COST ANALYSIS AND ECONOMIC EVALUATION OF ON-FARM BIOGAS PROJECTS: A CANADIAN PERSPECTIVE

By

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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. Therefore, estimating the costs of biogas plant components and the required initial investment for a farm-based biogas plant is essential. This study develops two methods to estimate the cost of farm-based biogas projects, determine their economic viability, predict the cost of each part of the plant, and analyze its related risks. The models base on available cost data of current on-farm biogas plants for dairy farms in Canada. First, by using regression analysis, cost predicting models are developed and used to indicate the costs related to biogas plant construction based on the number of cows (CN) housed in a farm. Furthermore, risk analysis is applied to investigate the most probable outcome of the cost models and the dataset with the help of Monte Carlo simulation. In general, the dataset included two groups of farms (less than or greater than 1000 cows). The capital cost is predicted mathematically based on the number of cows (CN) and hydraulic retention time (HRT). In addition, the study developed detailed models for major components of a biogas plant (anaerobic digester, pumping unit, upgrading unit, CHP unit). The result of the Monte Carlo simulation shows that the average cost for on-farm- biogas plants based on the currently available dataset would be about $4.3 million, with an average of 960 cows per farm. Finally, the results of this study have been applied on an actual farm (Lester's Dairy Farm)

located in St. John's, Newfoundland, as a case study. Almost $2.5 million investment is required to develop such a biogas plant on this farm, considering a herd of 550 cows housed in the farm.

Keywords: Anaerobic digestion, cost estimation, regression modeling, Monte Carlo simulation

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NOMENCLATURE

AD	Anaerobic Digestion
C/N	Carbon to Nitrogen
CAD	Canadian dollars
CC	Capital Costs
CH4	Methane
CHP	Combine heat and power
CN	Number of cows
CO2	Carbon dioxide
COD	Chemical oxygen demand
CSTR	Continuous stirred tank reactor
FFD	Fixed film digester
GHG	Greenhouse Gas
HRT	Hydraulic Retention Time
NL	Newfoundland and Labrador
OLR	Organic loading rate
PFD	Plug flow digester
PUP	Pumping Unit
TS	Total solids
UPG	Upgrading Unit
VS	Volatile solids

CHAPTER ONE

INTRODUCTION

1.1 Background

The energy demand is growing because of population growth and industrial activities. During the last two decades, the contribution of oil and gas industries to energy supplies has increased by more than 25% globally (Smil, 2017), which increases the impact on the environment and climate status. There is a huge gap between fossil fuel and renewable energy sources in the same period (i.e., 2000-2020). Therefore, countries invest in increasing the contribution of clean and renewable energies sources to meet their energy demand because renewable energy supports a more sustainable environment and enhances economic growth. The energy (TWh/year) derived from fossil fuel sources has increased during the last two decades. By the year 2020, it reached 53,000 (from oil), 44,000 (coal), and 39,000 (gas), while the renewable sources contribute less than 3,000 TWh/year for each source (hydropower, wind, nuclear, solar, and other sources) (Looney, 2020).

Biogas is a reliable renewable and clean biofuel that can generate energy. Biogas production can be part of waste management to produce clean, renewable, and environmentally friendly energy under anaerobic conditions in a process called anaerobic digestion (AD). A biogas plant is a system that consists of several components such as an anaerobic digester, heating system (heat exchanger), mixing device, gas storage vessel, combined heat and power (CHP) unit, etc. The AD is a natural process that can break down organic materials and produces biogas containing 60 – 70% methane (CH_4) and 30 – 40% carbon dioxide (CO_2); (EBA, 2018).

The objective of producing biogas is to produce methane that is convertible to vehicle fuel, electricity, and heat. A 1 m^3 of biogas contains 20 MJ of energy, generating 1.7 kWh of electricity or 7.7 MJ of heat (Alberta, 2011). In comparison, 1 m^3 of natural gas is convertible to 1 liter of diesel which contains 34.2 MJ (NGV, 2014); 1 m^3 biogas can provide 70% of the energy generated by 1 liter of diesel with less environmental emissions and hazards (U.S. Energy Information, 2021).

Europe is the leader of AD technology in the world. In 2017, Europe had 17,783 operating biogas plants, and Germany recorded the highest number of biogas plants among the European countries. The top five European countries with the largest number of biogas plants in 2017 were Germany (10971), Italy (1655), France (742), Switzerland (632), and the UK (613) (Scarlat et al., 2018). The total installed electric capacity of the biogas plants in Europe is 10,532 MW in the year 2017. The average European biogas plant size is 0.59 MW, and the total amount of electricity produced by anaerobic digestion facilities only in Europe is 65,179 GWh (Torrijos, 2016).

The Canadian Biogas Association reported in 2013 that five primary sources for biogas production in Canada are: agriculture, landfill gas, source separate organics (municipal/ residential), source-separated organics from commercial sources (such as hotels, restaurants, etc.), and wastewater treatment plant residuals. Agriculture has a significant potential to produce biogas; it currently provides 68% of the biogas produced in Canada. However, the total contribution of renewable energies to Canada's electricity and gas demand is 18.9% by the end of 2017 (Kelleher et al., 2013; Canada, 2017).

One of the great sources of renewable energy production in the agricultural sector is the on-farm biogas plants. The outcome of this system can be electricity or compressed natural gas which is useable as a fuel. Farm-based biogas production is significantly beneficial, and there are great opportunities in this field in Canada.

1.2 Benefits of on Farm Biogas Plants

On-farm biogas production is motivated by the many benefits to the farmer, community, society, and environment. These benefits include energy production, odor reduction, greenhouse gas (GHG) emission reduction, environmental protection, and revenue generation for the farmers and the country. On-farm biogas systems significantly reduce animal manures' pathogenic bacteria and the odor by 99% and 80%, respectively (Szogi et al., 2015). Additionally, soluble phosphorus and nitrogen can be partially converted to a solid form in the digestate enabling better control and higher efficiency in nutrients management.

An AD system can reduce 75% of on-farm methane (CH_4) emissions (Pekkarinen, 2020). Methane is the second most important contributor to climate change after CO_2 and its global warming potential (GWP) is 25 times higher than that of CO_2; thus, its emission can be much more destructive for the environment from the greenhouse gas (GHG) perspective (Pohlman et al., 2017). Digesting half of the Canadian animal manure and crop residual would reduce GHG emissions by 25.5 million tons of eCO_2 per year. This is equivalent to taking more than 5 million cars off roads. Besides the environmental benefits of an anaerobic digestion biogas plant, its economic benefits are undeniable (Pekkarinen, 2020).

Anaerobic digestion is a proven technology for manure and agri-food product treatment and management, and it is important for environmentalists, engineers, and economists because of its tremendous benefits. Based on the reports provided by the Government of Canada, the total electricity production potential from biogas sources (agriculture, landfill gas, wastewater, etc.) is 810 MW of electricity, and this amount can fulfill 1.3% of the total electricity needs of the country (Kelleher et al., 2013). Table 1-1 shows the bioenergy potential in four major Canadian provinces. The amount of possible energy production per year is estimated for each source of waste. It shows that about 1000 PJ/year can be generated. This number represents 10% of the Canadian energy demand (Pelkmans et al., 2018).

Renewable energy produced by AD can be used in different forms, such as renewable biogas which is similar to natural gas (RNG), compressed natural gas (CNG) for vehicle fuel, or electricity generation. A case study in Surrey, BC, in October 2012 revealed that gas-powered trucks, in general, emit 23% fewer carbon emissions and 90% less air particulates than diesel trucks (Kelleher et al., 2013). On the other hand, converting methane gas to electricity can meet the demand for energy in rural areas.

Table 1-1 Bioenergy potential in four major provinces in Canada

	Bioenergy potential (PJ/year)				
Biomass	British Columbia	Alberta	Ontario	Quebec	Current Canadian energy demand
Municipal wastes	15.2	1.5	48.7	15	N/A
Agricultural wastes	52.1	37.5	48.62	86	N/A
Forestry	273.8	19.3	175.57	233	N/A
Total	341.1	58.3	272.89	334	11,727
Source	(Ravelic et al., 2006)	(Alberta , 2011)	(Khan, 2009)	(Hydro, 2015)	(Pelkmans et al., 2018)

The government of Canada estimated that the full biogas development potential in Canada is 1,800 construction projects and requires around $7 billion capital investment, which will bring a $21 billion economic spin-off to the Canadian economy; this will provide an opportunity to increase the number of construction jobs by 16,800 in a year (Kelleher et al., 2013).

According to the Canadian Biogas Association, over 61 active anaerobic digestion plants are across Canada. These plants were organized into four subcategories: 1) livestock operations (52%); 2) Greenhouse operations (5%); 3) food processing facilities (33%), and 4) categorized as "other" (10%). Most of the anaerobic digestion plants are in Ontario, Alberta, and Quebec, with Ontario alone having 64% of the biogas plants across Canada (Kelleher et al., 2013).

1.3 Research Problem

The population growth induced similar growth in the food industry, and the rapid expansion of this sector poses challenges for the developers of the field. In 2020, Statista Research Department of the United States reported that the organic dairy product market was 18 billion dollars in 2017, and it is expected to grow to 28 billion dollars by 2023 (Statistia Research Department, 2020). Consequently, the number of livestock or dairy farms should be increased by 55%; this may lead to severe environmental and managerial issues for dairy farmers.

The environmental challenges facing dairy farms include soil degradation, water pollution, manure management, GHG emissions, and impacts on biodiversity or changes in the ecosystem. Soil degradation is not limited to the dairy farm itself; even off farmlands providing the corps required for animal feeding will have erosion in the soil. Manure management is one of the most significant issues farmers face (Clay et al., 2020). A dairy cow produces 62 kg of manure per day (Hofmann et al., 2015), and improper manure management can cause water and soil pollution, GHG emissions, and a permanent change in the ecosystem. For instance, two studies were conducted to observe the possible changes in the ecosystem due to dairy farm activities and their impacts on the population of birds and butterflies in the farm area. Both studies reported a significant decrease in the population of birds and butterflies compared to the remote locations which were not under the effect of dairy production (Jerrentrup et al., 2016; Dross et al., 2018).

While manure management poses a serious challenge, it offers an excellent opportunity for farmers to generate an additional source of income by converting animal wastes into energy, fertilizers, or animal bedding. This study focuses on on-farm biogas plants in which animal waste (manure) is fed to anaerobic digesters. By controlling the temperature and pH inside the digester at optimum levels, the microorganisms degrade the manure's organic matter and convert it to methane (CH_4) and CO_2 gases. The generated methane can be converted to heat and electricity, increasing the farm's income. At the same time, the leftovers of the digestion process can be used as animal bedding and/or soil amendments to reduce farm expenditure.

Because the objective of this study is to predict the costs related to developing an on-farm biogas plant, it is required to initially collect information about the existed biogas projects in Canada and their capital and operational costs. Then mathematical models will be used to simulate the same scenarios for future plants. The regression analysis was initially developed based on Canadian biogas facilities' currently available cost data in this study. Afterward, a Monte Carlo simulation is generated to estimate the cost of each component with a 90% probability of occurring based on the current prices in Canada. It also assesses the financial feasibility of such plants. The models would enable investors to make better predictions of the required investment to build an on-farm biogas plant, the operation cost, and the average annual income generated by the plant.

For more detailed estimation, some studies calculate the costs based on the input (feedstock) to the plant. This input can be the volume of the waste (manure) produced by animals in the same location, or it can be transported manure from other farms (in case of centralized or semi-centralized biogas plants) or transported off-farm organic waste from industries such as food processing plants (Stürmer, 2017). The results of this type of calculation are more realistic. One of the models that have been used is the Agricultural Anaerobic Digestion Calculation Spreadsheet (AADCS). AADCS uses the produced waste on-farm as input to estimate the output of the anaerobic digestion and the relevant costs of a biogas plant (Weersink et al., 2007). Similar financial models are used in the USA, such as the "Anaerobic Digester System Enterprise Budget Calculator," developed by the University of Washington (Astill et al., 2018). The model used Microsoft Excel spreadsheet modeling. However, this financial model needs adjustment to be applied to Canadian conditions. These changes are regarding the extra cost for transportation that may be required for the components that are going to ship from the US to Canada or the extra energy required for maintaining the digester warm in winter because of the colder climate conditions in Canada. Since the database that is used for the cost analysis in this study is related to Canada, these parameters are already included in the analysis and results (Astill et al., 2016).

This study will analyze the cost of the components of a biogas plant modify and combine the existing models to develop a new model that predicts a more accurate cost of biogas plant's construction, operation, and profitability. The modifications will be based on collecting a database related to North America's active projects and normalizing the results based on the current inflation rate reported by the Bank of Canada.

Most of the available models are outdated and require initial assumptions from the user to proceed. They also do not provide detailed predictions on the cost of each component; they usually predict the total cost of the whole project construction, which can be over- or under-estimated. For example, the user must first assume the volume of the wastewater of their farm, the conversion rate of the volatile solids to biogas, or the efficiency of the equipment that converts the biogas to electricity or heat. These assumptions need comprehensive research and modeling and would not be easy to apply by investors or farm owners. This study tries to minimize the input data to the simplest way (number of cows is the input variable for the models of this study), which is straightforward data to collect for the users, and it is possible to forecast the overall costs and cost of each component only based on one variable.

In addition, more detailed information on farms is put into consideration. The number of animals translates to the total volume of waste and the available volatile solids (VS) in its contents, then the amount of generated biogas is calculated based on the conversion rate of the VS to methane that is taken from the literature and laboratory reports (in this study the methane potential is assumed 170 NL CH_4 / kg VS by considering 25 days of Hydraulic Retention Time (HRT) from the cow manure (Pham et al., 2013)), and based on the co-generator efficiency, the total produced electricity is calculated. In the end, this study evaluates the economic benefits for farmers, owners, and investors of on-farm biogas plants.

1.4 Objectives

This study aims to address the research questions discussed in the previous sections and fill the current knowledge gap in predicting the costs and assessing the feasibility of on-farm biogas plants in Canada. These objectives are:

1. Developing mathematical models to predict the capital investment and cost of individual components (anaerobic digester, pumping unit, combined heat and power unit, and upgrading unit) of an on-farm biogas plant in Canada.
2. Assessing the operational costs, engineering costs, possible interest rate, and predicting the break-even point for on-farm biogas plants.
3. Investigating the bioenergy potential of the province of Newfoundland and Labrador
4. Applying the developed models on a case study for a typical Canadian dairy farm in Newfoundland (Lester’s Dairy Farm in St. john’s) to investigate the available potential for developing a biogas plant on this farm and conduct a detailed cost analysis.

The project is divided into the following steps to achieve these objectives (Figure 1-1) (Weersink et al., 2007).

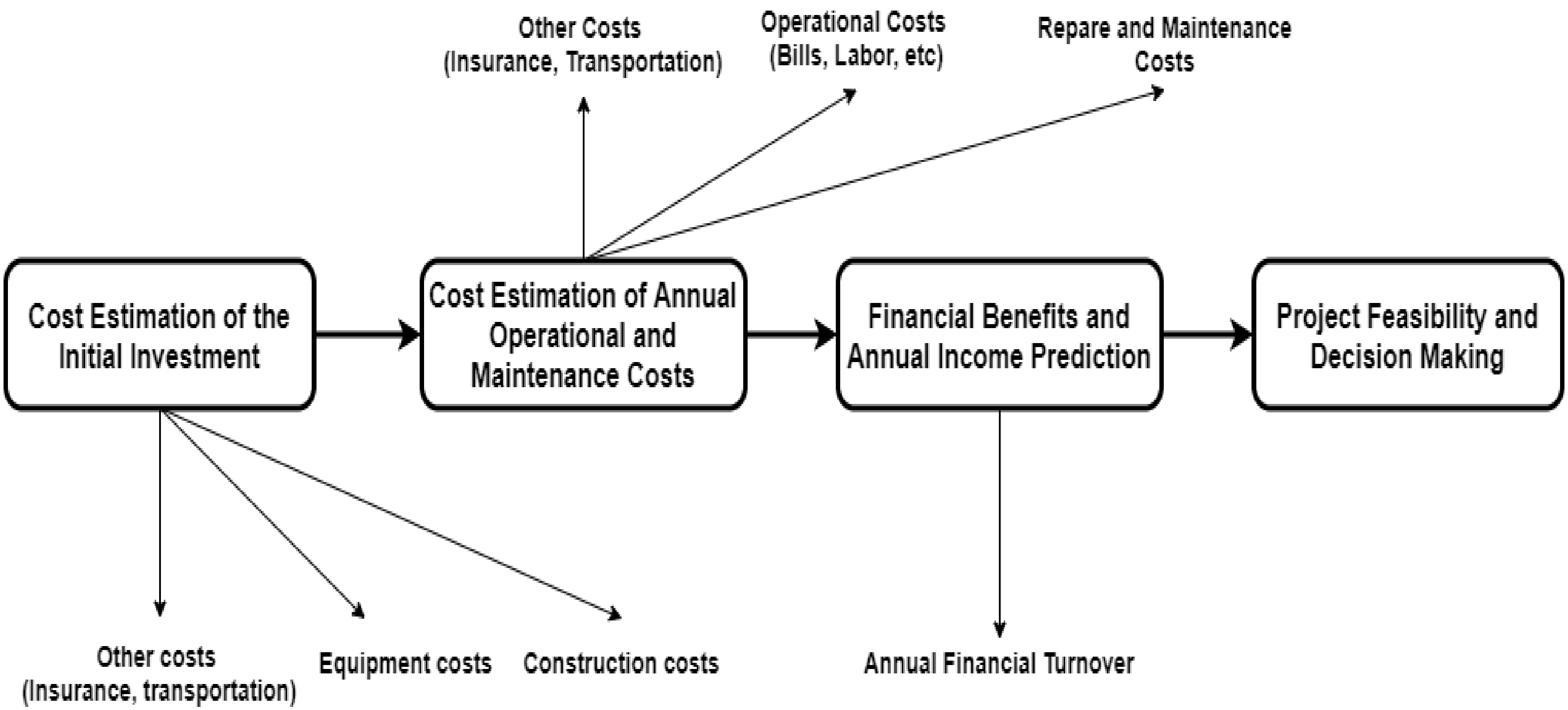


Figure 1-1 Schematic of the solution proposed to achieve this study's objective

Initial investment analysis: This step analyzes the financial (cost) of typical biogas projects on dairy farms. It estimates or predicts the initial capital investment for constructing an on-farm biogas plant considering the costs of material and equipment, cost of engineering and project management, and equipment transportation. Normally, the initial investment is high, and the farmer alone cannot afford it. Thus, governmental subsidies or other funding sources for capital investment through private sector businesses are required.

Analysis of operational costs: The operational costs will be included to predict the break-even point for the investment. The operating costs may include labor costs, transportation, insurance, repair, and equipment maintenance.

Financial benefits of the project: The study will investigate the amount of electricity produced from converting the feedstock to methane; energy will be converted to monetary equivalent using the current energy price in the Canadian provinces. In addition to electricity, high-quality fertilizer and animal bedding are other major by-products of the plant. Finally, the annual financial turnover of the plant is calculated.

Financial feasibility and decision making: A financial evaluation will be conducted for the project based on the factors mentioned above to assess the feasibility of dairy on-farm anaerobic digestion (biogas) plant in Canada and its applicability to Lester's Dairy Farm, St. john's, NL, at the current conditions of the farm.

1.5 Thesis Organization and Layout

This thesis includes six chapters. Chapter one starts with the introduction and background knowledge of biogas production, then states the research problem and scope and objectives of the research. Chapter two is a comprehensive literature review; it presents the operational parameters of a biogas plant and the typical components that are used for on-farm biogas production and their related costs. In addition, the previous models of estimating farm-based biogas plants have been reviewed and explained in detail. Chapter three introduces the scope of the study (cost estimation of biogas plants in North America) and the methodology used for developing the financial models (cost predictors) for on-farm biogas projects. Chapter four presents results and discussion about the dataset development steps, statistical analysis, and results of the generated models for cost estimation of overall costs and component costs of a biogas plant. This chapter also includes the results of comparing previous models in the field and the models developed in this thesis. Chapter five focuses on the local aspect of biogas potential and its benefit to the province of Newfoundland and Labrador. This chapter follows by a case study on a typical dairy farm in St. john’s area (Lester’s Dairy Farm). The models developed in this research are applied to the data from this farm to predict the development and operations costs of a proposed on-farm biogas facility. The last chapter of this study (Chapter six) provides the conclusion of this thesis and recommendations for future studies.

Contributions From This Thesis

This study extended the knowledge of the financial aspect and feasibility of biogas through anaerobic digestion in Canada. The results of this study and the procedures to develop the economic models for on-farms biogas production in Canada have been presented in conferences and academic journals as listed below:

1. Arash Samizadeh Mashhadi, Noori M. Cata Saady, Carlos Bazan (2021). "Predicting cost of dairy farm-based biogas plants: A North American perspective". *Journal of Energy Systems*, *5*(4), 365-375. DOI: 10.30521/jes.980467

2. Arash Samizadeh Mashhadi, Noori M. Cata Saady, Carlos Bazan (2021). " Predicting Cost of Farm-based Biogas Plants," oral presentation at 9th European Conference on Renewable Energy Systems. 23 April, Istanbul, Turkey. ISBN: 978-605-86911-9-3

3. Arash Samizadeh Mashhadi, Noori M. Cata Saady, Carlos Bazan (2021). "Cost Analysis and Economic Evaluation of on-Farm Biogas Projects: A Canadian Perspective," an unpublished report submitted to the Department of Fisheries, Forestry, and Agriculture. Government of Newfoundland and Labrador.

4. Arash Samizadeh Mashhadi, Noori M. Cata Saady, Carlos Bazan (2020). "Cost Analysis and Economic Evaluation of on-Farm Biogas Projects: A Canadian Perspective," Oral presentation at virtual annual research day at Memorial University, submitted to the Engineering Research Office and Office of Graduate Studies. Link:

https://www.youtube.com/watch?v=Q_rBrZFZRNs&list=PLV3LAfK0bhrzU2LOzpu_0hQcolTWjIAEJ&index=10

5. Abdollah Hajizadeh, Arash Samizadeh Mashhadi, Noori Saady, Sohrab Zendehboudi, Carlos Bazan (2020). “Cost Analysis of On-Farm Biogas Plants for Dairy Farms,” 1st Virtual Eastern Canadian Symposium on Water Quality Research organized by the Canadian Association on Water Quality (CAWQ). November 6th, 2020.

CHAPTER TWO

LITERATURE REVIEW

2.1 Introduction

It is essential to understand the anaerobic digestion (AD) process and the key parameters influencing its performance before conducting a cost analysis of on-farm biogas plants. This knowledge makes it possible for AD developers to increase the system's efficiency by achieving the optimum design and operation and producing the highest biogas yield while the system runs with the lowest energy consumption (Gavala et al., 2003); This maximizes the project's profitability and minimizes investment risk for financing agencies.

2.2 Mechanism of Bio-Methanation

Anaerobic digestion also referred to as bio-methanation, bio gasification, and anaerobic fermentation is the biochemical decomposition of organic matter by various bacterial activities in an oxygen-free environment (Braun et al., 2008). Typically, methane fermentation occurs in four steps: hydrolysis, acetogenesis, acetogenesis, and methanogenesis (Figure 2-1) (Sreekrishnan et al., 2004). These four steps are discussed in the following sections.

Hydrolysis: In hydrolysis, bacteria convert a mixture of polymers of organic materials into liquified monomers. They convert proteins into amino acids, carbohydrates polymers such as cellulose to simple sugars monomers such as glucose and xylose, and fats are converted to short-chain volatile fatty acids. Hence, the microorganisms transform most of the complex insoluble feedstock into soluble components to be ready for the next step (Werner et al., 2007) except for nonbiodegradable compounds such as lignin. Hydrolysis is normally the slowest degradation step, and it could determine the methane yield.

Acidogenesis is the second step; it uses the sugar and amino acids that have been produced in the previous step (hydrolysis) and converts them to short-chain volatile fatty acids such as acetate, propionic, and butyric acid plus hydrogen (H_2) and carbon dioxide (CO_2). The products of acidogenesis are the input of the next step (Voegeli, 2014). Notice that these products have an added value since they serve as feedstock for many industrial processes.
Acetogenesis bacteria transform all volatile fatty acids and alcohols into H_2, CO_2, and acetic acid (Weiland, 2010). Hydrogen plays an essential role in this stage. The reaction will only happen if the partial pressure is maintained as low as possible to allow the acid conversion. Therefore, hydrogen scavenging microorganisms consume H_2 and maintain low partial pressure. Accordingly, hydrogen concentration is a determining factor and indicator for the entire anaerobic digestion process stability (Parawira, 2004; Voegeli, 2014). Interestingly, H_2 production by dark fermentation is based on stopping the anaerobic digestion biological reactions at this stage so that H_2 accumulates and can be harvested as biofuel.

Methanogenesis is the last step where methanogenic microorganisms convert H_2 and acetic acid to methane (CH_4) and CO_2 with almost 60%:40% proportion (Amon et al., 2007). This step of biogas production is highly affected by conditions inside the digester, such as temperature, pH, feeding pattern, organic loading rate, hydraulic retention time, inhibitors, etc. These factors can directly influence the efficiency of the process and CH_4 concentration (Verma, 2002). In addition to CH_4 and CO_2, AD produces small amounts of other gases (less than 2% of the total collected biogas). These include water vapor (H_2O), hydrogen sulfide (H_2S), nitrogen (N_2), oxygen (O_2), hydrogen (H_2), ammonia (NH_3), and a biogas content with a minimum of 45% methane is flammable (Kapdi et al., 2005).

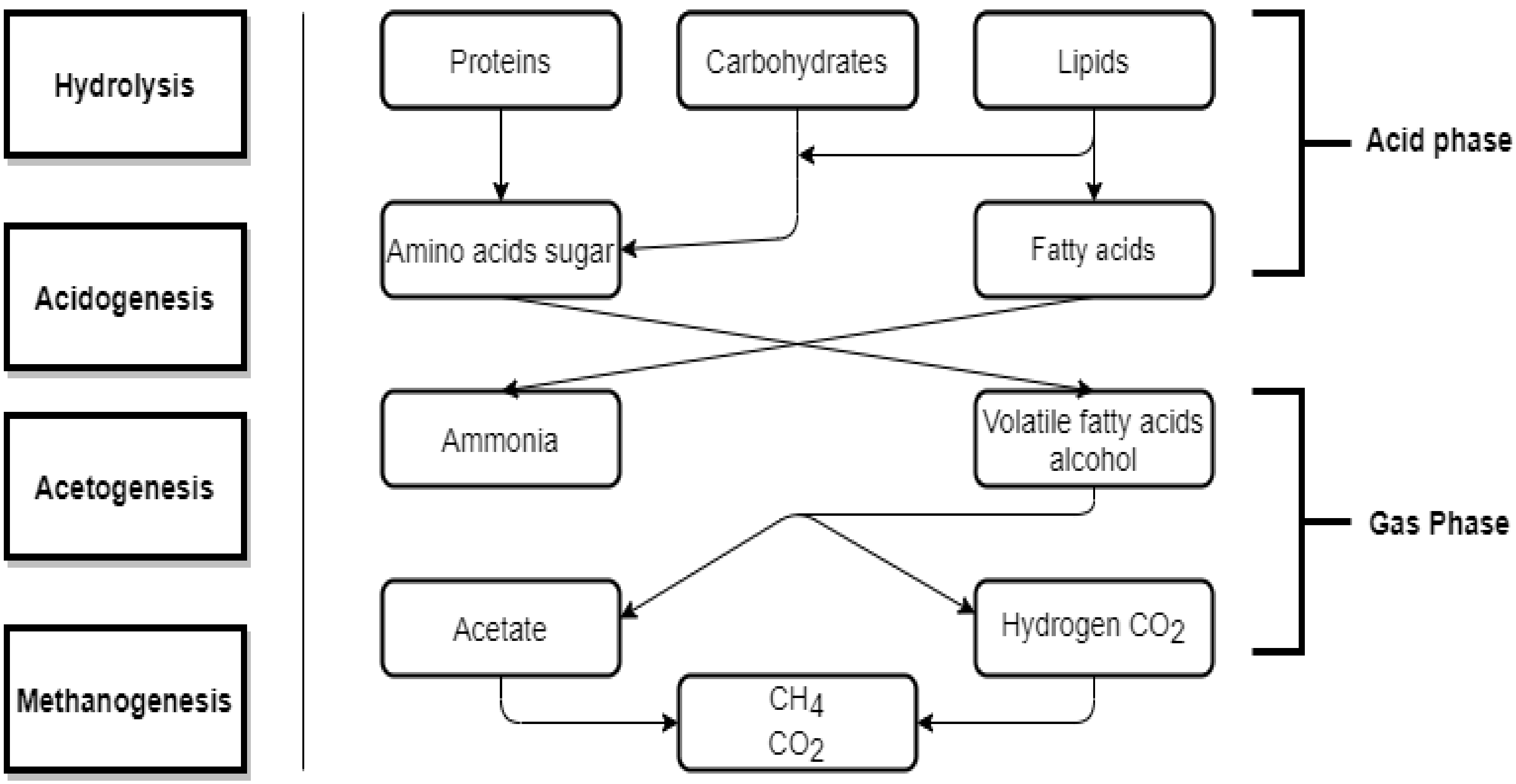


Figure 2-1 Schematic of steps of complex organic matter conversion to methane (Rea, 2014)

By reducing the number of unnecessary components in the biogas, the methane percentage will increase, and it will boost the system's efficiency. The purification and upgrading process is discussed in detail in section 2.4.4.

2.3 Operational Parameters

2.3.1 Temperature

The temperature is a crucial parameter in the operation of AD. Maintaining a constant temperature is vital for the microorganisms to carry out the bioreactions and complete the biogas production steps. Traditionally, AD is operated at three ranges of temperature: 30 – 40 ^{o}C (mesophilic), 45 – 60 ^{o}C (thermophilic) (Navickas et al., 2013), and < 20 ^{o}C (psychrophilic) (Connaughton et al., 2006).

The mesophilic range is more stable, and the system will run with less energy consumption than the thermophilic range. However, the process is slower than the thermophilic operation and needs a longer retention time in the digester to reach the maximum biogas yield. On the other hand, the thermophilic mode of the digester operation runs at a 50% higher rate of organic degradation and achieves the maximum yield of biogas in a shorter time (Pham et al., 2014). Despite the advantages of the operation at a higher temperature, it requires more energy input and increases the operational costs that can affect its economic feasibility. An actual biogas plant produced 8955 MWh thermal and electrical energy and consumed almost 50% (2720 MWh electricity and 1520 MWh thermal energy) to meet its operational energy demand (Szabó et al., 2014). Some of this consumed energy is lost income that could be saved by designing the plant more efficiently to reduce its energy consumption. In general, the average monthly energy cost of a biogas plant operation is around $5000, and any plant with an average annual income of $60,000 would be feasible and beneficial (E3A, 2011).

A study measured the biogas production rate in laboratory digesters for each temperature range while other parameters such as heat loss, wastewater quality and quantity, and retention time were constant. This study shows that at 35 ^{o}C the gas flow rate is 0.125 $L_{biogas}\ L^{-1}_{digestate}\ min^{-1}$, while at 55 ^{o}C and 70 ^{o}C the gas flow rate is 0.250 and 0.375 $L_{biogas}\ L^{-1}_{digestate}\ min^{-1}$, respectively. (De la Rubia et al., 2010). For instance, another laboratory test proved that increasing the temperature from the psychrophilic range (20^{o} C) to the thermophilic range (55^{o} C) would reduce the HRT from 94 days to 15 days (Saady et al., 2013). These studies show that the biogas production rate in the thermophilic range is higher by 2% compared to the mesophilic temperature range (Vindis et al., 2009). This 2% more biogas generation is not economically worthful, especially in Canada, because of the vast difference in the temperature between the outside and the inside of the digester when it operates at thermophilic range (Connaughton et al., 2006). This large temperature difference would make it costly to maintain the digester at a constant temperature, which is not beneficial, for only a 2% increase in the biogas yield and plant efficiency.

Significant temperature variations such as between the day and night or seasonal variation can also negatively affect the performance and efficiency of the biogas plant (Schmidt et al., 2019). Therefore, it is essential to design the digester for an optimum temperature and keep its temperature within a narrow range (± 2 ^{o}C) at all times (Al Seadi et al., 2008). Accordingly, a heat exchanger is an indispensable component of a biodigester or a biogas plant. A biogas plant could have multiple heat exchangers at several places for different purposes.

2.3.2 pH

Anaerobic digestion is a biochemical process occurring mostly in an acidic environment. The suitable pH range for a stable AD process with high biogas production is 6.5 – 7.5 (Budiyono et al., 2013). The optimal pH level for the methanogenesis stage to produce maximum biogas level is 7; however, the optimum pH for the hydrolysis and acidogenesis stages is 5.5 and 6.5, respectively (Khalid et al., 2011).

