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Feasibility of Biogas Production on Small Livestock Farms

Dr. Andrew Trivett and Matthew Hall

UPEI Department of Engineering

April 9, 2009

This project was supported by funding from the PEI ADAPT Council to the Environmental Coalition of PEI

Prince Edward Island ADAPT Council

The Environmental Coalition of Prince Edward Island

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Summary

This report discusses the feasibility of biogas digestion on a small PEI dairy or beef farm. Conventional wisdom in the agricultural industry is that biogas production from dairy farms smaller than 60 milking cows, or equivalent numbers of beef cattle in a barn are not practical. Commercial manufacturers have been installing systems in Canada and the United States for on-farm biogas that handle manure, but augment it with a substantial amount of non-manure co-substrate materials. A preliminary review of local co-substrates is presented based on published data.

There is no technical limitation, nor regulatory one for the establishment of a small on-farm digester which could generate sufficient electricity to supply the farm's average electrical needs. The technical challenge in building a small biogas plant will be in finding suitable small-size and price components for such system that can be accommodated in a reasonable capital budget. The business/policy challenge will be to ensure the regulatory climate helps to make small-farm systems economically attractive. These issues were discussed and potential risk factors are identified.

Recommendations

General

1. **The potential payback from a well-designed biogas system for 60 heard of cattle could be over 10,000$ per year, and would be attractive based on current electrical rates. This should be further pursued by PEI farmers.**

2. **An effective small demonstration biogas system should be built that supplies only the average annual energy from a single farm, but is not intended to supply farm peak demand**

3. **Site selection will need to be considered for any on-farm biogas systems: is it acceptable to use existing manure storage tanks or build on a new foundation ?**

4. **Availability of potential co-substrates need to be evaluated, including farm- and non-farm waste sources**

5. **Costs and shipping distance for potential co-substrate needs to be determined**

Regulatory

6. **New policies to encourage on-farm biogas should include potential for producers to earn money for electricity produced in excess of their demand.**

7. **Grouping of electrical meters for small communities or farms with several electrical meters should be allowed to be included in the net-metering calculation**

8. **Emergency flaring or venting regulations will have to be determined**

9. **Local regulations for application of digestate on farmland need to be determined**

10. **Local regulations for electrical safety of small biogas generators need to be verified by the utility, occupational health agencies, and local fire departments**

11. **Requirements for automatic or manual grid intertie need to be clearly established.**

Technical

12. **Potential co-substrate energy content needs to be evaluated.**

13. **Optimum digester tank size will require a detailed analysis of influent and digestion process in a demonstration biogas system.**

14. **Ideal operating temperature needs to be determined from testing.**

15. **Heat loss calculations are based on theoretical estimates, and these need to be properly verified by experimental testing.**

16. **Start-up heating procedures need to be established.**

17. **Seasonal variability in the digester heating will be needed for correct heat system sizing and design.**

18. **Materials compatibility should be investigated, and metal, concrete, plastic, or fibreglass tanks will need to be considered in final designs.**

19. **Shipping costs of completed tanks, or onsite costs for construction on the farm will need to be evaluated.**

20. **Digester maintenance and cleaning requirements for the heating surfaces will need to be established.**

21. **Suitable engine/generator models and manufacturers need to be found for single-phase installations, spark-ignited, 20kWe typical size.**

22. **Gas cleaning requirements specific to the target engine must be verified.**

23. **Alternatives for H_2S removal from the gas will need to be evaluated.**

24. **Engine reliability and cost needs to be evaluated.**

25. **Generator control, emergency shutoff, and protection needs to be determined.**

26. **Detailed control system designs for temperature control need to be developed, and the heating systems tested.**

I. Introduction

According to the 2006 farm census by Statistics Canada, there were 360 dairy farms in PEI, down from 435 in the 2001 census. In addition, there were 475 beef cattle farms, including feedlots, down from 575 in 2001. These farms have an inventory of 76,000 head of cattle as of January 2009 (down from 80,000 in January of 2008). 12,800 of these were listed as milk cows in January 2009, down from 13,500 the previous year. Clearly the business of farming has been tough in the livestock industry.

Figure 1: SandyRae farms from the farm driveway. This site uses silos for feed storage, and as a result has a very large electrical demand.

According to the census data, the average PEI dairy farm milks only 35 cows. Beef farms (including feedlots) have an average of 130 head of cattle. The PEI department of agriculture claims that PEI farms raise between 20-250 cows[1]. The reality is that there are only a handful of large farms on PEI, with the majority of farms having a very small number of cattle. These small farms are financially difficult to operate, with low revenues and high operating costs. The objective of this report is to provide some alternatives for farmers to consider that would improve their environmental performance while reducing their energy and operating costs. Specifically, we have focused on the potential for using on-farm waste from livestock as a source of fuel.

A remarkable amount of energy is contained in organic waste. Under the right conditions, this energy can be extracted in the form of a combustible hydrocarbon gas, called biogas. The biological process by which organic material can be converted to hydrocarbon gas is anaerobic digestion. Anaerobic digestion is a natural process that has been used in myriad applications in the past, including for the production of biogas energy from manure. It was thought to be economically impractical for farms with fewer than 200 head of cattle [2]. Using this yardstick, biogas is feasible for almost no PEI farms. This project is intended to evaluate the prospect for anaerobic digestion on PEI livestock farms, and propose a viable method for specific farm case studies.

Anaerobic digestion and biogas have been used for a long time. There is evidence that biogas from anaerobic digestion was used to heat water in Assyria in the 10th century BC and in Persia in the 16th century BC [3]. The basic notion arose in the Western scientific community from observations of flickering lights in swamps. In the 17th century the connection was made between decaying organic matter and the creation of an inflammable gas, and Alexander Volta observed that the latter was a function of the former in 1776. Through the 18th century, methane was found to be the main constituent of the inflammable gas, and a similar gas was observed from decomposing cattle manure [4]. The first recorded digestion plant was built in India in 1859 [3].

Currently, anaerobic digestion is used on a small scale by families and communities in a number of developing countries to generate gas for cooking from animal waste. Community-scale plants have been named one of the most useful decentralized energy sources by the United Nation Development Program. [5] In Canada, anaerobic digestion is used in the majority of large municipal wastewater treatment systems, and to treat many industrial food waste products.[6] In the agricultural industry, there are only approximately 110 on-farm digesters in the United States, and over 2000 in the European Union.[7, 8]. Compared to the number of livestock farms in these countries, the number of installations is very small indeed.

This report is the result of a feasibility study, not a detailed design. The sources that were used in preparation of this work were published papers, project reports, and interviews with local farmers. The authors of this report have not relied on information from any one manufacturer or supplier, but have tried to collect information from unbiased, informed sources. No analyses of samples were carried out, but typical properties for relevant systems were compared and reasonable estimates in the PEI context were made. Our goal was to determine from an unbiased point of view whether or not a typical small livestock farm on PEI could benefit from a biogas plant on the farm.

There are some manufacturers currently producing turn-key biogas plants in Canada, the United States and Europe. In general, they are focused on providing much larger installations than the one that would suit our model farm. The final design and implementation of a small biogas system on PEI should be done with input from businesses having a proven history of installations in other jurisdictions, but will require adaptations to be suited to our local conditions.

Biogas Production

When a quantity of organic material is left in an oxygen-free (anaerobic) environment, certain bacterial colonies develop and begin digesting the organic material. Some bacteria in the populations break down solid organic material into water-soluble constituents, while some bacteria convert the soluble organic components into volatile fatty acids, and other bacteria consume the fatty acids, creating methane gas as waste. This methane combined with carbon dioxide and traces of other gases excreted by the bacteria makes up biogas.

Since biogas production is a biological process that relies upon multiple strains of different bacteria which perform separate intermediate steps, the process is difficult to model, or to control with precision. In practice, a warm, oxygen free environment is provided by a sealed vessel (a digester). It usually takes around 15-30 days for the organic material inside a simple tank to be fully digested by bacteria. The populations of bacteria which grow in the organic material are influenced by temperature as well as feedstock. From an operational standpoint, digesters that are maintained at ambient temperature are slowest, those at a temperature of 35°C are significantly faster, and ones at a temperature of 50°C are faster still, but energy-intensive to maintain.

Usually about half of the available organic material is converted to gas in the digestion process. The majority of the feedstock mass remains in the digestate. Of particular importance, the organic nitrogen that was digested is converted into inorganic forms, mostly ammonia.[9] Inorganic nitrogen is more accessible to plants, thus the digested material is a more potent fertilizer. The odor of the digestate, which is largely due to release of volatile organic compounds, as well as organic pathogen levels, are greatly reduced during the digestion process. Appendix A provides a detailed discussion of different biogas digester designs and processes.

