Development of a Calculator for the Techno-economic Assessment of Anaerobic Digestion Systems

FINAL REPORT

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Executive Summary

A large amount of organic wastes such as manure and food waste are generated annually in the Fraser Valley of British Columbia (BC). Anaerobic Digestion (AD) for biogas utilization is considered a potentially viable renewable energy technology option. The most probable scenario for the development of anaerobic digestion in BC has been found to be on-farm manure-based systems accepting off-farm food processing wastes as opposed to large centralized complexes.

The main goal of this research project is to develop an Anaerobic Digestion Calculator that would assist farm and herd owners in the Fraser Valley in making decisions on choosing suitable anaerobic digestion technologies for their own farms. This goal can be separated into two connected objectives. The first objective is to inform potential users of the currently available technology options for both AD and biogas utilization. The second objective is to accurately model the selected AD and biogas utilization technology. The calculator software was constructed on Excel spreadsheets with simple user interfaces coded via Visual Basic applications. This makes it more flexible and more adaptable

Components of the computer model include mass balance, energy balance, reaction kinetics, biogas utilization, capital cost estimate and profitability analysis. Focus was placed upon the two most common configurations of AD systems – completely mixed (CSTR) and mixed plug flow (MPF). Kinetic parameters were estimated by calibrating the model with data from operating AD systems with manure as the feedstock. In order to test the stability, performance and accuracy of the calculator software, several case studies were conducted. Each case involves an operating digester for which sufficient information has been published in the literature. Predicted results are compared with the reported biogas production rate and digester volume. This report includes a more detailed guide of how to use the calculator to run a simulation.

A fictitious 450-cows dairy farm located in the Fraser Valley was used for performing overall technical and economic feasibility analyses, so as to assess project viability. Calculations were performed for CSTR and MPF, with different hydraulic retention times (HRTs). In scenario #1, off-farm food waste is not included in the influent (feedstock) to the AD system. Then, simulation is extended to scenario #2, with food waste added to the feedstock, resulting in a mixture of 80% dairy manure and 20% food waste. The computed results indicate that, among all configurations involved in the simulations (CSTR with HRT of 25, 28 and 30 days; MPF with HRT of 20, 22 and 25 days) a MPF system with HRT of 25 days has the best system performance. With mixed waste (80% dairy manure and 20% food waste), the methane (CH_4) production rate is 0.91 tonnes/day, leading to power production of 212 kW, which is equivalent to 0.47 kW/cow. The corresponding biogas yield is 58 m^3/tonne feed (wet basis). Percent volatile solids reduction is also the highest, at 80%, When compared to the digestion of dairy manure alone, expected biogas yield would be doubled, whereas power production would be greater by 2.5 times.

Results derived from the economic analysis of the 450-cow predictive case study for mixed waste (80% dairy manure and 20% food waste) suggest that MPF systems are less expensive than CSTR systems. For co-generation purposes, if selling price of the electricity is at 9 cents per kWh, none of the configurations investigated are economically feasible based on after-tax cash flows, since for all cases, net present values are negative. However, if economic feasibility is based on before-tax cash flow, then the net present values associated with MPF systems having HRT of 20 to 25 days are positive, and the internal rates of return are greater than a 10% minimum acceptable rate of return. Under these circumstances, simple payback period of 5-6 years is also achievable. Therefore, MPF digester was found to be the most suitable and profitable AD system for on-farm digestion of animal wastes. If the selling price of the electricity can be increased to 14 cents per kWh, a CSTR digester with 30 days HRT would have a positive net present value and a simple payback period of 6 years, based on before-tax cash flow, but its net present value is still negative based on after-tax cash flow. A MPF digester is projected to perform even better economically, with internal rates of return around 15%, based on before-tax cash flow.

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1. Introduction and Problem Definition

Anaerobic digestion (AD) is the decomposition of organic matter in the absence of oxygen. During this decomposition which is due to microbial activity, a gaseous mixture of methane (CH_4), carbon dioxide (CO_2) and trace amounts of hydrogen sulfide (H_2S) and hydrogen (H_2) are produced. Some nitrogen gas may be found if we abate the H_2S by biological oxidation (ventilation of 2-4% air into the biogas headspace in the digester).

Hence, AD systems are often referred to as "biogas systems". It is a process found in many naturally occurring anoxic environments including watercourses, sediments, waterlogged soils and the mammalian gut. It can also be applied to a wide range of feedstocks including industrial and municipal wastewater, agricultural, municipal, food industry wastes and plant residues.

In the 1940s, many municipal sewage treatment plants in the United States were already able to use anaerobic digestion while at the same time generating heat and electricity for the plant. This was the beginning of sustainable waste management and pollution control. After World War II, many nations developed biogas generation to enhance their economic recovery (Maramba 1978). Biogas from biomass has historically been used in Asia as a fuel for small farm operations or for household uses such as cooking. In the oil supply crisis of the 1970's and 1980's AD again become popular and in 1986, gas from the decomposition of sewage was used to light a street in Exeter, England. There was a lull in interest in AD until the most recent world-wide concerns about energy availability, sustainability and pollution control, which means that modern AD technologies once again are becoming relevant. Installations increased remarkably in Europe since the strong Danish Government commitments toward the technology in the late 1980s (Mattocks and Wilson, 2005). In Europe, over 5,000 facilities are currently in operation, and this figure is predicted to exceed 20,000 by 2015. For instance, in Germany alone, biogas is estimated to account for 17% of Germany's electricity mix by 2020. Other countries in the EU that do not have abundant natural sources of energy are also putting increasing emphasis on biogas development.

The Fraser Valley of BC consists of two regions - the urban region of Metro Vancouver (MV) and the rural region of Fraser Valley Regional District (FVRD). A large amount of organic wastes are generated annually. At present, 600,000 tonnes of municipal solid waste (about 30% of total) are disposed at the Cache Creek Landfill in the BC interior; however, this landfill will be closed soon. Therefore, MV is actively seeking alternative solutions for waste management. In a report by Electrigaz Technologies Inc. (2007), it is estimated that activities in the FVRD generate 3.3 million tonnes of organic wastes annually, some 85% of which (2.9 million tonnes) are considered readily available for AD. These materials are comprised of 82% manure, 8% food wastes and 10% municipal wastes. The most probable scenario for the development of AD in BC was concluded to be on-farm manure-based systems accepting off-farm food processing wastes as opposed to large centralized complexes.

Improved manure management practices would include the collection of manure as a liquid, slurry, or semi-solid, and the installation of anaerobic digesters. The environmental benefits of adapting AD include: odour control, pathogen reduction, improved water quality, reduced greenhouse gas (GHG) emissions and reduced volume of waste that needs disposal in landfills. Odor control was cited as the top priority for farmers who consider installing AD systems on farm (Tikalsky and Mullins, 2007). The economical benefits of adapting AD include heat production, cogeneration of heat and power (CHP), and biogas upgrading to renewable natural gas (RNG) as main products. It can also produce fertilizer, compost and bedding material from residues. For instance, after separating the effluent, the product solids may be used for bedding material on the farm (except for input manure with high sand content) or composted, and the liquid product may be sprayed crop fields as fertilizer (Kramer and Krom 2008b).

The overall potential for energy generation from biogas through AD in the Fraser Valley is estimated to be 30 MW. However, the electricity portion of the BC energy market is dominated by inexpensive and clean hydroelectric power. Although BC Hydro has developed programs to support energy conservation and the development of renewable energy production, such as the Net Metering Program, Standing Offer Program and Clean Power Call, the profits through these electricity sales programs for small biogas plants are very limited, given the current costs of electricity at about 65¢/kWh. Upgrading biogas to RNG would be more cost effective and is becoming a more attractive feature for AD in BC (and other places), though the associated increase in capital and operation costs needs to be accounted for (Electrigaz, 2007).

1.1 Project Objectives

Before users decide to invest in AD many factors need to be taken into account such as the degradability and CH_4 yield for different compositions of wastes, the choice of digester technology and the magnitude of environmental and economic benefits to the user and community. The main goal of this research project is to develop an Anaerobic Digestion Calculator that would assist farm and herd owners in the Fraser Valley in making decisions on choosing suitable AD technologies for their own farms. This goal can be separated into two connected objectives. The first objective is to inform potential users of the currently available technology options for both AD and biogas utilization. The second objective is to accurately model the selected AD and biogas utilization technology. The models used should be relatively simple yet providing fair estimation on vital biogas plant parameters, such as biogas yield, digester volume, capital cost, annual income, etc.

In order to achieve these two objectives, the calculator developed must include the following features:

a. The ability to input amounts of different types of wastes including animal, food, agricultural and municipal wastes.
b. A user-friendly interface for choosing from a selection of digester types and for selecting whether to use cogeneration or biogas upgrading.
c. A robust model parameter input interface, which should provide default values for average users, but also allow advanced users to input their own parameters to match their particular feed or design.
d. A detailed output including all the input information, model parameters used and calculated results. Users should be able to export and save this output as another file, so that it can be viewed as a report.
e. Help documentation for both basic and advanced users.

The first phase of this project was a literature review of the reactions involved in AD, the properties of organic wastes, kinetic models that have been developed for anaerobic degradation of these wastes and available reactor configurations for AD. Existing AD-related calculators also were compared and contrasted.

During the second phase of this project, an Excel-based calculator with a windows-like interface was developed.

Finally, this calculator was tested against several case studies collected during the literature review. It was then used to predict the techno-economic performance of a hypothetical case farm in the Fraser Valley of BC. The calculator’s advantages, limitations and possible further improvements were reported after the tests.

2. Literature Review

2.1 Reactions of Anaerobic Digestion

AD is a collection of many biological reactions occurring in the absence of oxygen. In reality, the biological pathways of the process depend on the concentration and nature of the substrate, bacteria and surrounding conditions. As shown schematically in Figure 1, AD takes place in three stages: hydrolysis, acidogenesis/acetogenesis and methanogenesis (Wilkie 2005). During the hydrolysis stage, complex organic polymers are broken down into their monomer intermediates: sugars, amino acids and volatile fatty acids (VFA). During acetogenesis, these intermediates are converted into acetate (acetic acid) with CO_2 and hydrogen as by-products. Finally in the methanogenesis stage, hydrogen and acetate are converted into CH_4 and CO_2. Table 1 is a brief summary of the main reactants and products during each phase. In general, the microorganisms involved in hydrolysis and acetogenesis grow more rapidly than the microorganisms involved in methanogenesis. As a result, methanogenesis tends to be the rate-limiting step. However, for some materials, such as grasses and newsprint, which contain more recalcitrant celluloses, hydrolysis may be very slow and become rate-limiting (Rittmann and McCarty 2001).