Although some studies have shown that the pH level may affect the speed of anaerobic bacteria growth in the digester and slow down the methane production, this effect may be mitigated by increasing the hydraulic retention time (HRT) inside the digester for complete digestion. However, This increase of the HRT may increase the operational costs and lower the plant's economic feasibility (Syaichurrozi et al., 2018). Hence, to obtain the maximum biogas yield, it is important to maintain the pH in the recommended range by monitoring and testing the digester's acidity or providing sufficient buffering capacity in the digester.

2.3.3 Moisture content

There are two types of AD processes based on the digester water content (or solid content). Wet AD operates at a total solids percent less than 15%, and the rest is liquid; the wet AD is more common for biogas plants because of its simple handling since the feed and digestate are pumpable (Milledge et al., 2018). The second type is dry AD, where the total solids are between 25 – 40% (Yu et al., 2019). Dry AD offers several advantages compared to wet AD; these include a less pre-treatment of feedstocks (no dilution, chopping, or grinding), no foam formation, no sedimentation in the digester, and no surface crust (Kothari et al., 2014). But dry feedstocks require a digester of larger volume and demand more labor during manure feeding and handling. For these reasons, dry systems have higher capital and operational costs compared to wet systems (Chiumenti et al., 2018). Therefore, wet anaerobic digesters are more common because the high moisture content enhances the digestion bioreaction. As the process of AD proceeds, the water level drops compared to its initial percentage in the mixture. The highest CH_4 concentration in biogas can be achieved with 60% - 80% humidity available in the digester (Khalid et al., 2011).

2.3.4 Carbon to nitrogen ratio

Another critical parameter is the relationship between carbon (C) and nitrogen (N) contents in the organic material. The suitable range for C:N ratio for AD is 16 – 25; A high C:N ratio results from the fast consumption of nitrogen in the tank, decreasing the biogas production in the methanogenesis stage (Wang et al., 2017). On the other hand, a low C:N ratio can cause an increase in the pH values; such conditions can be harmful to methanogenic microorganisms, and it decreases the efficiency of the plant. To ensure the optimum C:N ratio, it is recommended to mix different feedstock materials with high and low carbon and nitrogen contents to achieve a C:N ratio within the optimum range (Li et al., 2011).

2.3.5 Hydraulic retention time (HRT)

The hydraulic retention time (HRT) is when organic materials spend in the digester undergo the digestion process before they leave the digester as digestate. The HRT is highly related to the operating temperature, digester’s volume, and feedstock quality (Karaosmanoglu Gorgec et al., 2019). For a mesophilic (30-40 ^{o}C) digester, the HRT ranges between 10 and 40 days; the HRT of thermophilic (45-60 ^{o}C) digesters is shorter because of the higher operating temperature (Verma, 2002). A longer HRT would increase the biogas production; an extra 20 days of HRT increase the biogas production by 5% (Boe et al., 2009). However, it will increase the energy cost required for heating the digester by 30% (Shi et al., 2017). Based on the size of the digester, sometimes the extra biogas production is not financially viable.

2.3.6 Mixing

Mixing the feedstock and the microbial culture inside the digester is important for several reasons. First, stirring the content of the digester blends the fresh organic material with the digested material, which maintains a uniform temperature distribution inside the digester, prevents undesirable temperature gradients within the tank, and prevents the formation of a scum layer (Verhoff et al., 1974). Foam and scum increase the chance of blockage of the gas pipe. The top 20–60 cm layer of foam in large-scale plants is acceptable because it is easy to manage; however, if it gets thicker, it may prevent the gas release from the liquid and finally can cease the operation (Manea et al., 2012). One of the advantages of the mixing system is that it mixes different types of organic wastes to increase the quality of the feedstock, which increases the biogas production rate. There are two main types of digester mixing methods: 1- using recirculated compressed gas to mix the digester content; 2- using a pump to recirculate the digester content inside the digester (BioCycle, 2017). Systems of mixing by injecting compressed biogas in the digester are categorized into three groups based on their design:

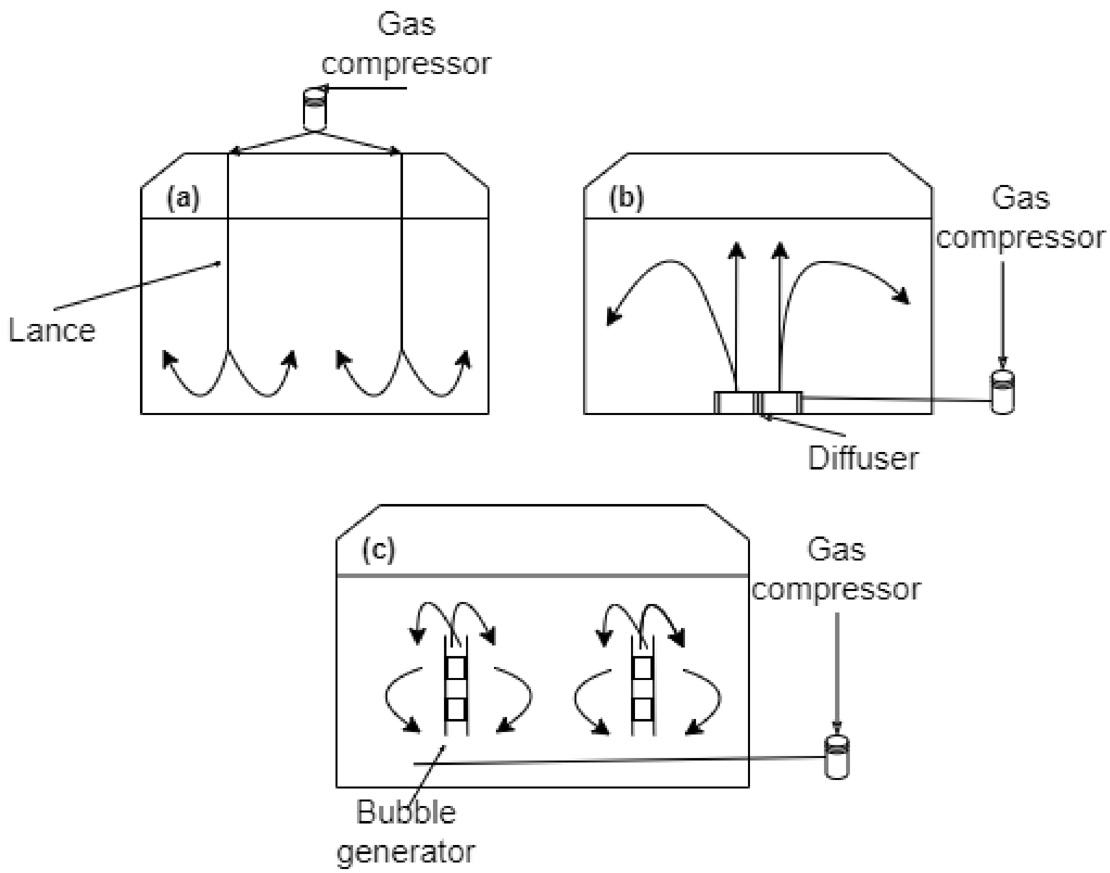
1) Gas injection diffusers system: diffusers are generally placed at the bottom of the digester to recirculate compressed biogas inside the digester and mix the feedstock thoroughly (Figure 2-2 (b)). This system requires high energy, which increases operational costs, but the efficiency is relatively low. Moreover, the repair and maintenance require dewatering the

digester, which means a shutdown time and no biogas production. Therefore, this type of mixing is not preferable by owners and investors (Schlicht, 2001).

2) Gas injection lances: this system is more efficient than the previous design. The gas lances are hanging from the digester ceiling, effectively preventing scum formation at the top layer (Figure 2-2 (a)). Because a sealed pipe surrounds each lance, it will allow an individual lance to be removed for inspection and repair without stopping the digestion operation. This system is very efficient and requires less energy for operation (Schlicht, 2001).

3) Gas injection eductor tubes: is also known as the "Bubble Gun" or the "Cannon" mixer (Figure 2-2(c)). The advantage of this design is that the eductor tubes are fed from the bottom of the digester, and the bubbles generated by the bubble maker do not break apart until it reaches the surface. This system prevents scum efficiently. This system is more complex than the other two systems. The inspection, maintenance, and repair of the bubble maker require dewatering the digester (Schlicht, 2001).

The second type of mixing system is mechanical mixing using pumps or internal stirring blades. These techniques mix all the layers of the digester content to keep the temperature uniform in the entire digester and prevent scum formation. Pump mixing is conducted by extracting the digester content from a certain level (e.g., bottom of the digester) and returning it to another level (e.g., top layer). The mixing by using an internal stirrer continuously agitates the digester’s content and produces uniform solid concentration and temperature through the entire digester (BioCycle, 2017).



a) Gas injection lance b) Gas injection diffuser
c) Gas injection eductor tubes

Figure 2-2 Types of digester gas mixing systems. (Adapted from (Wu, 2014))

Mechanical mixing is more effective than gas mixing systems. Gas mixing systems create more foam or scum than mechanical mixing because hydrophobic compounds floating on the surface of the digesting medium may prevent the bubble from bursting, and they form foams (Singh et al., 2019).

The author obtained cost data from vendors of the digester's mechanical mixing systems (specially agitator system); the equipment price (without considering the transportation and installation costs) is between $700 - $2,700 per mixer (Mingshuo_Tech_Co, 2021).

2.4 Biogas Plant System

A biogas plant (Figure 2-3) is a system that consists of several components such as a digester, heating system (heat exchanger), gas storage vessel, combined heat and power (CHP) unit, etc. Typically, on-farm biogas plants share a typical design (Barati et al., 2017). It is important to recognize each specific component in a biogas plant to estimate the costs related to the design and construction of the project accurately. In general, a biogas plant has three main elements. The first element is the feedstock which can be only manure or a mixture of organic wastes. The second element is the biogas production that is mainly occurring in the digester. The final element is the conversion of biogas to electricity or heat by co-generators in a CHP unit.

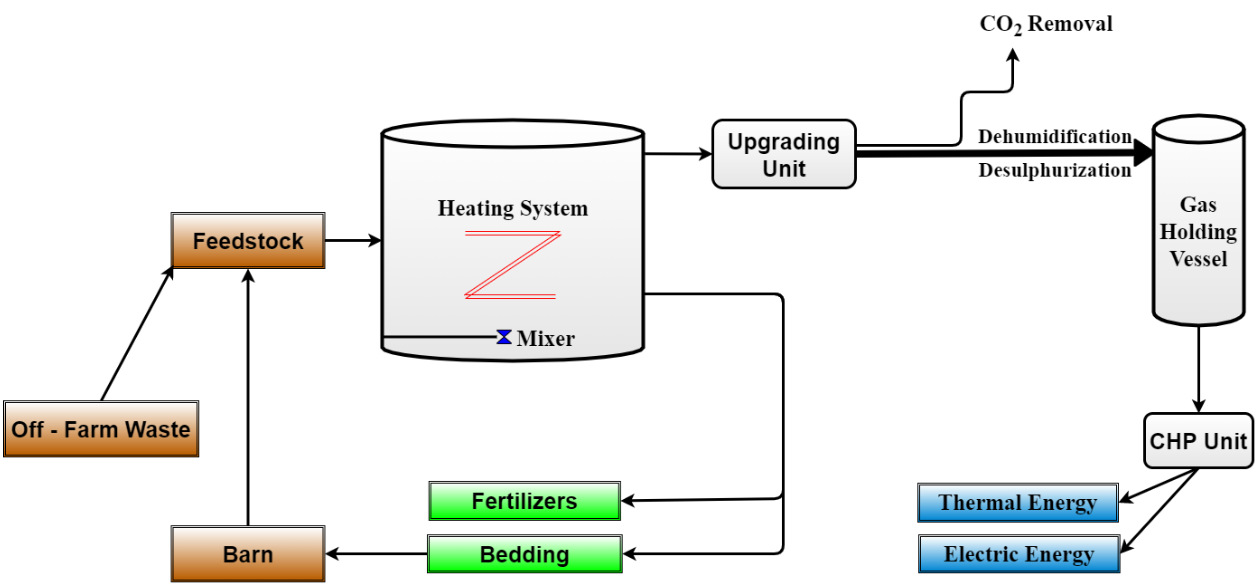


Figure 2-3 Typical biogas plant (Lettinga et al., 1993)

The system's output includes the biogas and digestate; the latter is the digested matter after leaving the digester. These outputs represent benefits because biogas can be converted to heat or electricity, and the digestate can be used as fertilizer and/or animal bedding (Walsh et al., 1989).

2.4.1 Feeding system

There are two modes for feeding the digester. The first mode is continuous feeding which means that a specific volume of fresh feedstock is added to the digester at regular intervals, while an equivalent volume of digestate (slurry) is pumped out of the digester (Kumar et al., 2016). The second mode is batch-feeding, where the digester is fed once and is then closed to complete the digestion (Tsapekos et al., 2018). Compared to continuous feeding, the batch mode is simple and easy to operate, requires less sophisticated technology, and its cost is lower; however, it is suitable for small scale only. Transport and supply of the feedstock are also important and significantly impact the biogas quality and quantity. In many cases, the plant receives additional off-farm co-substrates produced by neighboring farms and food processing industries. Thus, it is necessary to monitor and control the received feedstock with some laboratory tests such as the calculation of total solids (TS) and volatile solids (VS) to ensure its quality in terms of biogas yield and methane concentration in the biogas content before feeding it to the digester (Dumitru, 2014).

The other concern regarding the feedstock is the seasonal fluctuations of supplies, and storage facilities might be needed. The type of storage facilities depends on the feedstock condition; for solid feedstock (e.g., maize silage), bunker silos are common, and for liquid feedstock, storage tanks are required. The main difference between the bunker silos and storage tanks is the storage time. Usually, the solid feedstock can be stored for more than a year; on the other hand, liquid feedstock (e.g., animal manure) can be stored for several days (Chen et al., 2008).

A pumpable feedstock is generally stored in sealed, water-resistant concrete tanks to prevent emissions. The storage tank can be installed under or above the ground; this affects the heating requirement in cold regions. There are two precautions about storage tanks: 1- they should be easy to open for cleanup to remove the settled sediments; 2- if possible, it is better to place them on a higher level than the digester so that the liquid feedstock flows by gravity from the storage tank to the digester to reduce the capital and operational costs (Park et al., 2018).

After storing the feedstock and applying the pre-treatment to the content, it is pumped to the digester (or flow by gravity) in case of the wet AD, and the non-pumpable organic biomass such as fibrous materials, grass, maize silage, and manure with high solid contents can be fed to the digester by a loader.

2.4.1.1 Pumping system

Pumps connect the various sections of the biogas plant; they deliver the material from one unit to the next. They are one of the costly equipment in biogas projects. They consume a considerable amount of energy and need high repair and maintenance (Wang, 2010). For this reason, engineers try to avoid pumps where possible and use the natural gradient instead to lower the costs. If pumps cannot be avoided, there are several options to choose the most compatible pumps to get the best result.

Commonly, two types of pumps are frequently used: centrifugal and displacement pumps. Centrifugal (rotating) pumps are often submerged. They are placed next to the digester. Displacement pumps (turning piston pumps, eccentric screw pumps) are more compatible with high pressure than rotating pumps (Roos, 2013). They are self-sucking and work in two directions. However, rotating pumps are more frequently chosen based on economic reasons than displacement pumps (Dumitru, 2014). Table 2-1 gives the main characteristics of the pumps commonly used in biogas plants. The following sections discussed the typical pumps frequently used biogas plants.

1) Centrifugal pumps: These pumps operate by a rotating vane, screw, or gear, traps the liquid in the suction side, and push it to the end of the path by force (Elie Tawil et al., 1993). There are some cautions regarding the usage of these pumps. It is necessary to operate these pumps relatively with a low velocity to secure reliable operation and lower maintenance costs. Otherwise, the erosive action of the high velocities of the liquid passing through the pump will leak the fluid from the pump's discharge back to the suction side (EnergyPedia, 2015). It is essential to design the pumping unit very efficiently and be compatible with the type of feedstock used on the farm. A wrong selection can increase maintenance costs and increase the electricity bill, affecting the plant's net profit.

2) Pressure displacement pumps: They are used for feedstock with thick liquid and high solid content. Displacement pumps are self-sucking; their pressure is more stable than centrifugal pumps (Olugasa et al., 2014). Thus, the piping performance depends less on the height difference, and the feedstock dose can be adjusted by changing the pump's speed.

Table 2-1 Type of pumps used in biogas plants

Type of pump				
	Rotary	Chopper	Electric spiral	Rotary piston
Solid content (%)	< 8	< 8	< 15	< 15
Energy input (kW)	3 – 15	3 – 15	3 – 22	3 – 20
Discharge (m^3/min)	2 – 6	2 – 6	0.3 – 3.5	0.5 – 4
Pressure (bar)	0.8 – 3.5	0.8 – 3.5	< 25	< 10
Substrate fiber structure	Medium-long	Long	Short	Medium-long
Max. size of obstructive elements (cm)	5	Depending on the choppers	4	6
Suitability	Suitable for large quantities; simple and robust built	Suitable for long-fiber substrates which need to be chopped up	Suitable for high pressure but susceptible to obstructive bodies	Higher pressures than rotary pumps, but higher wear and tear
Price Comparison	Cheaper than positive displacement pumps	Depending on choppers	Similar to a rotary piston pump	Similar to eccentric spiral pump

*Source: (Roos, 2013), (EnergyPedia, 2015)

Besides the pumps, the connectors are also costly parts of the project. Pump delivery lines can be made of steel, PVC (rigid), or P.E. (rigid or flexible), as well as appropriate flexible pressure tubing made of reinforced plastic or rubber. Biogas pipes and valves are required to be very safe, economical, and provide a proper gas flow. Galvanized steel water supply pipes are used most frequently because the entire piping system (a gas pipe, valves, and accessories) can be made of universally applicable English/U.S. Customary system components, i.e., with all dimensions in inches (Wellinger et al., 1999). This can lower the system's risk and make the assembling process faster because the same standard is applied to design all parts. Polyvinyl chloride (PVC) pipes also have a relatively low price and are easily installed. PVC pipes are weak under UV radiation; thus, they should be placed underground wherever possible. This adds some extra expenses to the project's construction compared to the steel pipes.

Another critical part is the layout of the piping system. Specifically, if PVC pipes were chosen, they will need extra safety checks since the tubes will be placed at least 25 cm underground, and pipes should be covered by fine sand to avoid stones lying directly on the lines. When the piping is installed and before attachment to the system, it has to be tested for safety measurements (Moran et al., 2016). All the valves, fittings, and piping must be corrosion-resistant, and the system should be tested for possible gas leakage.

Due to the temperature changes in different pipeline sections, the moisture-saturated biogas undergoes condensation and forms water in the piping system. Ideally, the piping system should be laid out in a way that allows a free flow of condensation water back into the digester. In most projects, this goal cannot be achieved. Several water traps have to be installed at the lowest point of the depressions to solve this issue (Cheng et al., 2014). The condensation water will be trapped in the water trap; the traps are emptied regularly by an automatic system or manually.

Table 2-2 provides examples of the cost of pumping systems used in real on-farm biogas plants at farms with 100-2200 cows. It is important to know the manure collecting system and its physical characteristics before designing the pumping unit and pipelines. This is important because by changing the percentage of TS in the feedstock, the power of the pump and the diameters of the pipeline can be changed (Roos, 2013). It is recommended to design the pipelines' diameter to maintain the slurry velocity of approximately 1.5 m/s (5 ft/s) and maintain the velocity constant the whole time to avoid settling the solids in the system.

Typically, the cost of pumping units and pipelines is distributed among other costs, like the cost of a digester, CHP unit, or in some reports, it is called other costs. In Table 2-2, the pumping unit costs for BC are an average of 11 farms in Fraser Valley, which is a perfect guideline for Canadian biogas plants construction.

Table 2-2. Average costs of pumping unit

Location	Cows Numbers (CN)	Cost of pumping unit* (CAD)	Source
British Columbia, Canada	600	337,000	(Werner et al., 2007)
	1600	422,000	
	650	253,000	
	1200	505,000	
	1000	500,000	
	100	168,000	
	230	168,000	
	480	253,000	
	400	337,000	
	500	253,000	
Minnesota, USA	588	60,000	(Nelson et al., 2002)
Ankara, Turkey	2200	130,000	(Akbulut, 2012)
Average	800	283,000	

*All costs are inflated to the year 2020

2.4.2 Heating system

Anaerobic digestion needs constant environmental conditions to produce biogas at maximum sustained yield and quality levels successfully. The relationship between temperature and biogas production is such that as the temperature increases, biogas production increases as well (Shehu et al., 2012). An experimental study has tested the relationship between the temperature and the biogas production rate from fresh pig manure. The results show that, on average, over a five-day interval, the lowest temperature was 5.2 ^oC with the biogas production of 0.118 $m^3/m^3.d$. Increasing the temperature to 38.5 ^oC increased the biogas production by almost four times (0.515 $m^3/m^3.d$) (Guo et al., 2019). It is important to keep the temperature constant in all seasons to maximize the plant's efficiency. The purpose of the heating systems is to provide a stable temperature inside the digester (Rynkowski, 2018).

Heating is a major cost of the digester during operation. It is better to deliver systems that can decrease the relative heating costs, use insulation technologies, and prevent heat loss. There are several different ways to get the required amount of thermal energy into the AD. There are two major types of heating systems:

1- Direct heating: This type of heating requires a steam-generating system, including some water pre-treatment processes. The high costs are only justifiable for large-scale facilities. Generally, in this study and based on the average size of the farms in Canada, farms with more than 1000 cows are classified as large farms. On the other hand, hot water injection raises the slurry's water content and should be performed only when such dilution is required (Huchel et al., 2006). This system can also cause local overheating; thus, it needs a more precise mixing system inside the digester.

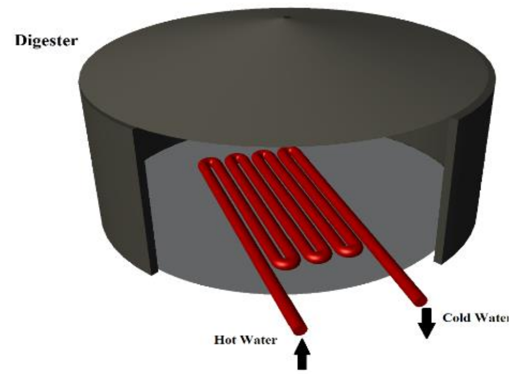
2- Indirect heating: The heating is achieved through a heat exchanger which carries a heating medium, usually hot water which transfers heat without mixing with the substrate (EnergyPedia, 2015). The heat exchanger can be placed inside, outside, or on the walls of the digester. The selection of the type of heat exchanger depends on the shape of the digester and the type of substrate. Four different indirect heating approaches are floor heating (Figure 2-4(a)), in-vessel heating (Figure 2-4(b)), on-vessel heating (Figure 2-4(c)), and ex-vessel heating (Figure 2-4(d)) (Makamure et al., 2020). Selecting the best heating system depends on the digester size and the amount of feedstock. Sometimes, the best system can combine two or more heat exchanging methods.

2.4.2.1 Floor heating system

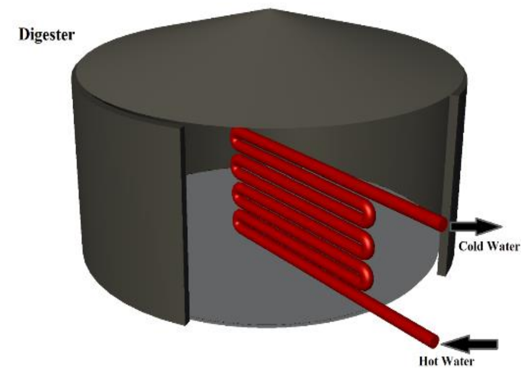
This type of heat exchanger is installed on the bottom of the digester. The system's effectiveness depends on the substrate's conductivity, and the best material for the heating element is copper. When using a floor heat exchanger, hot water or hot gases are passed through the conductor pipes placed under or on the digester floor to supply heat (Karimov et al., 2012). This system's main disadvantage is the uneven heat transfer inside the digester, especially when the mixing system is not working very well or in the case of thick feedstock. This will gradually result in sedimentation at the bottom of the digester that can block heat transfer and slow down the digestion process. The slurry at the base receives more heat than the top layer, increasing energy costs (Makamure et al., 2020). The only advantage of this system is that there would be no obstacle within most of the digester volume that interferes with the mixing system.

2.4.2.2 In-vessel heat exchanger

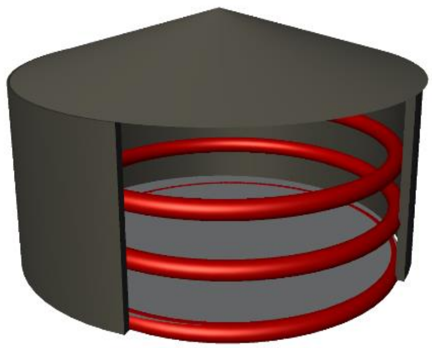
This type of heat exchanger is immersed inside the slurry. It must be in the center of the digester to ensure uniform heat distribution within the digester’s content. The major advantage of this system is that the heat can equally reach through the slurry's whole volume even without the mixing (Hilkiah Igoni et al., 2008). The pipes should be highly conductive and resistant to corrosion, such as steel and copper. However, the heat exchanger must be robust and well anchored in the digester to withstand the mixers’ mechanical stress. Thus, this can increase the construction cost, and it requires special skills for setup.



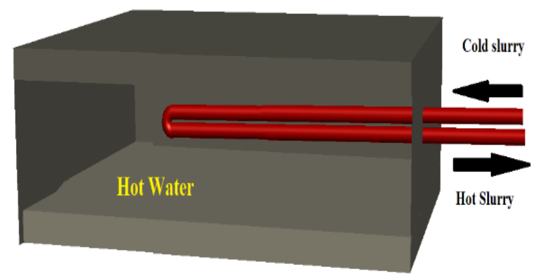
(a) Floor Heating System



(b) In-vessel heat exchanging system



(c) On-vessel heat exchanging system



(d) Ex-vessel heat exchanging system

Figure 2-4 Schematic of different types of heating systems (Makamure et al., 2020)

2.4.2.3 On-vessel heat exchangers

The heat exchanging pipelines are installed on the digester's inner walls. From one side, the hot water or gas comes into the digester and distributes the heat in each level of the digester, and from the other end, the cool water/gas leaves the digester towards the heater for heating up again. The advantages of this system are that the large heat transfer surface area can increase the heat transfer rate (Zupančič et al., 2003). Also, the heat exchanger does not hinder the movement of the digester's content through the digester because heat exchanger pipes are in the walls. However, this system has some serious disadvantages (Houngue et al., 2017). First, the heat exchanger should be robust to withstand the high pressure from the slurry and the biogas and be resistant to corrosion. The heat loss in this system is higher than in other heating systems, especially when the wall material has high conductivity, so more heat will be lost to the surrounding. The space between the heating pipes and walls could be insulated to achieve better heating efficiency.

2.4.2.4 Ex-Vessel heating systems

The other common type is the ex-vessel heat exchanger. The heating system is outside the digester, and the pipes in this system carry the feedstock instead of hot water/gas and transfer the slurry to a hot tank filled with hot water to reach the desired temperature (Han et al., 2016). The heat loss in this system is minimum. A disadvantage of this system is the excessive usage of pumps and pumping, which is an expensive process, and also pumping out the slurry negatively affects the biogas formation.

2.4.3 Anaerobic digester

Anaerobic digestion (AD) is a manure treatment gaining popularity to protect the environment and effectively recycle nutrients and materials into agricultural systems. The AD is carried out in a tank called an anaerobic digester, which is the core of the biogas plant. The digester plays a major role in biogas production and consumes significant energy. Anaerobic digestion works in two basic stages that produce biogas from organic wastes. In the first stage, the volatile solids in manure are transformed into fatty acids by anaerobic bacteria under specific conditions and temperatures. In the second stage, these acids are converted into biogas by methane-forming bacteria. This is a natural process that occurs globally, and AD technology tries to manage it for human and environmental benefits (Balsam et al., 2006). Table 2-3 provides the characteristics of the common types of anaerobic digester. The organic loading rate (OLR) indicates the organic loading fed to a digester unit volume per unit of time (mass/volume. time). An anaerobic digester's OLR is usually expressed in mass of chemical oxygen demand (COD) per digester volume per unit time, typically defined as COD per kilogram per cubic meter per day (kg COD/m^3.d) (Beddoes et al., 2007). A system's hydraulic retention time (HRT) is the digester's volume divided by the digester flux. The HRT represents the average time that the manure stays in the anaerobic digester and is usually expressed in days. Several digesters are commonly used for on-farm biogas plants (Table 2-3).

Table 2-3 Different types of digesters and their characteristics

Type of digesters							
	Covered lagoon	Plug flow	Complete mix	Induced bed reactor	Fixed film	Sequence batch reactor	High solids
Complexity	Min	Min	Medium	Max	Medium	Max	Min
Total solids (%)	< 5	12 - 15	3 - 10	6 - 12	< 1	2.5 - 8	> 25
HRT (day)	30 – 60	>20	5 – 20	<5	<5	<5	20 – 30
Suitable for weather condition	Warm & Humid	All	All	All	All	All	All
#USA on farm plants	60	100	95	5	5	5	5

Sources: (Wilkie, 2005), (Beddoes et al., 2007), (Elger et al., 2020), (Kumar et al., 2016)

The costs of biogas plants are mostly related to the digester and its mixing and heating. There is a direct relationship between the number of animals on a farm, the digester size, and the amount of energy generated. For instance, in Canada, a farm with 500 heads of dairy cows has the potential to generate 4000 MWh. So, it requires a generator with almost 500 kwe. The following sections discuss the most used types of anaerobic digesters for on-farm applications.

2.4.3.1 Covered lagoon

A covered lagoon digester (Figure 2-5) is a large, in-ground lagoon with a floating cover; a partial covering enables collecting biogas from the lagoon and drains rainwater from the digester. Covered lagoons are suitable for feedstock with less than 5% solids (Wilkie, 2005). Lagoons are not heated digesters, so it is essential to consider using them in temperate and warm climates. Additionally, biogas production fluctuates seasonally because of the significant drop in temperature in winter. The hydraulic retention time is usually 30 to 60 days (Chen et al., 2014).

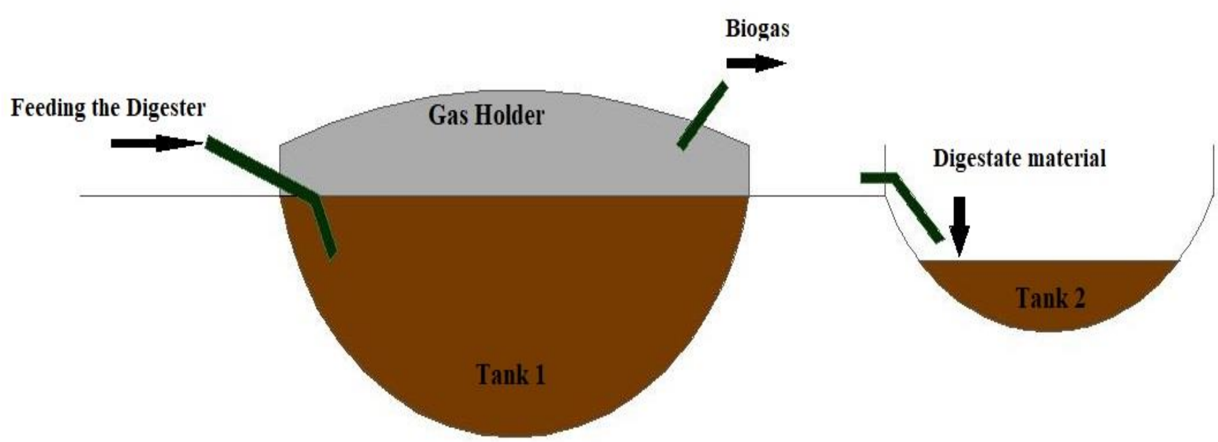


Figure 2-5 Schematic view of covered lagoon digester (Electrigaz, 2007)

The advantage of this system is the low capital costs compared to other types of digesters and relatively easy design and operation. This system requires a large area and suffers from solid settling because of the long HRT required for digestion. The settled solids require frequent removal from the lagoon (Beddoes et al., 2007). In terms of costs, the covered lagoon digester is simple in its design and construction; thus, it is less costly; typically covered lagoon digester will cost around 2400 – 3700 $/kWe.

2.4.3.2 Complete mix digester

The complete mix digester, also known as continuously stirred tank reactors (CSTR) (Figure 2-6), can be installed above or underground, and manure is continuously mixed. Mixed digesters can process manure over a wide range of total solids (TS) (Mutungwazi et al., 2018). The optimum TS content is 10%. The CSTR used to digest manure usually has OLRs ranging from 1 to 10 kilograms of COD /m^3.d. Usually, the HRT of the CSTR digesters treating manure is about 5 and 20 days. The major advantage of the CSTR is that it is not limited to animal manure and can digest high TS off-farm organic wastes. The CSTR requires less land compared to the lagoons and is usually heated.