Feedstock

The quality and quantity of biogas is closely tied to the type of feedstock that is available. The fundamental feedstock on a farm is, of course, manure from the livestock. This can be accurately predicted per head of cattle. However, in many on-farm digestion systems, it is assumed that there will be a large quantity of additional organic material (co-substrate) available. Our premise in this study is that the biogas plant will be a relatively small facility that augments the operation of a working livestock farm and that the primary source of organic material will be the manure. In some commercial systems, it is expected that a small farm of fewer than 100 head of cattle will supply manure for a digester, but that upwards of 5-10 times the amount of organic material supplied to the digester will come from some other source of organics, typically imported from beyond the farm gate[10-12]. In this sort of a system, the manure effectively is the bacterial culture feedstock, while the bulk of the energy comes from the co-substrate that typically comes from an industrial or process waste stream.

In some cases, this co-substrate is organic waste from food manufacturing plants, newsprint, or any number of other options. On PEI, as compared to other provinces in Canada, the availability of processing waste for digestion may be limited. There have been several reports addressing the availability of biomass on the Island[13-19], but none specifically for this sort of application.

Figure 2: a calf at Pleasant Valley farms settled in the calving barn.

Without a detailed assessment of the availability and potential for possible co-substrates to PEI farmers, it is difficult to give a definitive analysis of the options. It is certain that the potential co-substrates will make a big difference on the payback period for any biogas digestion system. Table 1 shows a prospective list of co-substrates based on other published reports [15, 16, 18, 19].

It is essential for a digester to have a consistent supply of co-substrate, so we have proposed a ranking for each source of the expected reliability of the source. A low reliability source is one that would be available only at certain times of the year, and its availability may depend upon many external factors. A source having high reliability would be one that can be reasonably predicted to be steady for most of the year and where there is a large potential supply. The energy content of each potential source would imply its suitability for use as a co-substrate. Some of the material listed will need development tests before being used in a system. The cost of the material will depend upon demand for its use in other applications. For example, wood waste is currently in demand for chip burning stoves or production of wood pellets, thus its cost is shown as “high” in the table. This table is by no means definitive, but should be considered a starting point for considering possible material that would be effective if added to a farm digester. The final column in the table labeled "potential" is our simple estimate of the prospect for this co-substrate based on the other factors.

Feedstock	**Reliability of source**	**Energy content**	**Cost**	**Potential**
Diseased grain	low	medium	Low	low
Fish plant waste	medium	high	low	high
Municipal sewage	high	high	low	high
Municipal solid waste	high	medium	low	high
Potato culls	medium	high	medium	medium
Potato processing waste	high	medium	low	high
Sea Lettuce	high	medium	low	high
Straw	medium	medium	medium	medium
Wood processing waste	high	medium	high	low

It is important to recognize that, if on-farm biogas systems are feasible for a small farm, then they will be installed by farmers as fuel costs and environmental pressures continue to grow. If many farms install on-site digestion, and they are all sized for large co-substrate supplies, the availability of the co-substrate will become limited. Thus, it is important that we consider the potential of a small digester system that will operate only on waste from the farm. While larger systems that import organic waste may be attractive, they cannot be a solution that will work on every farm.

Gas Yield

The biogas generated by anaerobic digestion typically contains 60-70% methane, with the remaining gas volume consisting of carbon-dioxide plus a fraction of a percent of hydrogen sulfide. [20, 21] Methane has a heating value of 37 MJ/m^3 (994 BTU/ft^3), so a 60% methane biogas has a heating value of just under 22 MJ/m^3 (600 BTU/ft^3). [22]. The gas is also fully saturated with water vapour at the ambient temperature. In small applications in developing countries, the biogas is simply burned directly from the digester with no pre-treatment. [5, 23] In larger applications involving power generation, the gas may be filtered to reduce the concentration of H_2S, which is corrosive to the combustion equipment and produces SO_2 gas in the exhaust, a major component of smog and acid rain.[4]

Healthy anaerobic digestion requires carefully controlled raw materials. Fortunately, maintaining adequate levels in the feedstock is not usually an issue with on-farm digesters; manure generally has all the nutrients needed by the bacteria.[4] However, a wide range of additional organic waste material (referred as co-substrates) can be added to the mix and generally have the effect of increasing the yield. Straw is a good example. Each 10g of straw added to 1kg of manure will increase the methane yield by about 10%, providing the straw is adequately digested. [24] The balance of nutrients can be a concern when large amounts of co-substrates are added to the feedstock. If manure provides the bulk substrate material, the nutrients will be suitable for healthy anaerobic digestion and methane production.

There is a large amount of uncertainty in published methane yields. In several cases, the yields reported from the digester operation far surpassed the levels predicted by the system designers [12, 25-28]. This may be in large part to the effect of various co-substrates added to the digestion. Which ones are used depends on what is readily available at each farm, or what waste material is brought in for disposal from other industrial processes. However, once a digester is operating with a particular mix of feedstock, it is best if the conditions of the feedstock are kept constant in order to maintain the bacterial population.

Published yields from healthy digesters range from 48ft3/cow-day to over 100 ft3/cow-day. 70-80 ft3/cow-day for dairy manure seems readily obtainable with reasonable design and operation of a digester, based on the published results from several authors looking at a number of different digester technologies [29, 30] . The simplest plug-flow digesters have lower yields than the more complex higher-temperature systems, but the trade-off in higher capital investment should be an important consideration in system design. For the purpose of this feasibility study, we have chosen to use a conservative estimate for biogas production from cow manure as 1.3m^3 (46 ft3) of biogas per cow per day. Using the typical gas composition, and typical efficiency of a small diesel-gas engine, this is enough to continuously provide 70W of electricity per cow, or 1.6 kWh of energy per day. One manufacturer (Genesys Biogas Inc.) claims 2kWh of electricity per day per cow, which is on par with the high estimates of yield from published data [29, 30].

Energy Conversion

Gas, once produced and collected contains significant chemical energy, but that energy must be converted to a useful form to be of any value to the farmer. The generated biogas can be burned directly for heating in devices designed for natural gas, or it can fuel a modified diesel engine either as a stationary generator to produce electricity or as a vehicle fuel.

The specific use for which the gas is intended has a huge impact on the feasibility of a biogas digestion system. In principle, we would like to replace the highest-cost energy form on a farm. The trade-off is in capital cost of gas upgrading storage and combustion equipment versus the value of the end-product energy that is replaced by biogas. All gas-powered devices require some upgrading of the biogas. The three major uses of biogas on the farm could be:

a) **Vehicle fuel**: Internal combustion engines are routinely operated on natural gas or propane. In theory, biogas could be used in a modified vehicle engine. In practice, however, the varying load on vehicle engines and the limited storage capacity of onboard fuel tanks means that the gas must first be treated to remove the CO2, moisture and corrosive compounds, and then compressed to get sufficient natural gas in a small tank. Thus, transport fuel is the most technically-demanding application for biogas.

b) **Generator fuel**: An internal combustion engine that is shaft-coupled to an electric generator can be fueled with biogas. The biogas must be dried, with any H_2S removed prior to use. It need not have the CO_2 removed if the engine is run at a steady load and if the engine controls (fuel/air ratio) are adjusted to burn the methane/CO_2 biogas mixture. It need not be compressed, so long as there is a steady supply at adequate pressure for the gas-fuel injectors. In some cases, spark ignition is a required modification to diesel engines.

c) **Boiler fuel**: Direct combustion in a gas-fired boiler requires little, if any, upgrading of the biogas provided the burner fuel nozzle is properly sized. The boiler or burner can be operated in the same way, using the same controls as with other fuels once the correct nozzle is installed.

The majority of stationary energy consumption on many large farms is electrical.[31] Part of the work of this project was to look at three examples of PEI farms to understand their specific energy demands, and recommend the best way to retrofit biogas on a typical PEI farm.

Digestate Uses

The digested slurry that is removed from a digester is called digestate. Nutrients in the raw manure are retained for potential use as fertilizer throughout the digestion process. During digestion, the organic nitrogen in the substrate is converted into ammonia, an inorganic form that is more easily consumed by plants. [30, 31] Phosphorous and potassium levels are also maintained.[32] In this way, the potency of the manure as fertilizer is increased by the digestion process.

An important benefit of manure digestion is the removal of organic compounds from the manure, which are the main components in the smell of manure fertilizer when it is applied to the field. The digestate can be sprayed on a field with little to no offensive smell, reducing some of the complaints against large farms in crowded areas.

In addition to the value of improved fertilizer, the solid matter in the digestate can be separated, composted, and used as animal bedding. [33] The liquid portion ("filtrate") contains the high-quality fertilizer. There is some evidence to suggest that filtrate from anaerobic digestion. can give better yields than conventional fertilizer.[30]

One cautionary note: some co-substrates that may contain inorganic material that is not suitable for field application. It would be important in selecting a co-substrate to ensure that it will produce a digestate that is acceptable for use as fertilizer. On PEI, we have already seen the impact of not heeding this sort of caution with the municipal compost facility. When the facility was first built, it was expected that the agricultural industry would use the compost. Once the plant was in operation, growers were barred from using it when major potato buyers rejected it for use on process potatoes [34, 35]. It would be an important step for the operator of a digester that is planning to use any industrial or municipal waste co-substrate to get confirmation in advance that the finished digestate will be acceptable for use as a fertilizer.