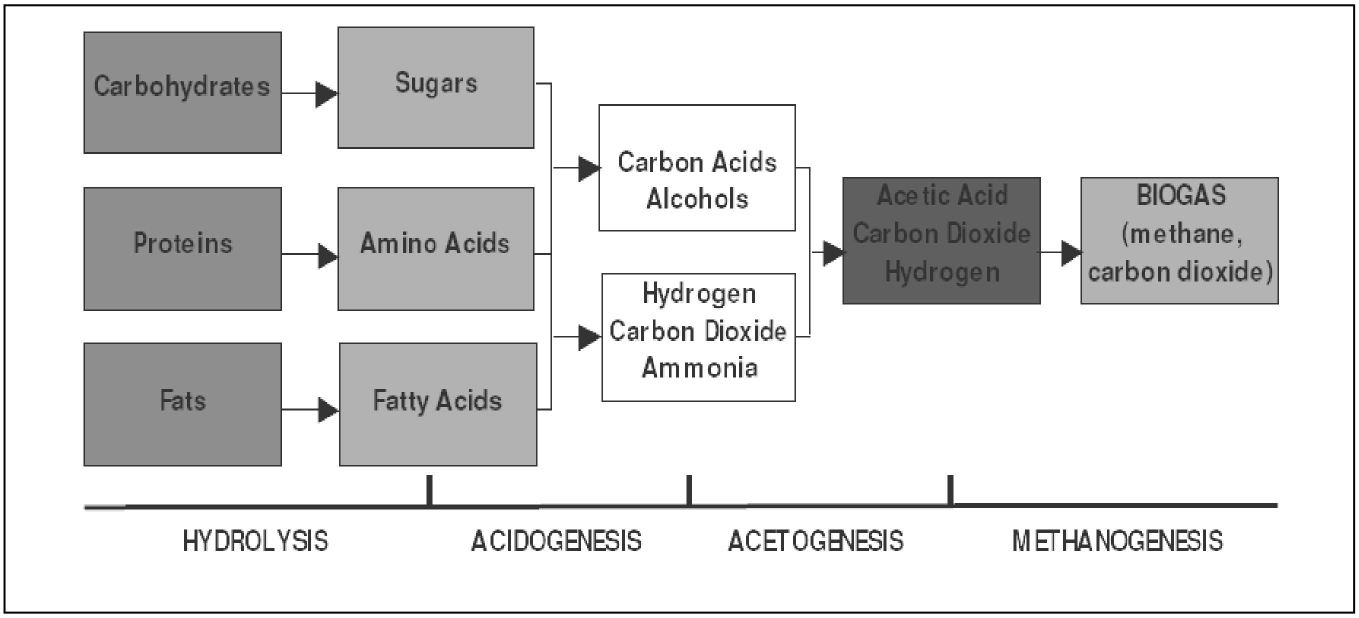


Figure 1: A scheme of anaerobic digestion pathways

Table 1: Reactants and products involved in the three phases of anaerobic digestion

Phase	Reactants	Products
Hydrolysis	Organic materials	Sugars, amino acids, volatile fatty acids (VFAs)
Acetogenesis	Sugars, amino acids, VFAs	CH_3COOH (acetic acid), alcohols, CO_2, H_2
	CO_2, H_2	CH_3COOH
Methanogenesis	CH_3COOH	CH_4, CO_2
	CO_2, H_2	CH_4

2.2 Biogas Yields and Power Generation

The biogas yield primarily depends on the type of feed. Most commonly used feeds for AD are animal manures from cattle, hog and poultry, crop residues as well as corn and grass silage. Organic wastes from food processing, restaurants, fish processing, slaughterhouse, sewage sludge (biosolids) and the organic fraction of municipal waste may also be used as feeds for AD. Table 2 shows the biogas generation potential of substrates, as compiled from Preusser (2006) and Electrigaz (2007), which are similar to the information provided in the Wisconsin Agricultural Biogas Casebook (Kramer and Krom 2008b). According to Birse (1999), these values should only be used as indicative values. Plaskett (1982) outlined the potential and scope of AD within the countries of the European Community back in 1980, and presented the results of an overview study; dairy manure had a biogas generation potential of 20-25 m^3/tonne (wet basis), which is in line with many reported values since that time. The biogas yields of food and yard wastes can be considerably higher than the biogas yields of animal wastes.

Table 2. Summary of biogas generation potential of substrates from three sources

	Biogas generation potential, m^3/tonne substrate (wet mass basis)		
Substrate	Electrigaz Technologies 2007	Preusser, 2006	Kramer and Krom 2008b
cow manure	25 (9% TS)	25	25
pig manure	25 (7% TS)	35	30
potato/vegetable waste	60 (10% TS)	70	39
corn/grass silage	175 (25% TS)	200	185
food waste	225 (20% TS)	175	265
fats and grease	500 (50% TS)	980	961

A large number of papers have been published in the past several decades dealing with the performance of different reactor configurations digesting and co-digesting organic solid wastes. According to Jerger and Tsao (1987), the theoretical CH_4 yields (about 60% of biogas yields) due to the action of most microbial species are similar, with a value of about 0.5 m^3 CH_4/kg VS added. Biogas yield data based on actual observations or monitoring records have been compiled and shown in Table 3 for lab-scale and pilot-scale studies and in Table 4 for full-scale systems. This information is not meant to be exhaustive, though these may be considered as representative values. Kelleher (2007) cited results obtained from studies by various researchers on the biodegradation of MSW components in lab-scale landfills; kitchen waste (TS 30%) and yard waste (TS 40%) have biogas yield of 113 m^3/tonne and 34 m^3/tonne (w.b.), respectively. Ward et al. (2008) conducted a review of the AD of agricultural resources and compiled the CH_4 producing potential of a wide range of substrates. Regardless of the scale of study, it is quite clear that animal manures provide lower yields while food processing wastes, especially fats oil and grease, provide higher yields.

Gregerson et al. (1999) reported that at the time in Denmark, approximately 75% of the biomass resource was manure mostly in the form of slurry, whereas the remaining biomass was waste that mainly originated from food processing industries. In these biogas plants, manure and organic waste were mixed and digested in AD tanks for a hydraulic retention time (HRT) of 12 - 25 days. The biogas produced was cleaned and normally utilized in CHP plants. The biogas yields from some of the 20 systems installed between 1984 and 1998 are shown in Table 4. The biogas yield ranged from 23 to 92 m^3/tonne biomass (wet mass basis).

DeBruyn (2008) reported recent changes to the Nutrient Management Act and Environmental Protection Act in Ontario to allow up to 25% low risk material to be brought to farms without designating the farm as a waste disposal site. He suggested that blending off-farm materials with manure would enhance biogas production 2 to 3 times versus manure alone. Manure-based anaerobic digesters built in Ontario in the 1980s failed due to poor economic returns or operational difficulties. However, new technologies and control systems have seen a new deployment of agri-food anaerobic digesters at present.

Table 3. Biogas yields (lab-scale and pilot-scale AD studies)

Substrate	Biogas Yield	Units	Reference
cattle slurry	0.25-0.30[1]	m^3/kg VS	Seadi, 2001
pig slurry	0.20-0.50		
poultry slurry	0.35-0.60		
whey	0.35-0.80		
food waste	0.25-0.60		
grass silage	0.56		
dairy cattle manure	0.25	m^3/kg VS[2]	Ward et al. 2008
beef cattle manure	0.55		
pig manure	0.53		
mixed food waste	0.80		
fruit and vegetable wastes	0.30-0.80		
corn silage	0.65		
horse manure	0.30[3]		Kusch et al. 2008
dairy manure/cheese whey (70/30)	0.44	m^3/kg VS	Sauve 2008
dairy manure/grease trap (70/30)	0.51		
dairy manure/corn silage (50/50)	0.51		
soup processing waste	112 (21.5% TS)	m^3/tonne feed[4] (wet mass basis)	Zhang et. 2007
cafeteria waste	150 (23.5% TS)		
kitchen waste	53 (9.7% TS)		
fish farm waste	472 (55.8% TS)		
grease trap	275 (29.4% TS)		
manure	21	m^3/tonne feed[2]	WestStart-CALSTART, Inc. 2004
OFMSW[5]	216		
slaughterhouse waste	270		
animal by-products	93[6] – 375[7]		

[1] Based on average manure generation characteristics, this may be converted to 26 m^3/tonne feed

[2] The reported yields were originally for CH_4; an average CH_4 content of 60% is assumed for units conversion.

[3] In this lab study, horse manure has similar biogas yield [m^3/kg VS] when compared to dairy manure. However, due to its high solids content (38% of wet mass), the biogas yield is ~ 100 m^3/tonne feed, which is much greater than dairy manure.

[4] The reported yields were originally in units of L/g VS; conversion was made knowing the TS and VS contents of the substrates.

[5] OFMSW: organic fraction of municipal solid waste

[6] Non-pasteurized

[7] Pasteurized via heating the waste to 70°C for one hour, for increased access to lipids

Table 4. Biogas yields (full scale AD systems)

Substrate	Facility/Location	Biogas Yield, m^3/tonne feed (wet mass basis)	Reactor type[1] or AD process	Reference
Dairy manure	Straus Creamery, CA	11.0	Covered lagoon	Anon, 2004
	Gordondale Farm, NY	40.0	MPF	Martin 2005
	AA Dairy, WI	35.7	HPF	Martin 2004
	Baldwin Farm, WI	28.0	MMPF	USEPA, 2009
	Sheland Farms, NY	20.0	CM	Pronto and Gooch 2008
Dairy manure and food waste	Ridgeline Farm, NY	73.5	CM	Pronto and Gooch 2008
	Holsworthy, UK	40.4	Wet, single-step	Beck Inc., 2004
OFMSW[2]	Geneva, Switzerland	120	Dry, single-step	Beck Inc., 2004
	Ameins, France	150	Wet, single-step	
	Vagron, The Netherlands	40.8		
	Wels, Austria	89.5-140	Wet, two-steps	
	Toronto, ON	95-110		Goldstein, 2005 and van Opstal, 2006
Manure and organic wastes [3]	Various locations in Denmark	23-98	Not specified	Gregerson et al., 1999

[1] HPF: horizontal plug flow; MPF: mixed plug flow; MMPF: modified MPF; CM: Complete mixed

[2] OFMSW: organic fraction (source separated) of municipal solid waste

[3] The feedstock was made up of 55-70% of cattle manure, and 6-38% of organic wastes which include some or all of the followings: slaughterhouse waste (intestinal contents), fats, fish processing.