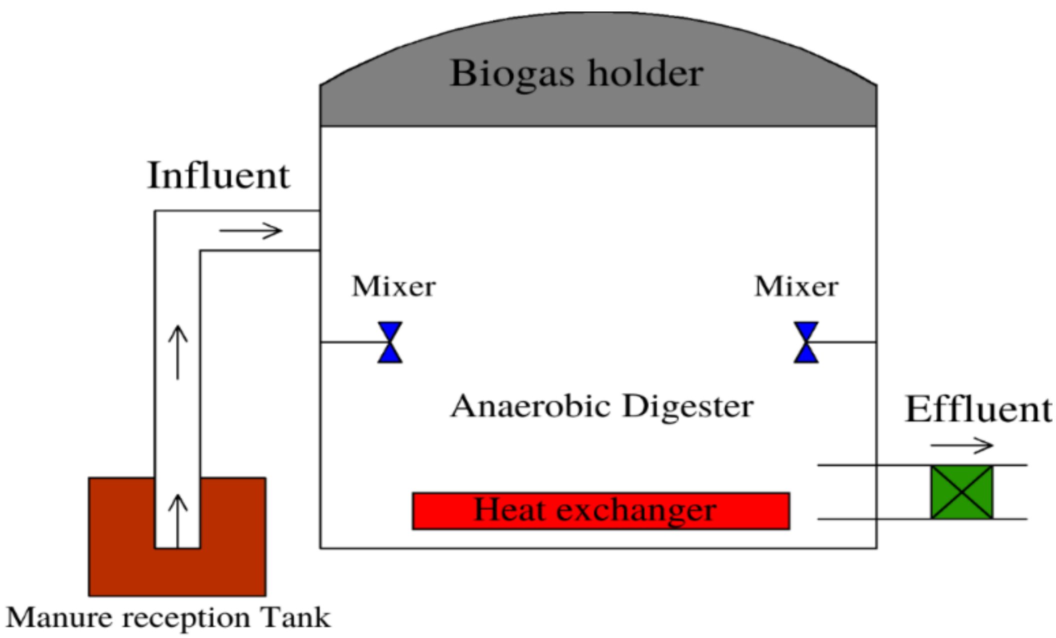


Figure 2-6 Schematic of complete mix digester (Electrigaz, 2007)

Feedstock can be mixed mechanically, hydraulically, or both. Complete mix digesters are compatible with combinations of livestock manure and work well with most co-digestion feedstock. Also, they are suitable for all types of weather conditions (Elger et al., 2020). A complete mix digester has a medium complexity in its design and construction. Thus, it requires specific engineering monitoring that increases plant costs. The capital costs of this type of digester are 4300 – 7300 $/ kWe (Electrigaz, 2007).

2.4.3.3 Plug flow digester

The plug flow digester (PF; Figure 2-7) can process a feedstock of 15% total solids, and it can be heated using hot water piping to maintain a constant temperature (Hamilton, 2014). The PF is usually a cylindrical tank with a roughly 1:5 ratio of width or height to length dimensions. Fresh manure is fed from one end of the tank, and the biogas is vented from the top while the digestate exits from the other end.

The PF digesters are typically installed below ground for insulation and are also provided with a heating system. Although the PF digesters usually do not include mixing, horizontal or vertical mixing techniques have been added recently (Rajendran et al., 2012). The PF digesters work perfectly with dairy manure that contains some bedding. Organic wastes with less fiber and TS content, such as swine manure, cannot be treated with a plug flow digester.

The cost of operation of plug flow digesters can be higher than other digesters because they need periodic cleanup. This is an extra task for the farmers. Usually, the retention time in PF digesters is more than 20 days. This PF-type digester is suitable for all weather conditions and has a simple design and construction. The capital cost for this type varies between 2400 and 3700 $/kWe (Electrigaz, 2007).

2014).

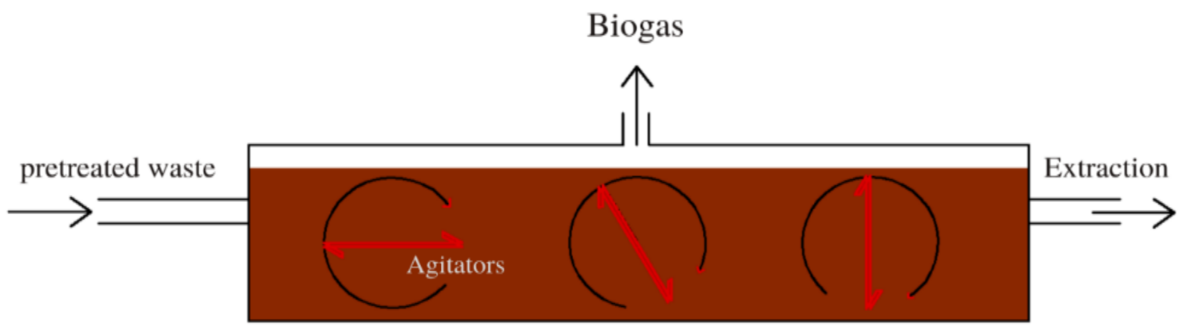


Figure 2-7 Schematic of plug flow digester (Electrigaz, 2007)

2.4.3.4 Fixed-film digester

A fixed-film digester (Figure 2-8) uses an attached growth process that digests waste as it moves through a system containing a fixed media. Thus, it is also known as "attached growth digesters" or "anaerobic filters." Anaerobic biomass attaches itself to the fixed media and encounters the substrate as it flows over the biomass fixed-film (Ghosh et al., 2013). Since the biomass within the digester is attached to the media, biomass immobilization is excellent and improves the performance of the fixed-film digesters. Such digesters operate at higher efficiencies due to their excellent biomass retention and can have shorter HRTs, even less than a week (Ghosh et al., 2013).

Fixed-film digesters need low TS content (< 1%) thus they are mainly utilized for fine or dissolved solids. When the feedstock contains large particles, a solid separation is needed before feeding the digester. Additionally, the digester design should consider the periodic removal of the solids that settle at the bottom of the tank without disrupting the digestion process (Kumar et al., 2017). Such digesters typically handle medium to high OLR (5 and 10 kilograms of COD per cubic meter per day), with a short HRT of 0.5 to 4 days when they digest manures (Chen et al., 2014).

Fixed-film digesters are typically built-in tanks, and biogas is collected in the same vessel. This type of digester is one of the most complicated designs and requires engineering supervision, making the process costly. The cost of the fixed-film digester is around 5500 – 7400 \$/ kWe (Electrigaz, 2007).

The digester, heating, and mixing equipment costs are usually reported as a single item called the cost of AD. Table 2-4 lists the cost of AD for different on-farms and different types of anaerobic digesters. For instance, in British Columbia, one of the most used digesters is a complete mix reactor that can digest a mixture of all types of feedstocks, and the average cost for this digester based on Table 2-4 is almost \$941,000.

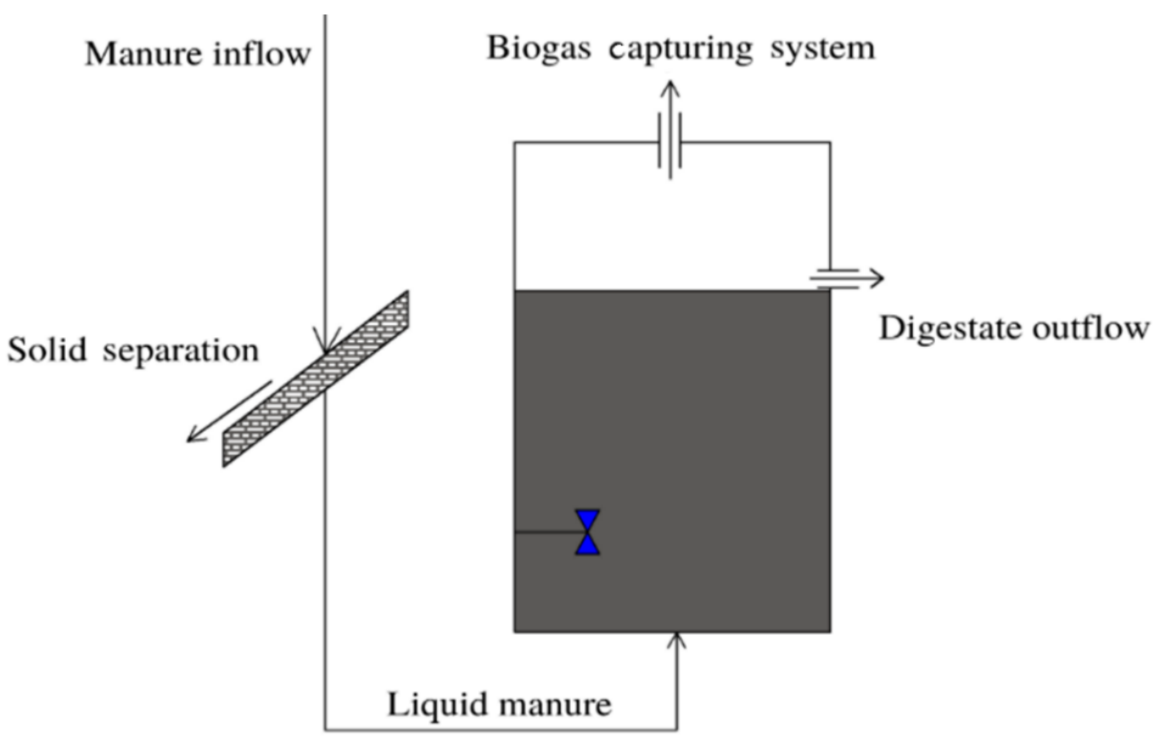


Figure 2-8 Schematic of fixed film digester (Electrigaz, 2007)

Table 2-4 Average cost for anaerobic digester and its components

Location	Cows number	Digester type	HRT (days)	Digester volume (m^3)	Digester cost* (CAD)	Source
British Columbia, Canada	600	Complete mix	22	1500	900,000	(Werner et al., 2007)
	1600		22	3000	1,262,000	
	650		24	2500	1,262,000	
	1200		28	1000	1,169,000	
	1000		27	3000	1,262,000	
	100		28	750	461,000	
	230		22	750	492,000	
	480		29	1500	631,000	
	400		24	3000	1,262,000	
	500		24	1750	708,000	
Minnesota, USA	588	Plug flow	20	-	225,000	(Nelson et al., 2002)
Ankara, Turkey	2200	Complete mix	33	-	210,000	(Akbulut, 2012)
Average cost	1000		25	1800	820,000	

*All costs are inflated to the year 2020

2.4.4 Biogas cleaning and upgrading unit

Besides biogas (CH_4 and CO_2), the digester produces unwanted gaseous products such as hydrogen sulfide (H_2S) and saturated water vapor. Table 2-5 shows the composition of typical biogas generated from digesting livestock manure. The unwanted components must be removed from the biogas before transferring them to the storage tank because hydrogen sulfide is a toxic and hazardous gas (Lau et al., 2011). First, the biogas must be dewatered and desulfurized to prevent corrosion. Finally, carbon dioxide removal is needed to enrich methane gas; this process is called upgrading (Popov, 2005). There are two methods for separating the saturated water vapor from the biogas (dewatering): 1) A gas-water separator can be used. This machine condenses the vapor water to large water drops and sends the dry gas out of the system; 2) Using an electric condenser to cool the biogas to below 10 ^oC and remove the remaining water. Cooled water should be heated up again to prevent vapor condensation downstream (Deng et al., 2020).

Table 2-5 Typical biogas composition from digesting cow manure

Component	Percentage
Methane	55 – 60
Carbon dioxide	35 – 40
Hydrogen sulphide	0 – 2
Nitrogen	0 – 1
Hydrogen	0 – 2
Carbon monoxide	0 – 3
Oxygen	0 – 2

Source: (Zhang et al., 1999; Kalia et al., 2000)

There are chemical and biological methods for H_2S removal (desulfurization). Chemical desulfurization is common for large, medium, or small biogas plants, while biological desulfurization is only adopted in mega biogas plants (Wellinger et al., 1999). The removal can be achieved either inside or outside the digester in the chemical method. Iron salts are added to the feedstock when the removal of H_2S is achieved inside the digester (in-situ desulfurization). When the removal is achieved outside the digester, the wet biogas (not dewatered) is passed through an absorbent such as sodium hydroxide or iron-bearing. Also, For dry biogas, iron oxide can be used in the desulfurization process (Xiao et al., 2017).

Biological methods can be used inside or outside the digester (Persson et al., 2006). For in-situ biological desulfurization, the air is injected into the digester (about 2 – 8% of the biogas output), and the microorganisms will oxidize H_2S. For ex-situ biological desulfurization (outside the digester), a tower similar to a scrubber is installed to control the process and regulate the oxygen feed. CO_2 removal is also known as upgrading. It can be achieved by absorption, where the biogas would be in contact with a liquid that absorbs CO_2 (Castellani et al., 2014). Three absorption methods are used for upgrading the biogas: 1- water scrubbing; 2- organic physical scrubbing; and 3- chemical scrubbing. Because the upgrading unit requires high investment, it is not feasible for small farms with a limited number of livestock, because it could increase the capital cost by 30% or more. However, for the larger farms with more than 1000 animals it can increase the efficiency of the plant.

Water scrubbing: Carbon dioxide dissolves easier than methane in water. In the water scrubber, CO_2 dissolves in water, and the gas with a higher concentration of methane is released back to the raw gas. It is possible to recycle the water in the scrubber. This technology is the most common upgrading method for most biogas plants (Persson et al., 2006).

Organic physical scrubbing: This method is similar to water scrubbing, but the solvent is an organic liquid such as polyethylene glycol. Compared to water scrubbing, with the same liquid and capacity flow rate, CO_2 is more soluble in polyethylene glycol than water (Starr et al., 2012). Additionally, the organic physical scrubbing removes H_2S, water, oxygen, and nitrogen with the CO_2 from the raw biogas.

Chemical scrubbing: Not only is CO_2 soluble in liquid, but it also reacts chemically with amine solutions. The advantage of this method is that the methane loss is very low (< 0.1%) compared to the other two methods (Toledo-Cervantes et al., 2017). In the operational costs, it should be considered that part of the liquid will be lost due to evaporation, and this will increase the amount needed to complete the process.

2.4.5 Gas storage tank

The amount of biogas generated is variable with the time, and the consumption of the generated gas may vary for different reasons. Thus, the produced biogas should be stored. If the biogas is not compressed, it requires a large storage volume even for a low energy density; for instance, 6 kWh is almost equal to 1 m^3 (Voegeli, 2014).

Biogas storage facilities must be gas-tight and pressure-resistant; if they are not placed inside a building, they should also be UV-, temperature-, and weather-proof. They may be built of rigid or flexible material (El-Halwagi, 1984). The size of the biogas storage depends on the gas production and usage rate. Some of the common types of gas storage are:

- Floating drum: This is one of the low-pressure storage systems; the floating drum on top of the digester represents a storage facility. The produced gas fills the drum, and the more gas is generated, the more the drum pushes upward and increases the volume of the tank (Figure 2-9) (Singh et al., 2004). Reciprocally, when the gas is extracted for subsequent use, the tank's volume will decrease, and the drum sinks down. In terms of pressure, the mass (weight) of the drum directly controls the gas pressure; the gas pressure is somehow constant regardless of how much gas is in the tank because the volume varies. Additionally, if a higher pressure is needed, the pressure increases quickly by adding extra mass (weight) on top of the drum (Voegeli et al., 2009). It should be mentioned that considerable gas losses may occur if the drum does not entirely fit the tank. A safety valve is not required in a floating-drum system. Suppose the gas pressure reaches the maximum level and pushes the drum to the highest possible height. In that case, the gas automatically releases into the atmosphere and brings the pressure to normal again.
- Fixed-dome: Fixed-dome storage is another low-pressure storage tank with the cover on top of the digester is gas-tight and non-moveable (Figure 2-9) (Mungwe et al., 2016). When the extracting valve is closed, the gas pressure increases and pushes the digester’s

content downwards to the slurry reservoir; when the gas is used, the slurry comes back to the reactor.

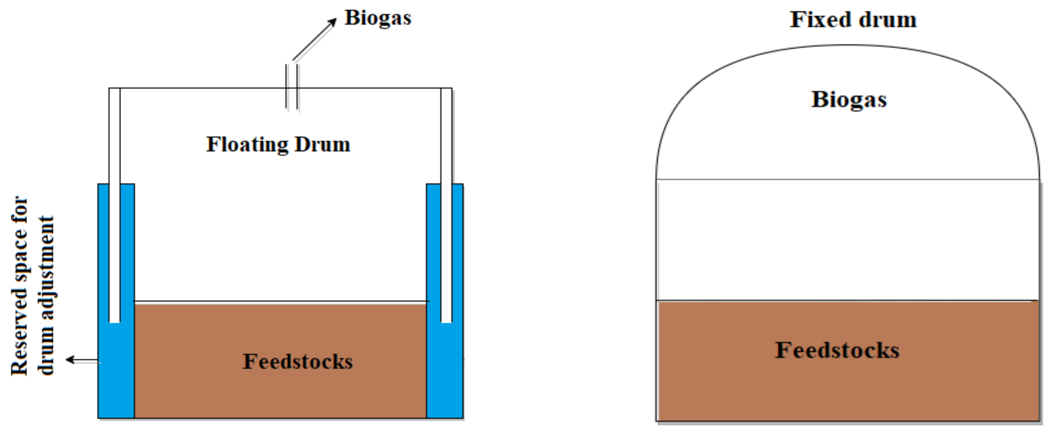


Figure 2-9 (A) Floating drum digester, and (B) Fixed drum digester. (Estoppey, 2010)

- Medium pressure storage tank: medium pressure storage tanks are usually under 5 – 20 bar pressure. This will allow storing more energy than normal pressure to decrease the gas tank's volume. A single compressor can achieve the needed compression, and the energy required for this purpose for a reservoir up to 10 bar is almost 0.22 kWh/m^3 (Al Seadi et al., 2008).
- High-pressure storage tank**:** It is also known as the gas cylinder. The compression pressure in this type of storage goes up to 200 bar. The energy required to run the compressor is relatively high, almost 20% of the generated biogas (1 – 1.5 kWh/m^3). This option is feasible only for large-scale biogas plants (Voegeli, 2014).

2.4.6 Feedstock characteristics

There are five categories of feedstock for a biogas plant in general: animal manure, crop straws, industrial wastes, municipal waste, and aquatic plants (Deng et al., 2020). In this study, the focus is on dairy cow manure and its characteristics. Some of the advantages of animal manure are:

1) C/N (Carbon/Nitrogen) ratio is 15 – 30:1, perfect for growing anaerobic microorganisms inside the digester.

2) Animal manure contains enough buffering capacity to reduce acidification.

3) Manure contains nutrients and rumen fluids that are useful for microbes in the digester.

For on-farm biogas plants, livestock manure is available free of charge. This feedstock has the ideal characteristics for AD because it contains many macro-and micro-nutrients and organisms (Wellinger et al., 1999). Dairy manure contains anaerobic bacteria that enhance the digester's methanogenic microorganisms. It is important to avoid entering large amounts of bedding or hard material such as rock into the digester since it can damage the mechanical parts inside the digester and decrease the tank's volume. Removing the settled solids from the bottom of the reactor is very expensive and needs vacuum trucks (Elger et al., 2020).

On average, dairy cows produce 31 kg (68 lb) of manure (urine + feces) per day. The manure contains about 11.3% volatile solids and 2% of fixed solids that are not degradable in the AD process. It contains small amounts (about 0.8%) of nutrients such as nitrogen, phosphorus, and potassium, and the rest of the manure is water (>80%) (American Society of Agricultural Engineers, 2005). Volatile solids (VS) are converted to biogas. However, it should be noted that only 35 – 40% of the total VS are microbiologically digestible. Biogas production and its feasibility are based on only 4% of the total manure (Shelford et al., 2019). There are other useful by-products such as bedding and/or fertilizers; they decrease the annual expenses of farmers.

2.4.6.1 Types of animal manure

The performance of the biogas plant depends on the characteristics of manure. Different animal species produce manure of different physical and chemical properties; thus, it will change the performance of the biogas plant. Table 2-6 shows how different types of manure with different solid contents have different biogas yields. Some parameters can help the project developers find the best compatible digester based on the manure characteristics such as TS%, climate condition, manure collecting system, etc. (Deng et al., 2020).

Table 2-6 Biogas potential of different types of manure

Manure type	TS (%)	VS/TS (%)	C:N ratio	Biogas
Swine	20 – 25	77– 84	13 – 15	0.252
Cow	16 – 18	70– 75	17– 26	0.180
Beef	17 – 20	79 – 83	18 – 28	0.180
Goat	30 – 32	65 – 70	26 – 29	0.206
Chicken	29 – 31	80 – 82	9 – 15	0.359
Duck	16 – 18	80 – 82	9 – 15	0.359
Rabbit	30 – 37	66 – 70	14 – 20	0.174
Animal fat	89 – 90	90 – 93	N/A	801 – 831**
Municipal wastewater sludge	30 – 20	90	N/A	17 – 140 **
Household waste	N/A	N/A	N/A	143 – 214 **

*Source: (Deng et al., 2020), (Alberta, 2011)
** The unit for the marked items are m^3/tonne

2.4.7 The control unit

Biogas plant needs continuous control and observation on every step of biogas production. Monitoring and documentation are necessary for process stability and to recognize any decrease in performance and implement corrective measures. Laboratory tests are needed to avoid inhibitors in the digester that would negatively affect biogas production (Samer, 2012). The parameters monitored frequently are feedstock quality and quantity, digester temperature, pH, TS% in the slurry, and biogas pressure.

Monitoring equipment should be resistant to corrosion, explosion, leakage, and easily cleanable (self-cleaning). Some units in a biogas plant can be controlled automatically, like the feeding system, heating system, sediment removal, upgrading the biogas, and power generation. Also, some units are capable of wireless control (Ghafoori et al., 2007). A centralized control system is practical for medium or small-scale plants. For large-scale plants, it is recommended to use an automatic control system since lots of machines and digesters are working together and making it difficult to operate manually.

2.4.8 Start-up stage

The start-up phase is important for AD. Initially, the digester needs to be inoculated with seed microorganisms necessary for the anaerobic process (Schnürer et al., 2016). This can be achieved by continuously increasing daily feeding to balance the microorganism population. It is important to know that initial overloading may cause the failure of the process (Strong et al., 1995). Feeding too much biodegradable organic components compared to the digesting capability of the microorganisms can rapidly destabilize the digester and cause the failure of the plant.

2.5 Analytical Methods for Cost Estimation

The analyses used in this study are mathematical and statistical regression modeling, which can provide a mathematical correlation between the cost and different biogas plant parameters. These analyses focus on finding the best relationship between the cost of each component and one of the input parameters. The input that will represent the size of the farm is the volume of the manure that can be collected at a specific time. This parameter is also convertible to the number of available animals on the farm since the generated manure per animal is roughly a fixed quantity for each species or type of animal (Wilkerson et al., 1997).

Regression modeling is a statistical process to formulate the relationships between variables in a dataset. Linear or nonlinear regression analysis provides the best specific equations to represent the relationship that minimizes the error (difference between the actual and predicted or estimated values of the dependent variables) (Montgomery et al., 2012). The linear modeling follows the equation (2-1).

$$y = ax + b \qquad \textit{(2-1)}$$

Where "y" is the dependent variable, and in this study, it can be the capital or operational costs of a biogas plant, and "x" is the independent variable which is the volume of the feedstock or number of cows, or hydraulic retention time. The nonlinear modeling can follow many forms such as equations (2-2) to (2-4).

$$y = a\,x\,b \quad => \quad ln(y) = ln(a) + b\,ln(x) \qquad \textit{(2-2)}$$

$$y = b\,10^{mx} => \quad y = mx + log(b) \qquad \textit{(2-3)}$$

$$y = 1\,/\,(mx + b) \;\; => \;\; 1/y = mx + b \qquad \textit{(2-4)}$$

Regression modeling is convenient, and the results of these analyses are very reliable. Since Europe is leading in the number of biogas plants, the financial analysis of on-farm biogas facilities and their modeling can be useful for the whole world (Hallbar, 2020). For example, Gebrezgabher et al. (2010) developed linear programming, which is a similar approach as regression modeling for a biogas plant's costs and revenue in the Netherland based on pig manure, food wastes, poultry manure, energy maize, and flower bulbs. The total biomass is 67,500 tons/year with 73% pig manure, 11% energy maize, 9% poultry manure, and 7% food waste and flower bulbs. This study shows that the costs for running a biogas plant would be roughly €1 million, while by selling the generated electricity (€900,000) plus the governmental subsidy (€1.45 million), the total revenue of the plant may reach €2.35 million before tax (Gebrezgabher et al., 2010). This can be a valid modeling procedure for other countries to follow and generate the best models that may fit their specific conditions.

The second method is Monte Carlo simulation which is useful for risk analysis, and it is part of our daily decision-making. Risk analysis becomes essential in more complicated studies with too many variables involved. The aim of the Monte Carlo simulation is to show all the possible outcomes of the decisions and assess the impact of risk and the possible results (Sugiyama, 2008). The Monte Carlo method is a mathematical technique that helps the user with quantitative analysis by randomizing and probability. It is widely used in fields such as finance, engineering, insurance, oil and gas, and the environment.

The Monte Carlo simulation builds a table of results by substituting a range of values for each variable and then repeats the calculation thousands of times to be able to calculate a mean value of the results (Bonate, 2001). This average value is the most probable outcome of the system. To generate random results, it is required to define a probability distribution for each variable, so it helps the model pick a value for each variable in the acceptable range that the user specifies (Palisade, 2016). Although Monte Carol simulation can use many probability distributions, the most common ones (Figure 2-10) are:

1. Normal distribution: Also known as the bell curve. The user simply defines the mean and standard deviation for the variable, and the variable is distributed symmetrically about the mean.
2. Lognormal distribution: The values are positively skewed, and the distribution is not symmetric like the normal distribution. The advantage of the lognormal distribution is that the value does not go below zero, and all the results are positive. This type of distribution is perfect for prices.
3. PERT distribution: In this type, the user defines the minimum, maximum, and most likely value for each variable. This will provide more detailed information for the variable, and the result is more accurate in this case.

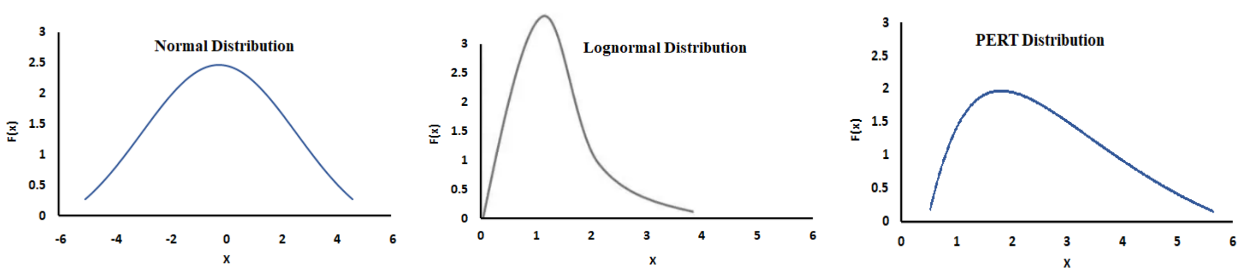


Figure 2-10 Three common probability distributions

Since this study is about cost modeling, negative values are not acceptable, so the normal distribution is not proper; instead, the PERT distribution is perfect for this purpose. Two main parameters need to be calculated for shaping the distribution graph. These two parameters, alpha and beta (equation (2-5) and (2-6), respectively), are formulated based on the minimum, maximum, and mode value of each variable (Owen, 2008). Where “a” is the pessimistic value, “b” is the most common value (mode), and “c” is the optimistic value. The graph shape and the distribution range for probability distribution would be assigned by having these three data for each variable.

$$\alpha = [4b + c - 5a] / [c - a] \quad (2\text{-}5)$$

$$\beta = [5c - a - 4b] / [c - a] \quad (2\text{-}6)$$

2.5.1 Existed Models of Cost Analysis

The major focus of this section is to analyze the existing models and methods used in the field, identify their pros and cons, and analyze their approaches. This will allow a valid reference for comparing the results of the methods used in this study with the existing models and provide an opportunity to improve them. The first existing model that is discussed in this section is a financial evaluator tool called the Cost of Renewable Energy Spreadsheet Tool (CREST); It is not a cost and revenue estimator, but by providing the costs and revenue of a specific farm as input information, a financial evaluation report would be generated to help the owners and investors in decision making (Gifford et al., 2011).

The second and third models are cost estimators for developing on-farm biogas plants in the USA. The fourth model is focused on the Canadian market; the latter models are developed based on the potential in Alberta. The advantages and disadvantages of each model are reviewed, and the results are compared to this study’s results. The biogas projects may report their component costs differently. For example, some projects report the actual equipment price separately from the overhead costs like construction and transportation, while others may lump sum them. However, most projects provide a total cost or capital investment representing the sum of all types of expenses. Table 2-7 presents an example of reported capital costs of on-farm biogas plants in the accessible literature.

Table 2-7 Typical initial investment of existing biogas projects

Location	Digester type	Cows Number	Total costs (CAD)	Operational costs (CAD/yr)	Sources
Ankara, Turkey	CSTR	2200	1,000,000	84,400	(Akbulut, 2012)
Jordan	CSTR	100	30,000	1,281	(Jarrar et al., 2020)
		500	140,000	6,000	
		1000	281,000	12,164	
		1500	385,000	17,500	
		2000	513,000	23,000	
Washington, USA	PFD	1000	626,000	17,000	(White et al., 1998)
		500	1,200,000	-	(Baldwin et al., 2009)
Minnesota, USA	CSTR	160	686,000	-	
		500	627,000	-	(Kramer et al., 2008)
		2000	1,154,000	-	
	PFD	588	640,000	27,000	(Nelson et al., 2002) (Lazarus et al., 2007)
Maine, USA	CSTR	870	7,700,000	-	(Boerman et al., 2013)
Ontario, Canada	-	280	1,490,000	-	(Biogas Association, 2019)
East Connecticut, USA	PFD	200	245,000	-	(Moser et al., 1998)
New York, USA	PFD	800	496,000	40,400	(Scott et al., 2010)
		850	1,767,000	168,400	(Pronto et al., 2008)
		236	248,300	13,850	(Wright et al., 2003)
		600	704,000	-	(Gooch, 2008)
		1600	1,291,000	152,700	(Gooch et al., 2009)
		1600	3,548,000	-	(White et al., 2011)
		400	1,478,000	-	
		1400	1,613,000	-	
		3300	6,942,000	-	
	CSRT	1000	2,488,000	-	
		600	1,117,000	-	

*All costs are converted to Canadian dollars and the year 2020. CSRT = completely stirred tank reactor

2.5.1.1 Cost of renewable energy spreadsheet tool (CREST)

The CREST is one of the initial models used for the economic evaluation of biogas plants in the USA, and it was developed within the AgSTAR program under the supervision of the National Renewable Energy Laboratory (NREL). The AgSTAR is a collaborative program sponsored by the United States Environmental Protection Agency (EPA) and The United States Department of Agriculture (USDA). The model is called the "Cost of Renewable Energy Spreadsheet Tool (CREST)" and is based on cash flow economic modeling on AD (Gifford et al., 2011).

