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Review Article

Predicting cost of dairy farm-based biogas plants: A North American perspective

Arash Samizadeh Mashhadi
Memorial University of Newfoundland, Civil Engineering Department, St. John's, NL, Canada, asamizadehma@mun.ca

Noori M. Cata Saady
Memorial University of Newfoundland, Civil Engineering Department, St. John's, NL, Canada, nsaady@mun.ca

Carlos Bazan
Memorial University of Newfoundland, Civil Engineering Department, St. John's, NL, Canada, carlos.bazan@mun.ca

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Abstract: Livestock manure and organic agriculture wastes are an environmental challenge because they contribute to climate change by emitting greenhouse gases. Converting these organic wastes to biogas and bioenergy is a sustainable solution. Farmers, investors, and governmental departments involved in developing on-farm biogas projects need an informed decision-making process to fund such projects. Thus, estimating the required initial investment for a farm-based biogas plant is crucial. This study aims to develop two methods to estimate the cost of farm-based biogas projects, determine their economic viability, and predict the cost of each part of the plant and its related risks. A database for farm-based biogas projects in Canada and the USA was established and analyzed before developing the models. First, six mathematical models were developed using linear regression to predict the capital cost, engineering and design, operation and maintenance, gross revenue, and net profit using Monte Carlo simulation. Second, the probability of cost of components is calculated. The marginal error of cost prediction in initial modeling is about 7% in total, and the economic viability of a biogas plant for a farm housing less than 300 cows is questionable.

***Keywords**:* *Biogas, Cost, Modeling, Monte Carlo, On-farm*

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Nomenclature	
$CC	Capital costs
$Eng	Cost of engineering and design
$N	Net profit
$O&M	Cost of operational and maintenance per year
$R	Annual revenue
AD	Anaerobic digestion
CAD	Canadian dollar
CH_4	Methane
CHP	Combined heat and power
CN	Number of cows
CNG	Compressed natural gas
CO_2	Carbon dioxide
DMS	Digester mixing system
FIT	Feed-in tariff
GCU	Gas cleaning and upgrading
GHG	Greenhouse gases
GST	Gas storage tank
HRT	Hydraulic retention time

1. INTRODUCTION

The energy demand is rapidly increasing because of the increasing population and industrial activity. Since the year 2000, the contribution of oil and gas industries increased by more than 25% globally [1], and it increases the impact on the environment and climate. Therefore, countries are willing to increase the contribution of clean and renewable energies to meet their demand [2]. At the same time, increasing agricultural resources is crucial to satisfy the ever-increasing population needs, which will increase agricultural wastes significantly [3]. Hence, sustainable development of the economy and energy resources is a major issue in this field.

Biogas is a reliable renewable biofuel that can be used to generate energy. Biogas production can be part of waste management to produce clean, renewable, and environmentally friendly energy under anaerobic conditions (in the absence of oxygen) in a process called Anaerobic Digestion (AD) [4]. AD is a natural process that can break down organic materials by various bacterial activities in anaerobic conditions to produce biogas. Typically, the biogas produced consists of 60% - 70% of CH_4 and 30 – 40% CO_2. Methane fermentation occurs in two phases, called the acid phase and the gas phase; these two phases occur in four steps: hydrolysis, acidogenesis (acid-production), acetogenesis (acetate-production), and methanogenesis (methane production). The purpose of producing biogas is to produce methane and use it as an energy source because it is convertible to vehicle fuel, electricity, and heat [5].

The benefits of AD include energy production (electricity and heat), odor reduction, greenhouse gas (GHG) emission reduction, control of pathogens, fertilizers and bedding fiber production, environmental protection, on-farm waste management, and revenue generation [6]. Farmers can benefit from selling the electricity generated to the government for extra income under the “Feed-In Tariff (FIT)” programs, such as in Ontario, Canada. At the same time, the farmers reduce their energy bill to zero. The FIT program was developed in 2009 to encourage developers and engineers to use and develop renewable energy sources. In this program, solar energy has the highest rate of return with 0.42 CAD/kWh, while other sources, such as wind power, hydropower, and bioenergy, can be sold at 0.11 CAD/kWh [7]. The governments can develop infrastructures to increase job opportunities and grow their green economy through supporting such projects [8].

Canada is one of the most carbon-intensive countries globally. More researchers and scientists investigate renewable energy topics to meet the national targets [9]. Based on the Paris agreement in 2017, Canada committed to reducing carbon emissions to the environment by 30% in 2030 and, for a long-term target, decrease it by 80 in 2050 [10]. Hence, developing renewable energy sources is the key to success in Canada's environment protection plan. Therefore, the economic aspects of these projects are undeniable, and the financial evaluations and cost analysis become a major part of feasibility studies in every project [11].