2.3 Existing Anaerobic Digestion Technologies and Suppliers

Due to the long history of AD, there are many types of anaerobic digesters around the world. The basic requirements of an anaerobic digester design are: to allow for a continuously high and sustainable organic load rate, a short hydraulic retention time (to minimize reactor volume) and to produce the maximum volume of CH_4. There are several types of reactor in use today, and the design is related to the material to be digested. There are three main groups - batch reactors, one-stage continuously fed systems, and two-stage (or even multi-stage) continuously fed systems (Ward et al. 2008). Figure 3 summarizes the six most common configurations of anaerobic digesters that are active today. There are various pretreatment and downstream processing units, and digesters can be connected in series or parallel.

Table 5 provides a condensed summary of power generation due to biogas from the digestion of cow manure, using different AD technologies. It is sub-divided into two periods: 1997-2002 and 2002-2008. There are many active suppliers of AD technology and biogas producers in North American and European markets. Statistics presented by Tikalsky and Mullins (2007) shows that the three vendors RCM Digesters Inc/ RCM International, GHD Inc and Microgy Inc. (a subsidiary of Environmental Power Corp.) have together provided 77% of the digesters installed in North America (primarily the US) over the past 10 years or so. Given the same technology, the greater values of power generation were generally associated with the co-digestion of manure and other organic wastes that have higher biogas generation potential or yield.

Table 5 does not include data pertinent to Microgy AD systems (Tarrytown, NY. www.environmentalpower.com). Literature review of several cases indicated that their generators are over-sized, likely for future expansion purposes to include higher percentage of off-farm wastes, with power generation ranging from 0.75-0.90 kW/cow. Upflow anaerobic sludge blanket reactors (UASB, or vertical induced blanket reactors) could also have the potential of generating more power per cow. Gorrie (2009) reported the performance of a continuous-flow AD system currently installed at Stanton Farm near London, Ontario. Off-farm wastes (mainly fats, oil and grease) in the amount of 25% by weight are mixed with manure generated from 2000 dairy cows in multiple reactors. This system requires a shorter HRT of 5-7 days because of the intense interaction between the slurry and the highly concentrated bacteria in the blanket. In the near future, waste from neighboring farms and food processors will be acquired to meet the 1.3 MW (or 0.65 kW/cow) power generation target

Table 6 contains more detailed information relevant to the dairy farms that have installed various types of AD systems in the US. Included in the summary are the following, wherever the information is available (AgStar website Feb 2009; Cornell University website accessed 2009; BioCycle various issues): farm name and location, manure generation rate, reactor type and technology supplier, biogas production rate, biogas yield, power generation rate and year of installation.

Table 5. Summary of power generation from anaerobic digestion of cow manure

	Power Generation (kW/cow)	
	1997-2002[a]	2002-2008[b, c]
PF Digester	0.08-0.17	0.16-0.21[d]
MPF Digester	0.15-0.23	0.16-0.28[e]
CM Digester (CSTR)	0.08-0.23	0.24-0.32[f]
Covered Lagoon	n/a	0.12

[a] USEPA - AgSTAR Handbook (http://www.epa.gov/agstar/resources/handbook.html)
[b] AgSTAR Program - Guide to anaerobic digesters (http://www.epa.gov/agstar/operational.html)
[c] Cornell University – Manure Management Program (http://www.manuremanagement.cornell.edu)
[d] mostly RCM Digesters Inc/RCM International Inc.
[e] mostly GHD Inc.
[f] various suppliers

At present, more vendors are entering the AD market in North America. The following section will briefly compare active suppliers of AD technology and biogas producers in North American and European markets, in several key design concepts - digesters configuration (CSTR vs. MPF), dry digestion vs. wet digestion, mesophilic digestion vs. thermophilic digestion, co-generation vs. biogas upgrading and simple feed vs. mixed feed. A complete list of suppliers can be viewed in “Appendix B: Current AD Technology Suppliers”.

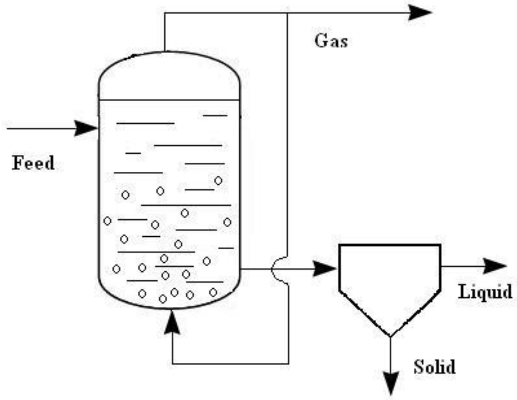
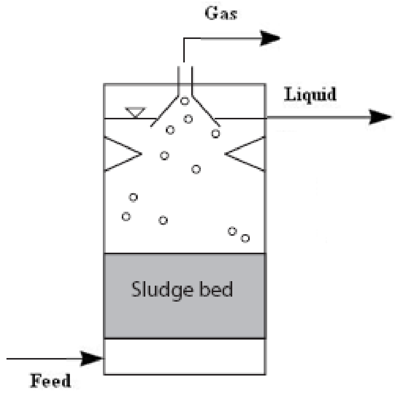
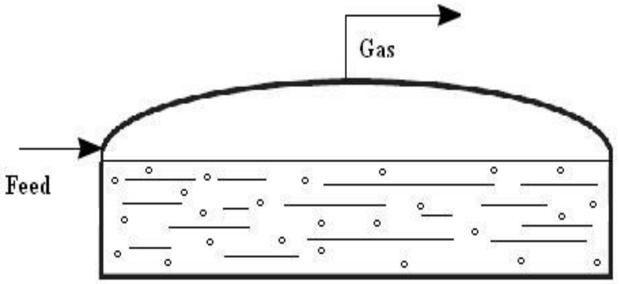
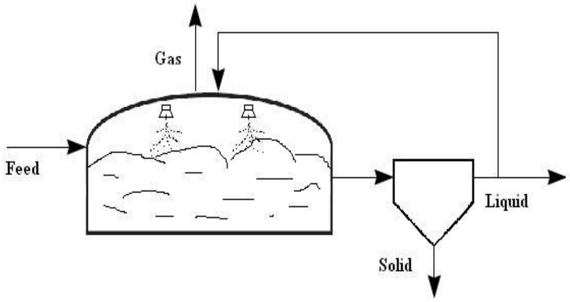
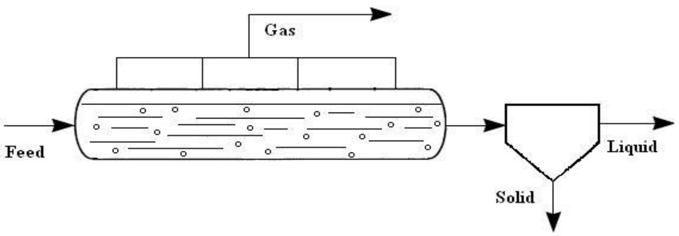
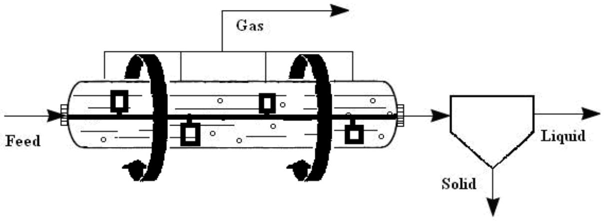
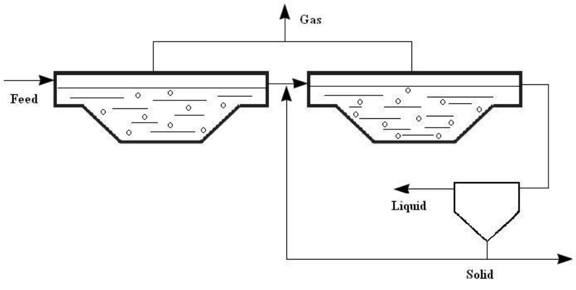
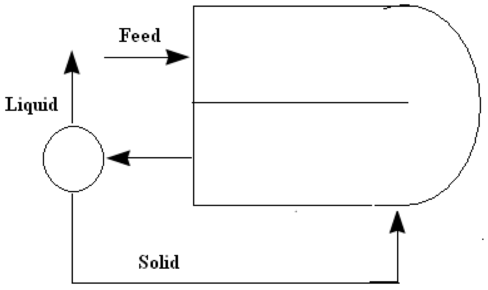
	
1. Completely Mixed Digester (CSTR)	2. Upflow Anaerobic Sludge Blanket (UASB)
	
3. Covered Lagoon	4. Fed Batch Digester (mechanical mixing optional)
	
5. Plug Flow Digester (PF)	6a. Rotary Mixed Plug Flow Digester (MPF)
	
6b. Dual Chamber MPF Digester (left) and its top view (right)	

Figure 2. Six common anaerobic digesters configuration

Table 6 Information relevant to a number of dairy farms in the US that have installed AD systems since 1999