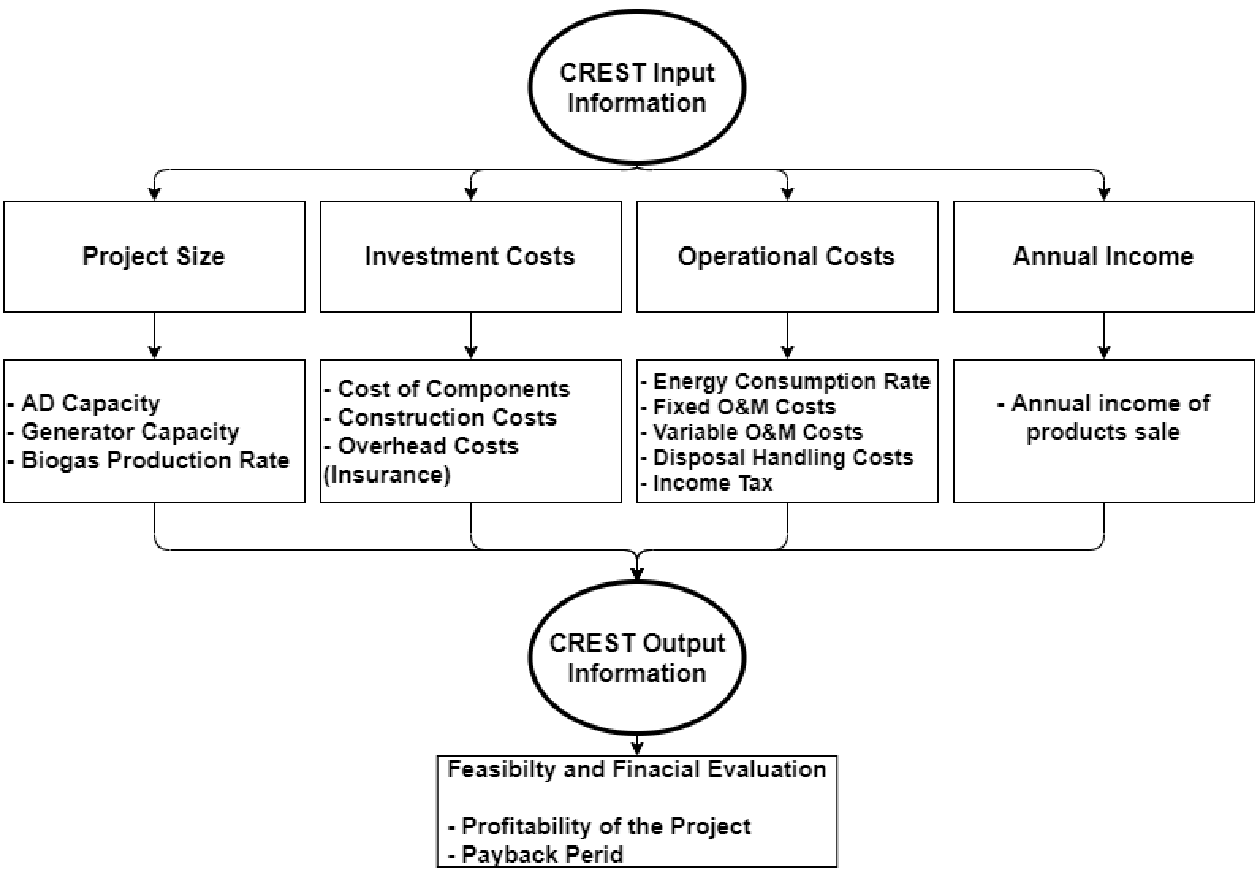


Figure 2-11 The Cost of Renewable Energy Spreadsheet Tool (CREST) model Input data

This model aims to provide a financial evaluation for the biogas plants developers based on the costs and revenue of each project. This model has four inputs, as shown in

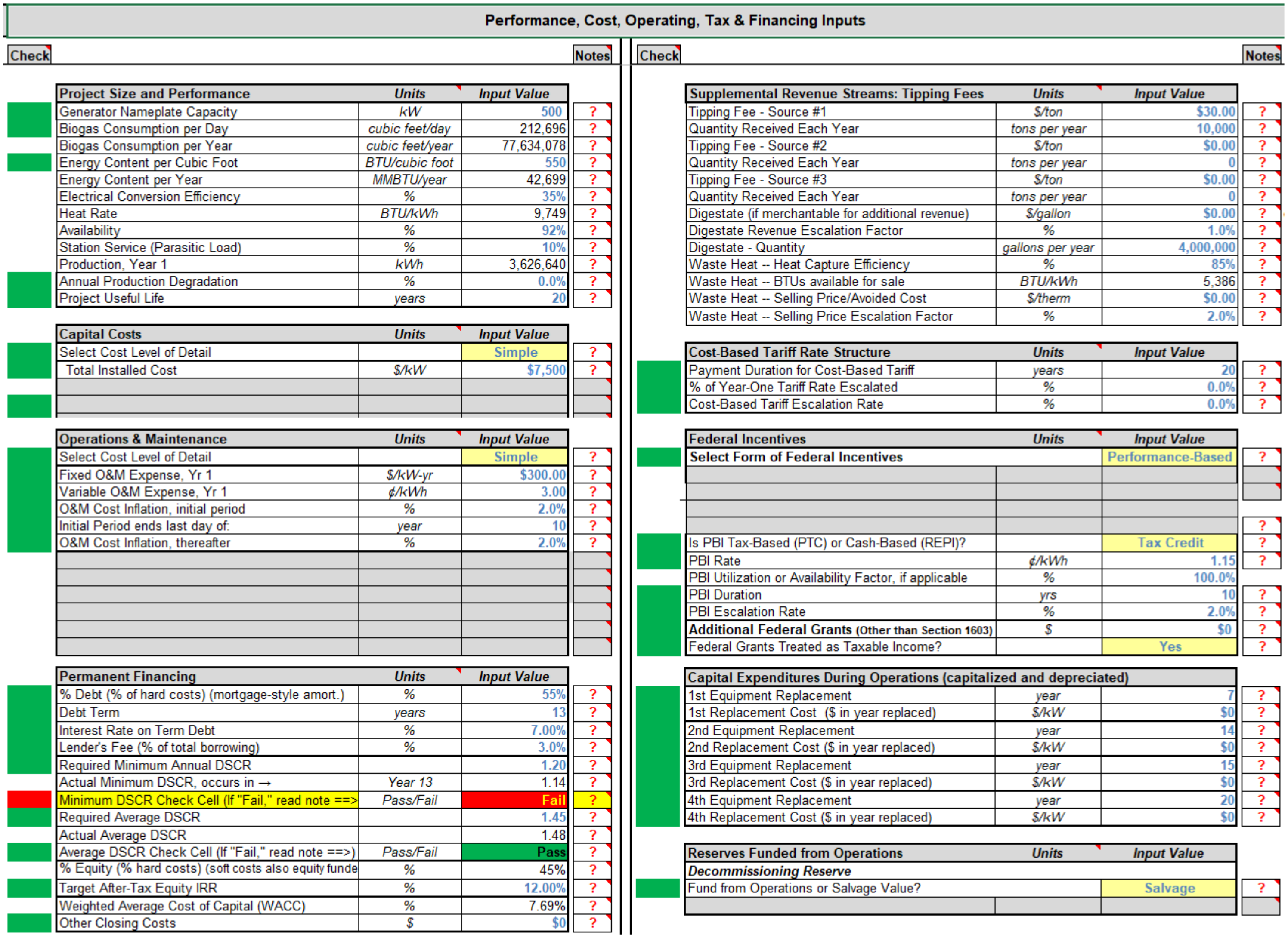
Figure 2-11. This figure shows how each parameter should be defined in this model to get the results. For instance, the project size defines the digester size, biogas production, and electricity generation. This general information regarding the size of the project is related to the capital costs that are required for developing the plant. The Microsoft Excel interface of the model is shown in Figure 2-12. After installation and start-up, the next input for cost analysis is operation and maintenance costs. These are fixed and variable costs continuously applied to the project every year, such as salaries for staff, management, repair and maintenance, insurance, etc. Some of these parameters may not apply to all farms because of the variety of operating systems or the differences in their feedstock. For example, suppose a farm accepts off-farm wastes. In that case, it may increase the cost of electricity usage for their mixers compared to a farm that digests only its own animal manure, or transportation fees are only applicable to the off-farm feedstock. The last input parameter is about yearly turnover for the investment, which depends highly on the country and the province in which the project is located. In Canada, most biogas plants can sell their excess amount of generated electricity to the grid for residential use which generates income. In addition, the digestate remaining after digestion can be used on the farm itself or can be sold to the market as fertilizer or bedding.

2.5.1.2 Budget calculator by Florida University (BCFU)

The University of Florida has developed this model to investigate AD feasibility for three dairy farms. This model initially selected four typical digesters (covered lagoon, fixed-film, complete mix, and plug flow) discussed in section 2.4.3. Since most of the manure collecting systems in dairy farms in Florida and elsewhere are manure flushing, the plug flow and complete mix digester are not feasible because total solids of flushed manure are low (details regarding the total solid content for each type of manure is provided in Table 2-6). Hence, the three farms have been evaluated for the covered lagoon and fixed film digester (Giesy et al., 2006). The interface of the Microsoft Excel-based model is shown in Figure 2-13. The benefit of this model is that it can calculate the project's economic feasibility based on the model assumptions and the data that the user inputs to the model. The required input data for the Florida model are listed below:

- Number of cows or wastewater volume
- Energy generation per day such as methane yield
- Price of gas per ft^3
- Its generated income by selling the electricity
- Size of the digester
- Income tax rate
- Net revenue

This model is implemented through a spreadsheet to calculate the feasibility of an on-farm biogas plant. By having the quantity (mass) of feedstock and the type of digester, the profit is calculated as the differences between the capital and operational costs and the generated income by selling the electricity. It is possible to conclude whether a biogas plant is feasible for a farm. The results show that by selling the electricity for 0.12$/kWh, the covered lagoon digester is feasible for farms with 650 and 2100 cows. However, the fixed film digester was only feasible for a farm with more than 1000 cows (Giesy et al., 2006).



Performance, Cost, Operating, Tax & Financing Inputs

Check | Notes

Project Size and Performance	Units	Input Value	Notes
Generator Nameplate Capacity	kW	500	?
Biogas Consumption per Day	cubic feet/day	212,696	?
Biogas Consumption per Year	cubic feet/year	77,634,078	?
Energy Content per Cubic Foot	BTU/cubic foot	550	?
Energy Content per Year	MMBTU/year	42,699	?
Electrical Conversion Efficiency	%	35%	?
Heat Rate	BTU/kWh	9,749	?
Availability	%	92%	?
Station Service (Parasitic Load)	%	10%	?
Production, Year 1	kWh	3,626,640	?
Annual Production Degradation	%	0.0%	?
Project Useful Life	years	20	?

Capital Costs	Units	Input Value	Notes
Select Cost Level of Detail		Simple	?
Total Installed Cost	$/kW	$7,500	?

Operations & Maintenance	Units	Input Value	Notes
Select Cost Level of Detail		Simple	?
Fixed O&M Expense, Yr 1	$/kW-yr	$300.00	?
Variable O&M Expense, Yr 1	¢/kWh	3.00	?
O&M Cost Inflation, initial period	%	2.0%	?
Initial Period ends last day of:	year	10	?
O&M Cost Inflation, thereafter	%	2.0%	?

Permanent Financing	Units	Input Value	Notes
% Debt (% of hard costs) (mortgage-style amort.)	%	55%	?
Debt Term	years	13	?
Interest Rate on Term Debt	%	7.00%	?
Lender's Fee (% of total borrowing)	%	3.0%	?
Required Minimum Annual DSCR		1.20	?
Actual Minimum DSCR, occurs in →	Year 13	1.14	?
Minimum DSCR Check Cell (If "Fail," read note ==>	Pass/Fail	Fail	?
Required Average DSCR		1.45	?
Actual Average DSCR		1.48	?
Average DSCR Check Cell (If "Fail," read note ==>)	Pass/Fail	Pass	?
% Equity (% hard costs) (soft costs also equity funde	%	45%	?
Target After-Tax Equity IRR	%	12.00%	?
Weighted Average Cost of Capital (WACC)	%	7.69%	?
Other Closing Costs	$	$0	?

Check | Notes

Supplemental Revenue Streams: Tipping Fees	Units	Input Value	Notes
Tipping Fee - Source #1	$/ton	$30.00	?
Quantity Received Each Year	tons per year	10,000	?
Tipping Fee - Source #2	$/ton	$0.00	?
Quantity Received Each Year	tons per year	0	?
Tipping Fee - Source #3	$/ton	$0.00	?
Quantity Received Each Year	tons per year	0	?
Digestate (if merchantable for additional revenue)	$/gallon	$0.00	?
Digestate Revenue Escalation Factor	%	1.0%	?
Digestate - Quantity	gallons per year	4,000,000	?
Waste Heat -- Heat Capture Efficiency	%	85%	?
Waste Heat -- BTUs available for sale	BTU/kWh	5,386	?
Waste Heat -- Selling Price/Avoided Cost	$/therm	$0.00	?
Waste Heat -- Selling Price Escalation Factor	%	2.0%	?

Cost-Based Tariff Rate Structure	Units	Input Value	Notes
Payment Duration for Cost-Based Tariff	years	20	?
% of Year-One Tariff Rate Escalated	%	0.0%	?
Cost-Based Tariff Escalation Rate	%	0.0%	?

Federal Incentives	Units	Input Value	Notes
Select Form of Federal Incentives		Performance-Based	?
Is PBI Tax-Based (PTC) or Cash-Based (REPI)?		Tax Credit	?
PBI Rate	¢/kWh	1.15	?
PBI Utilization or Availability Factor, if applicable	%	100.0%	
PBI Duration	yrs	10	?
PBI Escalation Rate	%	2.0%	?
Additional Federal Grants (Other than Section 1603)	$	$0	?
Federal Grants Treated as Taxable Income?		Yes	?

Capital Expenditures During Operations (capitalized and depreciated)	Units	Input Value	Notes
1st Equipment Replacement	year	7	?
1st Replacement Cost ($ in year replaced)	$/kW	$0	?
2nd Equipment Replacement	year	14	?
2nd Replacement Cost ($ in year replaced)	$/kW	$0	?
3rd Equipment Replacement	year	15	?
3rd Replacement Cost ($ in year replaced)	$/kW	$0	?
4th Equipment Replacement	year	20	?
4th Replacement Cost ($ in year replaced)	$/kW	$0	?

Reserves Funded from Operations	Units	Input Value	Notes
Decommissioning Reserve			
Fund from Operations or Salvage Value?		Salvage	?

Figure 2-12 CREST model Interface

Spreadsheet to Calculate the Economic Feasibility of Anaerobic Manure Digesters on Florida Dairy Farms

Albert de Vries, UF/IFAS Department of Animal Sciences | Ann Wilkie, UF/IFAS Soil and Water Science Department

Russ Giesy, UF/IFAS Exension Dairy Science | Roger Nordstedt, UF/IFAS Department of Agricultural and Biological Engineering

Contact: Albert de Vries, email: devries@ufl.edu, phone: (352) 392 7563 | Documentation: http://dairy.ifas.ufl.edu/tools

EDIS publication AN176

Version 1.1 (03JAN2007) Modify blue cells Do not modify black cells		Example Farm Fixed Film Digester	Example Farm Covered lagoon Digester	Your Farm Your Digester	Your Farm Your Digester	Your Farm Your Digester	Your Farm Your Digester	
Cows and Water								**Cows and Water**
Number of cows		550	700	100	0	0	0	Number of cows
Waste water volume	gal/cow/d	200	200	200	0	0	0	Waste water volume
Waste water volume	gal/d	5,500	140,000	20,000	0	0	0	Waste water volume
Methane and Energy Generation								**Methane and Energy Generation**
VS to digester	lbs/cow/d	12.00	12.00	12.00	12.00	12.00	12.00	VS to digester
VS to digester	lbs/d	6,600	8,400	1,200	0	0	0	VS to digester
Conversion factor VS to CH4	scf / lb VS	4.00	4.00	4.00	4.00	4.00	4.00	Conversion factor VS to CH4
CH4 methane yield	ft3/d	26,400	33,600	4,800	0	0	0	CH4 methane yield
CH4 methane yield	ft3/cow/d	48	48	48	#DIV/0!	#DIV/0!	#DIV/0!	CH4 methane yield
Conversion factor LHV	btu/ft3	1000	1000	1000	1000	1000	1000	Conversion factor LHV
LHV (Latent Heating Value)	btu/d	26,400,000	33,600,000	4,800,000	0	0	0	LHV (Latent Heating Value)
Electrical value constant	btu/kwh	3412	3412	3412	3412	3412	3412	Electrical value constant
LHV conversion efficiency	%	25%	25%	35%	25%	25%	25%	LHV conversion efficiency
Electricity generated	kwh/d	1,934	2,462	492	0	0	0	Electricity generated
Electricity generated	kwh/cow/d	3.52	3.52	4.92	#DIV/0!	#DIV/0!	#DIV/0!	Electricity generated

Figure 2-13 Spreadsheet to calculate the economic feasibility of anaerobic digesters (De Vries et al., 2007)

The most important part of this model is that it provides a scientific range for methane generation and electricity production of typical on-farm biogas plants that digest dairy manure. Since this model is designed for the US biogas plants, the parameters were converted to SI units and Canadian equivalents. Table 2-8 provides the assumptions for the calculation for US systems.

Table 2-8 Conversion factors and assumed parameters for the US Biogas plants

Methane and energy generation	Unit	Conversion factor
VS to digester	lbs/cow/d	12.00
Conversion factor VS to CH_4	scf / lb VS	4.00
CH_4 methane yield	ft^3/cow/d	48
Conversion factor LHV	btu/ft^3	1000
LHV (Latent Heating Value)	btu/d	26,400,000
Electrical value constant	btu/kwh	3412
LHV conversion efficiency	%	25%
Electricity generated	kwh/cow/d	3.52

2.5.1.3 Optimum sizing for anaerobic digestion in Alberta, Canada

This model is based on different scenarios for ten farms located between Calgary and Lethbridge, Alberta, with a mixed anaerobic digester. The study defined different situations for biogas development facilities in these farms and tried to find the best rate of return. These scenarios vary from having a single biogas production plant for each farm or having a shared (subcentral) facility for the farms closer to each other or having one centralized plant for the whole area (Ghafoori et al., 2007).

These scenarios were translated to the required plant size in the next step. In other words, the authors calculated the suitable plant size based on net MWe production per year and predicted the costs for each plant size. By drawing a graph based on the plant size and the assumed costs, the regression equations for this study becomes as below:

$$Operational \; \& \; Maintenance \; costs \; = \; 219.38 \, x^{-0.468} \qquad (2\text{-}7)$$

$$Capital \; Costs \; = \; 370.96 \, x^{-0.291} \qquad (2\text{-}8)$$

In the models (Eq. (2-7) and Eq. (2-8)) the only variable that can predict the costs is the plant size that should be converted to the net MW electricity that the plant can generate, and the results would be in $/MWh electricity generated. For instance, based on the data given in the Ghafoori et al., (2007), a biogas plant that can roughly generate 1MW electricity would require an investment of 340 $/MWh and 200 $/MWh cost of operation and maintenance.

2.5.1.4 Other models

A study conducted by Trivett, A., & Hall, M. (2009) estimated the capital cost for a biogas plant at the 500-cow level of approximately $1,500 per cow for a plug flow digester and $1,100 per cow for a complete mix system (Trivett et al., 2009). Another recent study by O'Connor et al. (2020) modeled the correlation between the installed electricity capacity and the capital costs. This model is provided in Eq. (2-9), where the prices are calculated based on euros, and "x" is the electrical capacity (kw_e) and the acceptable range for this equation is 0 – 120 kw_e (O'Connor et al., 2020).

$$Capital \; Costs \; (€) \; = \; 5733.2x \; + \; 192{,}911 \qquad (2\text{-}9)$$

O'Connor et al. (2020) also developed five different scenarios for capital cost estimation based on the herd size (CN). Table 2-9 provides the results of these scenarios. The results show that increasing the herd size gradually increases both the investment costs and profit growth.

Table 2-9 Economic results of small-scale AD plants over 20-years lifespan

	Scenario 1 CN = 50	Scenario 2 CN = 100	Scenario 3 CN = 150	Scenario 4 CN = 200	Scenario 5 CN = 250
Capital costs (€)	290,099	345,479	400,860	456,241	511,622
Operational costs (€)	274,704	343,588	412,472	481,356	551,241
Total revenue (€)	515,576	842,480	1,146,000	1,465,159	1,784,322
profit before Tax (€)	240,872	498,892	733,538	983,803	1,234,082

Source: (O'Connor et al., 2020)

Another provides two equations to estimate the capital costs of biogas plants on dairy farms and two equations for the anaerobic digester costs (Cassie et al., 2010). Eq. (2-10) calculates the total initial investments based on the number of cows, and Eq. (2-11) gives the price of this investment per cow.

$$Capital\ cost\ (\$) = 536CN + 678{,}064 \quad (2\text{-}10)$$

$$Capital\ cost\ (\$/cow) = (12{,}960CN)^{-0.332} \quad (2\text{-}11)$$

Baldwine et al. (2009) conducted a comprehensive study that modeled the digester costs for complete mix digester and plug flow digester. Eq. (2-12) calculate the cost of complete mix digester (CSTR) based on the number of cows for a farm size between 700 and 2300 cows, and Eq. (2-13) estimates the costs of plug flow digester (PFD) based on the number of cows for farms having between 650 and 4000 cows (Baldwin et al., 2009). This study modeled the digester costs based on the maximum power output for each digester type presented in Eq. (2-14) and Eq. (2-15).

$$CSTR\ costs\ (\$) = 615CN + 354{,}866 \quad (2\text{-}12)$$

$$PFD\ costs\ (\$) = 563CN + 678{,}064 \quad (2\text{-}13)$$

$$CSTR\ costs\ (\$) = 26920 * (maximum\ power\ output)^{0.7388} \quad (2\text{-}14)$$

$$PFD\ costs\ (\$) = 7570 * (maximum\ power\ output)^{0.8722} \quad (2\text{-}15)$$

Baldwin et al. (2009) also generated other mathematical models for capital cost estimation based on the number of cows. The capital cost calculation in this method is linked to the digester type. Eq. (2-16) and Eq. (2-17) represent the capital cost estimators for CSTR and PFD, respectively and the acceptable range for CN in these equations is between 250 – 2500 CN (Baldwin et al., 2009).

$$CSTR\ capital\ costs\ (\times\ \$1000) = 7.1901\ CN^{0.7737} \quad (2\text{-}16)$$

$$PFD\ capital\ costs\ (\times\ \$1000) = 0.2033\ CN^{1.1734} \quad (2\text{-}17)$$

CHAPTER THREE

MATERIAL AND METHODS

3.1 Introduction

This chapter focuses on the approaches and methodologies that are used predict the costs of an on-farm biogas plant. Figure 3-1 presents how this study is developed and what aspects of the topic are influential on the outcome. The research started by creating a comprehensive database of real existing on-farm biogas projects in Canada and the US dairy farms. This database will be used to conduct data analysis leading to developing mathematical models for cost estimation of construction and operation of on-farm anaerobic digestion process in Canadian dairy farms.

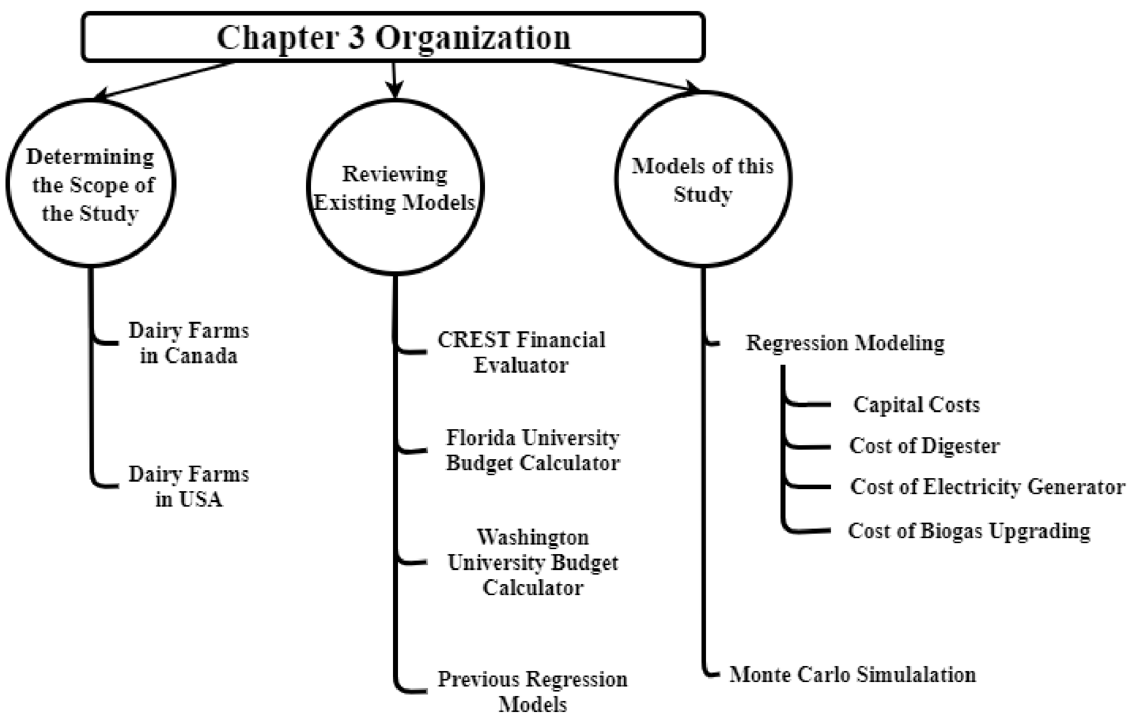


Figure 3-1 Steps of the methodology of this study

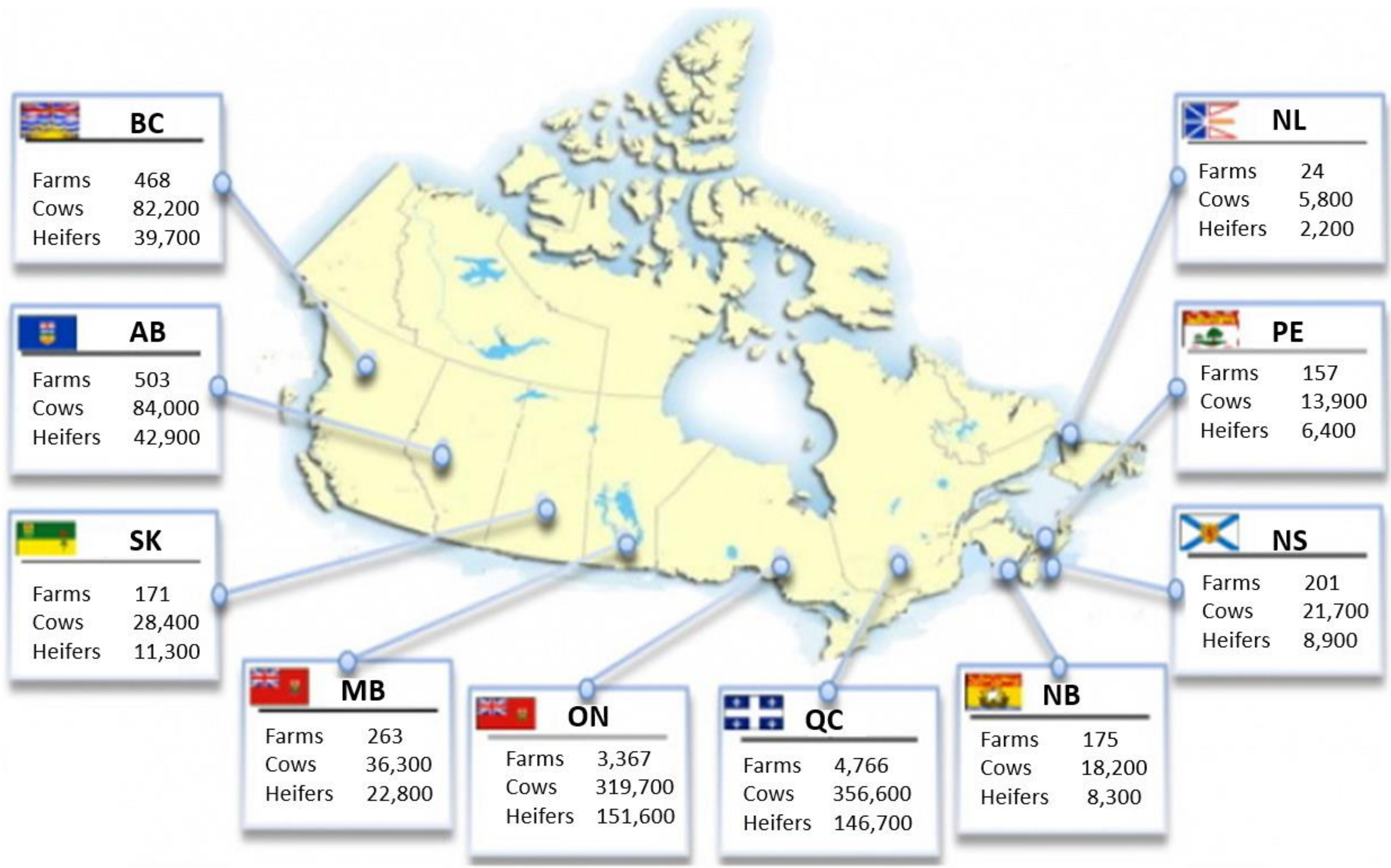


Figure 3-2 Number of farms and animals per province in Canada (Statistics Canada, 2021)

This study developed a database (APPENDIX A) to provide detailed information on Canadian biogas plants. The farms are selected only based on their relevancy to Canada and the US, given that these two countries share the same market and business model. The suppliers and factories that build the required components for biogas facilities are the same in these countries. Figure 3-2 shows the number of cows and the number of farms in each Canadian province, and the total number of animals is 1,407,600 while the number of farms across the country is 10,095, which brings the average number of cows to 140 per farm (Statistics Canada, 2021).

To have a more detailed perspective of the locations and size of the plants, Table 3-1 provides a list of on-farm biogas plants across Canada with information about their anaerobic digester volume. The collected data (from literature and papers plus filled questionnaires) from each farm were normalized to a single and comparable unit. The similarity of these farms (including Lester's Dairy Farm, St. John's, NL) is in the type and quality of the manure, which is only from dairy cows. The biogas plants on these farms convert the biogas to electricity and sell the generated power to the grid in their province according to feed-in-tariff programs. In addition, governmental funding and incentives help the agricultural sector to develop faster to reduce GHG emissions. On June 4th, 2021, the government of Canada announced the new $165 million agricultural clean technology program to support clean energy production (Biogas Association, 2021). Since the costs reported for each farm are based on the year of construction, there is 15 years difference between the start-up time of these farms. Hence, to harmonize the prices and make them comparable, the costs were converted to Canadian dollars and inflated to 2020, according to the Bank of Canada's inflation calculator (Statistic Canada, 2021). The data for each farm includes the name and location of the farm, the number of dairy cows, the operational hydraulic retention time, the individual cost of the pumping unit, digester, generator, biogas upgrading unit, and total capital costs, operating costs, year, and inflation rate.

Table 3-1 Digester volume in some Canadian on-farm biogas plants.

Item No.	Name of the project	Location	Digester volume (m^3)
1	Glenmore Landfill (Kelowna)	British Colombia, CA	-
2	Centre for Agricultural Renewable Energy	Ridgetown, Ontario, CA	1,527
3	StormFisher (BlueForest Company)	London, Ontario, CA	-
4	Greenholm Farms	Embro, Ontario, CA	2,077
5	Seacliff Energy	Leamington, Ontario, CA	-
6	Bayview Flowers Ltd	Jordan, Ontario, CA	1200
7	Delft Blue Veal Inc.	Ontario, CA	-
8	The Gardiner Farm	Ontario, CA	-
9	Koskamp Family Farms	Ontario, CA	3900
10	Athlone BioPower	Ontario, CA	2000
11	Eilers Farm	South Huron, Ontario, CA	-
12	Birchlawn Farms	Ontario, CA	1800
13	Woolwich Bio-en Inc.	Elmira, Ontario, CA	-
14	Clovermead Farms	Ontario, CA	1,300
15	CCI BioEnergy (CCI) Disco	Ontario, CA	10,600
16	CCI BioEnergy (CCI) Dufferin	Ontario, CA	8,800
17	Zooshare	Toronto, Ontario, CA	-
18	Marl Creek Renewables	Ontario, CA	4,200
19	Carbon Control Systems agriKomp	Millbrook, Ontario	680
20	Maryland Farms	Ontario, CA	1500
21	Chatsworth/Georgian Bluffs	Owen Sound, Ontario, CA	1000
22	Donnandale Farms	Ontario, CA	3200
23	Ledgecroft Farms	Seeley's Bay, Ontario, CA	1500
24	Fepro Farms	Cobden, Ontario, CA	2500
25	Clearydale Farms	Spencerville, Ontario, CA	-
26	Jockvalley Farms	Ashton, Ontario, CA	1500
27	Schouten Corner View Farms Ltd	Ottawa, ON, CA	4500
28	Carleton Corner Farms	Marionville, Ontario, CA	1500
29	Ferme Geranik	St-Albert, Ontario, CA	1000
30	Kirchmeier Farms	Ontario, CA	1500
31	Petrocorn Inc.	Pendleton, Ontario, CA	1500
32	Pinehedge Farms	Ontario, CA	-
33	Terryland Farm	St Eugene, Ontario, CA	1000

Sources: (Werner et al., 2007), (Gooch et al., 2009), (Kelleher et al., 2013)

3.2 Biogas Projects Distribution in North America

3.2.1 Canadian biogas plants

Based on the reports published by the Canadian Biogas Association in 2013 and 2019, the approximate number of active agricultural biogas projects in Canada is 61 plants, 86 wastewater treatment facilities, and 53 landfill gas projects, while the potential is much greater than these numbers (Biogas Association, 2019). The Canadian Biogas Association stated that the full potential of biogas generation in Canada based in the year 2019 could be 1,800 plants; and to reach this goal, a $7 billion investment is required for the construction of the project, and the economic spin-off of this investment would be about $21 billion for the Canadian economy.