II. Farm Visits

In this project, we identified two example small dairy farms as example sites, one with 70 milking head, and the other with 60. Based on the average numbers, these are not uncommon herd sizes on the Island. We did not look seriously for smaller farms to include in the study because the initial research showed that fewer than 60 milking head would be too small for a biogas system [36]. For comparison, we also reviewed a similar sized beef calving operation.

The most important information that we collected from the farm visits was regarding the current operations with a special interest in current energy use on the farm. Since the operation of a dairy farm is very energy-intensive, we compared the farms on the basis of number of animals, methods of manure handling, location, and other aspects of the farming operation. Equally important is the timing and amount of energy used on a daily and seasonal basis on each farm. Appendix B presents the raw datasheets that were collected from farm visits.

SandyRae Farms

SandyRae Farms has a herd of 70 milking cows kept in a tie stall barn. All of the farm vehicles are diesel-powered, and the major rolling stock are leased. The owner, Danny MacKinnon, has recently installed a new wood-burning furnace which heats the majority of the farm including process water for the milk-house and space heating for the farmhouse. There is a small propane-fired boiler which augments an electric boiler to boost the temperature of water for wash-down and sterilizing of the milk-house and milk handling equipment.

Electrical demand is around 300kWh per day. This relatively high demand was due to the extensive use of single-phase AC motors throughout the feed storage, feeding, cleaning, milk collection, milk storage and manure handling. The feed is stored in two large silos that with grain that is put up for silage by an electric elevator system. Cows are fed using a separate blower and auger system, all power by AC motors. A scrape chain collects the manure which is then pumped into a large holding tank through a large-bore buried pipeline.

Pleasant Valley Farm

Pleasant Valley Farm has 60 milking cows that are split between two free stall barns at two different sites separated by a few kilometers. The original farm has been in operation for more than 30 years as a dairy farm. The farmers have purchased a former hog farm and converted one of the barns for use as a milk-house with a free-stall barn adjacent. 30 milking head from the farm have been kept at the original farm, while the new site can milk 20 cows at a time but has housing capacity for as many as 80 in the future.

When we visited the farms, the herd had not yet been moved to the new site, so the details of operation for the future were still unknown. In its original arrangement, the farm used significantly less energy per day than SandyRae farms with a similar sized herd. The main reason for this was that Pleasant Valley Farm relies on tube rolls for feed, and these are wrapped, stored, moved and delivered to the cattle by tractor and skid-steer. Thus, all energy used in the feeding operation comes to the farm in the form of diesel fuel. Electricity consumption was around just 100kWh per day, but there is a need for increased lighting in both sites so this number may increase. Farm heating is accomplished with an old wood chip burner. A small electrical hot water heater is used to provide hot water for the milkhouse during warmer months.

In the original farm, manure is collected using a scrape chain system with a piston pump to deliver the manure to storage. Manure in the new site is collected by scraping with a skid steer. A large cylindrical buried manure tank that was used for the previous hog farm still exists in good condition, and is now being used for the cattle manure storage.

Campbell's Farm

We visited a similar-sized cow-calf farm to compare with the example dairy farms. Glenn and Rhonda Campbell run a 115-head calf-cow farm. The number of cattle in the barn at any one time is similar to that from the two dairy farms. Cattle are put to pasture when not calving. Calves are sold to a feedlot when they reach the desired weight.

The manure is collected roughly once every three weeks during the winter and most of the cows are in pasture during the summer. (60 were inside when we visited, which is comparable to the number of cattle in milking barns of the two dairy farms above). Notable about this farm is that the electricity bill (from several separate meters for different areas of the farm) is only around $100 per month. With the current net-metering electrical policy, this means that the electrical revenue can be no more than $100/month.

A farm of this size has adequate manure to feed a small digester, but without a large existing electrical load, the farm could not earn back from the electric utility any more than their monthly bill on one meter. This would be a major obstacle to a biogas system, but it also presents an opportunity to build support for lobbying to have the net-metering policy changed.

III. Preliminary Design of a BioGas Facility

This feasibility study is intended to determine whether a small biogas plant could be viable at a typical PEI livestock farm. In order to answer this, we will go through a prospective conceptual design of a biogas plant, selecting sizes and scope for major system components.

Through each specific section, we will highlight risk or questions that will point to significant risks or unknowns.

There are a number of alternatives to consider in the design of a farm biogas facility. Decisions made at the beginning of a design must be based on a clear design philosophy, or set of guiding principles to ensure that the final system fulfills its purpose.

Our guiding principles for this proposed design are:

- The system must be an add-on to an existing livestock farm,
- Minimum capital investment for the farmer is a priority.
- Operation of the biogas plant will improve the environmental footprint of a farm.
- The finished system must not take up a major portion of the farmer's labour to operate, so maximum reliability is a priority.
- Manure from the livestock on-site will be the prime feedstock. Transport of manure from other farms will not be accommodated by the system.
- The co-substrate will be waste straw, and will be a fraction of the manure mass.
- The system will not handle imported industrial or municipal waste material.

In light of our guiding principles, the first discussion to have is over the size and complexity of a biogas plant on the farm. The US department of agriculture's AgSTAR program recommends that on-farm biogas systems are suitable for more than 200 milking cows. If we follow this as a guide, then we need to look only at large farms, or we need to consider small farms and justify the system by using imported biomass for the bulk of digestion. The cost and complexity of such a system is large. For example, a system described by Genesys Biogas Inc would require an initial investment of between 750,000-1,000,000CDN$ and could generate 100-500kW of electricity. If the power could be sold to the electrical grid at 0.12$/kWh, this could provide 100,000-500,000$/yr in revenue, assuming the regulatory environment permitted the owner to sell power to the grid.

Due to the investment magnitude, the system will have to be managed aggressively in order to provide an acceptable payback on investment. In order to keep the system operating, a steady supply of biomass would be essential. The options for the farmer will be to either import waste material from beyond the farm-gate, or to grow crops specifically to feed the digester. The former alternative will require the farmer to manage a supply-chain of waste material. If there are many large digestion systems nearby, this could put farmers in a competitive environment for waste, each trying to secure a steady supply of biomass. The latter choice could force the farmer to take land out of production for food crops, a dilemma which has been controversial in the food versus energy debate. At the very least, it will mean the farmer will be locked-in to growing biomass to feed the investment instead of other crops, so the incremental revenue from a large plant could be very small, even though the capital committed to the plant is large. The recommendations from manufacturers and from AgSTAR can be summed up by the expression "go big or stay home". While there may be an economic justification for a large system that is designed to digest imported waste or purpose-grown organics, the plant could overwhelm the existing farm.

Ultimately, there certainly is a need for industrial-scale on-farm biogas plants. However, there is also a need for more modest biogas plants that digest only the organic material that is produced on a single farm as a waste from the main activity of farming. The small farm digester is this application that we are addressing in the current design.

Expected BioGas Yield

Estimating a farm's potential biogas production is straightforward. First, the rate of manure available must be determined on the farm. The concentration of volatile solids in the manure should then be estimated based from either laboratory analysis of a sample of manure or from typical published values for similar manure. Next, an appropriate Volatile Solids-to-methane conversion efficiency should be selected based on the proposed digestion technology and on properties of the manure. Different digester technologies, operating conditions, bacterial populations and other factors will influence this value dramatically. From published data, efficiencies have been reported from 30-65%. For a well-designed and well-run plug-flow digester 35-40% efficiency is attainable [9]. Finally, the ultimate yield for the type of manure can be found in the literature. Multiplying these four values together gives the methane production rate:

$$B_G = \frac{E_f M V_s Y}{100}$$

Where:

M = manure output in kg per day
V_S = Volatile solids mass (kg) per mass of the manure (kg), ideally from lab analysis, but typically
E_f = conversion efficiency (%) of the available volatile solids in the manure that is converted to methane by the digester, assumed to be 35-40% for plug flow digesters
Y = ultimate yield in cubic meters of methane per kg of Volatile Solids , assumed to be 0.35 m^3 of methane /kg of Volatile Solids
B_G = daily production of Biogas Methane in m^3

Based on the above calculation using published data, one cow will produce 1.3m^3 (46 ft^3) of biogas per day. Assuming a 60% methane concentration in the biogas, this translates into 1.54 kWh of electricity per cow per day or revenue of $67 per cow per year at an electricity price of $0.12/kWh. Published reports of practical operation of digesters have shown these numbers to be conservative. If the value of straw bedding added to the digester is included, the estimated biogas yield increases to 1.9m3/cow-day, which works out to 2.4 kWh/cow-day of electricity and potential revenue of $105/cow per year.

Using the quantity of available manure is a more exact way of calculating yield, but the per-cow figure is useful for comparison. 54 ft^3/cow-day is one published estimate, and the very-successful Haubenschild digester was designed with an expected yield of 65ft^3/cow-day.[29] The Haubenschild digester actually achieved an astounding 139ft^3/cow-day before settling at 93ft^3/cow-day, well above the design yield, which is likely due to the co-substrates they added, notably newspaper.[37] It is worth noting that well managed digesters tend to exceed the conventional yield expectations.

