (C - (\hat{a}_{10} + \hat{a}_{11} \text{Hnum}))}{\text{Lnum} \cdot (1 - \hat{b}_2)(Z - (\hat{a}_{20} + \hat{a}_{21} \text{Hnum})} = \hat{\beta}_5 \frac{P_Y Y}{L}$$

$$P_B B = \hat{\gamma}_1 P_G^* G$$

$$P_C C = \{(P_Y Y - P_M M - P_S S - P_K K - P_F F) + (P_G^* G - P_B B)\}/\text{Lnum}$$

$$T = L/\text{Lnum} + Z$$

However, it is very difficult to solve a large system of nonlinear equations. The main goal of this study is to determine how the optimal values of B and M move as P_G^* changes. Therefore, choice variables for items outside the main interest, $\bar{S}, \bar{K}, \bar{F}, \bar{L}$, are substituted using the sample mean values shown in Tableds for the simplicity of the calculation. This manipulation implies that the system of nonlinear equations is reduced to the following 4 equations.

$$\log Y = \hat{\beta}_0 + \hat{\beta}_1 \log M + \hat{\beta}_2 \log \bar{S} + \hat{\beta}_3 \log \bar{K} + \hat{\beta}_4 \log \bar{F} + \hat{\beta}_5 \log \bar{L} + \hat{\beta}_{24} 2010$$

$$\log G = \hat{\gamma}_0 + \hat{\gamma}_1 \log B + \hat{\gamma}_2 \log M$$

$$P_M M = \hat{\beta}_1 P_Y Y + \hat{\gamma}_2 P_G^* G$$

$$P_B B = \hat{\gamma}_1 P_G^* G$$

This study considers 4 possible different price levels of $P_G^*(4.5 - 48¥/kWh)$, which are shown in Table 7. In addition, power selling price levels above $50¥/kWh$,(from$50¥/kWh to 80¥/kWh$), are also considered for the purpose of comparison.

[7] The current year (2010) is assigned to TT. A dairy household with $SD4$ is considered in this analysis, because the introduction of a BGP is more conceivable for comparatively larger-scale dairy households

Figure 1 shows that the optimal scale of a biogas fermenter in a dairy household becomes larger as the price of generated electricity grows. It also shows that BGP are seldom introduced at the currently feasible price level of a feed-in tariff in Japan (4.5-48 ¥/kWh). However, BGP could be introduced above 50 ¥/kWh. Figure 2 indicates that the number of dairy cows must be increased as the biogas fermenter expands.

5 Conclusion

This study applies the household model to dairy households in Hokkaido to estimate the structural parameters of the production and utility functions. Furthermore, BGP production functions are estimated in this study. By employing the results of the estimation, a policy simulation analysis related to a feed-in tariff for generated power from BGP is implemented. The analysis shows that BGP would rarely be introduced under the current feasible power selling price. Therefore, in addition to a feed-in tariff policy, some other benefit for using a BGP seems necessary for its prevalence. Possible benefits include thermal usage of BGP and the utilization of digested slurry generated by BGP. The BGP converts only part (29.41%) of the energy of methane to electricity. Therefore, efficient utilization of the rest is very important. The digested slurry can be used as fertilizer for pastures. Furthermore, revenue sources other than power selling should be explored.

Further revision should be required for future studies. The production function was reduced to the Cobb-Douglas functional form. A more flexible functional form should be applied in the next study. This study employed only two factors (the scale of the biogas fermenter and the number of dairy cows) for biogas production. More factors should be used to accurately simulate biogas production. Furthermore, more variables should be treated as endogenous in the policy simulation analysis. In this study, all inputs of dairy and biogas production (except for the two previously mentioned factors) are fixed in the simulation analysis. However, these conditions are unnatural because the amount of input (e.g., feedstuff) must be changed when the number of dairy cows increases. More advanced and appropriate numerical techniques should be applied to the policy simulation in this study.