This study covers both cost analysis and risk analysis of dairy farm-based biogas plants by applying two separate models. The first methodology is regression analysis which provides a mathematical correlation between costs and components of the plant [12]. This modeling helps farmers and investors in the initial feasibility process, so they can have a reasonable estimation of the total capital costs and cost of each component based on the size of the farm that will be used. However, this model is not limited only to cost prediction. It also provides information about the annual revenue of such an investment in the project's life expectancy. The second method focuses on risk and probability analysis with the help of Monte Carlo simulation. All the major variables involved in the cost prediction served as statistical parameters in Monte Carlo simulation [13]. The most significant benefit of this modeling approach is that because of too many random repetitions in the calculation (5000 trials in this study), all the possible outcomes are considered in the final result, so the final result is unbiased and reliable.

The cost analysis framework of on-farm biogas production can be divided into three main parts: 1- Input; 2- Biogas plant's components; and 3- Output (Fig. 1). The input to the on-farm plant includes different types of waste such as dairy manure that is mostly collected from the farm and other organic wastes such as food processing wastes or municipal wastes that are collected off-farm and will be transported to the farm for treatment. The second part of the framework is the plant's components [14]. A large part of the required investments is for installing and constructing the plant. For example, one of the main components is the digester (reactor) tank (i.e., covered lagoon, complete mix, plug flow digester, fixed-film digester) that takes about 19% of the capital cost, and the main biogas production will happen in the digester [15].

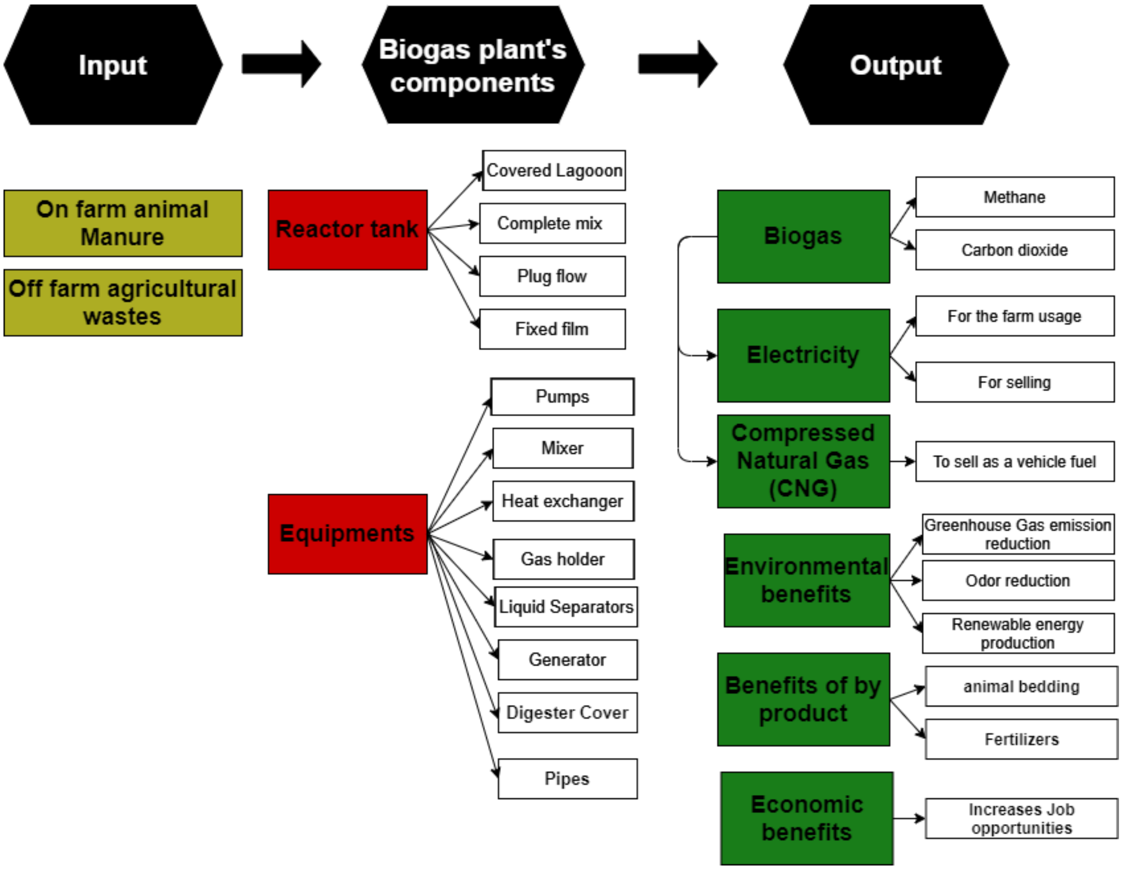


Figure 1. Comprehensive cost analysis and economic viability analysis of on-farm biogas plants.