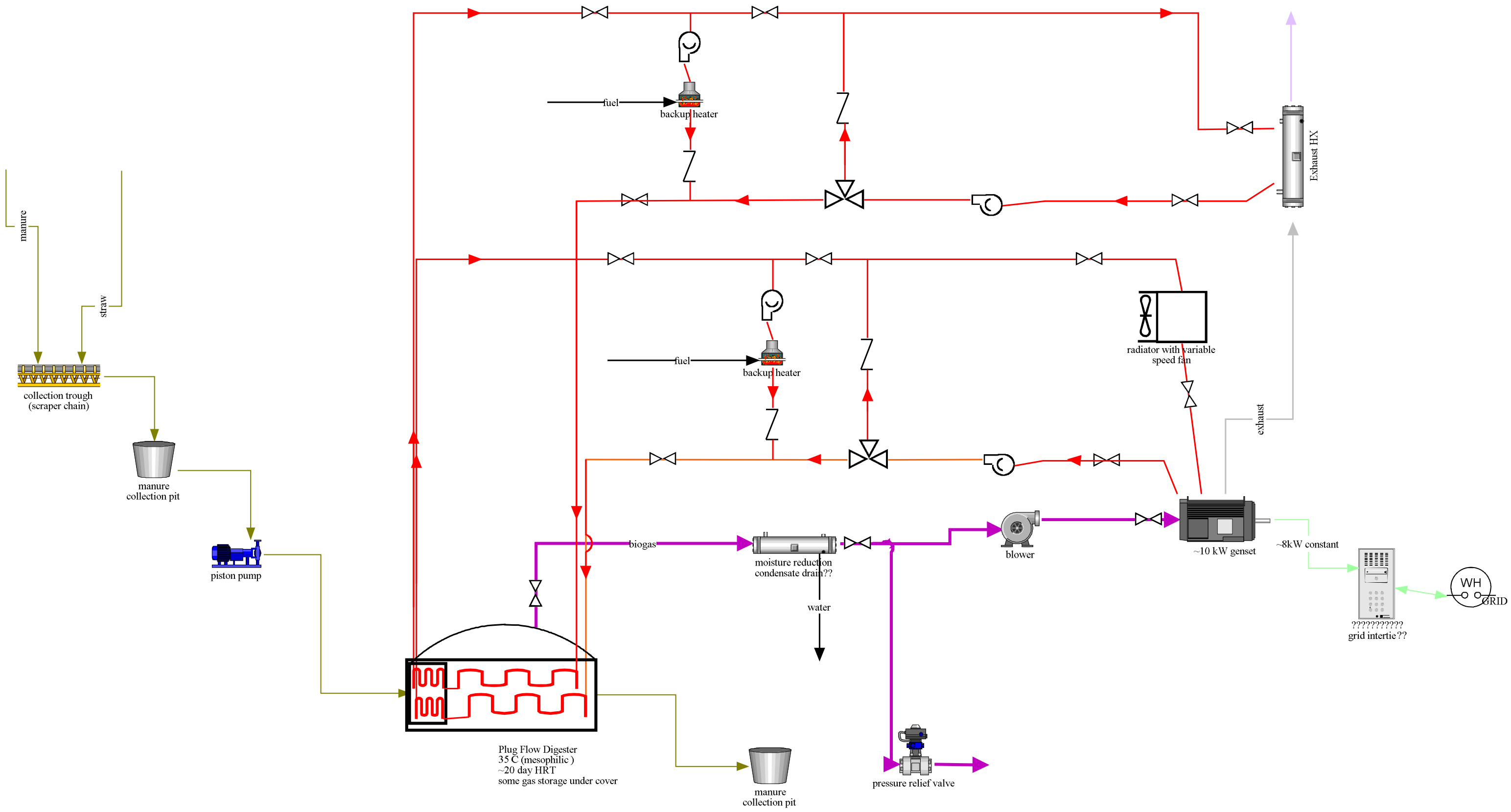

Figure 3: simplified Schematic of process diagram used in this report analysis. The manure input is on the left, while the heating system is shown with red lines. Biogas fuel is shown in purple. Electrical output is shown on the right.

Major System Components

The main components of a small digester system are:

- Manure and feedstock collection
- Digester Tank and Heating system
- Biogas cleaning and combustion
- Electricity generation and distribution
- Digestate storage and field application
- Process monitoring, control, and safety systems

Manure and Feedstock Collection

Two of the example PEI dairy farms use scraped manure collection systems that gather raw manure plus straw bedding twice daily. The scrape chain moves raw manure into a pit where a piston pump transfers the manure through a buried pipeline approximately 50-100m to the manure storage barn. The new site for Pleasant Valley farms uses a skid-steer to twice daily move manure to the storage pit. Any practical biogas plant will need to be designed to work with the existing solid manure collection system in order to keep retrofit costs low. A liquid manure system would require substantially different digester designs.

It is most economical to use the existing manure collection system entirely unmodified. This includes the scrape chain system, the piston pump, and possibly the pipe that carries the manure to the storage building. The question is whether the contents of the collection system are suitable for digestion. Given that in both example dairy farms this is relatively fresh manure, a regular amount of straw bedding, and perhaps a small amount of water, this doesn't seem to be a problem. It is worth noting how well-matched a plug flow digester is to this type of system. While other types of manure digesters can provide greater yield and shorter residence time, they would all require significant changes to the manure handling systems.

Digester Tank and Heating System

Digesting this mixture of undiluted manure and straw could be done effectively in a plug flow rector tank. Plug flow systems are simple to build, require no complex internal parts, and can handle a widely varied mixture of manure and straw. They typically operate at mesophilic temperatures between 35-40C. The gas yield from these type of digesters may not be as high as more advanced digesters, but they are commonly used in farm installations. The retention time is comparatively long, but given the simplicity of plug flow digesters, this solution would be suitable for on-farm operation with little attention from the farmer. For a detailed description of different digesters see Appendix A.

Tank Size

Rough sizing of the digester is accomplished by multiplying the volumetric flow rate of manure by the desired substrate retention time. We have assumed that 50 kg/cow-day as a reasonable standard manure supply rate [9]. For a model 60 milking cow dairy farm, this means a manure rate of 3.1 m^3 per day having a minimal component of straw bedding.

The desired retention time is not absolute. It is a balance between yield and cost; both increase with digester capacity, but at different rates. Based on researched cases of mesophilic plug flow digesters, 20 days is a good target; it seems to be the most common design retention time for plug flow digesters, including the Haubenschild digester, and published operational retention times seldom differ by more than a few days. [30] .

In both dairy farms we studied, the manure storage building is a covered rectangular concrete tank. Locating the digester inside or adjacent to the existing manure storage structure makes use of the existing manure pipe, reduces construction costs, and provides added thermal insulation thanks to the enclosed roof. Using this 20-day as a guide, the approximate size of a digester tank for our example farm would be 75m^3, or   2.5m wide by 2m deep by 15 m long (or 8ft wide by 7ft deep by 50 feet long). A tank of this size could be accommodated inside of one of the existing manure storage barns on either SandyRae Farm or Pleasant Valley Farms with room to spare.

Manure composition and co-substrate content can change the optimum retention time. The optimum retention time is influenced by organic loading rate, measured as the rate of volatile solids added to the digester per unit of digester capacity. For pure cow manure the recommended loading rate is 2.5-3.5 kg VS/m3-day and with the addition of co-substrates it is 5-7 kg VS/m3-day [3]. Careful consideration should be given to the future plans of the farm in question when deciding on digester capacity.

Significant Challenges:

- **Optimum tank size will require more detailed analysis of influent and digestion process**
- **Materials compatibility should be investigated, and metal, concrete, plastic, or fibreglass tanks will need to be considered in final designs**
- **Shipping costs of completed tanks, or onsite costs for construction on the farm will need to be evaluated**
- **Site selection will need to be considered, is it best to use existing manure storage tanks or build on a new foundation**

Digester Heating

In order for the digester to operate properly, it is essential that the temperature be kept carefully controlled. It is a living system, and extremes of temperature will harm, or kill the bacterial population which does the work of digesting organics. The standard for heating the digester is to use heat recovered from the genset. Heat can be recovered from the cooling jacket water and also from the exhaust gas through a heat exchanger. Both methods are used in systems on large dairy farms.[37][38] There are few published details available from cases on this. Also, most of the farm digesters are located in warmer climates than PEI. The digester bottom, walls and top will need to be insulated to prevent heat loss.

Manure, by the time it is collected by a scrape-chain system has cooled to ambient temperature of the barn. Heating the influent to digestion temperature (~35°C) before it enters the digestion tank is one of the largest heat demands, with the maintenance of temperature through the rest of a well-insulated digester as a smaller demand. If the only source of heat is from the cooling jacket of an engine, the adequate temperature control will be a problem. To supply the heat required to maintain the overall digester temperature, it is very likely that cooling jacket heat alone will not suffice. Thus, the exhaust gas heat from the genset as well as the cooling jacket water will be required to keep the digester at the proper temperature.