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Table 1: Data

Variables	Contents	Source
Y	Annual amount of produced milk (t)	PCFLP
M	The number of dairy cows (head)	PCFLP
S	Annual amount of feedstuffs	$P_S S$ P_S
K	The scale of plant for dairy production	Dividing $P_K K$ by P_K
F	Other input	Dividing $P_F F$ by P_F
L	Annual dairy labor time (hours)	PCFLP
G	Annual amount of generated biogas (m^3)	NDS
B	Cubic capacity of biogas fermented (m^3)	NDS
$P_Y Y$	Annual household revenue from dairy farming (¥)	PCFLP
$P_M M$	Annual expenditure for dairy cows (¥)	PCFLP
$P_S S$	Annual expenditure for feedstuffs and fertilizer (¥)	PCFLP
$P_K K$	Annual expenditure for building for dairy production (¥)	PCFLP
$P_F F$	Annual expenditure for other expenditures (¥)	PCFLP
$P_B B$	Annual expenditure for biogas fermenter (¥)	NDS
P_Y	Price of Y (¥)	Dividing $P_Y Y$ by Y
P_M	Price of M (¥)	Dividing $P_M M$ by P_M
P_S	Price of S	PICRA (ratio, baseline = 2005)
P_K	Price of K	PICRA (ratio, baseline = 2005)
P_F	Price of F	PICRA (ratio, baseline = 2005)
$SD1$	Management scale dummy less than 20 dairy cows	PCFLP
$SD2$	Management scale dummy from 20 to 50 dairy cows	PCFLP
$SD3$	Management scale dummy from 50 to 80 dairy cows	PCFLP
$SD4$	Management scale dummy more than 80 dairy cows	PCFLP
Lnum	The number of household members engaged in dairy farming	PCFLP
Hnum	The number of household members	PCFLP
C	Annual consumption per Lnum	Dividing $P_C C$ by P_C
$P_C C$	Annual Profit from dairy farming	PCFLP
P_C	Consumer Price Index in the Hokkaido region	ARCPI (ratio, baseline = 2005)
Z	Annual leisure time per capita	Subtracting L from 365 days $\times$ 16 hours

Table 2: Descriptive Statistics of the Data

Variables	Mean	Std.Dev
Y	401534.4827	325063.9445
M	46.82625	35.28625
S	11203952.816	8797027.542
K	2246568.734	2126410.23
F	1438247.11	1152012.599
L	4839.29793	1900.84165
p_Y	75.88675	2.6767
p_M	74315.8625	12846.15465
p_S	0.98134	0.077025
p_K	0.98779	0.035174
p_F	0.9894	0.024914
$SD1^*$	28.75%	
$SD2^*$	32.5%	
$SD3^*$	16.25%	
$SD4^*$	22.50%	
TT	2001.075	3.75778
C	9122628.478	6994547.378
Z	10280.46201	1172.20302
Lnum	2.589	0.36797
Hnum	5.035	0.80836
p_C	1.00806	0.0087531
w^*	10657.89007	7989.66868
N	80	

*) Dummy Variable

Table 3: Descriptive Statistics of Biogas Plant

Variables	Mean	Std.Dev
G	85817.11538	69204.01259
B	300.84615	234.53068
M	151.61538	88.67312
P_B	28215.72604	24243.31183
N	13	

Table 4: Estimation Results for the Dairy Production Function

Parameters	Estimates	Std.Err	t-value	p-value
β_0	-6.48079	3.25363	-1.99186	[.046]
β_1	0.120971	0.00199359	60.6802	[.000]
β_2	0.37371	0.00366346	102.01	[.000]
β_3	0.068832	0.00160945	42.7674	[.000]
β_4	0.049721	0.000972496	51.1267	[.000]
β_5	0.47861	0.061368	7.79907	[.000]
β_6	-0.456636	0.071605	-6.37713	[.000]
β_7	-0.271884	0.031572	-8.6115	[.000]
β_8	-0.114647	0.022822	-5.02359	[.000]
β_9	0.00359603	0.00168673	2.13195	[.033]
N	80			

Table 5: Estimation Results of the Parameters for the Utility Function

Parameter	Estimates	Std.Err	t-value	p-value
a_{10}	5288430	7453900	0.709484	[.478]
a_{11}	-3081670	2580990	-1.19399	[.232]
a_{20}	4495.06	832.85	5.3972	[.000]
a_{21}	-361.365	154.815	-2.33417	[.020]
b_2	0.184498	0.110274	1.67308	[.094]
N	80			