After biogas generation, the other costly component is the gas collection unit. Biogas must be transferred for the purification to the upgrading unit safely; after cooling down, it could be used as Compressed Natural Gas (CNG) or get injected into the co-generators for electricity production. These units constitute 38% of the total capital costs. Also, most of the repair and maintenance costs are toward these two sections or the ancillary units connected to them (e.g., pumps, valves, gas holding tank, connecting pipelines). The last part of the framework is the output and benefits of the plant. These benefits can be direct or indirect [16]. The direct benefits include the income generated from selling electricity or selling methane gas directly as a CNG. Indirect benefits include the savings achieved by the farm owners, like free access to hot water, animal beddings, and fertilizers that will remain at the bottom of the digester [17].

An on-farm biogas plant is a system comprised of several components such as a barn, manure collection system (scarping or flushing), manure pumping unit, solid-liquid separation unit, anaerobic digester, heating system, digester mixing system (DMS), gas storage tank (GST), gas cleaning and upgrading unit (GCU), combined heat and power (CHP) unit, the digestate-dewatering unit, and controlling unit (Fig. 2). It is essential to recognize each specific component in a biogas plant to 1) estimate the costs related to the project's design and construction accurately; 2) understand the environmental and operational factors that affect the performance of each component and decrease the efficiency of the plant. Consequently, they increase the operational and maintenance costs or shut down the entire project [17]. These factors include sudden variation in temperature, pH, the feedstock's moisture, carbon/nitrogen ratio, hydraulic retention time, foam, and scum formation [18].

This study objective is to analyze the cost of dairy on-farm biogas plants in North America to develop mathematical models to estimate the cost for dairy farms, particularly in Canada. This study also assesses the financial feasibility of such plants [19]. The models would provide investors with informed and better predictions of the required investment to build an on-farm biogas plant. Although other types of manure, such as sheep and goat manure, are digestible and can produce biogas, their small quantities generated on the individual farm do not justify an investment in an on-farm or off-farm biogas plant solely for this type of manure. Moreover, the high transportation cost would make their digestion at an off-farm biogas plant uneconomical. Sheep and goat manure is usually composted and sold as a fertilizer and soil amendment mainly for gardening.