Besides the financial benefits, these 1,800 projects will creat17,000 construction jobs, 2650 long-term operational jobs, and 100 new and expanded companies in the biogas field, including designers, developers, suppliers, and laboratories (Biogas Association, 2019). Ontario, one of Canada's largest provinces, has the highest number of operational biogas facilities. In the map (Figure 3-3), it is clear that the focus of biogas projects is on the southern part of Ontario, this part of Canada has 42 anaerobic digestion facilities, and 38 of them are on-farm plants. Ontario can process over 900,000 tons of off-farm wastes and on-farm manure per year. These facilities in Ontario currently process 450,000 tonnes of organic wastes and 300,000 tonnes of on-farm manures and agricultural residuals, which have an energy capacity of 12 MW (Biogas Association, 2019).

Figure 3-3 Distribution of Canadian biogas plants

(Biogas Association, 2021)

3.2.2 USA biogas plants

Anaerobic digestion and power generation at the farm level began in the United States in the early 1970s when several US universities conducted basic digester research. Afterward, in 1978, the first on-farm biogas plant was installed at Cornell University with a plug-flow digester of a capacity to digest the manure from 60 cows (White et al., 1998).

Figure 3-3 and Figure 3-4 show the distribution of biogas projects in North America. The similarity between Canada and the USA is that the biogas plants in the eastern region of the USA are denser in number than the biogas plants in the western regions.

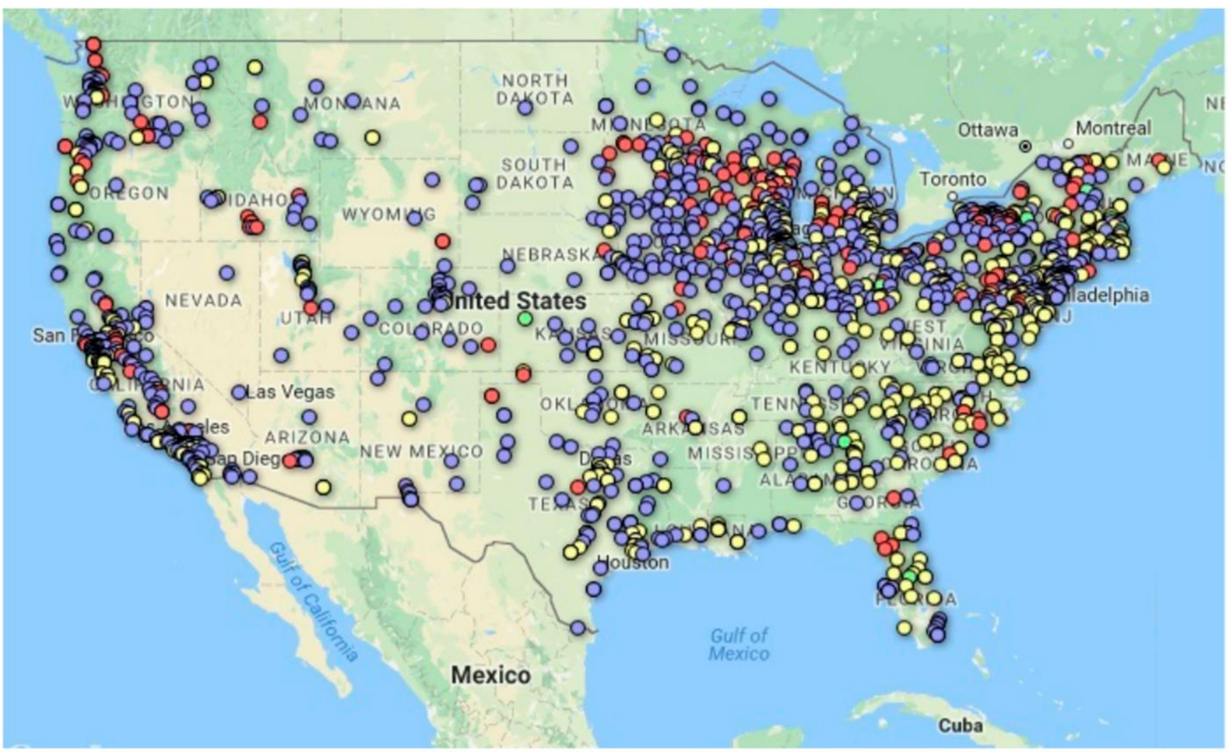


Figure 3-4 On-farm biogas plant distribution across the United States of America (Tanigawa et al., 2017)

It is evident that there are more biogas projects than in Canada because of the larger population and greater agriculture, industrial, and economic activity in the USA. The US has almost 2,200 biogas plants across its 50 states (American Biogas Council, 2014). About 250 anaerobic digesters are on farms, 1,269 are on waste resource recovery facilities, 66 stand-alone systems digest food waste, and 652 landfill gas projects (Tanigawa et al., 2017).

Based on the American Biogas Council report in 2018, although there are more than 2200 active projects in the US with 977 MW installed capacity there is potential to develop about 15,000 new biogas plants. These new biogas systems could produce 103 trillion kilowatt-hours of electricity each year and reduce GHG emissions by the equivalent of removing 117 million passenger vehicles from the road (Newman et al., 2018). The construction of these new facilities requires $45 billion in capital investment, and it would result in approximately 374,000 short-term construction jobs and 25,000 permanent jobs to operate them. Additional to these direct benefits, the indirect impacts along supply chains would be even greater benefits to the investors and the state's economy (American Biogas Council, 2014).

3.3 Existed Models of Biogas Cost Analysis

3.3.1 Anaerobic digester system budget calculator by Washington University

This model is one of the most updated/recent cost estimating models in this study. It is a spreadsheet developed on Microsoft Excel and designed to predict the costs based on common technologies available in the biogas field. The designer’s report can be useful for farm owners, researchers, and developers. The advantage of this model is that, in addition to the cost estimation based on the herd size, it predicts the annual result for 30 years of operation of the plant and generates graphs taking into account the variation in the parameters in each year. Figure 3-5 shows the interface of this model. The model can predict the costs based on different scenarios that may apply to a specific farm. For instance, the effect of some additional technologies on costs can be calculated individually, and the users can define different scenarios based on the needs of their own farm to minimize the cost of the biogas plant. It allows the user to apply/remove the effect of components on the costs or revenue of the plant. These components are anaerobic digester, compressed natural gas unit, combined heat and power unit, environmental credits, fiber separators, nutrient separators, and water recovery. This model predicts the capital cost, operational cost, and annual revenue, but it does not provide the individual cost of each component.

3.4 Models of This Study

This study aims to build a comprehensive database and develop models to estimate costs. The database is created using the available data from real biogas projects in Canada and the United States. A mathematical analysis (specifically regression modeling) is used to generate cost-estimating models based on the number of cows, or manure volume, or by using technical parameters like HRT. The models predict an on-farm biogas project's capital and operational costs and assess its feasibility. In addition to the models developed by regression analysis, a risk assessment analysis is applied to all models and the dataset to calculate the most probable outcome of the results. Using the Monte Carlo simulation, the most probable value for each variable based on the probability distribution is calculated. The average value with the highest probability of occurring for the system is presented. With the combination of the models and the Monte Carol simulation, a farmer can roughly estimate the required initial investment for the project and have a valid reference to compare their predicted costs with.

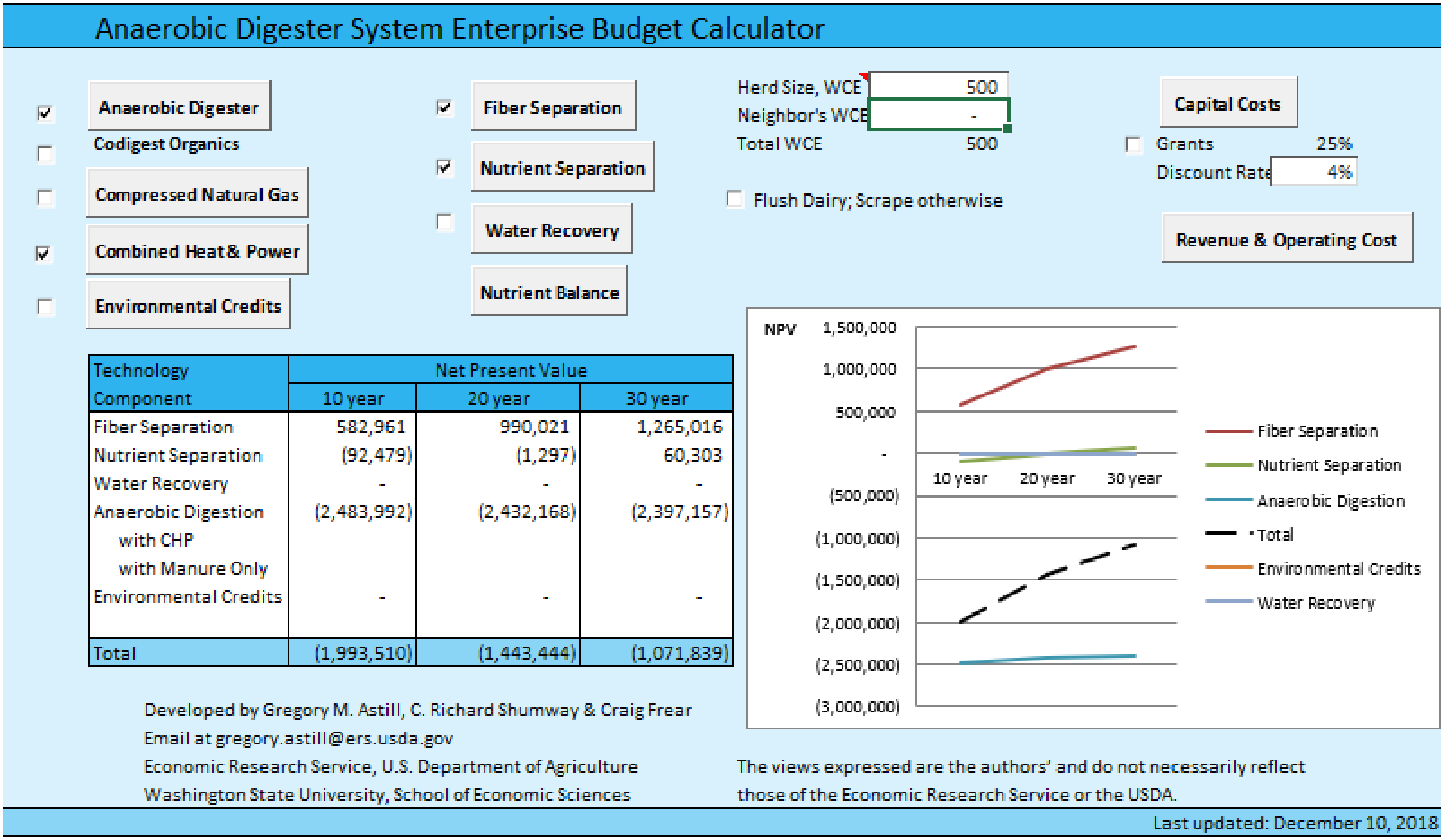


Figure 3-5 Budget calculator interface (Astill et al., 2018)

3.4.1 Regression modeling

The collected dataset is the foundation of the regression modelling in this study. This modeling generates graphs and equations that show the relationship between the data points of the database. The first step is to gather the cost data for the components of typical Canadian biogas plants. The more detailed information can provide a more accurate estimation of the total costs. The components are the costs of the anaerobic digester, powerhouse, generator, and gas upgrading unit; these costs information are assigned to the specification of each farm, such as the number of cows, the total quantity of manure, the total volume of off-farm organic wastes, HRT, and the year of projects' construction.

The collected data are harmonized in the type of currency and inflation factor because the projects are constructed over 15 years. The cost of building such projects differs from year to year due to the inflation rate and the development of new technologies being introduced. The prices are converted to the Canadian dollar and inflated to 2020 to exclude this variation from the analysis. A new data table is prepared for analysis (the dataset is provided in APPENDIX A).

During data collection, some data points are missing, and it is very common that there are some gaps in the dataset. Since financial information is mostly confidential, companies are not willing to share their detailed documentation with the public. Hence, to reduce the impact of these gaps in our analysis, Table 3-2 presents the parameters with the minimum gap and the least amount of error in the analysis.

Another approach that has been used in this study to cover the gaps in the dataset is using the Monte Carlo simulation, which generates random values for each parameter to fill the gaps. The Monte Carlo simulation is presented in section 3.4.2.

Table 3-2 List of variables and their appropriate correlation

Cost of component	Correlated item
Capital cost	Number of cows
Capital cost	HRT
Cost of anaerobic digester	Number of cows + HRT
Powerhouse and pumping unit	Number of cows
Cost of electric generator	Number of cows
Cost of biogas cleaning and upgrading	Number of cows

3.4.2 Monte Carlo simulation

The Monte Carlo method is a numerical approach to studying problems with large dimensions. This method uses random sampling and statistical modeling to minimize the possible error by repetition; a larger resampling provides a more reliable outcome (Katzgraber, 2009). This method is useful for this study because of two reasons. First, the number of active biogas projects in Canada is limited; the provided dataset is relatively small; this method can regenerate nonbiased samples to increase the study accuracy. In addition, this method can fill gaps in the data points and improve the accuracy of the results.

Independent and dependant variables are defined, and the probability distribution for each independent variable is calculated. Based on the objective of this study, the independent variables are the farm and biogas plant specifications, and the dependent variables are the cost data for each component of the plant. The correlation between the cost of the biogas plant and the farm specification can be investigated. Table 3-3 lists the independent and dependent variables used in the Monte Carlo simulation.

Second, specific values are needed for both groups of variables (independent and dependent) to give a scale and limitations to the simulator. These limitations and scales are mainly the upper and lower limits to force the simulator in the scope of the study; This will reduce the errors because the results that may be out of the acceptable range will be excluded from the calculations. Since the Monte Carlo Simulation is designed to predict the costs, the major applied limit to the simulator is the minimum and maximum cost for each component, so any prediction that is out of the defined range will not be included. In addition to the minimum and maximum, mean, standard deviation, mode, alpha, and beta are the other factors that the Monte Carlo simulation needs for the analysis. Alpha and beta are two parameters that can be calculated based on specific equations related to different probability distributions. As discussed in chapter two, PERT distribution is suitable for this study. Alpha (α) and beta (β) can be calculated using equations (2-5) and (2-6) that are introduced in Chapter 2.

Table 3-3 Monte Carlo simulation variables

Independent variables	Dependent variables
Number of cows	Cost of pumping unit
Volume of on-site manure	Cost of AD
Volume of off-farm organic waste	Cost of generator
Hydraulic retention time (HRT)	Cost of upgrading unit
	Cost of solid and liquid separator
	Engineering & design costs
	Operational and maintenance costs
	Total capital costs

Third, the results of the regression models are subjected to Monte Carlo simulation. This step improves the results since the cost estimating regression models are generated based on the actual data from the database. The outcome of these regression models can act as new data points in the Monte Carlo simulation. The calculated regression equations are based on three variables (number of cows, HRT, and total feedstock) depending on the first modeling. All the results fit into the simulator. When the model generates samples based on the independent and dependent variables, the same number of results (5000) would be generated from the regression equations.

The number of trials in the Monte Carlo simulation is 5000 times for each group of parameters: regression models and independent and dependent variables. In order to present the calculation process, there are four groups of variables generating 5000 outcomes based on the defined probability distributions (PERT distribution) for each group. Group one is the independent and dependent variables, group two is the regression equations based on the number of cows for each farm, group three is the regression equations based on HRT, and group four is the regression equations based on the total feedstock of each farm. The average results of the 20,000 outcomes would be the highest possible result of this simulator with a 90% coefficient.

Figure 3-6 shows the Monte Carlo simulation and its cost estimation process to visually present the analyses that are related to this modeling (APPENDIX D provides a Microsoft Excel interface of the simulator).

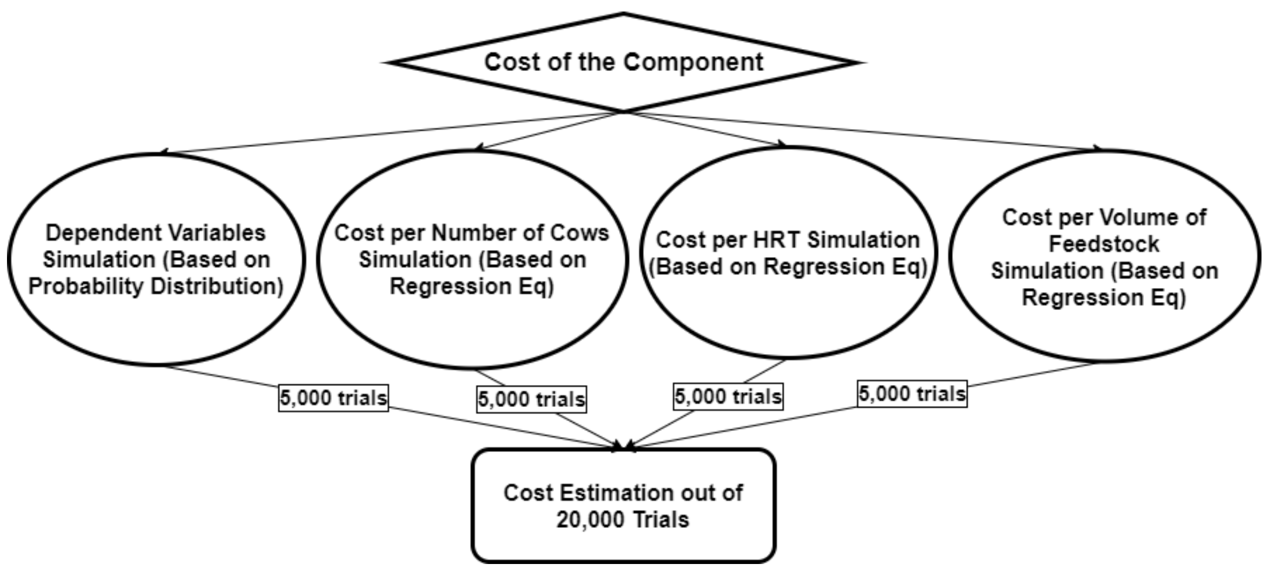


Figure 3-6 Flowchart showing the Monte Carlo simulation process

CHAPTER FOUR

RESULTS AND DISCUSSIONS

4.1 Introduction

This chapter presents the cost estimating models developed using the methods described in chapter 3. The flowchart (Figure 4-1) shows the steps taken to accomplish the result of this study. The analyses started by developing a dataset of actual active biogas projects in Canada and the USA and collecting their financial information. Second, this database has been used in two mathematical methods to develop models for cost prediction. The models (equations) and figures are presented in their respective sections.

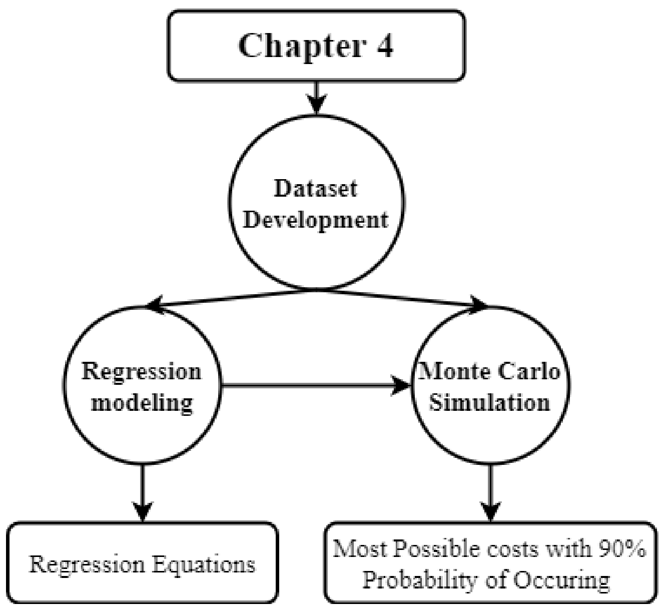


Figure 4-1 Flowchart presenting the content of Chapter 4

A part of chapter four has been published as a peer-reviewed journal paper:

Arash Samizadeh Mashhadi, Noori M. Cata Saady, Carlos Bazan (2021). “Predicting cost of dairy farm-based biogas plants: A North American perspective”. Journal of Energy Systems, 5(4), 365-375. DOI: 10.30521/jes.980467

4.2 Dataset Development

The main reason for developing a dataset comprised of the costs of the active biogas plants in Canada is that it enables defining a mathematical relation between the plant components. For example, suppose we know how much initial investment would be required to build a biogas plant in Ontario on a specific farm with a known number of cows. In that case, this cost is convertible to an equivalent of the same project with the same size in another province (e.g., Newfoundland and Labrador). The more data points that the dataset has, the more accurate prediction of the costs would be obtained. Figure 4-2 presents a schematic of the dataset development process.

The data collection started by first searching for active on-farm biogas plants in Canada. The majority of these projects are located in Ontario, British Columbia, Alberta, and Quebec. Therefore, two approaches have been determined for data collection. First, it started by searching the open accessed reports, literature, and governmental programs for such data. A dataset has been developed based on the available data in these sources. In addition, a questionnaire has been designed and distributed to owners or developers of active farm-based biogas plants. The questionnaire form is provided in APPENDIX C. By 2019, Canada had 61 active biogas plants (Biogas Association, 2019). Unfortunately, the complete financial information is not available for all of them due to the confidentiality of the data. The data available in the public domain is limited in number, particularly for the Canadian biogas plants. Statistical analysis would not be possible on such a small dataset with large gaps in the data points. Hence, the second approach was adopted to expand the dataset because of the similarities between Canada and the USA. These two countries share the same economic market, technologies, suppliers, and to some extent, policies. Precisely, they use the same suppliers of the required components for on-farm biogas plants. Therefore, data points from the United States have been included in the dataset to fill the gaps and make the results more reliable.

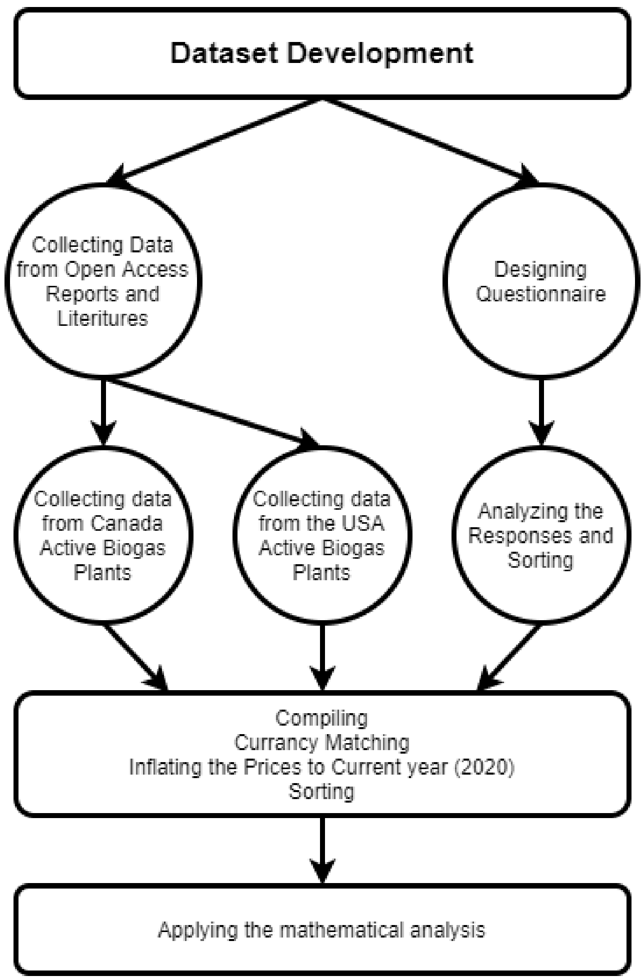


Figure 4-2 Steps of the dataset development

The next step in the dataset development is to check and maintain the uniformity of the data. The costs were in the USD and CAD currency, and they have been converted to CAD because the main focus of this study is the Canadian market. In addition, the projects in the dataset were started at different times. In this dataset, the oldest project was built in 1997. Due to the annual inflation, it is required to convert the costs from each year to their equivalent in the year 2020 to make all the numbers comparable to each other. This was done using the online inflation rate calculator of the Bank of Canada (Statistic Canada, 2021). After this stage, the database is ready for analysis, and each analytical method has been applied separately to the data; the results are presented in the next sections.

4.3 Correlation Analysis

The first step toward the statistical analysis is the correlation analysis to observe the correlation among the parameters. A correlation matrix has been created to visually present the relation between the seven primary parameters that affect the cost estimation of a biogas plant. These parameters are 1) number of cows, 2) HRT, 3) cost of pumping unit, 4) cost of the digester, 5) cost of the generator, 6) cost of the upgrading unit, and 7) capital cost. Figure 4-3 shows the graphical correlation matrix of these parameters graphically. In order to be able to review the correlation between every two parameters individually, the detailed graphs and the correlation equations for each cost parameter based on the “Number of cows” and “HRT” are provided in APPENDIX B.

4.4 Modeling the Cost of On-Farm Biogas Projects

The regression analysis has been conducted to the developed dataset based on the observed correlation between the cost of each component in a biogas plant and the number of cows. This is one of the direct ways to estimate the biogas plant costs with very little detailed information about the farm at the beginning. So, this model can be useful for farmers to calculate the required investment and help them in their decision-making process. In addition, this section will continue

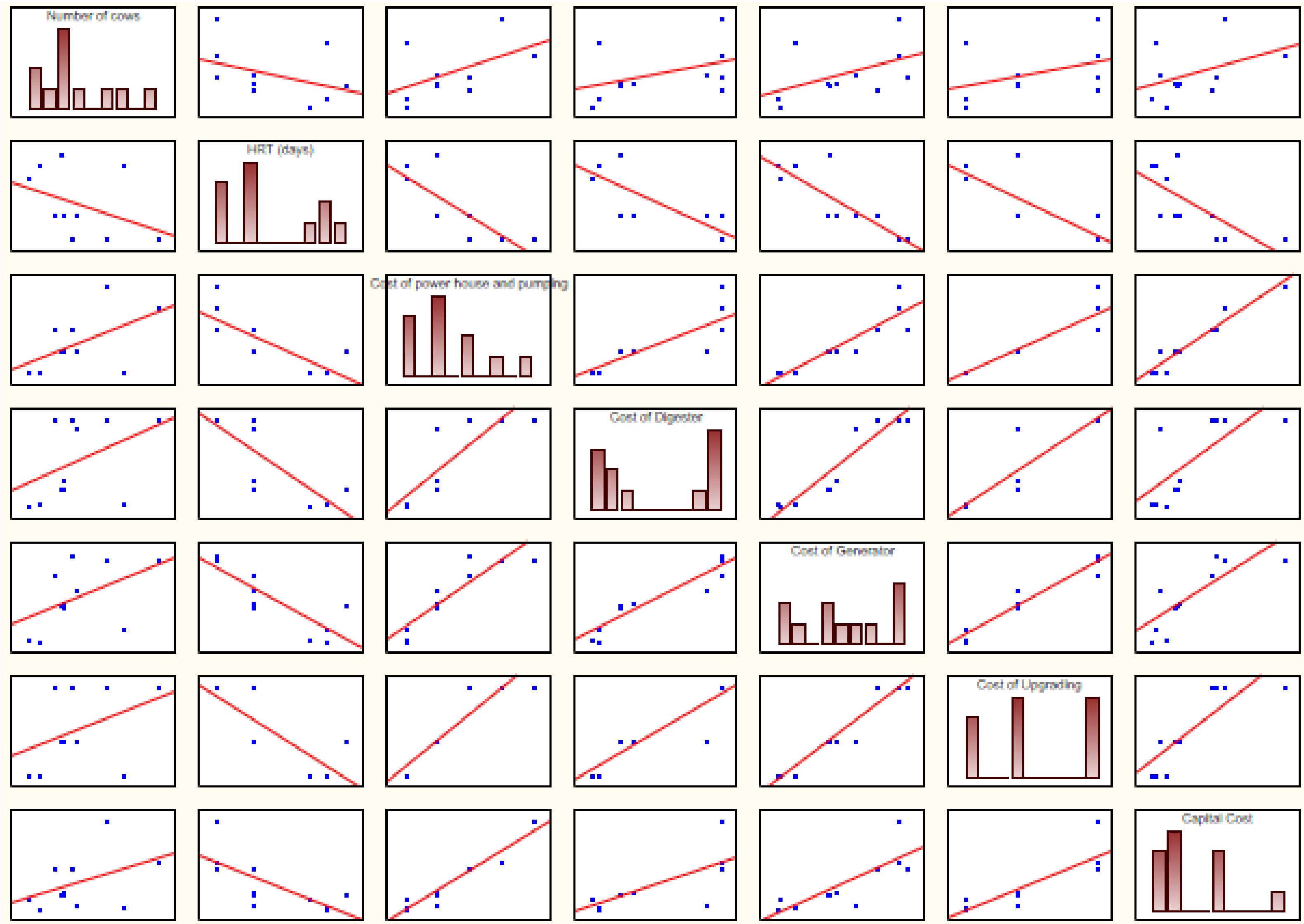


Figure 4-3 Correlation matrix of statistical parameters using the original dataset.

by adding risk analysis to the generated results and the original dataset using the Monte Carlo simulation. Although the simplicity of the first model is beneficial and provides an immediate estimation of all major costs, adding more information of the farms' specifications as input data to the simulator, a robust and reliable prediction of the costs can be generated. Finally, the most probable situation for an on-farm biogas plant in Canada that is best for Canadian markets is discussed.

The model's statistics describe the model's accuracy and reliability. The first statistic is the "Multiple R"; this value is always between 0 – 1. It represents the strength of the linear relationship of the model, and the more its value gets closer to 1, the stronger the model is (Salkind, 2015). The second statistic is "R Square," presenting how well the independent variable explains the variation of the dependent variable (Frost, 2021). The range of the value for this parameter is between 0 – 1, and the more closeness to 1 represents that the variation is closer to the mean; R Square can be calculated based on Equation (4-1).

$$R^2 = \frac{Variance\ explained\ by\ the\ model}{Total\ variance} \tag{4-1}$$

The third statistic representing the worthiness of the model is the "Standard Error." This value is calculated based on the average distance that the observed values fall from the regression line. Eventually, this statistic tells how much error the model has compared to the actual data. Since all the regression models in this study estimate costs, the standard error is the standard deviation for the predicted costs.

4.5 Modeling Based on Regression Analysis

4.5.1 Capital costs based on the number of animals

The capital cost of the on-farm biogas plants can be estimated based on the number of animals housed on the farm or the quantity of manure. This section develops a relationship between the capital costs of biogas plants and the number of cows. This relationship is based on the developed dataset of on-farm biogas plants in North America and their capital costs. Table 4-1 is extracted from the dataset developed in this study to give the capital costs and the corresponding number of cows.

The regression models have been developed based on Table 4-1, and the statistical analysis results are provided in Table 4-2 to Table 4-5.In order to decrease the marginal analysis error, the dataset farms are divided into two groups: group one is the farms with less than 1000 cows, and group two is the farms with more than 1000 cows. The main reason for this division is

Table 4-1 Number of cows and the corresponding capital costs.

Number of cows	Capital cost (CAD)
100	3,709,424
230	2,887,410
400	6,175,466
480	4,199,006
500	4,361,336
500	4,171,375
600	6,334,343
600	5,445,000
650	6,275,967
1000	2,100,000
1000	1,917,900
1200	3,080,825
1400	4,800,000
1600	6,842,748

the similarities that farms with less than 1000 cows share and the complexity that the farms with more than 1000 cows may have.

Most of the farms in each category use the same technologies, and the related costs are quite similar. The farms with 1000 cows and above have additional equipment, such as a biogas purification unit, that increases their capital cost and operational expenses; however, the enhanced biogas quality makes it feasible for large farms.

The simple linear regression model follows the basic rules given by Eq. (2-1). The linear regression model developed for the range of cows below 1000 is given in Eq. (4-2), and for the farms with more than 1000 cows is given in Eq. (4-3). It is essential to examine the models statistically to ensure they are strong and the original hypotheses are accurately chosen.

$$Capital\ Cost\ (CN < 1000) = 485CN + 2.65 \times 10^6 \qquad (4\text{-}2)$$

$$Capital\ Cost\ (CN > 1000) = 7882\ CN - 6.03 \times 10^6 \qquad (4\text{-}3)$$

The main statistical parameters that indicate the strength of the models are explained based on the F-test results. The F-test is applied on the dataset shown in Table 4-1 at a significance level (alpha) of 0.05, which is a standard significance level for statistical tests. If the calculated F-value is more than the F critical value, the model is significant and explains the hypothesis. In other words, if the F-value is not significant, the model needs to be revised.

Conducing the F-test on farms with less than and above 1000 cows separately, it is proven that both models of this study (Eq. (4-2) and Eq. (4-3)) are statistically significant. Not only the calculated F-value in both cases is highly greater than the F critical value, but also the p-value of the F-test is very close to zero, which means the models are highly significant and almost 100%

of the variance in the dependent variable is explained by the independent variable in these two models.