Theoretical calculations (Appendix C) for heat demand to maintain the digester temperatures yield a heat loss from the digester of 3kW of heat, while the demand to pre-heat the inflow manure will be approximately 4kW of heat. A 10kWe generator could supply this amount of waste heat if running continuously.

Cooling jacket heat from an engine is easily reclaimed by simply routing the cooling water through pipes in the digester tank walls. Reclaiming waste exhaust gas heat is more difficult. The heat exchangers required to reclaim heat from the exhaust face highly corrosive conditions. H_2S condensation inside the exchanger can result in the formation of sulfuric acid on the exchanger walls. There may be an opportunity to use anything from a simple water-jacket exhaust pipe to a small wet-muffler for direct contact between exhaust gas and water. This system could be in series with the cooling jacket water, or in some cases it may need to be a separate fluid loop. The design of the best alternative for the heating system will require dedicated effort, but there are a number of simple options that are possible.

During digester startup, on very cold days, or in the case of problems, a backup heating system capable of warming the digester to a suitable temperature will be required. Such a system would be in series with the regular heating loop. The cooling jacket loop would also need to run through a radiator before returning to the engine to ensure the engine is adequately cooled during warm months.

Significant Challenges:

- **Ideal operating temperature needs to be determined from testing**
- **Heat loss from a digester needs be determined from experience as well as calculation**
- **Start-up heating procedures need to be established**
- **Seasonal variability in the digester heating will be needed for correct heat system sizing and design**
- **Digester maintenance and cleaning requirements for the heating surfaces will need to be established**

Biogas Cleaning and Combustion

Given that the largest and most costly non-transport energy uses on dairy farms are electrical, running a biogas genset to create electricity is the most attractive option. It is one of the more cost-effective choices, as mentioned earlier requiring little to no gas cleaning before combustion. There is also more experience with using biogas gensets; from our literature research, the majority of existing farm biogas plants are designed for this type of use.

As it is produced, biogas will build up under the cover of the digester. With an inflatable cover, there is potential for a small amount of biogas storage – something like 5 hours of retention time. This would hopefully provide enough capacitance in the system for a smooth biogas supply. A pipe under the digester cover would the biogas away. Because the biogas is originally nearly saturated with water vapor (up to 50mg/L), condensation will occur as it flows through the pipe and cools. [39] A condensation trap to collect this would be important to avoid the formation of sulfuric acid inside the pipes.

Treatment of the biogas for further moisture removal, H_2S removal, or CO_2 removal seems to be unnecessary as far as genset operation is concerned. The majority of case studies make no mention of gas treatment, and according to [40] modified Caterpillar and Waukesha diesel gensets are known to handle unfiltered biogas without problems if engine maintenance such as oil changes are done at frequent intervals.

A pressure relief valve is required along the biogas supply pipe relieve pressure if any problem occurs with the combustion equipment, or if the engine needs to be shut down for any reason. This valve would ideally lead to a self igniting flare. This seems to be a standard feature on large biogas systems, but the size of the systems discussed in this report may be sufficiently small that a flare is not required in all cases. The low methane concentration, high moisture and low flow rates may make the use of a simple vent stack all that is required. Local fire regulations and provincial environmental policy will govern future installations.

Significant Challenges:

- **Condensation traps having the appropriate size and material service will be required**
- **Alternative for H_2S removal from the gas will need to be evaluated**
- **Emergency Flaring or venting regulations will have to be determined**

Electricity Generation and Distribution

An engine/generator running on biogas could be expected to convert around 20% of the heating value of the fuel into electrical power. For the volume of biogas that can be produced on a small farm, there may be enough electrical energy generated to supply the farm average electrical demand. In theory, this could allow the farmer to operate off the grid, but the trade-off between equipment costs to supply peak electrical demand versus the cost of equipment to supply only the average load is significant.

There are fundamentally two choices for system size. The first choice might supply a peak demand through the day for activities such as milking, feeding and cleaning twice per day. Dairy farms have very large cyclic demands for electricity that has been reported in the literature [36, 41]. For the farms studied in this project, a 100-150kW system would be needed, depending on the timing of different loads for cattle feeding and milking. A system in which the genset is matched to the farm's peak power demand and operated to coincide with those peaks will require significant biogas storage to satisfy the demand peaks. Such a system could supply the farm's power and sell excess back to the grid during times of low demand, or simply store gas onsite until peak load. A system could provide potential electrical self-sufficiency. However, the greater capacity and need for gas storage would mean larger capital costs, and the intermittent operation could increase system monitoring, control and safety requirements. This option would also require that a supply contract with the electrical utility be negotiated if there were any surplus electricity to be sold to the grid. The regulations currently have a break point for energy producers at 100kWe. Producers larger than this limit can sell electricity to the grid at a wholesale rate, currently 7.75c/kWh. Smaller producers fall under the net-metering regulations that effectively pays the retail market rate of approximately 12-15c/kWh, but the utility is not required to purchase more than the customer uses, effectively allowing the farmer to, at best, zero their bill on a monthly basis, but not be paid for net positive power generation.

The second option would be a constant-output system in which the generator is matched to the average biogas output of the digester and operates continuously; feeding all produced electricity to the electrical grid at a steady rate. It is important to know that an engine's capacity when on biogas can be 20% less than its rating due to the lower energy fuel [40]. Thus, for a typical 60-cow dairy farm, a system based on a generator smaller than 20kWe rating would be appropriate. The capacitance provided by the digester cover would be all the storage required. Such a system would deliver power at a consistent rate and would require that a contract with the electrical utility be negotiated with a separate demand-meter installed by the utility. The billing would be based on the net difference between the two meters on a monthly-average basis, according to current regulations, making the electricity generated worth the retail rate of 12-15c/kWh.

Advantages of this second option are minimal system costs and minimal complexity of the biogas system and generator; the equipment capacities and capital cost will be as small as possible and the operation will be constant, essentially getting as much energy as possible out of the investment. However, the peak energy demand of the farm would be essentially unchanged, and the electrical feed to the farm would be one-way from the grid. The biogas system would have its own separate hook-up to the grid with no intertie to the farm load. This is the energy use selected by the majority of North American farm digesters. This means there is a considerable amount of experience with this method, so it should have the lowest risks, as well as the lowest capital costs.

Regardless of which alternative is chosen, the electrical hookup would necessitate appropriate safety and isolation breakers as dictated by the electrical utility. In a meeting with Maritime electric staff in December 2008, we were told that the utility currently has no firm rules for such hookups, and that the net-supply meter to monitor the feed from the farm system would be supplied by the utility. It was their opinion that, other than routine switch gear for disconnects and fuse protection, there were no additional requirements.

Significant Challenges:

- **Suitable engine/generator models and manufacturers need to be found for single-phase installations, spark-ignited, 20kWe typical size**
- **Engine reliability and cost needs to be determined**
- **Gas cleaning requirements specific to the target engine must be verified**
- **Generator control, emergency shutoff, and protection needs to be determined**

Digestate Storage and Field Application

Storage of the digestate could likely be provided by the remaining space in the tank on the example farms. For a 6-month-capacity tank, a plug flow digester should only take up 12% of the existing volume in the covered manure storage (not including space required for walls, etc.). The solid digestate will be reduced in volume from the original manure source by as much as 80%, with much of the lost volume in the form of liquid digestate. The liquid can be separated from the digestate solids using the same settling pits in the current manure storage tanks, and this liquid digestate can be applied to the fields. A significant advantage will be a reduction in smell from the typical liquid manure spreading. The solid digestate would be stored and applied to fields or further composted for bedding after passive drying.

In this situation, the digestate requires no transportation, it goes directly from the digester to the adjacent storage space. Several farm digesters in the US are enclosed by purpose-built buildings or in at least one case a greenhouse, but there is no mention of digesters built inside pre-existing manure tanks[30]. The practicality of re-use for the existing manure storage in a digester/ digestate storage application would need to be investigated further.

Significant Challenges:

- **Local regulations for application of digestate on farmland need to be determined**
- **The acceptance of the digestate as a fertilizer needs to be assured**

Process Monitoring, Control and Safety Systems

Control of the biogas system can be divided into five sections: influent, digester, heating, generator and electrical hookup. Each of these systems will need some form of monitoring and control.

The existing method for controlling the manure collection should suffice to control the influent entering the digester. The scrape chains are turned on and off by the farmer before milking and the manure pump will be activated until the manure in the milking barn pit is emptied. The existing systems tend to collect and transport the manure twice daily, which should be fine for the digester. Potential difficulty could arise if the digester was full, and unable to handle the full manure load, or if co-substrates are added separately from this main manure supply. Aside from some indicator of the level of the manure in the digester, the pre-existing standard manure collection system would require no modification.

Control of the digester will be an important system. When manure is pumped from the barn to the digester, it could, in the simplest system, go directly into the digester. Unfortunately, this new manure will be too cold to digest, so it will need to be heated. This would be ideally accomplished by including the maximum number of heating coils at the inlet stage of the digester. A temperature sensor would be necessary at this inlet stage of the digester, as would some form of level indication, either electronic or mechanical.