Farm and Location		# cows	Manure Generation m^3/cow.d	Co-digestion Feedstock	Reactor type	Supplier	Biogas production m^3/d	Biogas yield m^3/t	Power Generation		Year
									kW	kW/cow	
Blue Spruce	VE	1200			MPF	GHD			240	0.20	07
Green Mountain		1050			MPF	GHD	3270		300		07
Montagne		1200					3740		300		07
Pleasant Valley		1950					6230		600		06
AA	NY	600			HPF[1]	RCM	1214	35.7	130	0.21	
Emerling		1200			HPF	RCM			230	0.19	
Patterson		1000		Cheese whey	CSTR	RCM			250	0.25	05
Ridgeline		525		Milk products waste	CSTR	RCM	9700	73.5	120	0.23	01
Sunnyside		6100			MPF	GHD			1600	0.27	08
Cayuga regional enterprise		1255		Food waste, FOG, potato wastewater sludge	CSTR	EcoTech and GBU	6110		625	0.50	08
Baldwin	WI	1050	0.14[3]		MPF[2]	Komro	3680	28			06
Clover Hill		1250			MPF	GHD			300	0.24	07
Double S		1100	0.13						200	0.18	04
Gordondale		850	0.16					40	140	0.16	02
Crave Brothers		800	0.14	Cheese whey 10%	CSTR				230	0.29	07
Five Star		850		Food waste (esp. FOG) 10%	CSTR	Microgy			750	0.89	05
Green Valley		2100	0.20		CSTR	Biogas Direct			600	0.29	07
Lake Breeze		2550	0.21	Corn syrup waste					600	0.24	06
Norwiss		1240		Food waste 10%	CSTR	Microgy			850	0.68	06
Suring		950	0.12		CSTR	Ambico			250	0.26	06
Vir-Clar		1200	0.10	On-farm organic waste	CSTR	Biogas Direct			350	0.29	04
Wild Rose		880	0.17	Food waste	CSTR	Microgy			750	0.85	05

Haubenschild	MN	850			HPF	RCM			135	0.16	99
Scenic View	MI	2200		Syrup stillage	CSTR	Phase 3/ Biogas Direct	13460		700	0.32	05
Van der Haak4	WA	1100a 750b		20% food and fish processing waste	MPF	GHD			285a 450b	0.26 0.60	05
Qualco Energy		2000		Food waste/whey			5750		450	0.23	08
G DeRuyter		3500			Flush system PF	GHD	12420		1200	0.34	08
Tillamook #1 #2	OR	2000 2000			HPF	RCM			250 300		07
Brabaker	PA	900			CSTR	RCM	2060		160	0.18	
Dovan		400			HPF	RCM	1250		100	0.25	
Fair Winds		650			HPF	RCM	1160		140	0.21	
Hill Crest		1150			HPF	Team Ag	1390		130	0.11	
Mains		600			CSTR	EMG			90	0.15	
Mason Dixon 5		2300			HPF	Energy Cycle			600	0.25	
Penn Englad		800			CSTR	RCM/ Team Ag	1420		130	0.16	
Reingrid		800			CSTR	RCM			130	0.16	
Wanner’s		400			CSTR	RCM	1720		160	0.40	

1 HPF is same as PF

2 modified with jet mixing

3 based on units conversion 1 gal = 4.4 L

4 Information about number of cows and power generation from two sources

- a BioCycle 2005 (number of cows indicate manure from owner’s farm plus a neighboring farm when system was initially designed)
- b AgStar website 2009 (updated information)

5 Operational since 1979

Digester Configurations (CSTR, PF and MPF)

Although other configurations such as the covered lagoon, UASB reactor and fixed film reactor have been used for AD, the completely mixed (CSTR in Figure 2), plug flow (PF in Figure 2) and mixed plug flow (MPF in Figure 2) configurations are the most common. Completely mixed systems consist of a large tank where fresh material is mixed with partially digested material. Material with higher dry matter content (> 12%) will work in completely mixed systems by recirculating the liquid effluent. Plug flow systems typically consist of long channels in which the manure and other inputs move along as a plug. Although, theoretically, PF is the more efficient reactor configuration, ideal plug flow is difficult to attain and sometimes problems are encountered with sand and other solids accumulating inside the digester vessel (Dennis and Burke 2001).

Since around 2002, development of mixed plug flow (MPF) digesters solved these problems to some extent. Advantages of MPF include the following. Biomass (microbes) is recirculated to the second tank to enhance digester performance, making it easier to separate the two groups of bacteria (acetogens and methanogens) involved. Since MPF is a partially mixed, plug flow digester, its HRT and volume will be less than that for a CSTR, but not as low as for an ideal PF digester. Without recirculation, the solids retention time (SRT) is equal to the hydraulic retention time (HRT), but with recirculation, SRT is the actual period of digestion. This is harder for CSTR and PF to achieve due to the lack of bacteria culture separation. Therefore, MPF can be viewed as a compromise between the stability of a CSTR and the efficiency of a PF digester. Through literature review, it was noticed that both CSTR and MPF are very popular among farm-sized digesters (combined they account for 95% of the digesters reviewed). However, the completely mixed configuration still seems to be the only feasible choice for large centralized AD plants.

Table 7 is a brief summary of their characteristics. It should be noticed that within high solids range, it is more common to use mechanical mixing rather than passive gas mixing.

Table 7. A summary of digester characteristics

Digester Type	Size	Total Solids	Retention Time	Temperature		Operation	
				Mesophilic	Thermophilic	Continuous	Fed-Batch
CSTR	All Range	8%-20%+	High	Y	Y	Y	Y
MPF	Farm	<12%	Medium	Y	Y	Y	N
PF	Farm	<10%	Low	Y	Y	Y	N

CSTR digester suppliers: Many active suppliers of AD technology, such as BTA (Pfaffenhofen, Germany. www.bta-technologie.de**)**, HAASE (Neumuenster, Germany) and RCM (Berkeley, CA, www.rcmdigesters.com) offer completely mixed digesters in various configurations with different mixing methods, digester shapes and gas capturing modes. Microgy Inc. also has a Danish style complete mix system (Matttocks and Wilson 2005). Performances of completely mixed digesters do not vary that much between the different configurations if they are operated under similar conditions.

MPF/PF digester suppliers: RCM, Alliant Energy and OWS (Ghent, Belgium. www.owe.com) are suppliers of PF systems. Active suppliers of MPF systems include GHD (Chilton, WI), RCM (Berkeley, CA, www.rcmdigesters.com), Kompogas (Glattbrugg, Switzerland, http://www.kompogas.com) and BIOTHANE (Delft, The Netherlands. www.biothane.com). GHD digesters are the most popular PF/MPF digesters used by the sites studied in this project.

Dry vs. Wet Digestion

Feed to the digester consists of aqueous slurry. In some cases this results from the way in which waste is collected. For example, in the case of manure, material is washed out of the barn area with water into a holding tank resulting in slurry with low solids content. In other cases, where less watery material is collected, such as food waste, water may need to be added to achieve a desired percent solids or a dry digestion process may be favoured. In general, dry digestion refers to an AD process with TS over 20%, whereas wet digestion refers to an AD process with less than 20% TS. However, AD is generally not economically feasible if the total solids content is lower than 5% since the material will likely have low energy contents (Strategic Policy Unit 2005). When the TS content is too high, agitation and pumping could be an issue, especially for dry digestion systems (Millen 2008). Besides, HRT is proportional to TS contents for a dry digestion process. Smaller biogas plants, such as the ones located on farm sites, normally operate around 10% TS (Van Buren 1979). Dry digestion is targeted towards processing the organic fraction of municipal solid waste (OFMSW) rather than manure. In Europe, approximately 38% of the large scale AD plants for OFMSW were using the dry digestion process (Beck Inc. 2004); this figure increased to 54% according to Mattheeuws of Organic Waste Systems (2008), and is expected to further increase to 75% in the next 3 years.

A representative wet digestion process (BTA) consists of three phases: acidification, hydrolysis and methanogenesis. Firstly, the solid organic waste is slurried with water and spontaneous acidification occurs during anaerobic storage of waste pulp. Next, dewatered waste pulp and effluent from the CH_4 reactor are fed into the hydrolysis reactor so as to avoid the inhibition of hydrolysis due to some readily soluble substances (such as fructose). Good process control for pH and TS contents is required to achieve high efficiency in the hydrolysis step. CH_4 reactor effluent is also recirculated to help improve the acidification rate of COD (chemical oxygen demand). Finally, liquor separated from the waste pulp and liquid obtained from solids/liquid separation of the hydrolysis reactor contents are fed to the CH_4 reactor.

Wet digestion process suppliers: GHD (Chilton, WI) is a major AD supplier in North America. It offers a specialized U-shaped, two-chamber MPF digester (as shown in Figures 2 and 3) that operates at less than 15% TS. BIOTHANE (Delft, The Netherlands. www.biothane.com) makes several digester types including an upflow anaerobic sludge bed reactor, which is most suitable for low solids content feeds. Another main North American AD supplier, RCM (Berkeley, CA, www.rcmdigesters.com) produces both completely mixed and horizontal plug flow digesters for 10-13% TS manure feed. Thus far, farm-sized digesters are dominated by wet digestion process, probably because most of them process manure. Dry digestion processes are more attractive for food and municipal solid wastes.

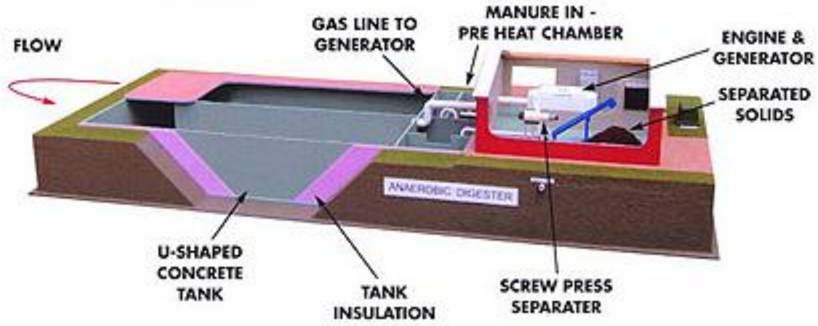


Figure 3: U-shaped two-chamber MPF digester from GHD (adapted from GHD, 2009)

Dry digestion process suppliers: There are several suppliers of dry digestion technology. For example, PlanET Biogastechnik (Germany) offers an anaerobic digester with a paddle inside for mechanical mixing. It has over 110 ADs (power generation from 35 kW to 6 MW) in operation in Germany and the Netherlands, with some more under construction. Initially, their system only treated low TS streams, typically operating at maximum TS of 6%, and a hydraulic retention time (HRT) of 25-27 days for wastewater treatment plant and manure. The Canadian operation is based in St. Catharines, Ontario (http://www.planet-biogas.ca) and started operating in 2006. The AD digester has a volume of 1200 m^3. Their Genset biogas cogeneration system has a size of 250 kWe and 250 kWt. Now it can operate at TS content of 12% and up to 30%. The operation receives a variety of organic inputs that include dairy manure, corn silage, grain-based feed and supplemented by off-farm organic wastes (glycerine, potato culls, greenhouse clippings and grape pomace). The organic loading rate had a maximum value of 4.5 kg VS (organic fraction of TS)/m^3.day.