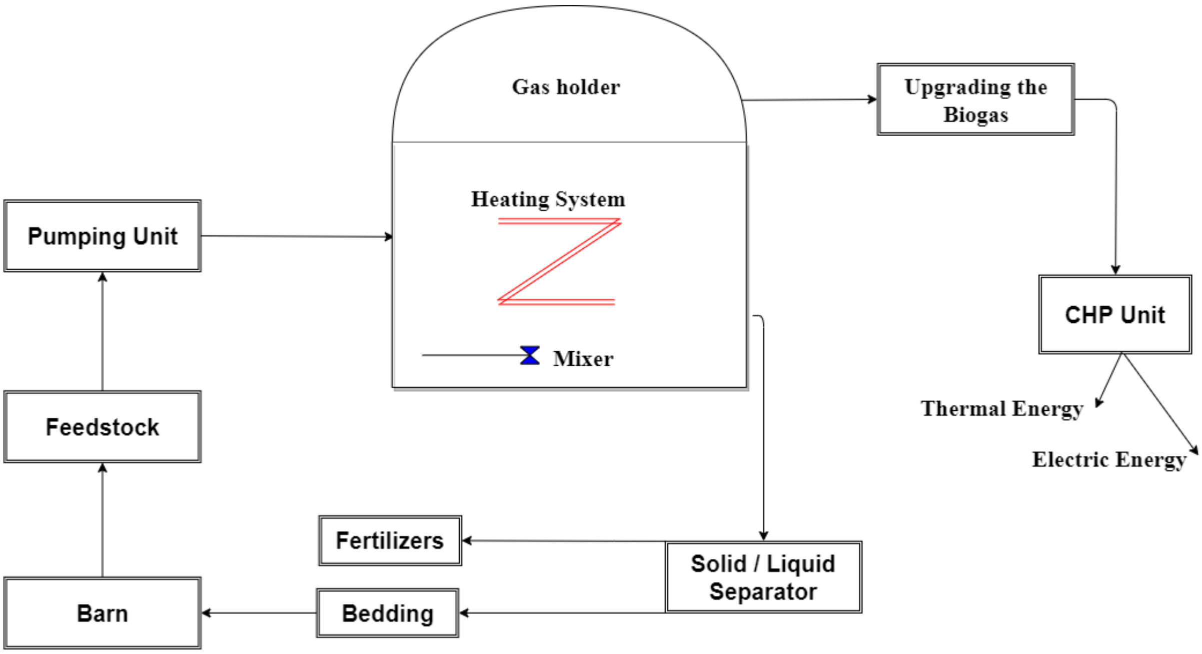


Figure 2. Infrastructure components of a typical biogas plant

2. METHODOLOGY

To be able to review the analytical process used in this paper in detail, This section will present each method separately. Firstly, it explains the regression modeling and reviews all the steps and required material for this method. Then, this section will present the details of the Monte Carlo simulation and its application to this study.

Regression modeling relies on finding a mathematical correlation between the cost and the different components of the biogas plant. This model can offer both linear and nonlinear equations between variables [20]. The independent variable is the number of cows that implicitly means the volume of generated manure in the farm. The dependent variable would be the costs (total or capital and that of the individual components), with a specific focus on the required capital cost at the beginning of the plant's construction, annual operational costs, and annual revenue.

This study developed a database to provide detailed information on Canadian biogas plants. The selected farms are chosen only based on their relevance to Canada and America. The farms' size was mostly limited to a range of 100 - 1600 cows because 1- most of the Canadian farms are in this range, and there are a very limited number of mega-sized farms out of this range. 2- this concentration on the size range increases the accuracy of the cost and revenue calculations. 3- Since both methods' results are strongly related to the data points, the more concentrated dataset for the country will bring more reliability to the results.

The data points represent the number of dairy cows in each farm, the costs of construction of the plant, cost of each component, revenue from the tipping fees of off-farm organic waste, selling electricity, fertilizer, biofiber, bedding, soil amendment. The dataset was checked for consistency and scope of coverage. Further, the collected data from each farm were normalized to a single and comparable unit among all of them. The similarity of these farms is in the type and quality of the feedstock, which is dairy manure. These plants convert biogas to electricity and sell the generated power to their province according to feed-in-tariff programs. Since the costs reported for each farm are based on the year of construction, there is almost 15 years difference between the start-up time of these farms. Hence, to harmonize the prices to make them comparable, all the costs were converted to Canadian dollars and inflated to the year 2020, according to the Bank of Canada's inflation calculator.

Most data are confidential because the projects are private. However, the collected database included the following parameters which have been used to develop the models: 1) the number of animals on the farm, 2) location, 3) cost of the powerhouse and the pumping unit, 4) cost of the digester, 5) cost of CHP unit, 6) cost of biogas upgrading system, 7) capital cost, 8) operational and maintenance costs, 9) revenue of sales, 10) year of the project completion, 11) inflation rate to the year 2020 [21,22].

Correlation analysis was conducted on the dataset to identify the relationships between the cost and the various components of the biogas plant. Based on the outcomes of the correlation analysis, regression has been used to develop linear and nonlinear models. The developed model consists of five major sections. 1) Farm's specification includes the number of cows and the generated wastewater volume per cow per day during the manure collecting process; 2) Biogas yield per day based on the given farm size. This section is a key element in income and financial benefits; 3) Total electricity generated (kWh/day). The main parameters involved in the total amount of electricity generated are methane concentration in the collected biogas and the CHP unit's efficiency during the conversion of CH_4 to energy; 4) Cost prediction for installation and operating the plant; and 5) annual gross income. Based on the reviewed literature, some technical factors were assumed to make the models effective and reduce the errors between the actual values (collected from real biogas projects in Canada) and models-estimated (predicted) values. These factors include biogas to electricity conversion coefficient, CHP unit efficiency, and the average wastewater generated during the manure collection.