In order to operate effectively, the digester temperature needs to be held at the desired temperature with as little variability as possible (ideally, within a few degrees C). The main body of the digester will need temperature sensors at several points to operate efficiently. It will have heating coils that these temperature sensors can activate through either solenoid valves in the waste heat line of the generator, or, in the case of system startup, relays to activate electrical water heaters. While there are many other factors than temperature that impact the biogas digestion process (See Appendix A), none of the factors are practical to include in a measurement/control system for a small scale plant.

The heating control system will be crucial. It serves two functions: maintaining the digester temperature, and regulating the engine/generator temperature. For the cooling jacket heating loop, the engine water pump will circulate the cooling jacket fluid continuously. The control system will operate a thermo-valve to regulate the flow through the digester heater, or a radiator connected in parallel to augment the engine cooling. A similar system would be used for the exhaust gas heating loop. If the digester required more heat than could be provided by both loops combined, the backup systems in either or both loops would be engaged.

The generator system would manage the power output of the generator and the rate of biogas use. The main goal would be to run the genset at peak efficiency given the limits of the biogas supply. A pressure sensor would indicate the amount of biogas in the system and the system would control the throttle of the genset. If the biogas pressure dropped below a certain threshold, the genset would need to be throttled back or shut off until the biogas supply regenerated. The system would require an indication of the gas pressure and state of electrical output for the farmer.

A decision would have to be made whether to run the genset at a continuous rate matched to the available biogas supply, or run it at its peak efficiency with occasional shut downs to allow the biogas supply to regenerate. In either case, excess biogas would need to be flared or vented, depending upon local fire and safety regulations.

The electrical hookup to the grid will require an intertie that can match the generator output to the correct voltage and phase of the system. Manual breakers, and safety dropout breakers would also be required. Similar equipment is used in many photo-voltaic installations that have a grid interconnect. There are numerous newer products available that are capable of handling the size of supply that this system would produce, between 10-20kWe. Larger systems than 100kW will require extensive safety and dropout protection.

Significant Challenges:

- **Local regulations for electrical safety need to be verified by both the utility, occupational health, and local fire departments**
- **Requirements for automatic or manual intertie need to be established**
- **Detailed control system designs for temperature control need to be developed, and the heating systems tested**
- **Heat loss calculations are based on theoretical estimates, and these need to be properly verified**
- **Regulations on venting or flaring of gas need to be determined**

Notes on Cost and Payback

The simplest way to estimate system cost for a small farm biogas system based on existing North American installations is to scale down the costs on a per cow basis. There are several published estimates of this per-cow cost. They range from $1200/cow down to $550/cow for the Haubenschild digester.[29, 42] The largest problem with this approach is that we know per-cow costs increase with smaller scales. If we use the high end of this estimate without further analysis, then we could predict a system capital cost for a 60-cow milking barn of 60,000$.

Without a detailed design of the system, an accurate cost estimate can't be reliably made. However, if we start from the recognition of what might be a reasonable target cost for the complete system, we can make some general targets for how to break down the total system:

Item	budget
site work	15000
digester tank	15000
control system	6000
20kW engine/generator	10000
electrical equipment	6000
installation	10000
shipping	8000
total	**70000**

The goal for a biogas system is to provide the farmer with an acceptable payback on investment while improving the environmental footprint of farming. Given reasonable operation of a biogas plant for 60 cows, the owner could generate an average of 10-15kW (a very conservative estimate) 24 hours per day, 365 days per year. The total energy generated and supplied to the grid per year would thus be 87,600-130,000kWh per year. At a retail rate of 12c/kWh, this would save the cost of 10,500-15,700$ of electricity through the year.

The biggest problem with the above is that it is purely dependent upon the individual farm electricity usage. The payback will be only equal to the total electrical utility bill per year, as the maximum under the current legislation. Thus, the utility of on-farm biogas depends upon electrical net-billing policy.

In the case of one of our example farms, the operation consumes over 100,000kWh per year. In this case, a 70,000$ investment in biogas could achieve a simple payback on capital investment in less than 6 years.

IV. Conclusion

Conventional wisdom in the agricultural industry is that biogas production from dairy farms smaller than 60 milking cows, or equivalent numbers of beef cattle in a barn are not practical. Meanwhile, tiny biogas production systems operate in many countries of the world on waste from a subsistence farm including a single cow plus a household of 4 or more people. There is clearly a huge disconnect between our industrialized agricultural wisdom and experience in other countries.

Commercial manufacturers have been installing systems in Canada and the United States for on-farm biogas that handle manure, but augment it with a substantial amount of non-manure additional materials. Doing so allows a large digestion system, permitting economies of scale. Such systems can continuously fuel electrical generators larger than several hundred kW.

This report has looked at issues around the implementation of biogas on a typical livestock farm on PEI, whether for dairy or beef cattle. There is no technical limitation, nor regulatory one for the establishment of a small on-farm digester which could generate sufficient electricity to more than supply the farm's average electrical needs. The technical challenge in building a small biogas plant will be in finding suitable small-size and price components for such system that can be accommodated in a reasonable capital budget.

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Appendix A: Anaerobic Digestion

Anaerobic digestion is a multi-step process in which different bacterial populations decompose different substances.

The first step in the anaerobic digestion of a substance is hydrolysis – enzymes from certain bacteria break down large organic polymers into smaller more usable substances. In the next steps, acidogenesis and acetogenesis, the monomers created by hydrolysis are converted into volatile fatty acids, ammonia, hydrogen, carbon-dioxide, and acetic acid. Finally, in methanogenesis, methane-forming bacteria consume the volatile fatty acids and especially acetic acid, and give off methane (and carbon-dioxide and water). [4]

The methanogens (methane-forming bacteria) are the most sensitive / slowest-growing bacteria population involved in the process. Most of the concerns with feedstock properties are aimed at supporting the methanogens.

Effects of Time and Temperature

There are many variables that effect the anaerobic digestion and production of biogas, but two stand out as the most essential: digestion time and temperature. The time duration for which a substrate is inside the digester is called the hydraulic retention time (HRT). The longer it is, the more digestion will occur and the more biogas will be produced, although this eventually levels off. If the time is too short, there will be insufficient time for the bacteria to keep up with the amount of substrate coming in, and very little biogas will be produced. The optimum HRT for most digester types is generally between 15 to 30 days.

Temperature is probably the most important environmental variable. Both biogas production and bacteria growth rates tend to increase with temperature. There are three temperature regimes that are considered optimal:

- Passive / Psychrophilic: This is an unheated digester. The temperature is at or slightly above ambient temperature.

- Mesophilic: Temperatures of 35-40°C provide increased conversion efficiencies and speeds over passive digesters. This is the most common for farm-scale digesters. Some degree of pathogen sterilization is present. Odor reduction is maximized.

- Thermophilic: Temperatures of 45-55°C. This higher temperature approximately doubles the biogas production rate compared to mesophilic temperatures. There is better sterilization of pathogens over mesophilic, but the effluent has a significant odour not present with mesophilic digesters.[4, 20]

The mesophilic and thermophilic temperatures reflect maximums of different methane-producing bacteria. For that reason operating at a temperature in between is not advisable. However, It is possible for digesters to be switched between mesophilic and thermophilic operation as long as the transition happens slowly enough for the required bacteria populations to grow. [3]

pH

The methanogens need a pH range of 6.8-8.5. [9] The main danger is the pH falling beneath 6.8. Acetate and fatty acids produced in the first phases of digestion (and consumed by the methanogens) act to lower the pH. Bicarbonate from dissolved CO2 acts as a buffer that resists this. There are two methods to raise the pH:

1. Stop the influent – this stops further acid and acetate production by the acidogens and acetogens, while allowing the methanogens to continue digesting these pH-lowering substances.

2. Add an alkaline substance to raise the pH without interrupting digestion. Lime and soda ash are both options. Lime leaves a precipitate but soda ash is more expensive.

It is unclear whether a low pH is a result or a cause of methanogen problems. [4]

Nutrients

Maintaining enough nutrients in the feedstock is not usually an issue; manure generally has all the nutrients needed by the bacteria. [4] The balance of nutrients is generally more important and requires management for optimum biogas production.