Kompogas (Glattbrugg, Switzerland, http://www.kompogas.com) supplies a horizontal plug flow digester that also operates at around 30% TS. Organic Waste Systems' (OWS, Ghent, Belgium. www.owe.com) Dranco process is a vertical plug flow reactor with no mixing that handles 25-40% TS.

Mesophilic vs. Thermophilic Digestion

Like most chemical reactions, the rate of AD increases with temperature. In practice, there are two temperature ranges for AD: mesophilic (around 35^{o}C) and thermophilic (from 55 to 60^{o}C). Psychrophilic AD systems running in Quebec and Manitoba have been designed to operate in the temperature range of 15-25°C. These systems are stable and easy to manage, however, much longer retention times are required to achieve equivalent gas production and pathogen removal (DeBruyn 2007).

Due to the faster kinetics, a thermophilic digester requires shorter HRT and hence smaller volume (Wilkie 2005). Other advantages of thermophilic digestion include possibly increased pathogen destruction and better dewatering characteristics of the digestate. In contrast, RCM International undertook a study to determine the effectiveness of pathogen reduction during mesophilic digestion of dairy manure in CSTRs that have already been operating anywhere from 1 to 4 years (Teigen and Moser, 2009). They observed a reduction in fecal coliform levels in the digested solids from over 50000 CFU/g to 10 CFU/g. However, they noted that values well over 500000 CFU/g in raw manure are common (for instance, Cornell University researchers had measured over 3.5 million CFU/g).

Disadvantages of thermophilic digestion include reduced stability and the need for greater process heating when compared to operating in the mesophilic temperature regime. Furthermore, unbalanced fermentation could occur due to prolonged exposure to high temperatures, thus favouring the sulphur-reducing bacteria, resulting in the formation of more hydrogen sulfide.

Thermophilic digesters did not necessarily generate more biogas than mesophilic ones among the Danish centralized AD plants installed during the 1980's and 1990's (Gregerson et al. 1999). Zhang et al. (2007) studied the effects of temperature on AD of five food wastes in the laboratory. They observed that the biogas yields under thermophilic conditions were not significantly different from those for mesophilic temperatures except for the grease trap waste (Table 8). Biogas yield from grease trap waste under thermophilic conditions was much lower, though the authors did not report the reason.

Table 8. Effects of temperature on anaerobic digestion (Zhang et al. 2007)

Temperature	Mesophilic, 35 ± 2°C			Thermophilic, 50 ± 2°C		
F/M ratio	0.47			0.91		
digestibility parameters	biogas yield, L/g VS	CH4 content, %	VS reduction, %	biogas yield, L/g VS	CH4 content, %	VS reduction, %
cafeteria waste	0.683	60.9	87.4	0.601	46.2	88.1
commercial kitchen waste	0.600	70.5	82.9	0.656	63.2	88.2
grease trap	0.949	72.3	87.8	0.237	42.0	66.5

Some studies have shown that biogas yields are higher during thermophilic digestion (Svoboda 2003), and that dry rather than wet digestion is more favourable for thermophilic systems (Beck Inc. 2004). In North America, most AD technology suppliers of on-farm systems offer digesters that operate in the mesophilic range. However, some dry digestion processes operate at thermophilic temperatures. For example, Kompogas builds horizontal PF digesters that run at 30% TS and 55-60°C. Microgy is the only supplier encountered in this study that specializes in thermophilic digestion. Unlike the other thermophilic digester suppliers, Microgy builds completely mixed digesters operating at less than 10% TS.

Generally speaking, because of the additional heating requirements (Demuynck et al 1984), thermophilic digestion is only economically viable at high organic loading rates (Mackie and Bryant 1995). Incentives for thermophilic digestion might not be compelling. Nevertheless, according to the statistics presented by Mattheeuws (2008), 71% of digesters in Europe operated with mesophilic temperature regime in 2008 and this percentage is expected to decrease to 45% in the next 3 years.

Examples of operating plants

In 1987, the French company Valorga (Montpellier. www.valorgainternational.fr) designed and built three vertical MPF-type 2,400 m^3 digesters at Ameins to treat 55000 tonnes/yr of municipal solid waste (MSW) with a TS content of 25-35%. The treatment capacity was extended to 85000 tonnes/yr in 1996 with an additional 3500 m^3 digester. The estimated hydraulic retention time (HRT) is between 18 to 22 days. The biogas yield was about 150 m^3/tonne, and it was used to produce high pressure steam for industrial purposes (Valorga 2009).

In 2001, Deere Ridge Dairy installed a farm-scale MPF digester designed by GHD. This digester treats about 113 m^3/day of manure at 8-9% TS with 22 days HRT under mesophilic conditions. The biogas produced generates between 60000-90000 kWh of electricity per month (0.19 kW/cow), which is sold to Alliant Energy. The heat produced is used for heating the digester, milking parlor and facility water. The solid product is removed and dewatered with a fan screw press and used entirely for bedding on the farm (Kramer and Krom 2008a).

Norswiss Farms in Rice Lake has a thermophilic completely mixed system installed by Microgy. A mixture of manure from 1240 Holsteins and Swiss cows and food waste is pumped into the digester every half hour at about 10% TS. The HRT is about 20 days. The biogas produced is used to power an 848 kW engine generator (Kramer and Krom 2008b). Approximately 55000 kWh of electricity is produced each month, which is enough to power some 600 homes.

In Denmark, Wisconsin, the 1000 cow Stencil Farm has a below grade, concrete, straight plug flow system installed by RCM in 2002. This system operates with 9% to 12% TS at mesophilic temperatures. The biogas is captured by a flexible cover and used to generate electricity and heat with a 123 kW engine generator. The electricity is used on the farm and the recovered heat maintains the digester temperature (Agstar website:
ttp://www.epa.gov/agstar/profiles/stencilfarm.html).

In 2005, a GHD MPF digester became operational at Quantum Dairy in Weyauwega treating 208 m^3/day of manure at 11% TS. The biogas produced is sent through a 300 kW turbocharged engine generator to produce heat and electricity. Under a sell-all contract, the electricity is sold entirely to We Energies. The recovered heat is used to maintain digester temperature, two milking parlors and other facilities on the farm (Kramer and Krom 2008b).

Single Phase vs. Two Phase Digestion

Verma (2002) examined in depth AD technologies in order to determine their economic and environmental competitiveness, as one of the options for processing the biodegradable organic materials in MSW. The study showed that multi-stage processes provide biological stability by keeping the acidogenesis and methanogenesis separately and allowing higher organic loading rates without shocking the methanogenic bacteria. However, multi-stage systems are complex and the benefits do not necessarily justify high investment costs. Single stage AD processes might dominate the market because of the simpler reactor design and lower investment and operational costs. Mattheeuws (2008) showed some up-to-date statistics from Europe, suggesting that 8% of the AD systems are two-phase in 2008 and within the next 3 years, this is expected to further decrease to less than 1% of the installed systems.

Co-Generation vs. Biogas Upgrading

Most of the operating on-farm AD facilities that we surveyed use biogas for heat and electricity production through combined heat and power (CHP) generators. Two primary types of power generation equipment are microturbines and reciprocating gas engines. Microturbines are small gas engines that burn CH_4 mixed with compressed air. Reciprocating gas engines are essentially natural gas engines that have been transformed to handle the larger volumes of biogas because of its higher CO_2 content (Goldstein, 2006).

Many engine vendors, such as Capstone, Ingersoll Rand, Caterpillar, General Electric (GE)’s Jenbacher, Entec and Linde-KCA supply co-generation engines for farm-sized biogas utilization. For farm-sized co-generation with biogas, about 30% of the total heat of combustion is converted to electricity and about 50% is captured as usable heat.

Biogas upgrading systems are not yet popular in North America market, but some suppliers, such as QuestAir Technologies (Vancouver, BC), have patented technologies for farm-sized biogas upgrading systems. Bioenergy Solutions (Bakerfield, CA) is one other such supplier (Greer, 2009). According the recent report by Electigaz (2007) upgrading biogas to natural gas grade CH_4 increases the economic feasibility of AD in BC.

Examples of biogas upgrading

In 2007, Scenic View Dairy's (Holland, Michigan) biogas production system started operating in full capacity. Their AD system consists of three 3300 m^3 mesophilic CSTRs treating manure and syrup stillage from a nearby ethanol plant with 5% to 20% TS. In addition to the two 350 kW reciprocating gas engines, the farm also installed a biogas upgrading system that incorporates a QuesetAir Technologies pressure swing absorption (PSA) unit to convert the additional biogas to pipeline-grade natural gas. As a result, after the power demand on the farm site is met, the dairy can make an economic decision between selling excess electricity to grid and selling upgraded biogas to Michigan Gas Utilities (Hauska, 2007).

In 2005, Emerald Dairy replaced an old covered lagoon system with a MPF digester designed by GHD. This digester treats about 170 m^3/day of manure at 8% TS under mesophilic conditions. A moisture trap and iron sponge removes water and hydrogen sulfide from the biogas. The remaining biogas is upgraded into compressed natural gas (CNG) using water column technology.

Simple Feed vs. Mixed Feed

Many different types of organic material can be digested anaerobically. As shown in Tables 2 and 3 the biogas yield can be very different depending on the nature of the substrate, with fatty materials yielding more CH_4 than recalcitrant carbohydrates, for example. In many cases combining food or another agricultural waste with manure results in increased biogas production (SPU, 2005). Often the additional substrate helps to optimize the nutrient ratio. As shown in Table 9, the optimal C:N:P ratio for farm-sized AD process (low organic loading) is between 150:5:1 and 330:5:1. Since manure has a high fibre content and is low in N, more readily digestible food wastes with more N increase nutrient availability and therefore the kinetics and yields of AD. Sauve (2008) performed lab batch tests for biochemical CH_4 potential BMP) to verify the interaction between different mixes of co-substrate volatile solids (VS), and suggested that manure is considered an important “buffer”; it is necessary to have a good ratio of manure to other co-digested organic wastes.