Monte Carlo Simulation is used as the supporting method to help in making a decision. The simulation is run with the help of @Risk adds-in to the Microsoft Excel. @Risk works similar to "what-if" analysis. At the same time, it can repeat the simulation for hundreds or thousands of scenarios and provides graphical results at the end of the simulation [23]. The major advantage of using this software is that it is not necessary to assign a specific number to each variable; instead, we can define a range of possible answers for each parameter, and @Risk will use all the information to generate a possible range of outcomes. The simulation started with defining the independent and dependent variables [24]. The independent variables were 1- the number of cows; 2- the volume of on-site manure; 3- the volume of off-site organic waste; and 4- hydraulic retention time (HRT). For each variable, a set of statistics such as the minimum, maximum, mean, standard deviation, and most common value are extracted from the dataset and listed separately (Table 1). The data in Table 1 is needed to define a specific probability distribution for each variable. Since the objective of this study is all about cost and revenue, it is crucial to select a proper statistical distribution for each variable that would not result in a negative number. For this reason, two commonly used probability distributions are Lognormal distribution and PERT distribution [25]. PERT distribution allows the user to define a minimum and maximum threshold for each variable. This feature makes it suitable for financial and costs analysis.

Table 1. Independent variable

Parameter	Cows number	On-site manure volume (m^3/cow/day)	Off-site organic wastes volume (m^3/cow/day)	HRT (days)
Mean	840	0.067	29.70	24.43
Std. dev	664.19	0.032	14.09	8.75
Min	100	0.012	10.55	10.00
Max	3300	0.116	46.58	57.00
Mode	600.00	0.05	46.58	22.00

In addition to the parameters in Table 1, PERT distribution needs two shape parameters, Alpha (α) and Beta (β), as extra values that are calculated based on the minimum, maximum, and most common values of each variable [26]. The Eqs. (1) and (2) calculate Alpha and Beta, respectively. The next step is to determine alpha and beta for each variable and then run the Monte Carlo simulation to randomly pick a number based on the chosen probability distribution. The calculations have been repeated 5,000 times, and the average value of these trials has been used as the input value for cost calculation. The dependent variables also follow the same process in the modeling procedure. Dependent variables are actually the components of a biogas plant that any change in the value of the independent variables may cause a difference in the calculated cost for each element. In these equations, "a" is the pessimistic value, "c" is the optimistic value, and "b" is the most common value of each variable.

$$\alpha = [4b + c - 5a] / [c - a] \quad (1)$$

$$\beta = [5c - a - 4b] / [c - a] \quad (2)$$

For instance, if the volume of the on-site manure increases, it means that the total amount of feedstock would be greater than before, and it requires a larger digester to digest the increased amount of feedstock in the same period. This increase in the digester size would need more investment. The dependent components in this simulation are the costs of the pumping unit, the digester, generator, upgrading unit, engineering and design fees, and operational costs. The capital cost is the sum of these individual costs. Finally, the cost of engineering and design is calculated based on 5% of the total cost. Typically, engineering fees depend on both parties' agreement, and the farm specifics are not involved [27]. The same 5000 trials were applied to the variables in Table 2, and the average result for each of them was considered the cost of component for Canadian biogas plants.

3. RESULTS AND DISCUSSION

The following two sections present the results of both modeling approaches. Section 1 presents the results of the regression modeling and cost prediction method, and Section 2 discusses the Monte Carlo simulation and the risk analysis. Table 2 provides the values for the dependent variables.

Table 2. Dependent variables.

Parameter	Cost of (CAD)				
	Pumping	Digester	Generator	Upgrading	O&M*
Mean	260,989.58	703,954.10	702,667.09	1,543,090.91	50,582
Std. dev	129,252.17	384,246.73	446,798.28	260,130.53	38,218
Min	14,440.00	53,824.68	36,061.20	1,230,000.00	3,656
Max	505,530.00	1,261,980.00	1,416,960.00	1,845,000.00	153,089
Mode	252,765	1,000,000	1,351,647	1,845,000	46,500
Alpha (α)	2.94	4.13	4.81	5.00	2.15
Beta (β)	3.06	1.87	1.19	1.00	3.85

*Cost of O&M is based on CAD/year

3.1. Cost Estimate Models

The models were developed based on a regression analysis to provide a cost calculator for feasibility studies of on-farm biogas projects. Six models (Table 3) predict the cost of each component of the on-farm biogas plant based on the number of cows (CN) in the farm. These models represent the total capital cost and operational expenses and the total generated income per year as a function of the number of available cows.

The model of the capital costs estimation is divided into two ranges in terms of the number of cows. These ranges are: 1) Small farms with a herd size of up to 1000 cows. 2) Large farms with a herd size of 1000 cows. This separation is because larger farms may require complicated technologies such as biogas purification and upgrading unit that are very expensive and increase the capital and operational costs. Although these technologies would increase the efficiency of the energy conversion from biogas to the electricity of CNG, which increases the relevant income, the significant increase in the costs that these technologies add to the project would not be financially feasible for small farms (CN < 1000 cows).