For instance, the calculated F-value for farms with less than 1000 cows is 4.8E+7, while the critical F-value is 3; this large gap between these two factors highly shows the significance level of the model. In addition to that, the p-value for the same farms in the F-test is 6.73E-30 which can be considered as zero that confirms the highest significance level of this model; the detailed results of the F-tests for both models are provided in Table 4-2 and Table 4-3.

Table 4-2 F-Test variances for farms with CN<1000

	Capital Cost	Number of cows
Mean	4839925	451
Variance	1.5778E+12	33036
Observations	9	9
df	8	8
F	47759928.12	
P(F<=f) one-tail	6.72687E-30	
F Critical one-tail	3.4381	

Table 4-3 F-Test variances for farms with CN>1000

	Capital Costs	Number of Cows
Mean	3748294	1240
Variance	4.29862E+12	68000
Observations	5	5
df	4	4
F	63214931.03	
P(F<=f) one-tail	7.50727E-16	
F-Critical one-tail	6.3882	

The next step toward validating the models is conducting a t-test for the models to see whether the p-value for each independent variable is significant or not. In Table 4-4, the p-value for CN is 0.035, which is less than 0.05. This means that this independent variable, “Number of cows," in this model significantly explains the capital costs of biogas plants. The same scenario is accurate for the results shown in Table 4-5 that the p-value for CN is 0.001, and the model is highly significant.

Table 4-4 Regression analysis for capital costs for farms with below 1000 cows.

Regression Statistics		
Multiple R	0.7030	
R Square	0.4942	
Adjusted R Square	0.4220	
Standard Error	955012.4	
Observations	9	
	Coefficients	p-value
Intercept	2648284	0.021
CN	485	0.035

Table 4-5 Regression analysis for capital costs for farms with more than1000 cows

Regression Statistics		
Multiple R	0.9913	
R Square	0.9827	
Adjusted R Square	0.9770	
Standard Error	314589.2	
Observations	5	
	Coefficients	p-value
Intercept	-6025186	0.004
CN	7882	0.001

This section proves that the models are strong and statistically significant. The initial hypothesis, capital cost estimation based on the number of cows, is a significant parameter to explain the objective. To see how much of the capital cost variability is explained by the CN, the R square and adjusted R square should be considered.

For instance, in the first model for farms with less than 1000 cows, the R square and adjusted R are 0.49 and 0.42, respectively. It means that the number of cows can explain roughly

49% of the capital costs. The higher R square indeed gives more power to the predictor, but it does not mean that the models in not useful. The lower R square in this model is that the capital cost is sensitive to the cost of other components that in the next sections, major components of a typical biogas plant are modeled separately. Adjusted R square has the same interpretation as R square basically; it is adjusted based on the size of the dataset and the number of independent variables, which is a useful parameter for comparison between models. For example, the adjusted R square for farms with less than 1000 cows is 0.42, while for the farms with more than 1000 cows is 0.97. It can be realized that the model for CN>1000 has a better prediction than the CN<1000.

Finally, to examine the models and find the prediction error, capital costs for two farms with 650 cows and 1600 cows are estimated by the models (Eq. (4-2) and Eq. (4-2)) and compared to the actual reported costs in the dataset. A farm with 650 cows in Canada, the capital costs of its biogas plant would be around $2.8 million, and a farm with 1600 cows would cost $6.6 million, respectively. The limitation of this model is that it predicts the capital cost of on-farm biogas plants assuming the feedstock is only dairy manure. Some farms may digest off-farm waste such as the organic fraction of municipal solid waste, food-processing waste, or even organic biodegradable industrial waste. Digesting off-far waste and manure will affect the capital costs and revenue and may introduce an error in the model prediction. A farm with 650 cows located in British Columbia acquired its biogas facility for $3.2 million (Werner et al., 2007). It shows that the total error in these two models is 10% which is an acceptable margin because of the possible variations in the development process. Not only the number of cows for a comparison between two farms are important, but also the quality of the manure, the climate temperature, the type of the digester, and the operational parameters, are essential.

4.5.2 Capital cost based on the hydraulic retention time (HRT)

The second model uses the digester hydraulic retention time (HRT) to predict the capital costs. A longer HRT increases the expenses because a larger digester is required, and more energy is consumed to maintain the digester at the desired operating temperature. Thus, this parameter can affect the costs strongly. The HRT is highly dependent on the volume of the digester, the larger the digester, the longer the HRT for the same volumetric flow rate of the feedstock.

The HRT is also significantly related to the operating temperature and total volatile solids in the manure reflected by the organic loading rate. The longer HRT increases the volume of the biogas produced from the same feedstock since it allows a greater extent of completion of the bioreactions, but it is not always beneficial. Therefore, it is better to determine the optimum range for HRT to get the maximum benefit of the plant from an economic point of view.

The optimum range for the HRT is usually between 20 to 30 days. Table 4-6 shows the HRTs of active biogas plants in Canada and the USA and their reported capital costs. The regression modeling has been applied to this table, and the developed regression linear model is given in Eq. (4-4), and Table 4-8 presents the regression analysis results.

In Eq. (4-4), the independent variable is the HRT of the biogas digester, which depends on the type of digester or the available liquid volume in the feedstock. The minimum HRT in the provided dataset in Table 4-6 is 20 days, the average is 24 days, and the maximum HRT is 37 days. Hence, the respective capital costs based on minimum, mean, and maximum HRT would be \$2.2 million, \$2.6 million, and \$3.7 million (Werner et al., 2007). Estimating the costs based on the HRT only is not recommended since the range of changes in this factor is very limited. The capital cost would not be sensitive to the size of the farm because other parameters such as the operating temperature or total solid percentage of the feedstock have more impact on the HRT, which are not related to the farm's size optimum range.

Table 4-6 Variation of the capital cost with the hydraulic retention time

Hydraulic retention time (days)	Capital costs (CAD)
22	6334343
22	6842748
24	3275967
22	10205925
29	4199006
24	6175466
24	4361336
24	4171375
28	2887410
28	3080825
27	3709424
20	484044
37	544500

$$Capital\ Costs\ =\ 414017\ +\ 87690 * HRT \qquad (4\text{-}4)$$

The same statistical tests are applied to this model to indicate its validity. Table 4-7 provided the results of the F-test. It is clear that the F value (3.5E+11) is significantly larger than the F critical value (2.87) and the p-value (almost zero) for the F-test is highly significant. By considering only the F-test, it is concluded that the model is perfectly suitable for the capital cost estimation of a biogas plant. In contrast, when we run the t-test on this model (Eq.4-4), HRT does not show a significant parameter in this modeling. Based on the results of the t-test (Table 4-8), the p-value (0.09) for the HRT passed the alpha limit (0.05), and it means that the capital cost cannot be predicted accurately by only HRT.

In addition to those two statistical tests, the R square (0.24) and adjusted R square (0.17) are very. It means only 17% of the capital costs can be explained by the HRT; hence, the model which predicts the capital cost based on the HRT is not as strong as the previous model (capital cost/number of cows).

Table 4-7 F-test variances for capital costs based on HRT

	Capital Cost	HRT
Mean	4328643	25
Variance	6.88E+12	19
Observations	13	13
df	12	12
F	3.51E+11	
P(F<=f) one-tail	2.47E-67	
F Critical one-tail	2.687	

Table 4-8 Regression analysis of the capital costs based on the hydraulic retention time.

Regression Statistics		
Multiple R	0.6546	
R Square	0.2371	
Adjusted R Square	0.1678	
Standard Error	1226013.183	
Observations	13	
	Coefficients	p-value
Intercept	414017	0.015
HRT	87690	0.091

This weakness is due to the lack of information on the relevant factors not involved in this analysis, such as the operating temperature, digester size, organic load rate, etc. Therefore, capital cost estimation is suggested based on the cow numbers. Nevertheless, this model (Eq. 4-4) can adjust the final result when all the estimations are combined. In other words, this model might not be helpful by itself, but combining its results with the first model gives more accurate results because it will add additional parameters to the analysis.

4.5.3 Cost of the digester based on Multiple variables (CN and HRT)

The digester is the most expensive part of the plant. It is the unit in which the biological process takes place, and if the digester works more efficiently, the net profit would be higher. The digester efficiency is affected by thermal insulation to decrease the heat loss and reduce the plant's electricity consumption to heat the digester to maintain its temperature. Initial prediction of the digester costs can be based on the number of animals housed on the farm, and this section develops this relationship. Table 4-9 presents the digester cost for active biogas plants in Canada and the USA based on the number of cows and the design HRT. It is clear that the total generated manure and collected wastewater on the farm increase with the number of cows. The volume of organic waste and the digester's operational HRT can directly determine the size of the digester and the required heat exchanging unit. Thus, these two factors (number of cows and HRT) can both be used to determine the digester costs. Therefore, multiple linear regression has been used to generate the regression equation for the cost of the digester.

Table 4-9 Variation of the digester cost with the number of cows

Number of cows	HRT (days)	Digester cost (CAD)
600	22	1,026,000
1600	22	1,026,000
650	24	950,000
1000	22	1,026,000
480	29	513,000
400	24	1,026,000
500	24	575,000
500	24	513,000
230	28	400,000
1200	28	400,000
100	27	375,000

$$Digester\ cost\ =\ 2851912\ +\ 72\ CN\ -\ 87834 * HRT \qquad (4\text{-}5)$$

The linear model predicting the cost of the digester as a function of the cow number and HRT is given in Eq. (4-5). The intercept coefficient in Eq. (4-5) represents fixed costs without considering neither the number of animals nor the HRT on the farm. This fixed cost includes labor or feedstock transportation costs, insurance prices, and construction and management fees.

The independent variable dictates the variable costs based on the size of the farm and the amount of the collected waste. The model may adjust to any farm size within the range of the dataset used in this study.

The F-test and t-test have been applied to the model to indicate the significance level of the parameters to ensure that the generated model is statistically valid. Based on the F-test results provided in Table 4-10, the F-value for the cost of AD/CN (4.41E+5) is higher than the F critical value (2.978). The same difference is visible with the F-value for AD/HRT (1.24E+10) cost with the F critical value (2.978). In addition, the p-value is extremely low in both parameters and shows a highly significant level for the generated model (Eq. 4-5). As mentioned earlier, the F-test is not a determining test by itself. It is recommended to run the t-test and analyze the result to ensure the significance level of the results. The results of the t-test conducted on the cost

Table 4-10 F-test variances for the cost of AD based on two variables

	Cost of AD/CN	Cost of AD/HRT	CN	HRT
Mean	N/A	N/A	660	24
Variance	N/A	N/A	194420	6.9
Observation	N/A	N/A	11	11
F	4.41E+05	1.24E+10	N/A	N/A
P(F<=f) one-tail	7.56E-27	4.23E-49	N/A	N/A
F Critical one-tail	2.978	2.978	N/A	N/A

estimator model for anaerobic digester (Eq. 4-5) are presented in Table 4-11. At first glance, the p-value for CN (0.62) is considerably high and is not

Table 4-11 Regression analysis of the cost of digester based on the HRT and CN

Regression Statistics			
Multiple R	0.8367		
R Square	0.7000		
Adjusted R Square	0.6250		
Standard Error	179300.3		
Observations	11		
	Coefficients	Standard Error	p-value
Intercept	2851912	630485.3	0.002
HRT	-87834	23518.99	0.006
CN	72	140.0188	0.620

significant; this would be a sign for analyzers to revise the model and eliminate the CN factor from the calculations and regenerate the cost predictor model based on only HRT. However, by having a close look at the result, it can be understood that the standard error is reasonably low for this variable (CN standard error = 140), and the R square (0.7) and adjusted R square (0.63) are at the acceptable range that gives the model enough credit to remain useable.

Additionally, in real projects, the amount of generated manure on-farm or the number of cows can directly influence the cost of digester because the size of the reactor is highly dependent on the loading rate of the feedstock. Hence, although the CN is not showing any significant level in the results, it can still be helpful in the model and bring more accuracy to the predictions.

To compare the result of this model (Eq. 4-5) with the data available in academic studies, For the same farm size as in the previous example, if we consider the CN = 650 cows and the HRT = 22 days, the cost for the anaerobic digester would be estimated $ 921,148. The digester cost in an actual project is reported $1 million (Manea et al., 2012), so the error in the cost of digester based on two factors (HRT and CN) for this specific farm is 8.9%. This price is about

33% of the predicted capital cost by the first regression model. This model is only related to the component of the digester and its construction. Other expenses, like the engineering and management costs, should be added separately.

4.5.4 Cost of the Combined heat and power unit (CHP)

After the digester, the second most important unit in a biogas plant is the combined heat and power (CHP) generating unit. Initial prediction for the CHP unit cost can be calculated based on the number of animals housed on the farm. Table 4-12 provides the variation of the CHP cost with the number of cows on the farm. The Table is based on the data collected from active biogas plants in Canada and the USA and provides reliable information for future predictions.

Table 4-12 Variation of the CHP unit cost with the number of cows.

CHP unit costs (CAD)	Number of cows
1416960	600
1721647	1600
1018440	650
1470720	1200
452640	100
1351647	1000
432960	230
831480	480
1180800	400
870840	500
811800	500
805600	1000
915000	600
727524	1000
681374	600
541200	560
1699855	1400
360610	236

The result of the regression analysis is provided in Table 4-14 shows a strong relationship between the variables (R^2 = 0.618). The intercept coefficient represents the fixed costs without considering the number of animals on the farm, which means there is a minimum required investment for providing an on-farm generator regardless of the amount of biogas produced. The cow number provides the variable costs based on the size of the farm and the amount of collected manure. Eq. (4-6) is the generated model for this specific component based on the real data given in Table 4-12.

The initial step is to test the model statistically by F-test and t-test to determine the significance level of the variables in the model. The results of the F-test presented in Table 4-13, the F value (1.07E+06) is much greater than the F critical value (2.272), which brings us to a conclusion that the model is significant in total. So, the t-test should be conducted to check the significance level of the CN. The results of the t-test are perfectly shown how significant is the model. Based on the result in Table 4-14 CN is highly significant because of the p-value (0.0001), which is extremely lower than alpha (0.05). In addition, the R square (0.62) and adjusted R square (0.59) are in an acceptable range; it means that 62% of the results may explain by the dataset.

$$Cost\ of\ CHP\ unit\ =\ 390078\ +\ 811\ CN \qquad (4\text{-}6)$$

Table 4-13 F-test variances for the cost of CHP unit based on CN

	Cost of CHP	CN
Mean	960616	703
Variance	1.80971E+11	169795
Observations	18	18
df	17	17
F	1.07E+06	
P(F<=f) one-tail	7.26944E-48	
F Critical one-tail	2.272	

Table 4-14 Regression analysis of the cost of CHP unit based on the CN

Regression Statistics			
Multiple R	0.786		
R Square	0.618		
Adjusted R Square	0.594		
Standard Error	271095.3		
Observations	18		
	Coefficients	Standard Error	p-value
Intercept	390078	129111.5	0.008
CN	811	159.564	0.000

In order to test the model and calculate the possible error, the same example as in the previous sections is applied to the model, a farm with 650 cows using Eq. (4-6), the average required investment for the CHP unit would be 917,520 CAD. In comparison to the actual cost of this component, which is $1 million (Werner et al., 2007), the average error of the provided model is 10%.

4.5.5 Cost of biogas cleaning and upgrading unit

The biogas cleaning and upgrading unit can open several opportunities for the farmers to sell their biogas in various forms. The two main forms of selling the biogas are converting it to electricity and then selling it to the power grid, purifying it, and selling it as compressed natural gas (CNG) (Kaur et al., 2020). The main purpose of the upgrading unit is to eliminate the impurities such as CO_2, water vapor, H_2S, NH_3, and trace gases from the produced biogas.

The biogas cleaning and upgrading unit increases the methane concentration to be sold directly as a compressed natural gas or injected into high-efficiency thermal generators to produce more electricity and fewer emissions during combustion. It should be noted that based on the collected dataset for this study, the costs of the upgrading systems are almost equal to the digester cost and may increase the capital costs by more than 50% (APPENDIX A provides details of the upgrading cost). Therefore, to make the plant feasible for farms with a smaller size, the price of biogas upgrading unit is applied only to farms with a minimum of 1000 cows.

The efficiency of the electricity generation without biogas upgrading is indeed lower compared to the upgraded biogas. However, the farms with less than 1000 cows still profit because of the reduction in the initial investment. Farms with 1000 cows and more were selected from the dataset (APPENDIX A) and presented in Table 4-15 to run the analysis and develop the cost estimator model. The best linear regression equation that fits these data points is generated to estimate the cost of upgrading units for any large farm in Canada by Eq. (4-7).

Table 4-15 Variation of upgrading unit costs based on number of cows

Number of cows (CN)	Upgrading unit cost (CAD)
1600	1,845,000
1200	1,230,000
1000	1,845,000
1000	1,600,000
1000	1,450,000
3300	3,000,000
1600	2,200,000
1200	1,500,000

*The modeling is limited to the CN>1000 based on the original assumption of this study

$$Cost\ of\ upgrading\ system\ =\ 867341\ +\ 650\ CN \tag{4-7}$$

It is important to statistically verify the generated model, so as the previous models, this model is also tested under the F-test and t-test to see whether the model is significant or not. The result of the F-test is shown in Table 4-16, and the F value (5.19E+05) in this analysis is significantly higher than F critical value (3.79) which mean the model is very reliable and based on the p-value (1.85E-19) in the same result's table, the model (Eq. 4-7) is highly significant.

Table 4-16 F-test variances for farms with CN>1000

	Cost of Upgrading unit	CN
Mean	1833750	1487
Variance	3.10E+11	5.98E+05
Observations	8	8
df	7	7
F	5.19E+05	
P(F<=f) one-tail	1.85E-19	
F Critical one-tail	3.79	

Table 4-17 Regression analysis of the cost of upgrading unit based on CN

Regression Statistics			
Multiple R	0.9022		
R Square	0.8139		
Adjusted R Square	0.7829		
Standard Error	259581.8637		
Observations	8		
	Coefficients	Standard Error	p-value
Intercept	867341	209802.188	0.006
CN	650	126.833	0.002

The second step of the analysis is the t-test results (Table 4-17). The p-value for the CN in this test is 0.002, which means the independent variable is also significant in the model. In addition, based on the value of R square (0.8139) and adjusted R square (0.78), the model can explain 81% of the results, which means the model perfectly fits the dataset and the predictions have a very low error for this specific component.

The linear model of predicting the CHP cost as a function of the cow number for on-farm biogas plants in North America for farms of more than 1000 cows (digesting only manure) is given in Eq. (4-7). This model is helpful mainly for farms with very high biogas production. For instance, the cost of the upgrading unit for a farm with 1000 cows is estimated by Eq. (4-7) is over \$1.5 million, which has only 6% error compared to the real available data (\$1.6 million (Werner et al., 2007)).

4.5.6 Cost of pumping unit based on number of cows

Powerhouse and pumping unit is the link between all the unit and plays an important role in a biogas plant. The pumping unit transfers the wastewater from the barn (collected manure) to the mixing tanks and again pumps it to the digester for biogas formation. After the digestion process, the remaining material at the bottom of the reactor is needed to pump out for further usage as a fertilizer or animal bedding.

Since cost prediction based on the number of cows was one of the successful models so far in this study, the cost of the last component will be calculated based on the number of cows (CN). Hence, Table 4-18 is extracted from the dataset for modeling this component and testing the model statistically.

Table 4-18 Cost of pumping unit based on CN

Number of cows	Cost of pumping unit ($)
600	337020
1600	1421275
650	252765
1200	1285100
100	168510
1000	505530
230	168510
480	252765
400	337020
500	252765
500	252765
1000	744000
1400	2000000

The initial step before the statistical tests is to generate the regression equation from Table 4-18. The Eq. (4-8) is a cost estimator for the pumping unit that predicts the costs based on the data collected from active biogas plants in Canada. The F-test and t-test should be conducted to ensure that the model is accurate and statistically significant. The results of the F-test are given in Table 4-19, and the F value (1.64E+06) is extremely higher than F critical value (2.69), and the p-value (2.36E-35) is near to zero, which means the model (Eq. (4-8)) has a significantly high level.

$$Cost\ of\ pumping\ unit\ =\ 1139CN\ -\ 232903 \qquad (4\text{-}8)$$

Table 4-19 F-test variance for the cost of pumping unit per CN

	Cost of pumping unit	CN
Mean	613694	743
Variance	3.437E+11	2.10E+05
Observations	13	13
df	12	12
F	1.64E+06	
P(F<=f) one-tail	2.39E-35	
F Critical one-tail	2.69	

The second statistical test is the t-test, and the results are shown in Table 4-20. The previous test indicated the significance level of the whole model, and it is also important to verify the significance level of each variable (CN). So, the p-value for CN (0.00005) is an important factor, and since it is less than alpha (0.05), the model is significant based on both models. Not only the p-value shows the significance of the results. The R square (0.792) and adjusted R square (0.774) are reasonably high in this model. The R square confirms that almost 78% of the results are explained by the independent variable, a high response rate for these analyses.

Table 4-20 Regression analysis of the cost of pumping unit per CN

Regression Statistics			
Multiple R	0.890		
R Square	0.792		
Adjusted R Square	0.774		
Standard Error	2.79E+05		
Observations	13		
	Coefficients	t Stat	p-value
Intercept	-232902	-1.53	0.153
CN	1139	6.48	0.000

4.6 Modeling Based on Monte Carlo Simulation

Monte Carlo Simulation is a supporting method to help in the decision-making process. The simulation started with defining the independent and dependent variables. The independent variables are the number of cows, on-site manure volume, received off-site organic waste volume, and hydraulic retention time (HRT). For each variable, a set of statistics such as the minimum, maximum, mean, standard deviation, and mode (most common value) are extracted from the dataset and listed separately (Table 4-21). The data in this table are needed to define a specific probability distribution for each variable. Since the objective of this study is 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 (Salling et al., 2009). PERT distribution is selected

Table 4-21 Independent variables based on the original dataset

	Number of cows	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

for the analysis in this study because it allows the user to define minimum and maximum threshold values for each variable. This feature makes it suitable for financial and cost analysis (Moitra, 1990; Salling et al., 2011).

In addition to the parameters in Table 4-21, PERT distribution needs two shape parameters, Alpha (α) and Beta (β), as extra values that are calculated based on the minimum, maximum, and mode (most common) values of each variable (Davis, 2008). The equations to calculate Alpha and Beta are Eq. (2-5) and Eq. (2-6). In these equations, "a" is the pessimistic value, "c" is the optimistic value, and "b" is the most common value of each variable.

The next step is to determine alpha and beta for each variable and then run the Monte Carlo simulation to pick a number based on the chosen probability distribution randomly. The simulation is developed on Excel by an add-in called @Risk (developed by Palisade.co) to get an extra feature on Microsoft Excel for this simulation. The Monte Carlo simulation was developed based on the parameters and requirements defined on @Risk. 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 procedure in the modeling. Dependent variables are the components of a biogas plant that any change in the value of the independent variables may change their calculated costs. 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 (HRT); as a result, this increase in the size would need more initial 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.

Summing all these individual costs results in the total capital cost needed. The values for each dependent variable (pumping unit, digester, generator, upgrading unit, and maintenance costs) are provided in Table 4-22. Finally, the cost of engineering and design is calculated based on a rate of 5% of the total cost. Typically, engineering fees are based on both parties' agreement, and the farm specifics are not involved (Amigun et al., 2007). The same 5000 trials were applied to the variables in (Table 4-22), and the average result for each of them was considered the cost of component for Canadian biogas plants.

The purpose of the Monte Carlo modeling is to provide a robust foundation for the regression modeling results. The Monte Carlo simulation applies to the regression equations that have been developed in this study, and 5000 results from each equation would be calculated. A large number of repetitions can reduce the error in the modeling. The average result of these 5000 values would be more realistic than the dataset's actual data. Not only is the Monte Carlo simulation applied to the regression models, but it is also applied to the original dataset.

Table 4-22 Dependent variables based on the original dataset

	Component Cost (CAD)				
	Pumping system	Digester	Generator	Upgrading	O&M (CAD/yr)
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	2.94	4.13	4.81	5.00	2.15
Beta	3.06	1.87	1.19	1.00	3.85

For instance, for a specific cost such as the operational and maintenance costs, the model generated 5000 results out of the dataset, and additional 5000 results were generated based on the regression equation, and the average of these 10,000 values would be the predicted cost for the

O&M costs. Finally, the results of both methods were combined, and an average result was calculated for each variable. The advantage of this method is that it reduces the error and provides a more realistic outcome. Figure 4-4 shows the result of the Monte Carlo simulation. The most common value in this analysis for capital costs is CAD 4.3 million. It means that based on the data collected and the regression equations provided, the most potential investment for a farm-based biogas plant in Canada is around CAD 4.3 million. It should be mentioned that this price is more accurate for the farms between 300 to 1600 cows. Farms with more than 1600 cows might need a higher investment for their construction. Based on different types of skewness for

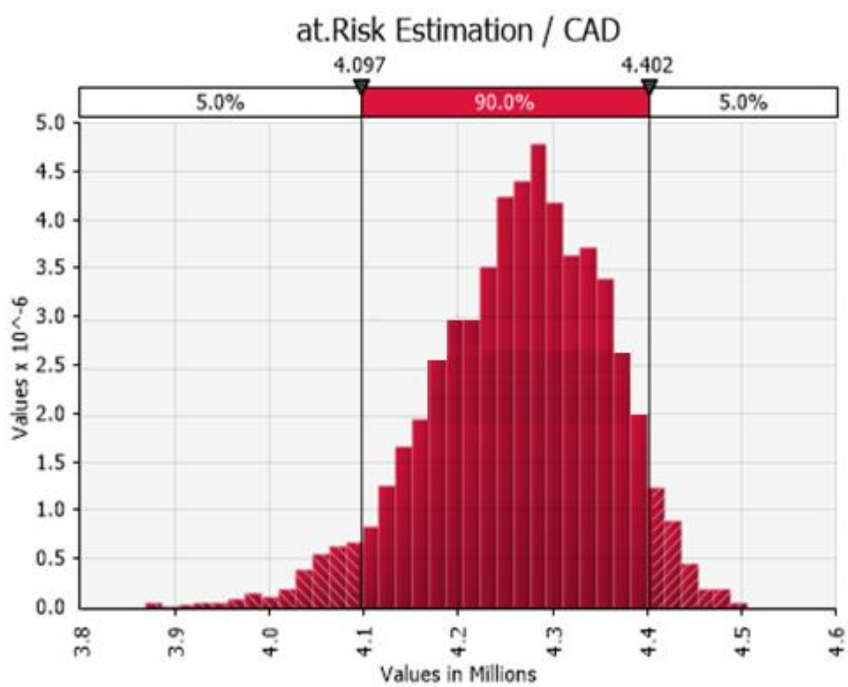


Figure 4-4 Monte Carlo simulation results

statistical distributions, the results (Figure 4-4) are 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 mode (most common value) in this analysis (Moitra, 1990).

One of the reasons for negative or positive skewness is when some datapoint is very far from the average value and causes a long tail of the distribution graph. In this case, because the skewness is negative, it shows that there are more gaps between the datapoint 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., 500 – 800 cows).

4.7 Summary of the Results

Several models have been developed for the relationship between the size of the farm or the operation parameters and the investment costs. The models can estimate the capital costs, cost of the digester, biogas cleaning and upgrading system, and the combined heat and power generation unit. The operational and maintenance (O&M) costs are typically considered 2 - 4% of the capital cost, although it can be different since many factors are involved in O&M expenses. The equations in Table 4-23 can help farmers or developers of biogas plants to have an initial prediction of investment and component costs of a typical biogas plant in Canada based on only

Table 4-23 Mathematical models for cost estimation of biogas plants in Canada

Item #	Model description	Equation (CAD)	R^2	Equation
1	Capital Cost per CN (CN<1000)	$485CN + 2.65 \times 10^6$	0.494	Eq. (4-2)
2	Capital Cost per CN (CN>1000)	$7882CN - 6.03 \times 10^6$	0.983	Eq. (4-3)
3	Capital Costs per HRT	$87690HRT + 414017$	0.237	Eq. (4-4)
4	Digester cost per CN	$72CN - 87834HRT + 2851912$	0.7	Eq. (4-5)
5	CHP unit cost per CN	$811CN + 390078$	0.618	Eq. (4-6)
6	Upgrading system cost per CN	$649CN + 867341$	0.814	Eq. (4-7)
7	Cost of pumping unit per CN	$1139CN - 232903$	0.792	Eq. (4-8)

two variables, number of cows that represents the farm size, and hydraulic retention time (HRT) that specifically affects on the cost of the digester.

The ones that are only based on the number of cows (CN) are presented in Table 4-23, which means 2 out of 7 models are excluded. Those two models are the capital costs based on HRT and digester costs. The capital cost based on HRT is excluded because it is already proven that this model is not as reliable as other models by itself, and it is only useful if we add it to other analytical methods for more accuracy and this had been done by using Eq.(4-4) in the Monte Carlo modeling. Secondly, the digester cost is excluded because it is based on two variables (HRT and CN) while HRT is highly related to the operational temperature of the digester and the size of the farm is not effective. For instance, both farms with 100 cows or 1000 cows may have a similar HRT, so this equation is important to be reviewed case by case. In general, the cost of the digester is assumed to be equal to 20-25 % on average of the capital cost (based on the data collected from the real projects (APPENDIX A)).

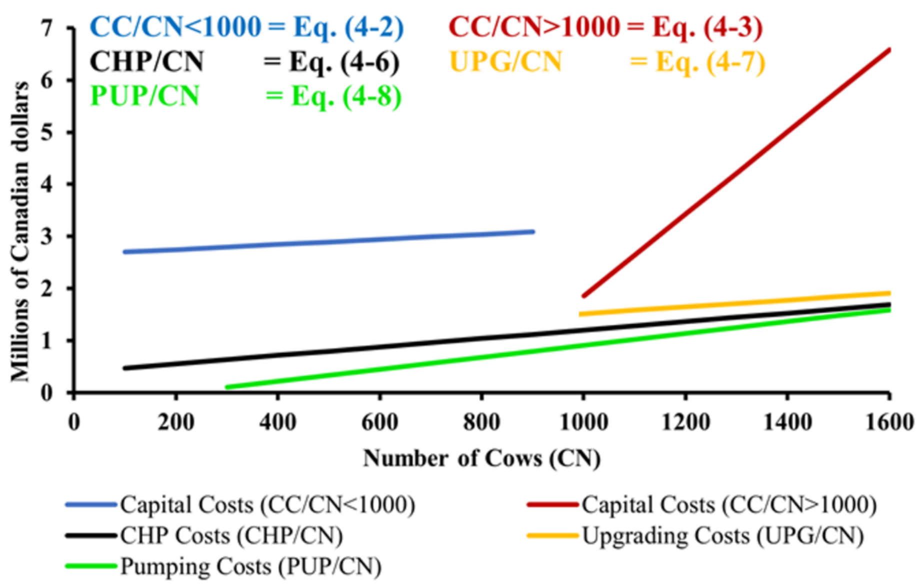


Figure 4-5 Generated models of this study

The equations provided in Figure 4-5 are based on the regression modeling presented in Table 4-23; the applicable range of the farm's size for these equations is 100 - 1600 cows, and for the farms out of this range, the models should be used with more caution. Because the large size plants will have extra complexity in their construction or might use expensive technologies to increase their performance and efficiency (such as biogas purification system), they would need separate modeling not included in this study. However, most of the farms in Canada will fit in the range of this study because the collected dataset is based on the Canadian biogas plants market.

It is essential to determine the minimum farm size that the biogas plant is feasible based on the generated models. In order to find the minimum number of cows that the biogas plants can run with profit, the annual operating costs and the total yearly revenue should be calculated, and the difference between these two numbers would be the net profit (net income). For conditions that the calculated net profit is negative or zero, the biogas plant is not feasible, and the positive net profit shows the profitability of the plant. Figure 4-6 is created to reveal the cost and revenue growth as the size of the farm increases. It was mentioned earlier; the operational costs are roughly estimated based on 2 – 4% of the total capital costs so that the larger farms would have higher expenses during their operation. On the other hand, revenue is estimated based on the available financial predictors in this field of study.

Since the income of the active farms was not possible to collect due to confidentiality, instead of modeling the revenue of the farms, the existed model that has been presented in chapter two was used for income prediction of biogas plants. The most compatible study that has predicted the costs and revenue of biogas plants based on the number of cows has been done by researchers at Florida University, which is fully explained in Chapter 2 (Section. 2.5.1.2). This study's key parameters and assumptions are converted based on Canadian perspectives, such as biogas to electricity conversion rate, biogas yield, CHP unit efficiency, and generated electricity average selling rate in Canada are used to plot Figure 4-6 for farms with 100 to 1600 cows.

The analysis in Figure 4-6 shows that the minimum expenses for on-farm biogas plants in Canada would be roughly $60,000 per year and with a minimum of 160 cows and based on the average manure production of each cow, these expenses would be covered and by increasing the size of the farm, profitability and feasibility of the plant will increases. In other words, based on the generated models of this study, a farm with less than 155 cows cannot generate income since the net revenue is negative in that zone.