Table 9: Recommended nutrient ratio

Ratio	Value	Organic Loading	Reference
COD:N:P	400:7:1	High	Malina and Pohland, 1992
	1000:7:1	Low	
	1000:5:1	Low	Buvet et al. 1982
	250:5:1	High	
C:N:P	330:5:1	Low	
	130:5:1	High	
	100:6:1	n/a	Cheremisinoff, 1994
C:N	10:1	High	Timbers and Marshall, 1981
	30:1	Low	

Monou et al. (2009) conducted small-scale (400 mL rectors) experimental investigations on the co-digestion of livestock waste and industrial biowastes. They cautioned that anaerobic co-digestion of wastes with low pH and/or high fat or sugar contents (such as solid fruits, ice-cream, yoghurt and abattoir wastewater) is potentially problematic and, whilst anaerobic degradation of these waste types proceeds rapidly, methanogenesis could be inhibited, possibly by the low pH value and long-chain fatty acids. They suggested approaches to overcome CH4 inhibition, for instance, reducing the loading rate to provide a longer acclimatization period and limiting the fats content.

Examples

In 2003, the Klaesi brothers, owners of Fepro Farms in Cobden, Ottawa, Ontario, followed Swiss design literature and built an elliptical-shaped 500 m^3 mesophilic digester covered with a fixed membrane. This digester initially treated manure from 300 animals at 8-9% TS. The overall capital investment was about $250,000 with an estimated 10-year payback. Two years later, the Klaesi brothers received the first ever issued Ontario Ministry of the Environment Provisional Certificate of Approval for a Waste Disposal Site permitting them to process 5000 tonnes per year of off-farm organic waste originating in Ontario and Quebec. Allowable materials include a variety of agricultural residues, ethanol and biodiesel by-products, food processing wastes, leaf and yard wastes, fishery waste as well as flocculation and scum wastes from dissolved air floatation (DAF) systems at large food and meat processors. With these additional complex organic wastes, Fepro Farms expect to upgrade the 50 kW diesel engine running approximately 14 hours per day to a 100 kW engine running 24 hours per day 7 days a week, which will more than double the original energy output. The Klaesi brothers believe that with higher power prices and more government assistance, many Ontario farmers will consider installing AD systems to treat energy crops (Goldstein, 2007). As this example demonstrated, having additional off-farm organic wastes (especially food wastes and FOG) can improve the biogas yield, thus, generate more revenue.

2.4 Existing Kinetic Models of Anaerobic Digestion

In order to accurately design and optimize an anaerobic digester, a mathematical model describing substrate uptake rate, bacteria growth rate, and ultimately CH_4 production rate, must be constructed. Many theories and kinetic models were developed in the past 50 years, and new studies on this topic are published every year. All of these models may be categorized into two types: step-wise model and one-step model. In these sections, both types will be discussed and compared.

Step-wise Models

A more detailed model of AD would include all the main steps (as shown in Figure 1) in decomposition of organic matter and methanogenesis, each of which can be described by an overall stoichiometric equation and its own rate expression. The overall rate of substrate uptake and methane production can be calculated by combining all these rates. Garcia-Ochoa et al. (1999) developed a model taking this approach by considering six subprocesses: hydrolysis of particulate organic materials, growth of acetogenic bacteria, production of organic acids, consumption of substrate for acetogenic bacteria maintenance, growth of methanogenic bacteria and organic acids consumption for methanogenic bacteria maintenance.

With the exception of the hydrolysis step, all other subprocesses of anaerobic treatment have been successfully modeled by following Monod kinetics. Even in cases where acidogenesis or methanogenesis are considered to be limiting steps, hydrolysis may affect the overall process kinetics. The process failure point at which washout of methanogens occurs is influenced by preceding steps such as hydrolysis (Pavlostathis and Giraldo-Gomez 1991). Nevertheless, due to the complexity of these step-wise models, they are primarily used for laboratory scale studies.

One-step Models

Although AD is carried out by many groups of microorganisms in several stages, it is more common to model the kinetics with an overall growth-dependent reaction rate. As shown in Table 10, in these overall growth models, the cell specific bacterial growth rate, μ, is proportional to the substrate concentration, S, in Monod-like expressions. In some cases the growth rate is inhibited by the feed substrate concentration, S_o. The maintenance activity of the bacteria is modeled by the decay factor, b, in most of these models.

Table 10: A brief summary of one-step models

Model (equation for bacteria growth rate)	Reference
$\mu = \frac{\mu_{max} S}{S_0} - b$	Grau et al. 1975
$\mu = \frac{\mu_{max} S}{BX + S} - b$	Contois 1959
$\mu = \frac{\mu_{max} S}{KS_0 + (1 - K)S} - b$	Chen and Hashimoto 1979
$\mu = \frac{a\,k\,S}{K_s + S} - b$	Lawrence and McCarty 1967
$\mu = \frac{k}{\frac{S}{S_0} - 1}$	Linke 2006

μ: growth rate of microorganisms (1/day); μ_{max}: maximum growth rate of microorganisms (1/day)
S: concentration of substrate (mg/L); S_0: initial concentration of substrate in digester (mg/L)
X: microorganisms concentration (mg/L)
a: growth yield constant (mg/mg)
k: maximum rate of substrate utilization (mg/mg day),
K_s: half-growth velocity (mg/L)
b: decay rate (1/day)
B, K, Y: constant parameters developed for their corresponding model

Barthakur et al. (1991) suggested that when substrate hydrolysis is poor and rate limiting, as would be the case for fibrous materials, the Contois-type equation is more applicable, whereas a Monod-type relationship better represents the kinetics for soluble substrates. Based on our literature review, the Chen and Hashimoto model and the Lawrence and McCarty model have been found to be more accurate and widely used than the others; both models are modifications of Monod kinetics. The Lawrence and McCarty model (1967) is essentially Monod kinetics and it emphasizes the effect of current substrate concentration, whereas the Chen and Hashimoto model (1979) takes both initial (or feed) substrate concentration and current substrate concentration into consideration. To compare the two models, the Chen and Hashimoto model may be re-written as:

$$\mu = \frac{\mu_{\max} S}{K(S_0 - S) + S} - b \tag{1}$$

where

$$K(S_0 - S) \equiv K_m$$

K_m represents the ease with which the substrate is digested. For example, easily digested substrates have a low K_m value, whereas more complex or recalcitrant substrates have a higher K_m value. According to the Chen and Hashimoto model the feed substrate concentration (or organic loading rate to the digester) also influences the ease of substrate degradation in that high feed loading rates inhibit the growth kinetics.

In this sense, the inhibition for Chen and Hashimoto model is from the initial or feed substrate concentration, whereas for Lawrence and McCarty model, the inhibition is from the nature of the substrate. Currently, both assumptions about inhibition are accepted by scientific community. In practice, kinetic models' accuracy may vary depending on the configuration of digesters. Lawrence and McCarty's model has been used in studies of anaerobic CH_4 production (Sanchez et al 2004) and it can predict kinetics of anaerobic bacterial growth accurately (Kumar et al 2007). Therefore, the Lawrence and McCarty model was chosen for this study.

Like most microbial bioreactors, so-called wash-out can occur in anaerobic digesters operating in the CSTR configuration. This is predicted by Monod-like expressions such as the Lawrence and McCarty model as the minimum allowable HRT. For a CSTR operating under steady-state conditions the final substrate concentration can be calculated with Equation 1, which uses the Lawrence and McCarty model for the kinetic expression. If $HRT(ak - b) \leq 1$, then according to Equation 1 the value of *S* is negative, which is not possible. This is because HRT is too small leading to wash out.

$$S = \frac{Ks(1+bHRT)}{HRT(ak-b)-1} \tag{2}$$

In order to prevent wash out, the range of HRT must be limited for a set of fixed kinetic parameters:

$$HRT > \frac{1}{ak-b} \tag{3}$$

2.5 Capital Cost Estimation

Capital cost estimation is perhaps the most important item within economic analysis of AD systems. The cost of AD of manure for biogas production and utilization will vary with system type and size, type of livestock operation and site-specific conditions.

Verma (2002) cited comments by De Baere (1999) that the economic differences between the low-solids CSTR systems with complete mixing and the high-solids PF systems without mechanical devices within the reactor are small.

At the University of Alberta, Ghafoori and Flynn (2006) have summarized capital cost data in terms of biogas production rate. Different curves were generated using cost indexing to 2005 US dollars, and plotted for centralized plants in Denmark (1999-2002), another Danish study by Nielsen (2002) and farm AD systems (Hashimoto et al 1979). Although the types of reactor are not cited in their study, in general, the capital costs exhibit economy of scale, and the exponent 0.60 usually adopted for processing plants was found to be valid for AD systems. Calculations from FarmWare 3.0 (USEPA, 2003) were also included in their analysis; however, the capital cost values are substantially lower and the authors have cast doubt about the accuracy and consistency of the AgStar estimating basis.

Enahoro and Gloy (2008) at the Department of Applied Economics and Management, Cornell University conducted a financial analysis of AD systems on dairy farms and described a financial model developed for this purpose. The model is illustrated with two sources of data. The “base” case is a more flexible model that can be utilized with farm-specific data to assist in the evaluation of an AD system, and its parameters were developed from a wide range of resources. The second model is meant to be used in conjunction with FarmWare 3.1 which is the updated version of FarmWare 3.0, developed and distributed by the USEPA’s AgStar Program. Their analysis explicitly incorporates the financial incentives offered under the New York State Energy Research and Development Authority’s Customer-Sited Tier Anaerobic Digester Gas-to-Electricity Program. A variety of parameters was considered very important in determining the economic viability of anaerobic digester projects. These key variables include the biogas energy yield, current on-farm energy use, prices paid for electricity, the price received for excess electricity generation, the ability to co-digest other waste streams and capital and operating costs.