Table 3. Linear regression models predicting various costs of on-farm biogas plants.

Predicted variable	Unit	Prediction model
Capital cost (CN<1000)	CAD	$1203.9\ CN^{*} + 2 \times 10^{6}$
Capital cost (CN>1000)	CAD	$1442.9\ CN + 4 \times 10^{6}$
Cost of engineering and design	CAD	109.44 CN + 216361
Operational & maintenance costs	CAD/year	48.155 CN + 95199
Revenue	CAD/year	376.05 CN
Net revenue	CAD/year	264.26 CN - 70786

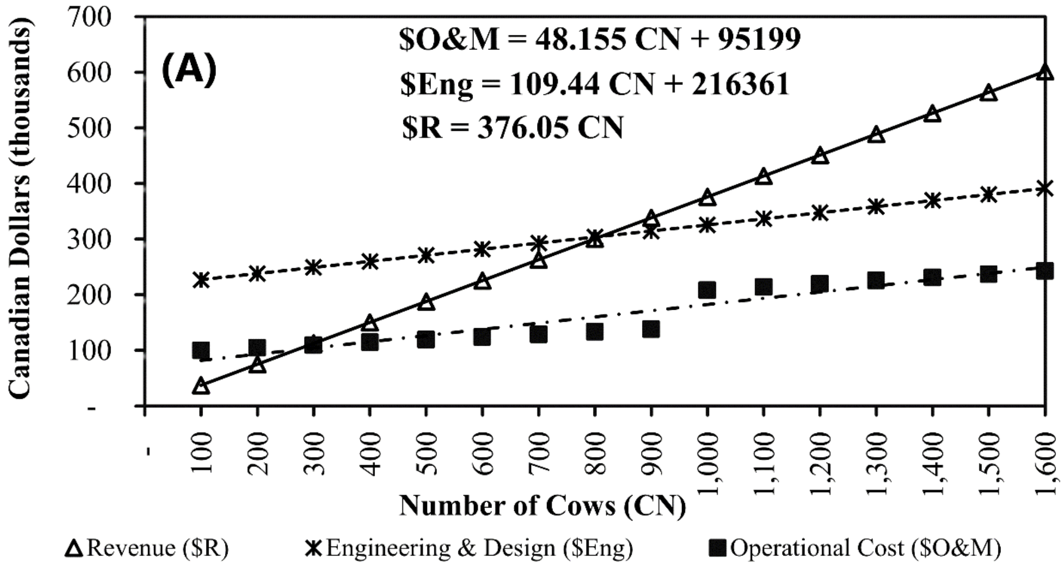
*CN = number of cows.

The models have been validated by applying them to 16 farms with a herd size of 100 - 1600 cows. The results are shown in Fig. 3. To construct an on-farm biogas plant in North America, the minimum required investment (in Canadian Dollars) for a farm that houses 100 dairy cows is about 2 million dollars, and it can increase to about 6.3 million dollars for 1600 cows farm. For the same scope, the change in revenue will start from 37,000 CAD for a farm with 100 cows, and it will increase to 600,000 CAD for a farm with 1600 cows. This is the gross income, and the operational and maintenance costs should be deducted from these numbers. This income is from selling the electricity produced by the farm's biogas plant or selling the biogas as CNG.