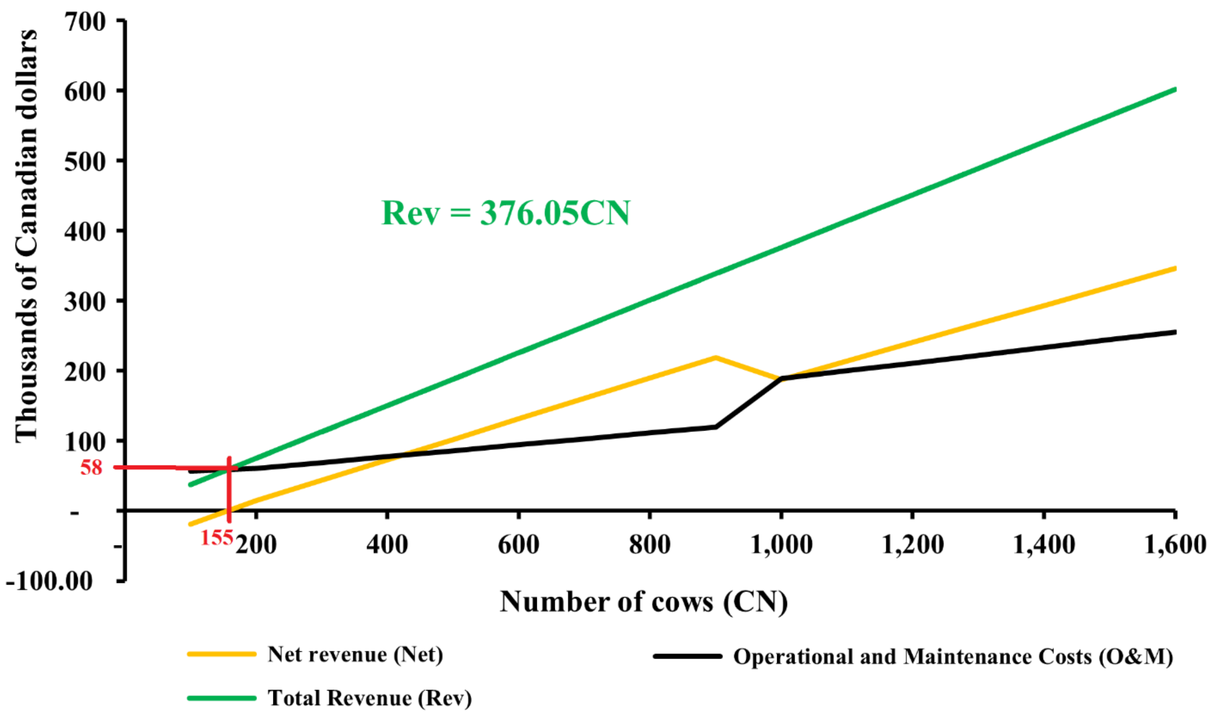


Figure 4-6 Cost and revenue for typical biogas plants

4.7.1 Results Comparison

This section compares the results of the developed models of this study with the results of the budget calculator developed by Washington University (section 3.3.1) because of the similarities in the approach to achieve the objectives. The equations provided in Figure 4-7 are the results of Washington University modeling. The capital costs, operational costs, and revenue are based on the number of cows. For example, based on the models generated in this study, a farm with 650 cows needs CAD 2.97 million of initial investment, CAD119,000 operational costs per year, and generates CAD 245,000 revenue per year. While the Washington study regression analysis for the same farm with 650 cows shows that the required capital cost is CAD 2.8 million, and operational costs are CAD 280,000 per year. Figure 4-7 also presents the growth of costs and revenue based on the size of the farms (number of animals).

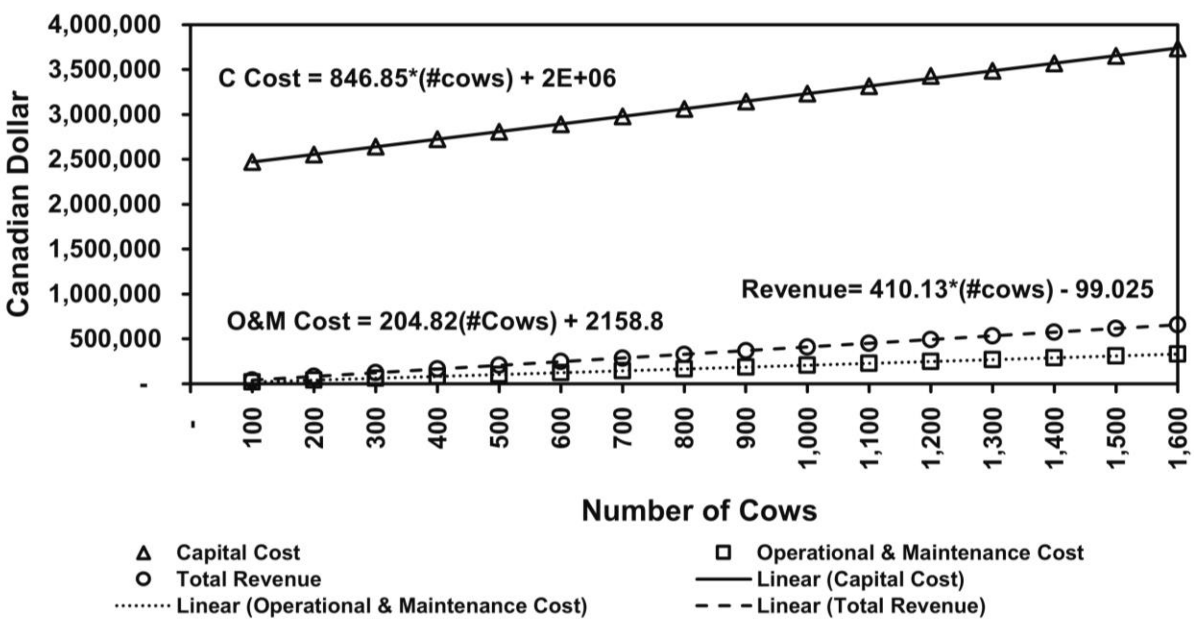


Figure 4-7 Results of the budget calculator developed by Washington University

The results presented in Table 4-24 shows that the error for capital cost is minor (5.7%), while the operational costs are almost 57% lower in this study. The reason is because of improvements in the equipment and technologies used in new projects compared to old ones, and the operational costs declined while the revenue remained the same.

Table 4-24 Comparison of the results between two studies

	Washington study results	This thesis results	Dispute to Washington study (%)
Farm size (#)	650	650	0
Capital cost ($ million)	2.8	2.97	5.7%
Operational costs ($)	280,000	119,000	57%
Revenue ($)	246,000	245,000	0.01%

CHAPTER FIVE

Newfoundland and Labrador Economical Assessment

5.1 Introduction

Newfoundland and Labrador (NL) is the eastern province in Canada with a population of 520,553 in 2021 (Statistics Canada, 2021), and almost 40 percent of the population lives in Northeast Avalon. NL residences produce 20 kg more municipal waste during a year per person compared to the country's average. The average estimated amount of waste produced by Canada is 720 kg/person/year, while in NL, it goes up to 740 kg/person/year (Guy et al., 2015).

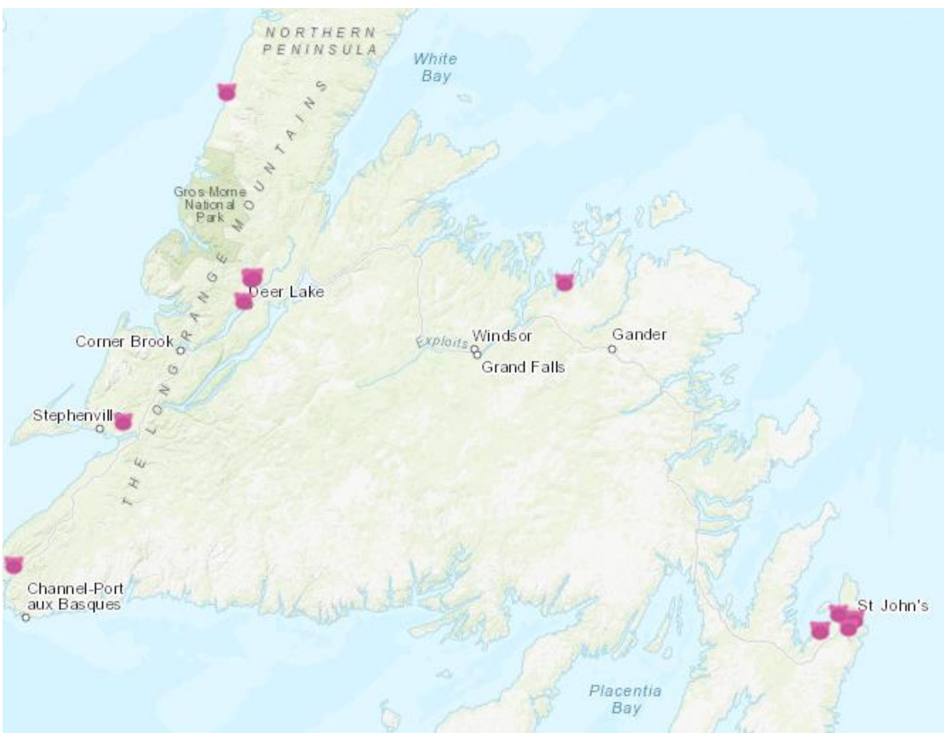


Figure 5-1 Newfoundland dairy farms distribution (Newfoundland, 2021)

The total amount of produced municipal waste in Newfoundland is 400,000 to 500,000 metric tonnes per year, and about 30% of this amount is organic wastes that are convertible to renewable energy (Butler et al., 2017). There are several separated organic waste streams in NL: i) municipal wastewater and municipal organic waste; ii) agricultural waste; iii) sawmill waste; iv) fisheries; and v) forestry. This chapter gives detailed data on these waste categories, the potential of on-farm bioenergy generation, and reviewing a case study of a farm and cost estimation of its biogas plant development based on the models designed in this study.

5.2 Organic Wastes in Newfoundland and Labrador

5.2.1 Forestry

With 3.47 million km^2 (347 million hectares), Canada has about 9% of the world's forests and is the 3rd most forested country in the world (Statistic Canada, 2018). Businesses related to forest harvesting, paper production companies, or commercial sawmills across the country would produce a considerable amount of waste. Forest biomass is the second-largest source of renewable energy after hydro energy that generates both heat and electricity (Canada, 2020).

In 2011, 16,992 hectares of the forests in Newfoundland and Labrador were harvested, and the residue of this amount of harvest and sawmill is the primary source of the forestry biomass production. Out of 581 commercial sawmill companies in NL, about 90% of the total residue comes from 6 companies (Canada, 2020). This concentration of forestry waste generation helps the government of Newfoundland in managing forestry and handling the organic waste; it decreases the price of labor and transportation because of this (Butler et al., 2017). A study conducted by Natural Resources in NL found that the forestry waste includes (tonnes/year) about 24,414 dry in-forest residues, 41,211 green active sawmill residue, 174,000 pulp mill residue, and 5,041 construction/demolition residue. (Consulting, 2014). The Multi-Materials Stewardship Board (MMSB) estimated the total annual amount of residue in the province to be around 41,211 metric tonnes of forestry biomass, with 7,585 metric tonnes of wood waste stockpiled at mills across the province (Consulting, 2014).

5.2.2 Agriculture

Newfoundland and Labrador have a diverse agricultural sector with a high potential for organic waste production. The sources of these organic wastes can vary from woodchip, manure, mortalities, discards, and offal. Based on Table 5-1 in terms of dairy farms, 96 farms in Newfoundland all together have almost 10000 cattle and calves, which shows the available potential of biogas production based on the manure generation of these animals.

Table 5-1 Number of farms and animals in Newfoundland by 2016

	Number of Farms	Number of animals	Average
Cattle & Calves	96	9995	104
Pigs	6	1017	170
Sheep & Lambs	49	2645	54
Hens & Chicken	47	N/A	N/A
Turkey	7	189	27

(Statistics Canada, 2017)

Based on studies in Europe (EU) and the USA, the biogas potential of common livestock was analyzed, and the results for EU show that each dairy cow produces roughly 53 kg of manure per day (19.3 tons of manure per year) (Scarlat et al., 2018), and for the USA is 54.4 - 68 kg/day based on the size of the animals (Ciborowski, 2001; Chen et al., 2014).

This amount of livestock manure can generate 302.6 m^3 of methane per year per animal, producing 10,862 MJ/cow/year of energy or 1056 kWh/cow/year of electricity. The energy generated is not the only benefit of anaerobic digestion; the by-products such as animal bedding, fertilizers, and soil amendments increase the farm's income. The largest farm in Newfoundland is the New World Dairy (address: 748 Maidstone Rd, Saint David's, NL) with more than 1200 cows and is the third-largest dairy farm in Canada (Consulting, 2014). This farm in NL generates about 4 GWh of electricity per year (CBC News, 2013). Based on the Newfoundland power reports, the average residential power consumption is 1264 kWh/household/month (NLPower, 2021). The amount of produced electricity by the New World Dairy farm can supply more than 1000 homes across the province.

5.2.3 Fisheries

Fish processing residues are another potential source of biomass in Newfoundland. There are about 94 licensed fish processing plants across the province that produce a wide range of products like groundfish, shellfish, pelagic, and seals the amount of organic wastes in them is significant (Consulting, 2014). To better understand the amount of possible wastes, fileting the groundfish and cod results in 40 – 60%waste, salmon is about 30%, and shellfish is the highest wasting at about 80% of the total mass. Based on the reports of Statistics Canada regarding the amount of aquaculture waste in each province, the average annual fish processing waste in NL is estimated at 10,620 metric tonnes (Statistics Canada, 2021).

5.2.4 Aquaculture

Aquaculture produces organic waste in the province. There are 145 licensed issued in Newfoundland for aquaculture processing with the majority of them are located at Notre Dame Bay and the Connaigre Penninsula area. This industry produced 17,655 metric tonnes by 2019, with almost 5,000 to 6,000 metric tonnes of organic wastes, including the mortalities (Statistics Canada, 2021). In contrast to fisheries residue that some companies are allowed to dispose of into the ocean, the aquacultural wastes are not permitted to be dumped, and they should be managed onshore. This increases the importance of developing biomass infrastructures to facilitate waste management in this sector.

5.2.5 Municipal wastes

Municipal wastes are another potential source of organic waste. The trend of the amount of residential and non-residential wastes is increasing. Based on the latest report of the Government of Newfoundland in the year 2012, the provincial population was 514,536 (which is very close to the population in 2020 (522,994) (Statistics Canada, 2022)), and the amount of disposed of solid waste 517.229 metric tonnes or 2.75 kg/person/day (Newfoundland, 2017). The province has one of the highest rates of waste disposals in Canada.

The National Canadian average waste disposal in 2016 was 2.58 kg/person/day, and Newfoundland has a 3.1% higher rate of waste generation (Canada, 2022). About 30% of the total wastes in the province are organic; this means that almost 30% of the total wastes are useable and convertible to renewable energy and beneficial by-products (Newfoundland, 2019).

Considering all the available potential sources of organic wastes in Newfoundland, the advantages of on-farm biogas plants, and its compatibility to variations of organic wastes makes it one of the best choices regarding waste management in this province. Since the majority of the population is focused on or near the capital. The capital (St. John’s) has almost 35% of the total province’s population (reported by Statistic Canada: https://www12.statcan.gc.ca/), and it would be more beneficial to select a location near this area. Such location decreases the transportation costs of the wastes to the biogas plant.

Lester’s Dairy Farm is above medium size (650 cows) and is located in a densely populated area. It produces around 21 m^3/day of manure, offering excellent potential for the project's profitability and efficiency. The next section of this chapter provides a detailed economic assessment of Lester’s Dairy Farm plus a cost and revenue modeling for biogas plant development in this specific location.

5.3 Case Study of Lester’s Dairy Farm

Lester's dairy farm is the largest dairy farm on the Avalon Peninsula in NL. This section investigates the available potential of developing on-farm anaerobic digestion on this farm. The section presents the farm characteristics and applies the models developed in chapter four to the data collected from this farm to investigate the feasibility of a biogas plant on this farm. Figure 5-2 shows a satellite view of Lester’s airy Farm. It shows the location of barns, manure storage tank, and access roads to this facility. Since the manure storage tank is already built based on the government of Newfoundland regulations, there is also a reserved space around it. There is no need for facility rearrangement, which is a costly process and reduces the project development timetable to become ready in a shorter amount of time. Lester's farm is located on the south of St. john's city. The farm has 30 employees and houses 600-650 cows for dairy production with a continuous plan to expand. Because of the large variation in temperature during the cold and warm seasons in NL, electricity consumption varies significantly. Based on one-year monitoring of Lester’s Dairy Farm electricity consumption in 2018, the highest amount of usage is 30,000 kWh in April, and the lowest amount is 20,000 kWh in August (Figure 5-3). This variation is relatively large (almost a 50% increase from summer to winter consumption). The average power usage is equal to 25,000 kWh per month. Since the province's current power price rate is 12.3 cents/kWh (Hydro, 2021), the total monthly bill for Lester's Dairy Farm would be over $30,000 or $36,000 per year based on the average consumption.

Figure 5-2 Map of Lester's farm, St. John's, NL

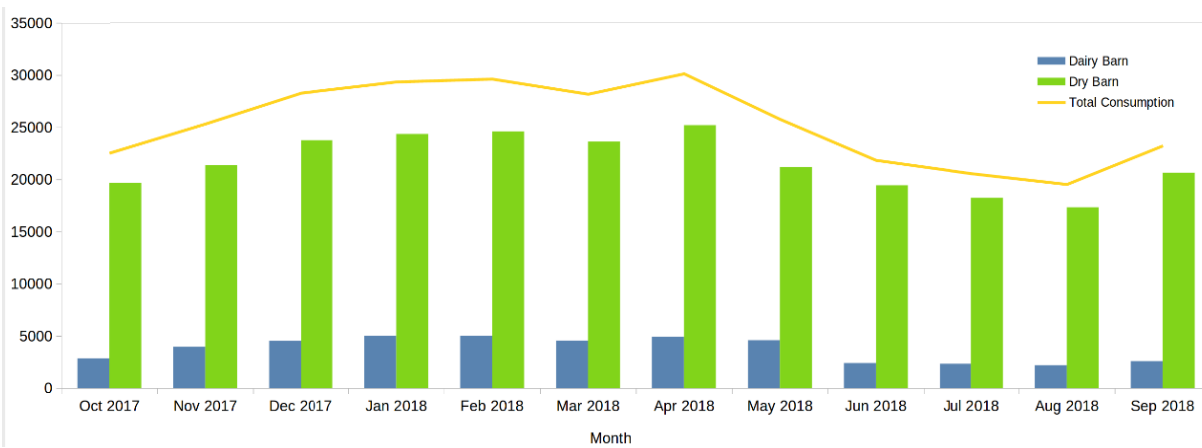


Figure 5-3 Lester's Dairy Farm monthly electricity usage

The waste management system in the farm is a manure scraping system. The total collected manure (20.6 m^3 per day) is transferred to a manure storage tank. The manure collection tank is 8.53 m in height and 39.93 m in diameter and can hold 10,600 m^3 of manure. Based on the regulations of the province of Newfoundland and Labrador, the following specifications must be applied to any manure storage tank across the province (Newfoundland, 2020):

- The distance between the barn and the storage tank should be enough to permit the further expansion of the facilities while providing a convenient filling process.

- There must be an access road to the tank in any weather conditions, and if it is possible, it should be located out of sight. Constructing the storage on the water banks such as a river, drainer, and channel ponds must be avoided.
- In terms of the size of the tank, the tank should be able to store at least 180 days' worth of manure while having a minimum of 60 cm for earthen storage or 45 cm for concrete manure storage of unused free space on top of the tank.

The manure storage tank (Figure 5-4) is a slurry-store aboveground model. It has no top cover and is not thermally insulated; its structure is made of bolted glass fused to steel panels. Corrosion is prevented by lining the steel with fiberglass. It was designed to be easily expandable, covered, and relocated. The tank was purchased in 2004, and its original cost was CAD 750,000.

Since some components that are needed for constructing a biogas plant already exist on Lester’s Dairy Farm, this will decrease the initial investment for developing the biogas facility. For instance, the current pumping system that transfers the scrapped manure to the storage tank is also useful for the biogas plant. The existing manure tank can store all on-farm manure which could be mixed with any off-farm organic wastes before feeding to the digester. Thus, the significant investment required on this farm is regarding the construction of the anaerobic digester to capture the biogas and CHP unit for generating electricity.

Figure 5-4 Lester's farm manure tank

5.3.1 Lester's Farm Cost Analysis and Results

In this section, the developed models are applied to the Lester's Dairy Farm collected data to predict the needed funding for a biogas plant to be developed on this farm. The model is divided into six sections:

1) **Farm size**: The number of the cow for Lester's Dairy Farm is 550 cows, and the total volume of flushed manure is 20.6 m^3/day.

2) **Biogas generation:** It estimates the amount of generated biogas, which directly relates to the amount of collected organic waste assuming a conversion rate of waste to methane based on the data gathered from active biogas plants in Canada and the USA. This factor is a function of the type and quality of the manure, the digester type, and the AD's operational temperature.

3) **Electricity generation:** It estimates the total amount of generated electricity under the effect of methane yield and the co-generator efficiency. The average efficiency for combined heat and power (CHP) system is between 30 – 40% (Saadabadi et al., 2019).

4) **Carbon credit:** It is an extra benefit for the farmers because an on-farm biogas plant reduces the equivalent greenhouse gas and carbon emission compared to the same amount of generated electricity by fossil fuels. Suppose the plant is assumed to be working 365 days of the year. In that case, the amount of credit for each kW of generated electricity is calculated based on the Feed-in Tariff program in Ontario, which is the province with the highest number of biogas projects in Canada (Biogas Association, 2019).

5) **Cost estimation based on the regression modeling**: This section predicts the costs of the individual components, capital costs, and operation costs. Based on the study on the anaerobic digestion projects in Ontario, the average operating cost is about 1.5% of the total capital costs based on the mathematical models and results of this study (the average cost was calculated based on the collected data provided in APPENDIX A). The labor costs are considered zero since the farmers can take care of the operational activities for midsize farms (White et al., 2011).

6) **The revenue:** This is the last section in this model, and it determines the project's feasibility and estimates the annual net income. Based on the average life expectancy for typical on-farm biogas plants, which is 30 years (Pääkkönen et al., 2018).

The predicted components', capital, and operation costs as given in Table 5-2. The models which have been developed and presented in chapter 4 fully adjusted to Lester's Dairy Farm data. A spreadsheet processor has been used to conduct the calculations and analysis for the Lester's Dairy Farm data. Figure 5-5 shows the interface of the spreadsheet processor modeling.

Financial modeling for Lester's farm biogas plant			
Farm Size	**Units**	**Farm results**	**Info**
Number of Cows		550	i
Amount waste water valume	m3/cow/day	0.04	i
Conversion Factor	m3/kg	1	
Total amount of waste water	kg/day	20	
Biogas Generation			
Volatile Solid content in manure	kg/cow/day	5.50	
Total Volatile Solid content in manure	kg/day	3,025	i
Conversion factor: feedstock to Biogas	m3/ kg	0.24	i
Total Methane yield	m3/day	726	
Electricity generation			
Methane Heating value	MJ/m3	38	
Conversion factor MJ to kWh @ 33% efficiency	kWh/m3	0.10	i
Total Electricity generated	kWh/day	2,759	
Carbon Credit			
Natural gas carbon credit	$/kW	0.01	i
Carbon Credit	$/day	15	
Total Carbon Credit per year	$/yr	5,437	
Costs			
Average life expectancy	yr	30	
Biogas Upgrading system Cost	$	-	
Cost of CHP Unit	$	652,851	
Cost of Power house and Pumping	$	218,718	
Solid and liquid separator	$	278,527	
Digester and Heat exchanger costs	$	974,844	
Engineering & design Costs	$	212,494	
Capital Cost (based on farm size)	$	2,337,433	
Operational and Maintenance Costs	$/yr	35,061	
Revenue			
Price of selling Generated Electricity	$/kWh	0.20	i
Total Revenue	$/yr	206,830	
Net Profit	$/yr	171,768	

Figure 5-5 Interface of the spreadsheet of modeling Lester's Dairy Farm data

Table 5-2. Results of Lester's Dairy Farm analysis

Item no	Items	Unit	Price (CAD)
1	Cost of CHP unit	$	652,851
2	Cost of powerhouse and pumping	$	218,718
3	Solid and liquid separator	$	278,527
4	Digester and heat exchanger costs	$	974,844
5	Engineering & design costs	$	212,494
6	Capital cost (based on farm size)	$	2,337,433
7	Operational and maintenance costs	$/yr	35,061
8	Total revenue	$/yr	206,830
9	Net profit	$/yr	171,768

The estimated total capital cost for building a biogas plant on Lester's Dairy Farm is about $2.4 million (Figure 5-5), and the cost of each component is listed separately on Figure 5-5 and Table 5-2. It should be noted that the deduction of the loan for the capital costs is not included in the net profit calculation because it is subjected to mutual agreements among the involved parties: the owner, the developer, and the funding institution. The loan and its annual payment should be deducted from the net profit according to the agreed-on schedule.

It is easier to interpret the costs on an annual basis. All the capital and operational costs are converted to an annual average of up to 30 years of the plant operation. The comparison between the costs and the revenue is provided in Figure 5-6.

Figure 5-6 shows two equations for the costs and income based on the annual average. These equations are important for the break-even point calculation. In other words, by solving the equation of "Costs = Income," the exact number of years that the plant needs to operate to cover all the expenses will be calculated (payback period). It is assumed that the number of cows and the amount of electricity generation is fixed during the plant's life expectancy.

Costs = Income

$35{,}061 * (\text{year}) + 2 * 10^6 = 206{,}830 * (\text{year})$

$\text{year} \approx 11.5$

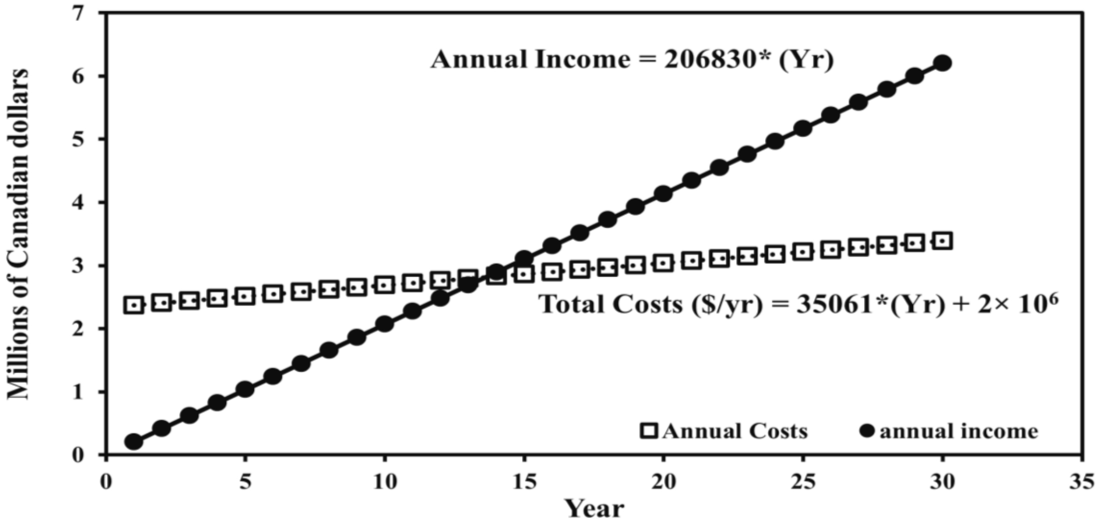


Figure 5-6 Project costs and revenue in 30 years of operation

Therefore, the payback period for an on-farm biogas plant at Lester's Dairy Farm would be 11.5 years. Selling the generated electricity only for 11.5 years would recover the investment. If the farmers need a banking loan for the initial investment, a $3 million loan with a payback period of 12 years would satisfy their needs. It is clear that this number is sensitive to the yearly income of the digester, so any operational failure (details of these parameters are provided in section 2.3) that leads to shutting down the plant would increase the payback period.

In addition to the generated income through selling the electricity, there are other sources that generate revenue such as tipping fees or saving on animal bedding and fertilizers by replacing them with the digestate material from biogas production. In a study of 8 Canadian biogas plants in British Columbia, the income of the additional sources is reported. Table 5-3 presents the average possible income of the other sources as more than $300,000. By adding this income to the payback period calculation for Lester's farm, the actual payback period for Lester's farm would decrease from 11.5 years to 9 years which is more favorable for owners.

Table 5-3 Secondary source of income of biogas plants

Farms	Farm A	Farm B	Farm C	Farm E	Farm F	Farm H	Farm I	Farm J	Average
Number of cows (#)	600	1,600	650	100	1,000	480	400	500	522
Total generated electricity (kWh/day)	3,074,760	7,876,116	5,439,960	1,813,320	7,876,116	4,099,680	7,568,640	4,651,560	5,241,546
Feedstock (m^3/yr)	33,600	54,850	24,000	8,000	52,850	18,000	34,000	20,250	26,183
Tipping fees ($/yr)	378,000	382,500	270,000	90,000	337,500	202,500	382,500	225,000	251,250
Saving due to digestate replacement ($)	72,000	50,000	65,000	12,000	100,000	60,000	90,000	70,000	66,167
Total income ($)	450,000	432,500	335,000	102,000	437,500	262,500	472,500	295,000	317,417
Income per cow ($/cow)	750	270	515	1020	437	546	1181	590	715
Income per generated kW ($/kWh)	0.15	0.05	0.06	0.06	0.06	0.06	0.06	0.06	0.06
Income per amount of feedstock ($/$m^3$/yr)	13.39	7.89	13.96	12.75	8.28	14.58	13.90	14.57	13.01

Source: (Werner et al., 2007)

CHAPTER SIX

CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions

This study developed mathematical models to estimate the costs of on-farm biogas plants for dairy farms in Canada. Two approaches have been used to develop cost estimators for major components of a biogas plant and simulate the most probable expenses of biogas plant construction. Initially, a dataset has been created to collect cost information of active biogas in Canada and the USA to develop the models. This dataset is synchronized to the Canadian perspective; all prices converted to Canadian dollars and inflated to the year 2020.

The first method used regression analysis. The equations generated by this method are the best to describe the cost-farm size (number of cows (CN)) relationship. Seven mathematical models have been generated in this research, including prediction of capital costs for farms with less than 1000 cows ($CS = 485CN + 2.65 \times 10^6$), capital cost for farms with more than 1000 cows ($7882CN - 6.03 \times 10^6$), capital cost based on HRT ($CS = 87690\,HRT + 414017$), digester costs ($DC = 72CN - 87834\,HRT + 2851912$), CHP unit costs ($CHPC = 811\,CN + 390078$), upgrading unit costs ($Upgrading\ C = 649\,CN + 867341$), cost of pumping unit ($Pumping\ C = 1139CN - 232903$).

Afterward, these equations have been used to develop a second method to find the most probable price of an on-farm biogas plant in the Canadian biogas market. In this method, Monte Carlo simulation is developed, and the results of regression modeling have been incorporated into the simulator to reduce the prediction error. After 20,000 trials, the average cost for typical biogas plants in Canada has been calculated ($4.3 million based on a farm size of 960 cows).

Despite the excellent potential of biogas in Canada it is still very limited. Therefore, the Canadian biogas market has great potential for expanding on-farm biogas plant facilities; it requires more focus from developers, scientists, and environmental agencies.

Some limitations in the developed models require further research and studies. First, the models apply only to Canadian farms and are not recommended for other countries. Second, based on the dataset used to develop the current models has approximately 7% marginal error, and the models are applicable to farms with a herd size of 300 to 1600 cows. Any farm with a herd size not in this range the models may have a significant error in the predicted costs. The models showed that farms with less than 300 cows are not feasible for biogas plant development since there are minimum expenses for running the plant. Less than 300 cows will not generate sufficient manure for the system's input. As a consequence of low manure production, the generated electricity by the biogas plant may not be adequate even to keep the digester at the desired temperature.

Finally, the models accounted for only the financial aspects. The environmental benefits are not accounted for to provide non-partisan information for the owners. Most importantly, the models are developed based on information accessible on open-access websites, reports, and journal articles because most companies are sensitive to sharing their cost and income information.

6.2 Recommendations for future studies

The biogas industry is relatively new in North America and needs more research and development to exploit its potential. This potential can be developed by adding new mathematical methods for better cost prediction, like using machine learning on more extensive datasets.

Since the current primary issue in the cost studies on on-farm biogas plants is the lack of information, particularly data on the costs and finance, developing an online dataset that biogas plants developers, specialists, and owners continuously update would be beneficial for future modeling and investigations. It will increase the data availability needed for modeling and provide an infrastructure to link the manufacturers and the developers and facilitate the communication process.