Lazarus (2009) at the University of Minnesota performed an economic analysis and confirmed the economy-of-scale via cost-capacity relationship for dairy farm digesters. With manure alone as feedstock, a digester for a 500-cow operation in 2006 would have cost $805/cow while at 2,000 cows the cost would decline to $371/cow. A plug-flow digester installed on a Washington state 500-cow dairy farm in 2005 cost approximately $1.1 million or $1,515/cow. The digester also received manure trucked in from an additional 250 cows, as well as addition of food processing wastes and fiber separation. A complete mix digester with separator installed on a 160-cow Minnesota dairy farm in 2008 cost $460,000, or $2,875/cow. Another analysis found that the electrical generation equipment made up on average 36 percent of total investment for a group of 36 digesters, suggesting that substantial cost savings may be possible in situations where the biogas can be used for heating rather than to produce electricity.

In the AD system feasibility study reports (Electrigaz Technologies Inc., 2007, 2008), a rule of thumb was cited as $5,000/kW power generated, but regardless of the type of digester. Moreover, this shall be considered valid for smaller-size dairy farms (like, fewer than 500 cows). Carruthers of Organic Resources Management Inc., Ontario (2009) also cited a figure of ~ $4,500/kW. For an average power production of 0.20 kW/cow (Enahoro and Gloy 2008), this would then work out to be $1,000/cow.

According to USEPA AgSTAR program, as-built costs generally are not available. Nevertheless, based on vendor quotes between 2005-2008, they analyzed AD system capital cost data for 28 dairy farms for which itemized cost estimates for the digester, the engine-generator set, engineering design and installation were available. The AD systems included 10 complete mix digesters, 16 plug flow digesters and 2 covered lagoons. Systems designed for co-digestion with other wastes were excluded from their analyses. They are also aware of the fact that not all reported costs include the same equipment, thus introducing variability in the reported costs of digesters. To analyze costs on a common basis, they excluded costs of system components that were not included in all of the available cost estimates. These components were post-digestion solids separation, hydrogen sulfide reduction systems, and utility charges including line upgrades and interconnection equipment costs and fees. With the aforementioned items excluded, the remaining capital costs were then scaled to August 2008 dollars using the Chemical Engineering Plant Cost Index (CEPCI). The CEPCI index has been used for cost indexing purposes for more than half a century. The resulting linear regression equations were as follows:

Complete Mix digester (700 - 2300 cows):

$$\text{Capital cost} = 615\ (\text{Number of dairy cows}) + 354{,}866 \tag{4}$$

Plug Flow digester (650 - 4000 head):

$$\text{Capital Cost} = 563\ (\text{Number of dairy cows}) + 678{,}064 \tag{5}$$

The above relations clearly show that plug flow (PF/MPF) digesters are more expensive than complete mix digesters (CSTR). Expressing capital investment per cow basis, PF digester costs \$1,450/cow and \$1,000/cow respectively when the number of cows increases from 750 to 2,000. These values are some 25% greater than the corresponding costs for CSTR digester, being \$1,150/cow and \$800/cow, respectively. This trend appears to have a discrepancy with that derived from estimates made by Lazarus (2009), which suggested CSTR digesters are more costly.

For preliminary capital cost estimates, the total capital cost may be assumed to be proportional to the number of animals (dairy cows) on farm site. Alternatively, the total capital cost may be assumed to be proportional to the maximum power output of the plant.

Before we proceed with our capital cost estimate, we checked the factsheets published by Cornell University's Manure Management Program (CUMMP 2008, www.manuremanagement.cornell.edu), which are based on surveys of individual dairy farms. We realize cross references are often made by the CUMMP to information provided by USEPA on their website (USEPA AgSTAR Program: Guide to anaerobic digesters 2009; http://www.epa.gov/agstar/operational.html). However, the data compiled and analyzed by USEPA AgStar program about capital costs of CSTR versus MPF/PF systems (Eqns 4 and 5) appear to be contradictory to what are reported in these factsheets. Table 11 contains our findings about the capital cost data reported in these factsheets, illustrating that the capital cost for CSTR digesters can be much higher than PF/MPF digesters.

We applied regression analysis and summarize the data in two graphs - capital cost versus number of cows (Figure 4) and capital cost versus maximum power output (Figure 5). As shown in Figure 4, the economy-of-scale factor for completely mixed digesters (CSTR) and mixed plug-flow (MPF/PF) digesters are 0.77 and 1.16 respectively. When the economy-of-scale factor is greater than 1.0, the cost per unit capacity actually increases with capacity. In Figure 5, the economy-of-scale factor for CSTR and MPF/PF digesters are 0.74 and 0.87 respectively. Hence, with the limited data that we have analyzed, economy-of-scale is only valid for MPF/PF digesters when capital cost is plotted against maximum power output. These curve fitting results imply that the economy-of-scale factor for completely mixed digesters is closer to the general adopted value of 0.60.

Consequently, the capital costs of AD systems are estimated as a function of maximum power output in this study.

CSTR Digesters: $$Capital = 26920 \times MaximumPowerOutput^{0.7388} \quad (6)$$

MPF/PF Digesters: $$Capital = 7570 \times MaximumPowerOutput^{0.8722} \quad (7)$$

The regression equation (Eqn. 6) for CSTR digesters is based on few data points. Yet, if we remove Green Valley Farm from the data set because it induces an unnecessarily broad range of data, the resulting correlation thus obtained is essentially the same as Eqn. 6.

Table 11. A summary of case studies for capital cost estimation

Name and location of facility		#cows	Power, kW	Digester type	Capital cost, $[1]	Reference[2]
AA	NY	1000	130	PF	292000	Martin 2004
Gordondale	WI	860	135	MPF	550000	Martin 2005
Haubenschild	MN	850	135	PF	423000	Lazarus 2006
Noblehurst	NY	1300	130	PF	747700	Wright and Ma 2003
Spring Valley	NY	236	25	PF	143650	Wright and Ma 2003
Sunny Knoll	NY	1400	230	PF	1084500	Pronto and Gooch 2008
Van der Haak	WA	1200	285	MPF	1200000	Goldstein 2004
Crave Brothers	WI	1000	200	CSTR	1500000	Ballenger 2008
Green Valley	WI	2500	600	CSTR	2550000	Jacobs 2007
Patterson	NY	1000	250	CSTR	1508630	Gooch and Inglis 2008
Ridgeline	NY	525	130	CSTR	740800	Pronto and Gooch 2008
Sheland	NY	560	125	CSTR	1199717	Pronto and Gooch 2008

[1] All capital costs are indexed to 2005 values, using the Chemical Engineering Plant Cost Index (CEPCI)

[2] From Cornell University website, AgStar website or BioCycle, with authors specified in the table.