C:N:P

One key balance is the carbon to nitrogen ratio. A 10:1 to 23:1 ratio is often cited as optimal for bacteria digestion. Higher nitrogen levels result in raised ammonia levels, which help maintain a higher pH but inhibit methane production at higher levels. Ammonia concentration should generally be kept below 80ppm. [4] Anhydrous ammonia (NH3) rather than ammonium (NH4+) seems to be responsible for inhibiting methanogenesis. pH (which changes the balance between NH3 and NH4+) is significant in the degree of inhibition. A maximum NH3 concentration of 0.7g/L was found to apply for thermophilic digestion. [3] As-excreted manure typically has a C/N ratio of 10. [9] Cow dung has a C/N ratio of 25, higher than that of swine and poultry. [4] The carbon to nitrogen ratio should always be kept below 43. Similarly, the carbon to phosphorous ratio should be below 187. [9]

F/M ratio and Loading

The food to microorganism ratio is a key factor in digester performance. It is controlled by changing the loading of the digester (i.e. how much food is added). Loading is measured as the mass of volatile solids added per day divided by the digester volume. [9] Lower ratios (more microorganisms) result in more of the influent being converted to biogas. Higher ratios result in reduced conversion efficiency of the volatile solids to biogas. [9] At the same time however, higher ratios result in higher methane outputs for a given digester size. [43] Higher loadings can also increase the temperature variation tolerances of the bacteria. [4]

Digestion Control

As methane formation is the most sensitive step in digestion, control processes aim to prevent inhibition of methanogenesis.

The important parameters (other than temperature) most commonly measured in a digester are pH, biogas composition, and volatile fatty acid concentration. pH can indicate when a serious problem is occurring, but because the substrate is so highly-buffered, serious imbalances can occur without a significant change in pH. Similarly, biogas composition indicates when inhibition is occurring, but the response is too slow to indicate issues before they become serious problems. [3]

The concentration of volatile fatty acids (VFAs) indicates the balance between acidogens and methanogens because VFAs are an intermediate product. When methane production is inhibited, the methanogens consume less of the VFAs, causing the pH to drop, which further inhibits methane production.

Measuring specific VFAs can give an indication of the stability of the digestion. Unfortunately, even the VFA measurement is not responsive enough to help avoid system failures. [4]

Productivity

The amount of volatile solids in the substrate indicates the potential for biogas creation. Not all volatile solids are digestible however. Particulate solid matter (much of which may be filtered out before digestion in non-plug flow digesters) contains the higher portion of indigestible volatile solids. This means that filtered influent will have a higher conversion or treatment efficiency than unfiltered influent. [43] It is important to note that this efficiency is measured as the percentage of volatile solids inside the digester converted to biogas. It is efficiency based on reactor load, not the total available biomass, because some has been removed from the digestion stream. Fifty percent conversion is a reasonable average value.[9] The reduction of chemical oxygen demand is directly linked to methane production. 0.35 m3 of methane (equivalent heating value of 12 000 BTU) is created for every kg of COD destroyed.[43]

Methane yield is a per-unit measure of methane production. Theoretical yield (BU), as the name suggests, is a calculated value based on the complete conversion of organic matter to methane. It is measured in L CH4 / kg VSdes. (Theoretically, all the VS are destroyed, so it could be per VS loaded, but using VSdes allows the number to be applied to actual systems where the VS reduction can be measured.) Ultimate yield (BO) is measured per VS loaded, and it is an experimental result based on how much methane is produced if retention time is essentially infinite. It is often measured in L CH4 / kg VSload. The proportion of VS consumed in a digestion (the treatment efficiency or biodegradability) can be practically found by dividing BO by BU. [24]

Manure Handling Systems and Total Solids Levels

The concentration of solids in the manure is the main criterion for digester selection. The total solids (TS) level reflects the liquidity of the mixture, as well as the concentration of organic matter available for digestion. These parameters determine the size and type of digester that can be used.

As-excreted manure generally represents the highest solids concentrations available to a manure digester. Manure from dairy cows has a TS level of around 12%. Such solids levels would be seen by a digester if a scrape system was used to move the manure, providing no water was added. A scrape system simply scrapes the manure into a sump from which it is then moved into the digester system.[9] If some water is added to the manure but a scrape system is still used, the digester might see TS levels of 5-10%.[31] In pit recharge or pull-plug systems, the manure is diluted to less than 3% TS. In a flush system where the water flows down the manure channels, the solids concentration is reduced to less than 2% TS. [31]

Digester Types

There are many types of anaerobic digesters. The following are the basic types applicable for small farm use.

Covered Lagoon

Covered lagoon digesters can are formed by covering a lagoon with either a flexible cover spanning the entire lagoon or smaller modular floating covers. The covers contain and pipe away the generated biogas. Advantages of the lagoon digester are low cost, minimal installation effort, and the flexibility provided by modular covers.

Lagoon digesters are suited for flush manure systems, as they need influents with 0.5% to 3% TS. [44] Lagoons operate in the passive / psychrophilic temperature range and have retention times of at least 30 days, due to the cooler temperatures and relatively uncontrolled environment. Lagoons can produce useful biogas in warm regions, but in cooler climates (such as Canada, according to AgSTAR) the intermittent biogas production is only suitable for flaring. [31][45]

Plug Flow

Plug flow digesters are relatively simple. The influent enters at one end, and as the biomass flows through the digester, effluent is pushed out the other end. The main requirement for plug flow digesters is that the influent has the necessary level of solids (10-13% TS) to flow through the reactor tank as a plug, rather than mixing or stratifying and settling. [46] Only scrape systems for dairy/beef meet this criterion, pig manure cannot normally give the required solids levels. However, there is a possibility of increasing the solids content by adding straw, bedding, etc. Sun drying is not recommended due to decomposition of volatile solids. [31]

The simplicity of the plug flow idea has made the type popular on two very different scales: large cattle farms and individual households in developing countries. In the case of large farms, the digesters take the form of rectangular in-ground covered concrete tanks with capacities in the range of hundreds of thousands of gallons. [47] For individual families mostly in regions in Africa and Asia, ¬the digesters are inflated tubes of flexible polyethylene bag material with capacities usually less than 10m3. [48]

Farm-scale plug flow digesters have standard retention times of 15-30 days and operate in either mesophilic or thermophilic temperature ranges. [33, 45] Family-sized units are unheated (psychrophilic), with consequently longer retention times of 20 to 60 days. [4]

Modified, or ‘slurry loop,’ plug flow digesters are distinguished by a central dividing wall and U-shaped manure flow as viewed from above. Manure enters and exits at the same side of the digestion tank. In addition to providing a more compact layout, it was thought that this design would allow separation of the two main bacterial activities, acidogenesis and methanogenesis, into the two sides of the tank. [49] A comparison of a conventional and a modified plug flow digester concluded that differences in performance were most likely due to influent differences, and that the ‘modification’ makes little difference to a digester’s performance. [33]

Complete Mix

Complete mix digesters usually use a cylindrical reactor vessel and feature a mixing device that continually stirs the contents so that settling cannot occur. Gas is collected under a fixed or floating top. Digesters in this category can handle influents with a wide range of solids content from 3% to 10% TS. [45] The mixing action does consume energy. Complete mix digesters have the advantage of being a proven technology with reasonable conversion efficiencies and shorter retention times than plug flow and covered lagoon digesters. [9] Hydraulic retention times are 10-20 days. The tanks can be kept at either mesophilic or thermophilic temperatures. [45]

Fixed Film

The above digester types have the same characteristic of unseparated output in which the effluent discharge has the same concentrations as everything in the reactor tank. This means some of the bacteria population is being continually flushed out, requiring an equivalent level of bacteria growth at the influent end to maintain steady-state conditions. Because methane-forming bacteria are slow to grow, this limits the overall methanogen population in the digester. A minimum HRT is also imposed because enough time must be left for the bacteria population to regrow before the biomass leaves the system.

Fixed film digesters remedy this by providing a fixed medium inside the reactor for the bacteria to grow on and adhere to. The medium, made of plastic or some other inert material, is arranged to have maximum surface area. The bacteria adhere to the medium and form a layer covering its surface(s) – hence the name 'fixed film.' Because of the packed nature of such a reactor vessel, solids in the influent could easily cause clogging and shutdown the reactor. Fixed film reactors require filtering out of solids and dilution so that total solid levels in the influent are less than 1%. Dilution generally means larger reactor tanks are needed. However, because the bacteria stay inside the reactor and aren't flushed out, the HRT for a fixed film digester is an amazing 3-4 days. The short HRT in turn means that the reactor vessel can be much smaller than the equivalent complete mix or plug flow reactor. Fixed film reactors are operated in the mesophilic or thermophilic temperature ranges. Because of the extremely low solids levels, external heat exchangers can be used. [50]

The most common layout for a fixed film reactor is a vertical cylindrical tank with arrays of 3" or 4" corrugated polyethylene drainage pipe arranged vertically as the medium. The contents flow parallel to the pipes. [43, 50] Flow direction is usually upward, but a reactor at the University of Florida allows easy switching between upward and downward flow. [32]

Upflow Anaerobic Sludge Blanket

The UASB reactor retains the bacteria by simple settling action. It uses a tall cylindrical vessel with an inverted cone on the top leading into the gas outlet. The cone encourages settling of the solids. Over time a layer of sludge filling roughly half the volume of the vessel forms on the bottom. The substrate enters at the bottom and flows out the top. UASB reactors are very effective converters but cannot handle particulate/insoluble feedstocks, making them incompatible with manure. [9]

Contact reactor

Another way to solve the problem of escaping bacteria is the contact digester. The contact system uses a digester tank similar to a complete mix reactor, but the solids in the effluent are piped back into the influent entering the digester tank. This means (1) the bacteria tends to stay in the reactor rather than simply being pumped out, and (2) the solid matter goes through the reactor several times, so that the solids retention time (SRT) ends up being several times the hydraulic retention time (HRT). [9] This increases the methane yield from a given feedstock.