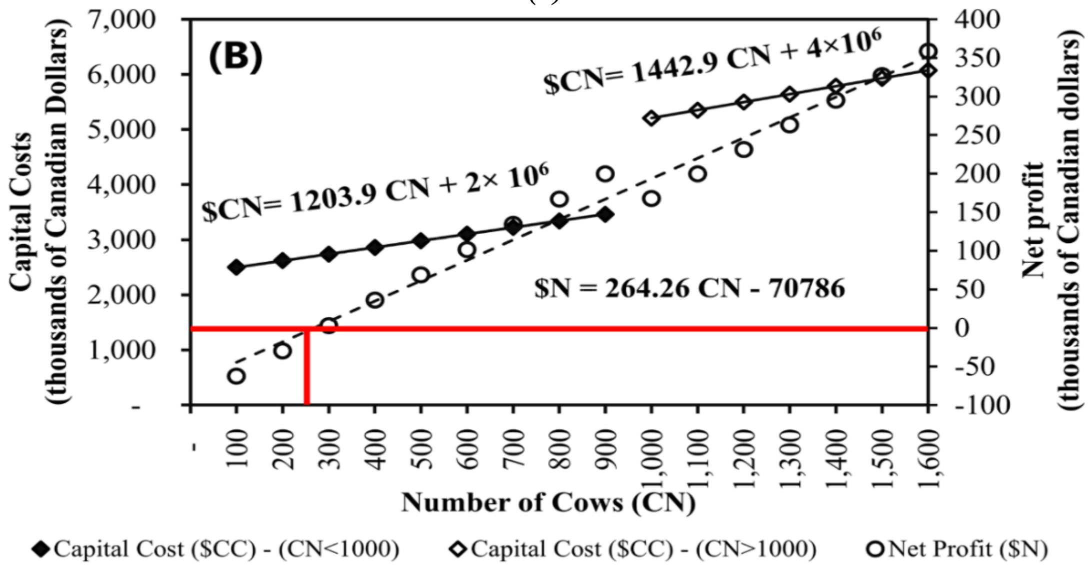
The economic viability of the biogas projects relies on the difference between the annual revenue and the annual operational costs. Based on the results of this study shown in Fig. 3, a farm with 500 dairy cows has an annual operating cost of CAD 138,000, and there is a potential of generating CAD 177,000 income which means an annual net income of CAD 40,000. Notice that a biogas project on a farm housing less than 300 cows might not be economically feasible because the operational expenses would be higher than the annual benefit.

However, besides selling electricity, there are some additional benefits for the farmers, such as decreasing the energy bill to zero, availability of free hot water on the farm, and free high-quality fertilizers that the farm itself could use to grow crops or to sell them for gardening or as soil amendments [28]. In addition to the direct benefits of biogas projects, indirect benefits like lower tax rates for renewable energy producers compared to oil and gas-based projects can benefit the farmers. In Canada, as of April 1, 2021, the federal carbon tax is $40 per tonne of CO_2e. It will reach $50 per tonne in 2022 and then increases $15 per year until it reaches $170 per tonne in 2030 [29].

A limitation of the current model is that the intangible environmental benefits of on-farm biogas plants are not factored in the cost analysis. This limitation is observed in most cost analysis models. It is probably because of the not so well-defined tag value assigned for these intangible benefits. Errors are inevitable in mathematical modeling, particularly for cost and economic data. A slight discrepancy exists between the cost predicted by some of the models developed in this study and the real data point. For example, a farm with 1600 cows needs an investment of 6.3 million CAD based on this study's results, and the exact data point in the collected database was 6.8 million CAD. The error in this specific example is 500,000 CAD, which is less than 7% of the total capital cost. However, this error margin is acceptable for these projects because of the large scale of investment and the wide variability depending on the circumstance of the area, type of farm, relevant regulations, and policies.



(a)



(b)

Figure 3. Developed models of costs of biogas plants on Canadian dairy farms: (a) Cost of engineering and design, operational and maintenance, and revenue, (b) Capital costs and the net profits.

The net profit (net revenue) is the difference between the total (gross) revenue and the operational costs. The latter increases with the herd size; however, for farms with less than 268 cows, the operational costs are greater than the gross revenue; only when the herd size exceeds 300 cows, the farm starts making a profit. Of course, this scenario is a function of the specific circumstances of the farm. For example, there is a biogas plant at Dawson Creek, British Columbia, that owns 230 cows. However, their biogas plant is still economically profitable because 49% of the feedstock is off-farm non-agricultural wastes, which increases the biogas production of the project [30]. The models take into account only the manure and do not consider off-farm waste. The exact farm circumstance should be taken into account carefully on a case-by-case basis. The results of the models provided in this paper might be used as an approximate estimation only.

3.2. Risk Assessment Simulation

The purpose of the second modeling is to provide a robust foundation for the regression modeling results. Thus, the Monte Carlo simulation has been applied to the regression equations (Table 3), and 5000 results from each equation would be calculated. A large number of repetitions can reduce the error in the modeling, and the average result of these 5000 values would be more realistic compared to the actual data in the dataset. Not only is the Monte Carlo simulation applied to the regression models, but it is also applied to the original dataset. For instance, for a specific cost like the operational and maintenance costs. The model generated 5000 results from the dataset, and additional 5000 results were generated based on the regression equation (48.155 CN + 95199). The average of these 10,000 values would be the predicted cost for the O&M costs.