Table 6: Estimation Results of the Biogas Production Function

Parameter	Estimates	Std.Err	t-value	p-value
γ_0	3.46124	0.692765	4.99626	[.001]
γ_1	0.74506	0.089243	8.34864	[.000]
γ_2	0.727843	0.149292	4.87529	[.001]
N	13			

Table 7: Power Selling Price

Price(¥/kWh)	P_G^*(¥/kWh)	
4.5	7.7805	Ongoing Power Selling price in accordance with the RPS low
14.5	25.071	Electricity price for dairy farms in Hokkaido
23.7	40.978	Electricity price for general households in Hokkaido
48	82.992	Electricity price for solar energy in accordance with the RPS low

*) P_G is calculated based on the average methane density in biogas(58.79%) and average power energy conversion efficiency (29.41%)

Table 8: The Optimal B and M

Price(¥/kWh)	P_G^*(¥/kWh)	B	M
4.5	7.7805	0.00031039	59.156
14.5	25.071	0.030578	59.169
23.7	40.978	0.21086	59.245
48	82.992	3.5948	60.671
50	86.450	4.2763	60.957
55	95.096	6.4892	61.887
60	103.74	9.7088	63.236
65	112.39	14.537	65.254
70	121.03	22.326	68.495
75	129.68	37.690	74.843
80	138.32	79.805	92.061

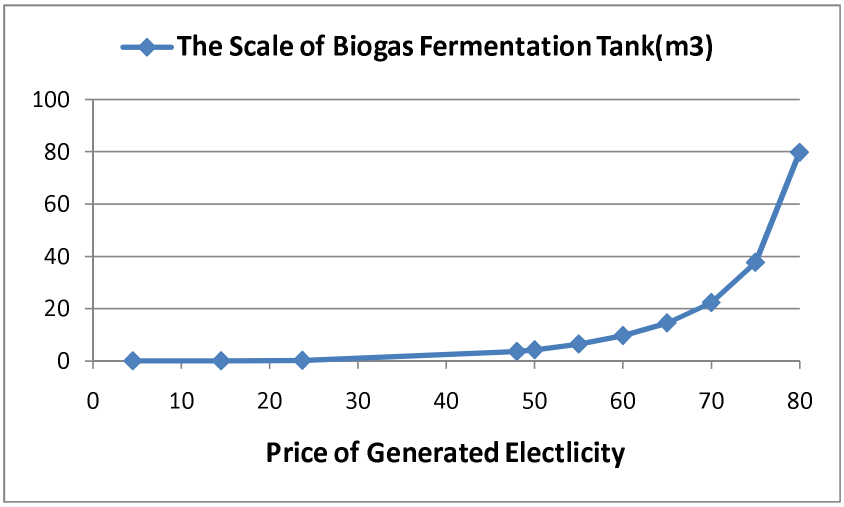

Figure 1: The Scale of Biogas Fermenter

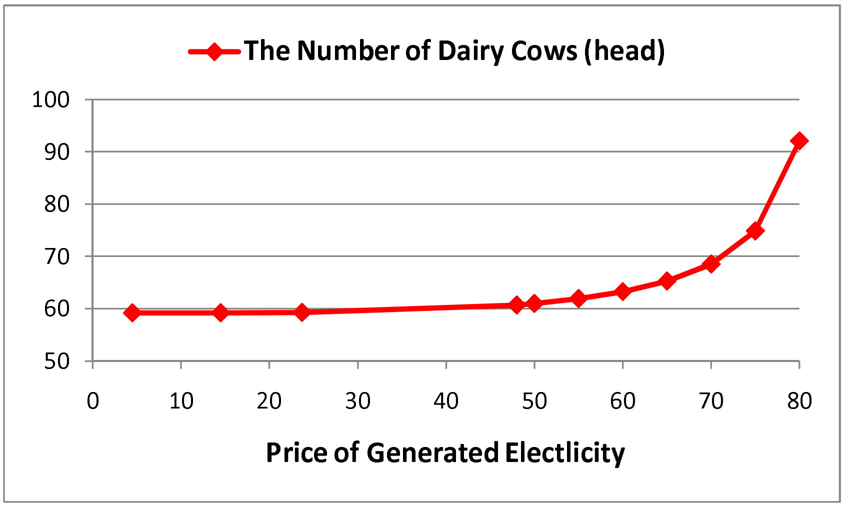

Figure 2: The Number of Dairy Cows