Acid Phased Reactor

This reactor type splits the digestion into two tanks, the first for acid formation and the second for methane formation. Methane-forming bacteria are slower to grow than the other bacterial populations, so whereas a single tank requires a large volume to allow the methanogens to regenerate, the phased approach allows a reduced size for the first tank. [9]

Temperature Phased Reactor

This reactor arrangement consists of a thermophilic reactor followed by a mesophilic reactor. The first reactor destroys the pathogens and rapidly digests part of the feedstock, while the second reactor deals with the odour in the first reactor's effluent and further digests the material. [9].

Appendix B: Site Visit Data

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Site Visit: Small Farm Biogas Project

Farm: Sandy Rae Farm, Brooklyn – Dannie MacKinnon
Date: June 12, 2008
Animals: 130-140 Dairy
Report by: Matthew Hall

VI. Inputs

Available manure

Animals	130-140 cows total 70 milking at a given time (or 65???) 10 'resting' Others in pasture		
Feed amounts	Ensiled grass 51 kg/cow-day	Meal mixture 10kg/cow-day	Hay 4 bales/day = ???
Feed details	Best harvested just before it heads After 3 days in silo, pH drops to <5 Mixture of grasses (incl. Timothy) and alfalfa (to be changed to clover?) 17% protein	Mixture of barley, wheat corn, roll roasted beans, protein supplement 17.5% protein	
Feed notes	Waste silage from barn is given to heifers and dry cows, applied to field??? Each silo holds 90 tons, which feeds milkers for 90 days		
Animal locations, manure distribution	70 milking cows in barn full time – 100% of manure goes to handling system 10 milkers + the remaining cows (heifers): • summer: in pasture – manure is distributed on fields • winter: in building – manure builds up under foot and is periodically		

	removed an put into piles on fields for future spreading
Bedding & others	
Bedding type	Wheat straw
Bedding amount	360lb/day
Bedding disposal and frequency	Goes into manure handling system, which operates twice per day
Other inputs or potential co-substrates	
Manure Handling	
Inputs and amounts	Manure, straw bedding 175 ft^3/day
Water additions, TS level?	TS unknown Water inputs: small drinking spills and occasional pipe-washing water
Time since excretion	~12 hrs
Operation frequency	Twice per day
System description	Trench running behind cows contains ~1 ft wide belt/chain apparatus that pulls waste into sump pit 18" piston pumps waste out of sump into pipe Waste travels through 110 ft of 2 ft dia. Pipe into storage tank
Changeability comment	$120 000 system??? System is very well suited to high-solids waste Would probably be costly to change collection system
Time duration	
Energy use	Chain is powered by 7.5 hp motor
Output properties / description	Manure mixed with lots of straw

Output storage	Storage tanks is rectangular concrete with tension fabric roof Rectangular: 88' long x 50' wide x 8' high walls Fills 90% in 6 months
Output usage	Emptied every spring and fall Liquid portion is pumped out and applied to field Solid portion is removed with front end loader and spread on field

VII. Uses of AD products

Digestate

Would composted bedding be compatible?	Yes, it would seem so
Current fertilizer situation	Silage crops are fertilized entirely be dairy waste
Fertiliser amount, cost	-

Heating

System description	Wood Furnace Outdoor wood furnace heats barn, main house, and preheats hot water for both.
Performance specs	Preheats barn water to 160℉
Energy use	20 cords wood / year
Costs/ age	new

Heating

System description	Propane water heater Inside milk / control room Boosts water temperature for pipe cleaning system
Performance	284 L, $125/6 wks

specs	(John Wood model JWS75-175P cat no. G7511)
Energy use	
Costs/ age	
Heating	
System description	Electrical Boosts hot water for main house and does all heating for Mother's house
Performance specs	
Energy use	
Costs/ age	
Refrigeration	
System description	2 x 4hp compressors runs refrigeration system MILK PROCESS: 2000L/day milk comes at 90℉, runs th rough heat exchanger with drinking water and is cooled to 60-65℉, runs through refrigeration system and is chilled to 37℉, enters 7700L milk tank
Performance specs	
Energy use	
Costs/ age	
Electrical	
Overall consumption	300kWh/day
Loads the could be biogas powered	All electrical heating applications, milk chiller system
Vehicle fuel	
Diesel vehicles	JD 6430 · JD 6420 · JD 5425 · Ford 5610 · '83 Chev Kodiac

					(3208 cat engine)
Age/ownership	new	3 years	new	1984	
	Tractors are leased every 3 years???				
Annual usage	500-600hrs	500-600hrs	500-600hrs	200hrs	1000km
Total fuel consumption/cost	To be found				

VIII. Notes on economics, future plans for farm, etc

	Possibility of switching to organic in the next few years
	Very successful farming operation
	Considerable progress and interest in sustainable operation
	Interest in renewable energy (solar heating, wind turbine)

Questions:

- how much feed hay? 4 bales/day but how big is a bale?
- Fuel bills
- Measure of peak electricity demand

Site Visit: Small Farm Biogas Project

Farm: Ryan Weeks, (current farm)
Date: June 27, 2008
Animals: Dairy
Report by: Matthew Hall

I. Inputs

Available manure	
Animals	160 Dairy Cows
	70 are milking (with 29 in milking barn, 29 in manure building during the winter)
Feed amounts	½ round bale of silage daily (for milkers)
Feed details	Silage contains clover, alfalfa, Timothy
	Also fed corn distillers, soybean meal, roasted beans, barley
	250 acres harvested 2.5 times / year into round bales
Feed notes	Automatic rail feeder
Animal locations, manure distribution	During winter: 29 in milk barn, 29 in manure building
	During summer: they are mostly outside ???
Barn	Milking barn is 34x100 ft
	Want more light in barn for optimum milk production
	Barn is heated only by cows, often need windows open in winter
	Automatic rail feeder
	Barn needs renovations soon
	Houses 29 – eventually will house 40
Bedding & others	

Bedding type	
Bedding amount	
Bedding disposal and frequency	
Other inputs or potential co-substrates	
Manure Handling Inputs and amounts	
Water additions, TS level?	
Time since excretion	
Operation frequency	
System description	Scrap chain pulls waste into sump, Piston pump pumps it out to manure building
Changeability comment	Simple system, just 2 straight runs of chain Since 1992
Time duration	
Energy use	5hp pump, 2hp chain drive motor
Output properties / description	Lots of straw 15-16 tandem loads of manure / month
Output storage	Concrete tank building with steel roof and upper walls 40x100 ft, 6 ft high concrete walls 2 ft slope to hold manure in (doesn't entirely work; liquid seeps out) One 12 ft length of the building holds one month's worth of manure 30 milkers are housed in front half of building during winter

Output usage	Desire to expand building Emptied several times/ year Moved into piles on fields

II. Uses of AD products

Digestate

Would composted bedding be compatible?	If current bedding is straw ???
Current fertilizer situation	
Fertiliser amount, cost	

Heating

System description	Wood chip burner – located in workshop building hopper fed Chips piled in building during winter Heats: milk room, house, workshop There was a pipe-freezing issue last winter; there may be a leak
Performance specs	
Energy use	20 cords of wood chips annually from November to April
Costs/ age	Operating since 1989 (may be a good candidate for replacement...)

Heating

System description	Electric water heater for milk line cleaning GSW 6ETF-1-175
Performance specs	3000W

Energy use			
Costs/ age	???		
Other Loads			
System description	Milk tank agitator	¼-1/2 hp fan in barn running 2h/day	Vacuum pump for moving milk Interest in getting heat of muffler for heating calf milk
Performance specs	1/6 hp		3hp, 2000L/day
Energy use			
Costs/ age			
Refrigeration			
System description	Single system – there is a need to get a second one Milk is first cooled through heat exchange with spring water headed toward outside drinking water for		
Performance specs	3hp system 2000 L/day		
Energy use			
Costs/ age			
Electrical			
Overall consumption	Bill is ~$420/month on residential metering (should mean 2970kWh/mo based on rural residential rates. So: 100kWh/day)		

Loads the could be biogas powered	
Vehicle fuel	
Diesel vehicles	Two JD 2140 Tractors
Age/ownership	
Annual usage	
Total fuel consumption/cost	

III. Notes on future plans for farm, etc.

	Quota is around $32000 / Cow

Site Visit: Small Farm Biogas Project

Farm: Ryan Weeks (old pig farm, not yet operational)
Date: 27, 2008
Animals: Dairy
Report by: Matthew Hall

I. Notes on future plans for farm, etc.

216 acres

32 milking stalls. Animals move through milking barn before feeding

Total of 80 milking cows

Skid steer scrapes manure out of center aisle

In floor heating for milk room

Very well-insulated barn with geothermal air input

Farm house would need heat

Good spot for a wind turbine