To finalize the calculations, both streams have been combined, and an average result has been calculated for each variable. The advantage of this method is that it reduces the possible error and provides a more realistic outcome. Fig. 4 shows the result of the Monte Carlo simulation. The most common value in this analysis for capital costs is

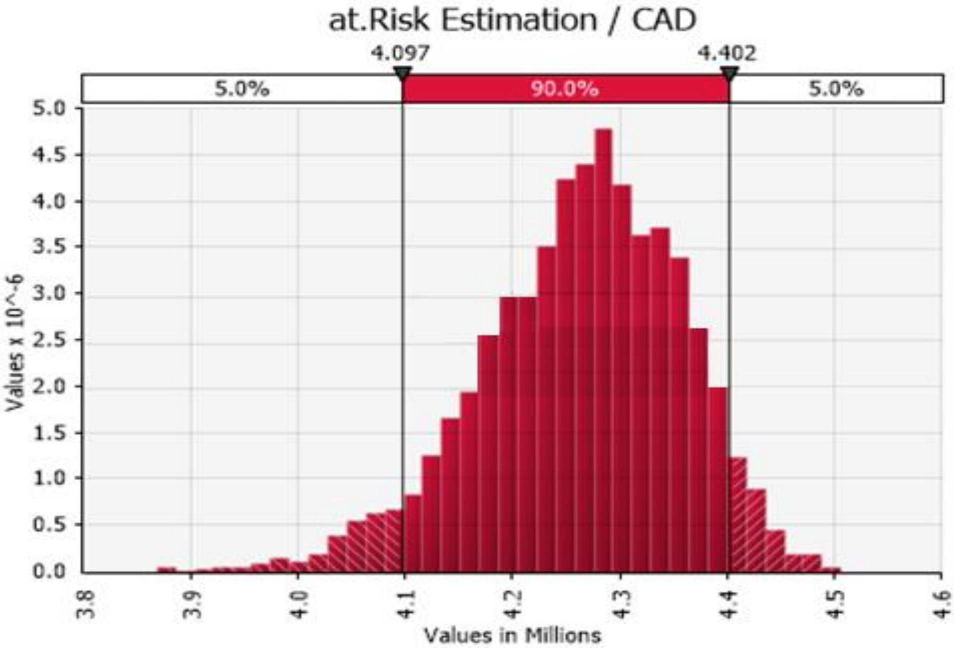


Figure 4. Monte Carlo simulation results

4.3 million dollars. It means that based on the data collected and the regression equations provided, the most probable investment for a farm-based biogas plant in Canada is around 4.3 million dollars; this price is more accurate for the farms with 300 to 1600 cows. Large farms might need a more extensive investment for their construction. Based on different types of skewness for statistical distributions, the result of Fig. 4 is very similar to the medium negative skewness. This means the tail of the left side of the distribution is longer than the tail on the right side, and it shows that the mean value is less than the most common value in this analysis.

One of the reasons for negative or positive skewness is when some data point is very far from the average value that causes the long tail of the graph. In this case, because the skewness is negative, it shows that there are more gaps between the data point less than the average in the dataset. In other words, there are fewer data points that represent on-farm biogas plants for small-sized farms, and most of the biogas plants are built on medium-sized farms (e.g., the farm houses 500 – 800 cows).

4. CONCLUSIONS

This paper followed two main approaches to provide cost prediction and probability analysis for on-farm biogas plants in Canada. The first approach developed six mathematical models to predict the costs by using mathematical analysis. These six regression models have been developed to assist farmers and project developers in evaluating the economic feasibility of such projects. The models take the herd size (number of cows) housed as input and estimate the capital cost for farms with less and more than 1000 cows, design and engineering cost, operation and maintenance cost, gross revenue, and net revenue.

The second approach focused on risk and probability of costs using Monte Carlo simulation. In this simulation, a statistical distribution is defined for each variable. This study applied PERT distribution to avoid getting any negative results, and the simulation conducted 5000 trials for each variable to cover the possible outcomes. The simulation results show that with a 90% confidence interval, the most probable cost for an on-farm biogas plant in Canada is around 4.3 million dollars.

The models have three limitations: 1- they are applicable for on-farm biogas projects in Canada only; 2- the marginal error in the predicted capital cost is 7% for farms with around 1600 cows; and 3- the models are applicable for farms with a herd size of up to 1600 cows. The models developed showed that the viability of an on-farm biogas project digesting manure only for farms of less than 300 cows is questionable. Since there are minimum costs for running the plant, less than 300 cows on a farm will not produce a sufficient quantity of manure for the system's input. They will generate less electricity that may not be adequate even for maintaining the digester temperature as the optimum level. Further work could incorporate the intangible benefits (environmental, job creation, improving soil and water quality, control of odors and pathogens, etc.) in the cost analysis and the economic viability evaluation by generating tag values for the intangible benefits of such projects.

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