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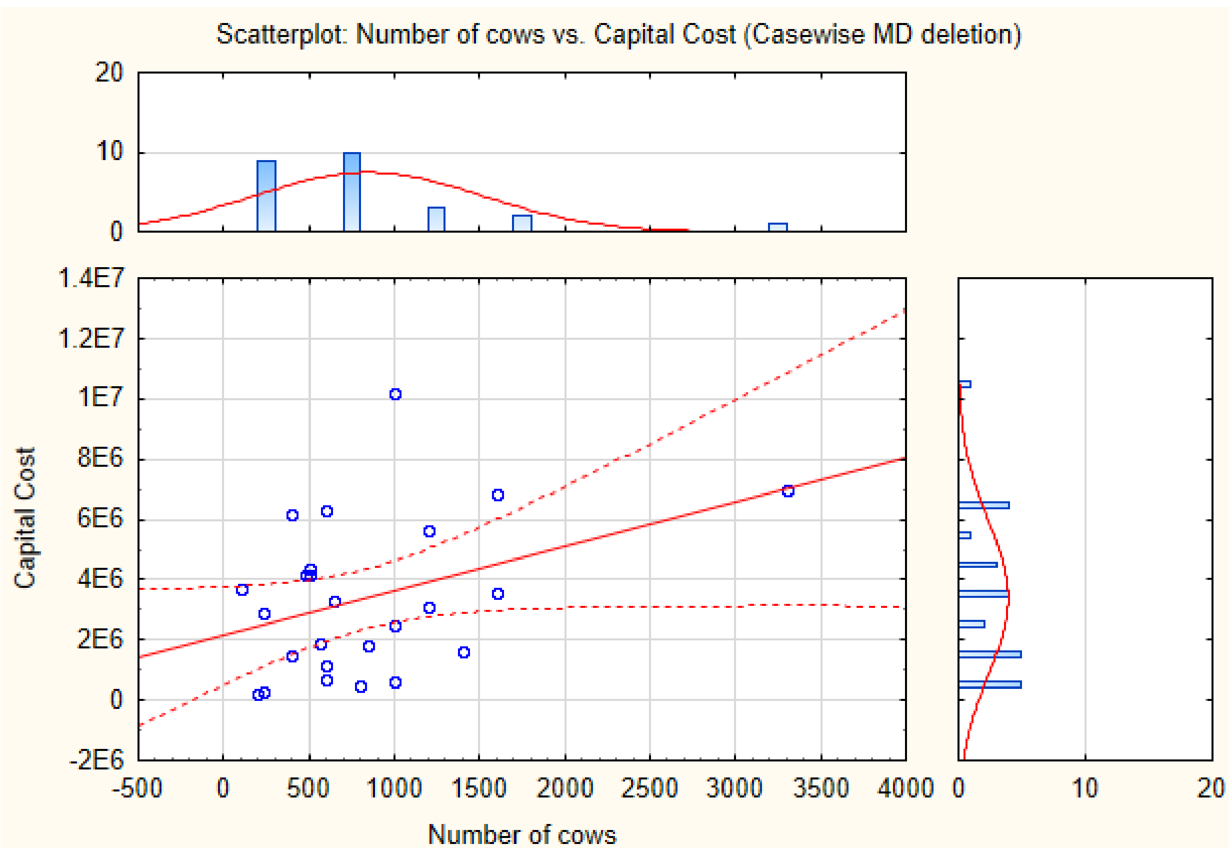
APPENDIX A

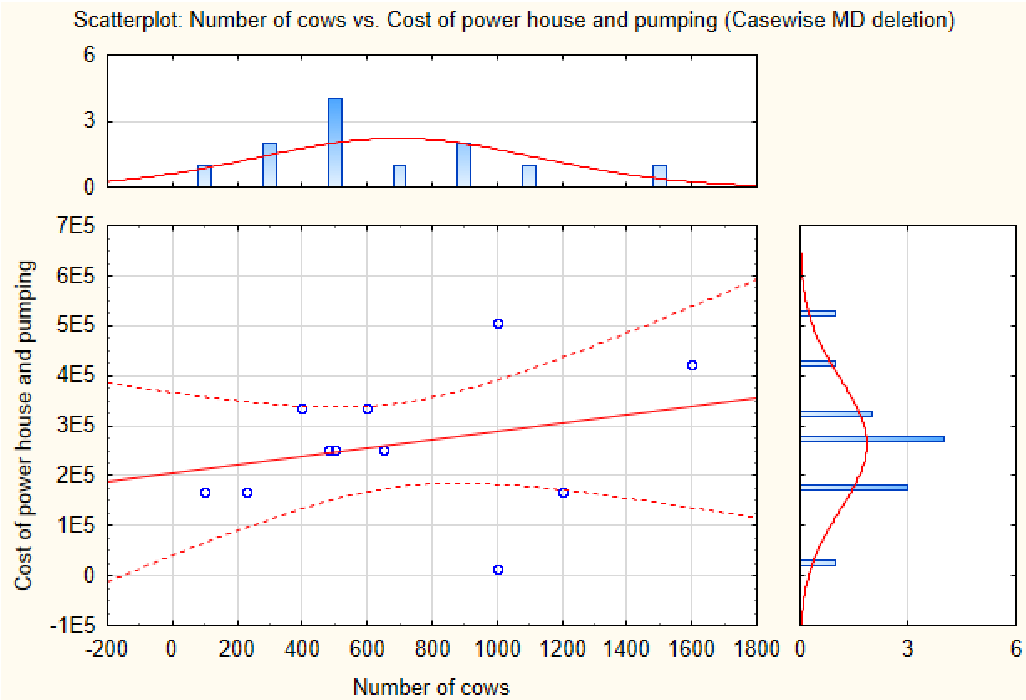
Name of the Farm	Location	Number of Cows	HRT (days)	Year of the cost	Inflation rate to year 2020	Cost of Pumping unit in year 2020 (CAD)	Cost of digester in year 2020 (CAD)	Cost of Generator in year 2020 (CAD)	Cost of Upgrading in year 2020 (CAD)	Capital cost in year 2020
Farm A	Abbotsford, BC, CA	600	22	2007	23%	337020	1,261,980	1,416,960	1,845,000	6334343
Farm B	Rosedale, BC, CA	1600	22	2007	23%	1421275	1,261,980	1,351,647	1,845,000	6842748
Farm C	Chilliwack, BC, CA	650	24	2007	23%	252765	1,168,500	1,018,440	1,476,000	6275967
Farm D	Vanderhoof, BC, CA	1200	28	2007	23%	1285100	492,000	570,720	1,230,000	3080825
Farm E	Black Creek, BC, CA	100	27	2007	23%	168510	461,250	452,640	1,230,000	3709424
Farm F	Armstrong, BC, CA	1000	22	2007	23%	505530	1,261,980	1,351,647	1,845,000	4458627
Farm G	Dawson Creek, BC, CA	230	28	2007	23%	168510	492,000	432,960	1,230,000	2887410
Farm H	North Saanich, BC, CA	480	29	2007	23%	252765	630,990	831,480	1,476,000	4199006
Farm I	Deroche, BC, CA	400	24	2007	23%	337020	1,261,980	1,180,800	1,845,000	6175466
Farm J	Delta, BC, CA	500	24	2007	23%	252765	707,250	870,840	1,476,000	4361336
Farm L	Agassiz, BC, CA	500	24	2007	23%	252765	630,990	811,800	1,476,000	4171375
Craven Farms	Washington, U.S	1000	20	1997	52%	744000	194,560	80,560	-	2100000
AA Dairy	Candor, NY, U.S	600	37	1998	50.00%	-	283,500	91,500	-	5445000
Patterson Farms	Auburn, NY, U.S	1,000	22	2005	28%	-	970,457	727,523	-	1917900
Ridgeline Farm	Clymer, NY, U.S	600	20	2001	41%	-	473,822	181,374	-	874532
Sheland Farms	Adams, NY, U.S	560	17	2007	23%	-	934,800	541,200	-	1476000
Sunny Knoll Farm	Perry, NY, U.S	1,400	18	2006	26%	2000000	658,242	699,855	-	4800000
Spring Valley Dairy	Rensselaer County, NY, U.S	236	20	2003	33.56%	-	53,825	36,061	-	191859

APPENDIX B

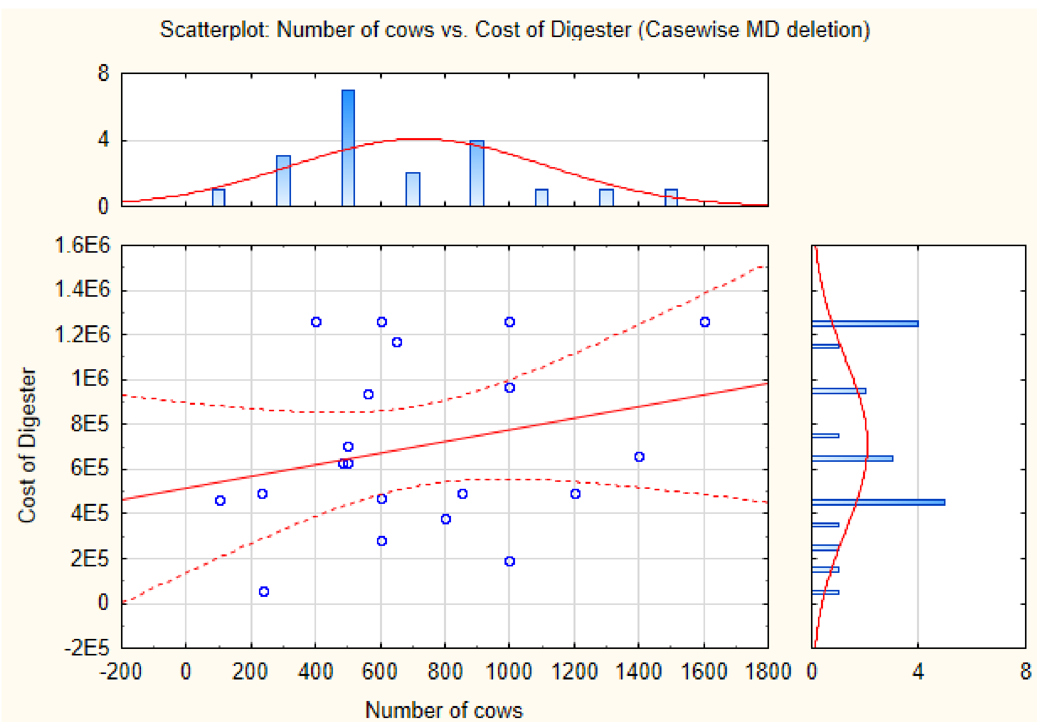
The graphs below show the correlation between seven parameters that are important in the cost estimation of a biogas plant. These parameters are 1) number of cows, 2) HRT, 3) cost of pumping unit, 4) cost of digester, 5) cost of generator, 6) cost of upgrading unit, and 7) capital cost. All the correlation graphs are generaed based on the original dataset.



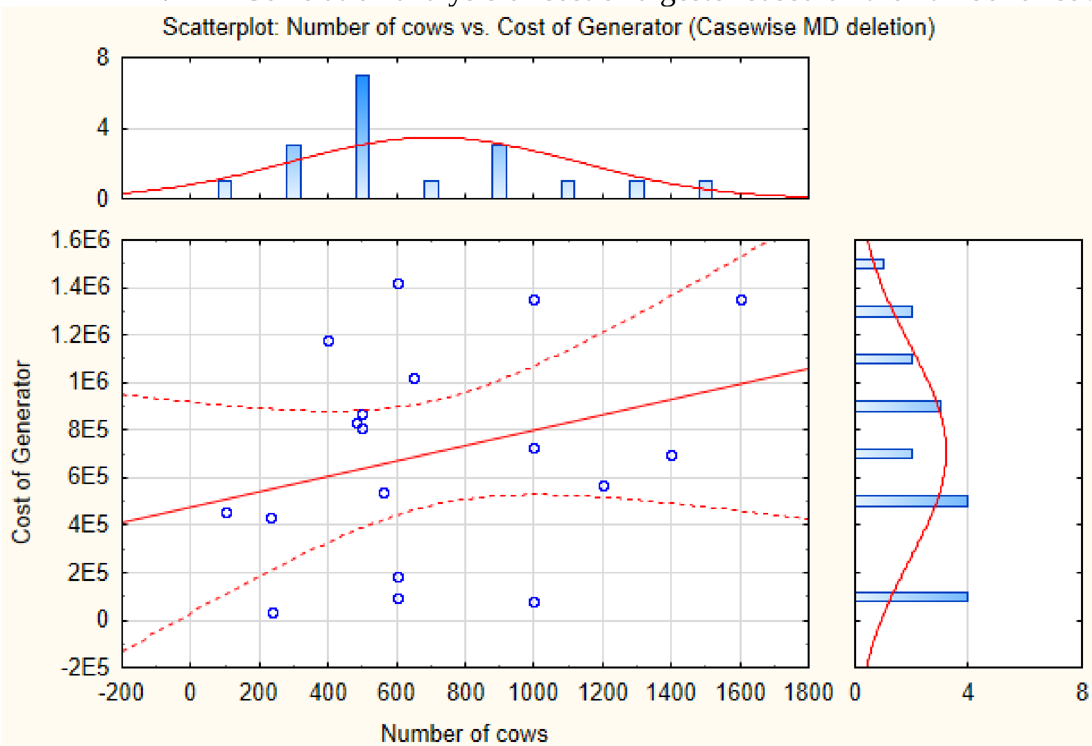
1. Correlation analysis of capital cost based on the number of cows
2.



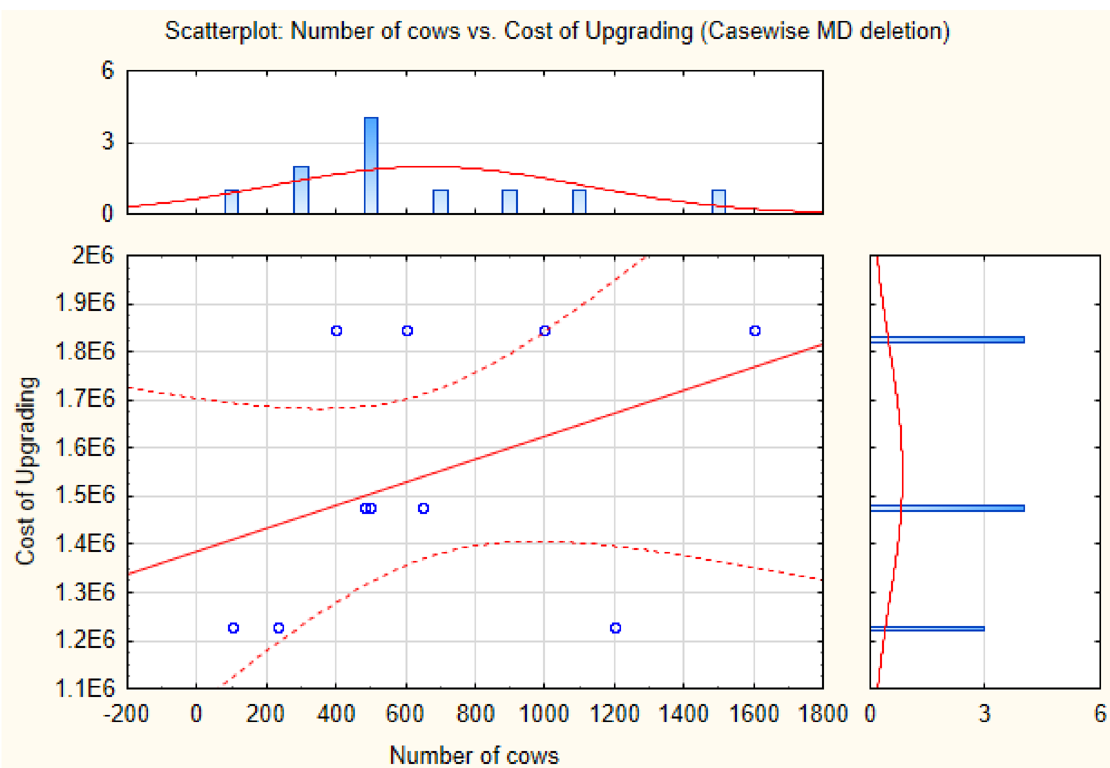
3. Correlation analysis of cost of powerhouse and pumping unit based on the number of cows



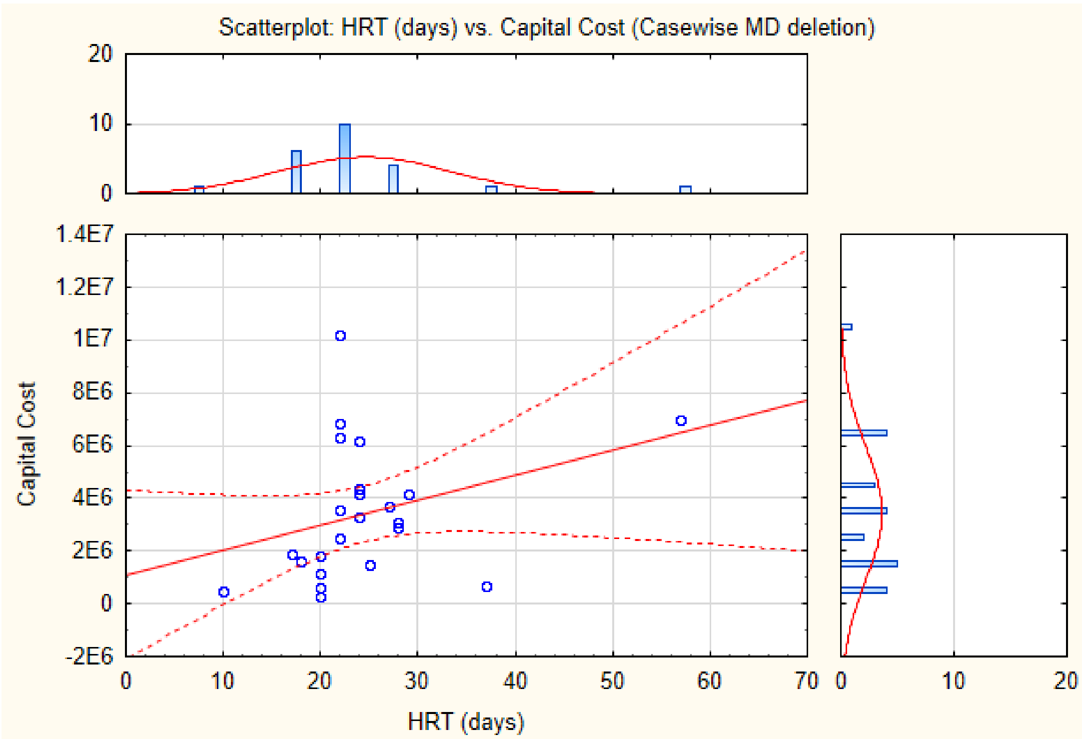
4. Correlation analysis of cost of digester based on the number of cows.



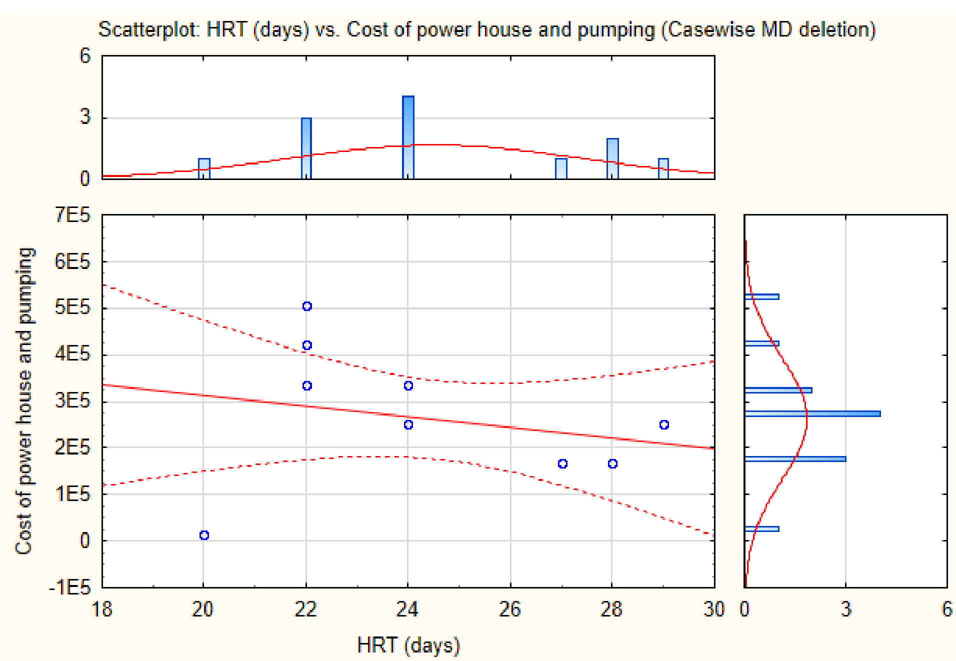
5. Correlation analysis of cost of Generator based on the number of cows



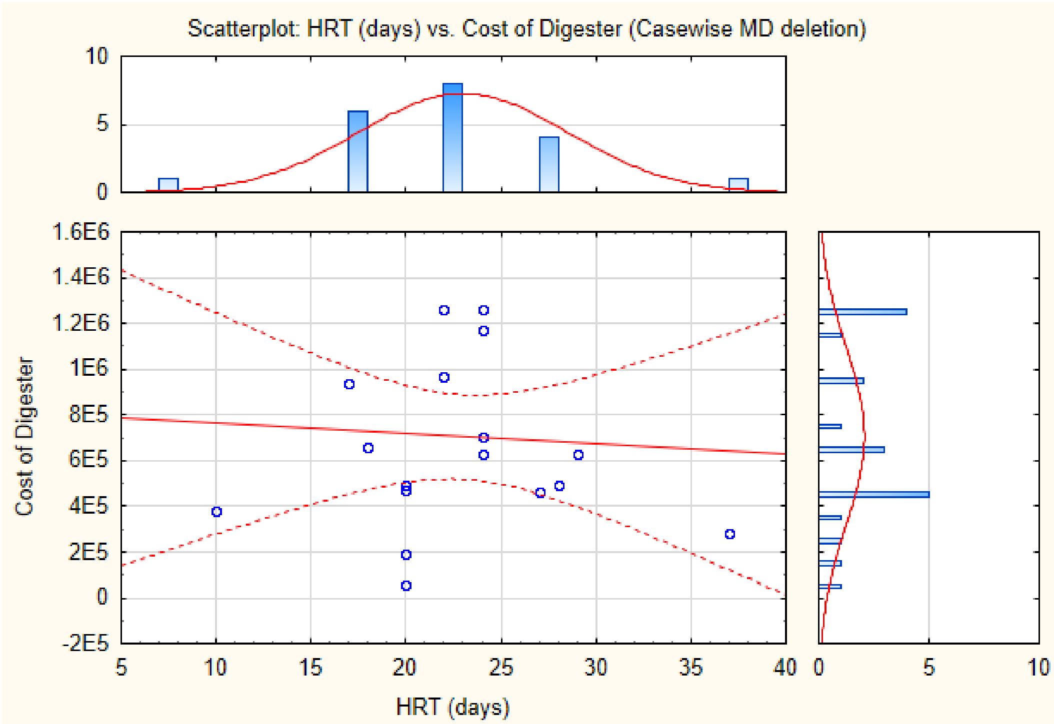
5. Correlation analysis of cost of upgrading unit based on number of cows.



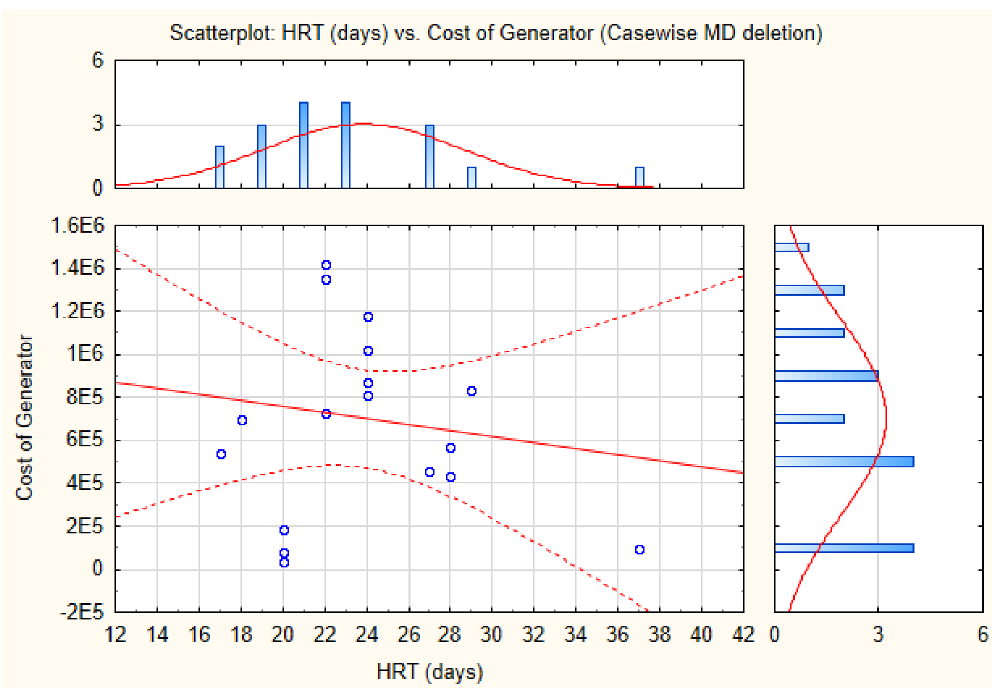
6. Correlation analysis of capital costs based on HRT



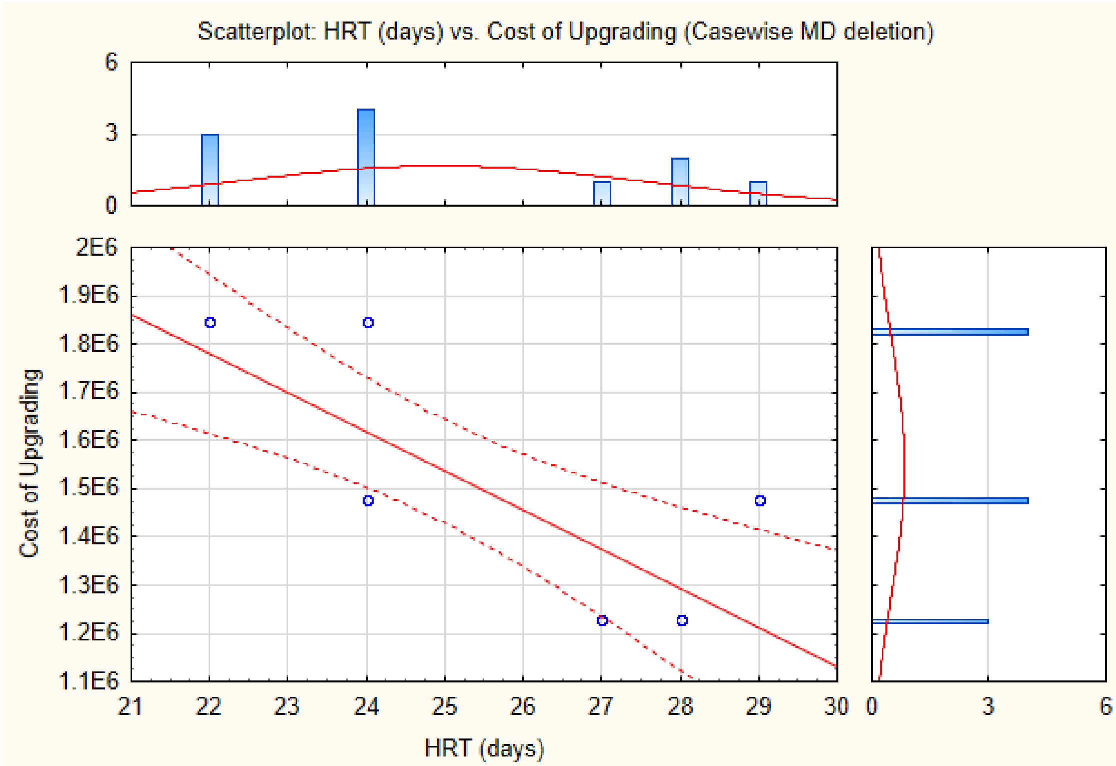
7. Correlation analysis of cost of powerhouse and pumping unit based on HRT



8. Correlation analysis of cost of digester based on HRT



9. Correlation analysis of cost of generator based on HRT



10. Correlation analysis of cost of upgrading unit based on HRT

Table of the correlation significance between all parameters on the original dataset

	Mean	Std.Dev	Number of cows	HRT	Cost of powerhouse and pumping unit	Cost of digester	Cost of generator	Cost of upgrading unit	Capital cost
Number of cows	660.000	440.931	1.000	-0.396	0.534	0.421	0.490	0.405	0.424
HRT	24.909	2.625	-0.396	1.000	-0.789	-0.831	-0.854	-0.819	-0.711
Cost of powerhouse and pumping	283403.182	108376.478	0.534	-0.789	1.000	0.839	0.899	0.912	0.958
Cost of digester	875536.364	360130.817	0.421	-0.831	0.839	1.000	0.946	0.919	0.731
Cost of generator	935448.545	359760.883	0.490	-0.854	0.899	0.946	1.000	0.970	0.802
Cost of upgrading unit	1543090.909	260130.527	0.405	-0.819	0.912	0.919	0.970	1.000	0.844
Capital cost	5022166.036	2194866.864	0.424	-0.711	0.958	0.731	0.802	0.844	1.000

APPENDIX C

Data collection of active on-farm biogas plants in Canada

	Please mark (x) in the box that describes your answer the best (You can check more than one option)									
Farm name										
Address										
Year the biogas project started										
Number of livestock on-farm (#)										
Types of the animal housed in the farm	Dairy		Beef		Swine		Mink		Poultry	
Manure collection system	Flushing System				Scrubbing System				Other	
Amount of collected wastewater (m^3)										
Number of digesters (#)										
Digester type	Complete Mix		Plug flow		Fixed film		Covered lagoon		Other	
Digester feeding rate (tonne or m^3 per day)										
Digester temperature	<20 ^{0}C		30 ^{0}C – 38 ^{0}C				49 ^{0}C – 57 ^{0}C			
Biogas production rate										
Electricity generation (kWh/day)										
Digested material discharged (kg/day)										

Capital cost ($)	
Operational & Maintenance cost ($/year)	

Cost of individual components

Pumping unit (including the pumps and pipeline)	
Anaerobic Digester	
Biogas collection tank	
Biogas purification system	
Combined Heat and Power unit (CHP)	
Solid and liquid separator	

A webform of this questionnaire is also provided online (link: https://forms.gle/D1FcHYvPk3gsA64r7) to give a more convenient way to collect the responses.

APPENDIX D

	Number of Cows	Volume On-site manure	Off farm organic feedstock	HRT	Total Manure
Unit	#	m3/cow/day	m3/day	days	kg/cow/day
Mean	840	0.067	29.70	24.43	23.8
Standard dev	664.19	0.032	14.09	8.75	6.4
Min	100	0.012	10.55	10.00	9.5
Max	3300	0.116	46.58	57.00	54.7
Mode	600.00	0.05	46.58	22.00	33
Alpha	1.63	2.46	5.00	2.02	3.08
Beta	4.38	3.54	1.00	3.98	2.92
Excel Estimation	974	0.054	40.55	25.76	32.71
Trial (×5000)	PERT Dist	PERT Dist	PERT Dist	PERT Dist	PERT Dist
1	1313	0.0540	40.55	32.03	43.02
2	378	0.0408	45.36	24.14	28.22

	Cost of power house and pumping based on Probability distribution	Cost of power house and pumping				Cost of Digester based on Probability distribution	Cost of Digester			
Unit	CAD	Number of Cows	HRT	Total Feedstock	Total AVERAGE	CAD	Number of Cows	HRT	Totla Feestock	Total AVERAGE
Mean	260,989.58					703,954.10				
Standard dev	129,252.17					384,246.73				
Min	14,440.00	Based on regression equation	Based on regression equation	Based on regression equation		53,824.68	Based on regression equation	Based on regression equation	Based on regression equation	
Max	505,530.00					1,261,980.00				
Mode	252,765					1,000,000				
Alpha	2.94					4.13				
Beta	3.06					1.87				
Excel Estimation	256,692.55	283,292.37	243,008.61	246,718.69	**257,428.05**	889,062.86	769,564.83	690,312.69	690,916.70	**759,964.27**
Trial (×5000)	PERT Dist	PERT Dist	PERT Dist	PERT Dist		PERT Dist	PERT Dist	PERT Dist	PERT Dist	
1	182,295.67	254,860.73	283,664.00	246,788.75		764,295.53	659,143.97	675,634.64	691,257.81	
2	349,600.48	277,870.98	34,312.98	246,693.41		1,056,416.87	1,008,258.20	707,147.82	691,266.55	