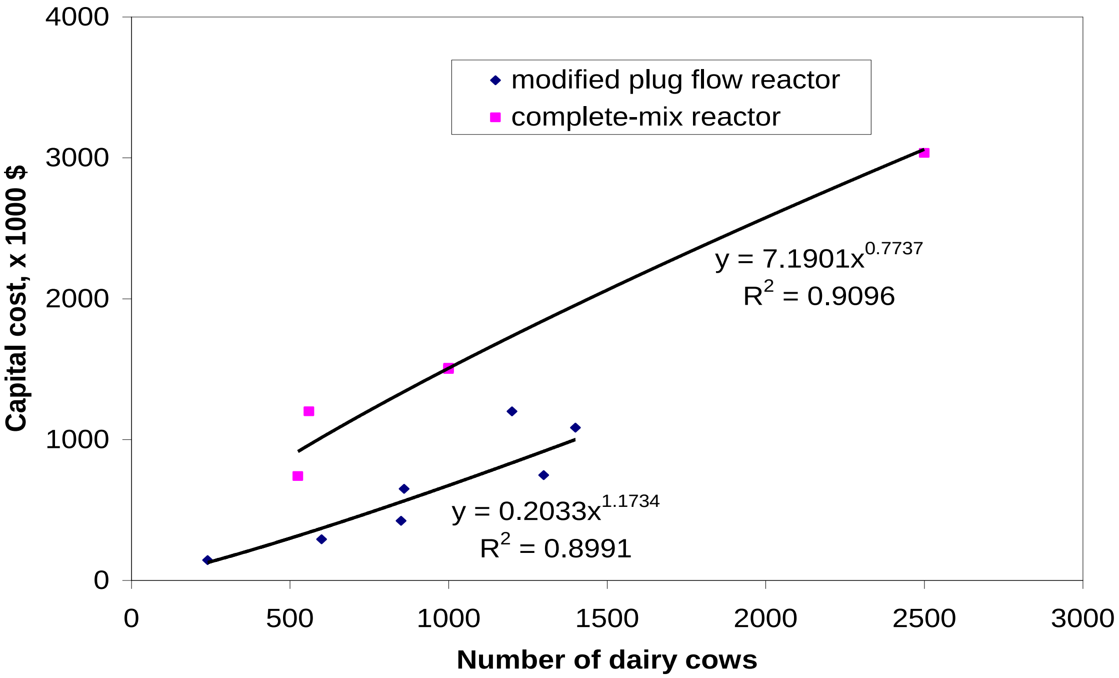


Figure 4. Capital cost as a function of the number of cows

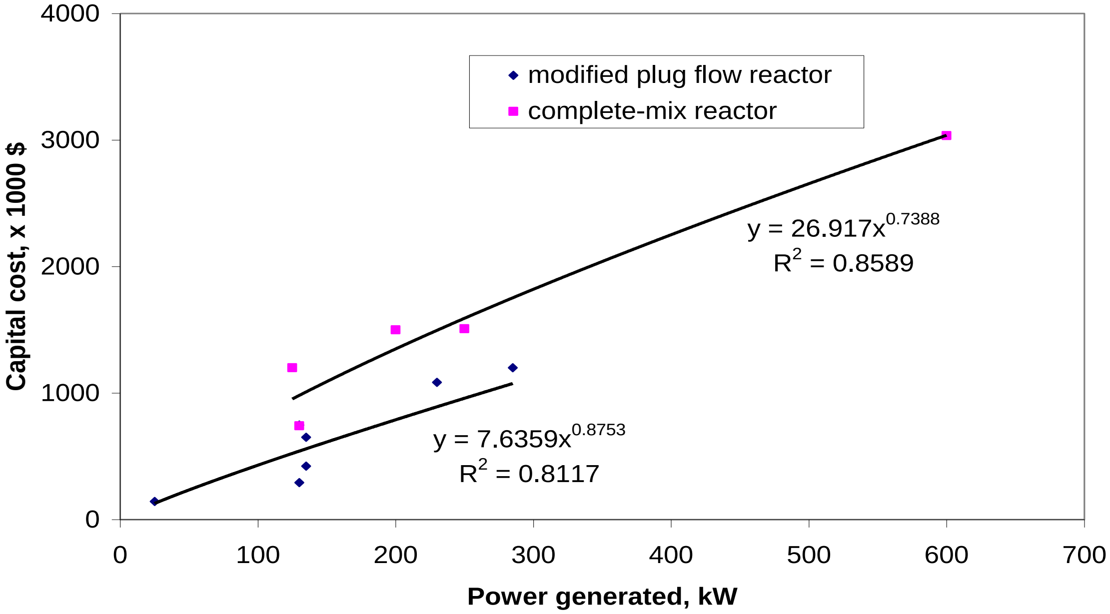


Figure 5. Capital cost as a function of maximum power output

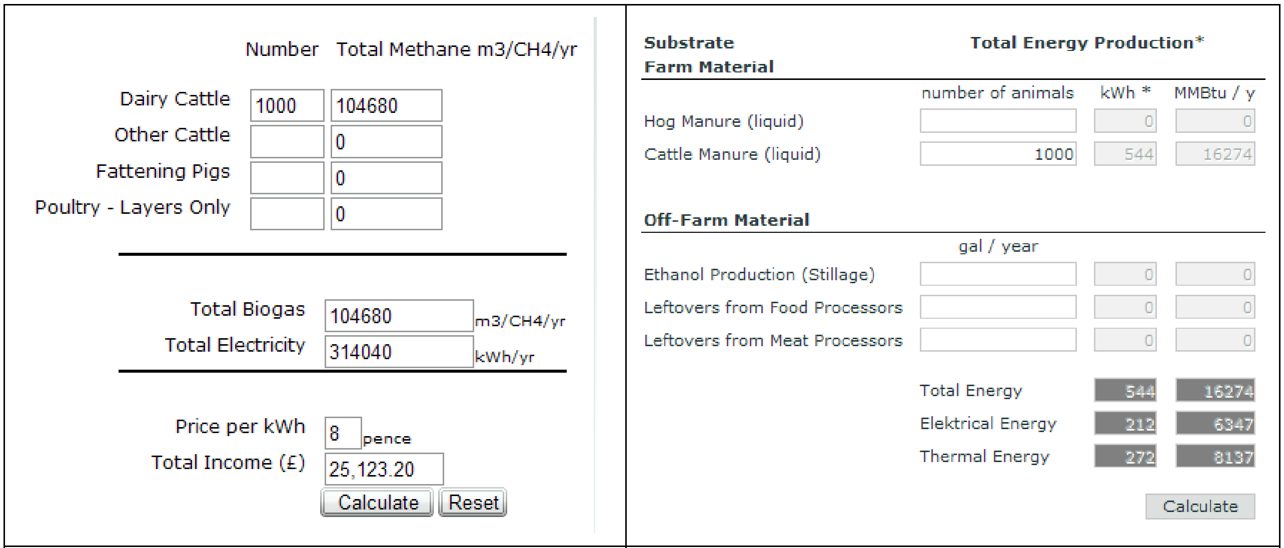
3. Existing Anaerobic Digestion (AD) Calculators

3.1 Coefficient-based Software

Many AD calculators are already available on the Internet. Most are simple web-based calculators.

MacDougall (2007) presented a predictive model for co-digestion in dairy manure digester. As an example, the feed is made up of 80% dairy manure (85 tons/d at 13% TS) and 20% food waste (23 tons/d at 27% TS) diluted by 161 tons of water to achieve the targeted 7% TS in the digester. For an influent biomass of 255 tons/d, and operating conditions of 20 days HRT and mesophilic temperature of 35^{o}C, the predicted biogas yield is 26.6 m^3/ton feed (wet mass basis). This biogas yield is much closer to the typical yield for dairy manure as compared to food waste.

Other examples are two web-based calculators as shown in Figures 8a and 8b. These are easy to use and require only a few inputs about the quantities of organic wastes. However, the results obtained from these calculators are limited. The Renewable Energy Concepts (http://www.renewable-energy-concepts.com) software only provides the electricity and thermal energy generation through a co-generation system. The AD Community (http://www.anaerobic-digestion.com/index.php) software provides a bit more information including CH_4 production and total gross income.



	Number	Total Methane m3/CH4/yr
Dairy Cattle	1000	104680
Other Cattle		0
Fattening Pigs		0
Poultry - Layers Only		0

Total Biogas	104680	m3/CH4/yr
Total Electricity	314040	kWh/yr
Price per kWh	8	pence
Total Income (£)	25,123.20	

Substrate
Farm Material
Total Energy Production*

	number of animals	kWh *	MMBtu / y
Hog Manure (liquid)		0	0
Cattle Manure (liquid)	1000	544	16274

Off-Farm Material

	gal / year		
Ethanol Production (Stillage)		0	0
Leftovers from Food Processors		0	0
Leftovers from Meat Processors		0	0
Total Energy		544	16274
Elektrical Energy		212	6347
Thermal Energy		272	8137

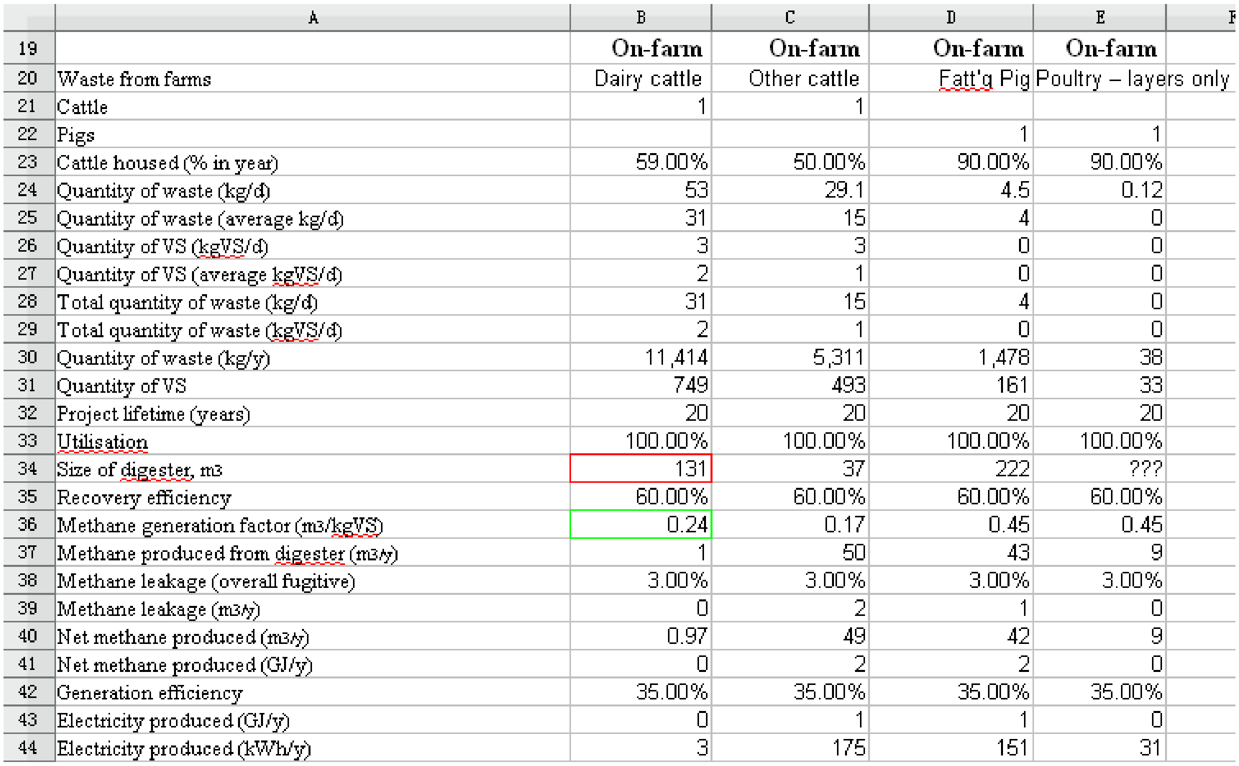
a. AD Community software (Last 2009)

b. Renewable Energy Concept software (2009)

Figure 6: Two examples of simple web-based calculators

As a trial use of these two calculators, the number of dairy cattle was set at 1000 and input into each one. The electricity production predictions were very different, assuming 360 operating days per year: 314040 kWh/yr (AD Community software) and 76320 kWh/yr (Renewable Energy Concepts software). Since the algorithm behind the Renewable Energy Concepts calculator is hidden from users, it is not possible to determine the reliability of its calculations.

The AD Community website provided a spreadsheet file to illustrate its calculator's algorithm. As shown in Figure 9, different coefficients are assigned to each type of livestock. For instance, in order to obtain the digester volume for a dairy farm, the algorithm is to multiply the number of dairy cattle by the size of digester per animal. Similarly, to calculate CH_4 generation, we can multiply the total amount of VS in the feed by the CH_4 yield/kg VS. For mixed feed from dairy cattle, other cattle, pig and poultry manure, it calculates the digester volume and CH_4 yield for each type of livestock individually, and sums up the individual results to obtain the overall output. The fundamental concept of this algorithm is that the digester volume and CH_4 yield are proportional to the number of livestock. Their additional assumption of 100% conversion (all of the VS are digested to completion) may not be accurate for all types of feeds and HRTs. For example, in practice, the ultimate biodegradable fraction of dairy manure is only approximately 40% (Wilkie, 2005). Conversion depends on the rate of digestion and the HRT. For the same HRT, the conversion of recalcitrant materials will be less than the conversion of more readily available substrates. Another disadvantage of these simple calculators is they consider only one type of digester and co-generation is the only option for biogas use. The overall performance of AD depends on the type of digester used, which impacts conversion as well as capital cost, and whether the biogas is used for co-generation or upgrading to pipeline grade CH_4. Thus, the simplicity of a coefficient-based approach leads to highly variable predictions and these calculators do not provide the user with enough specific information for them to make an informed choice of what technology to use.

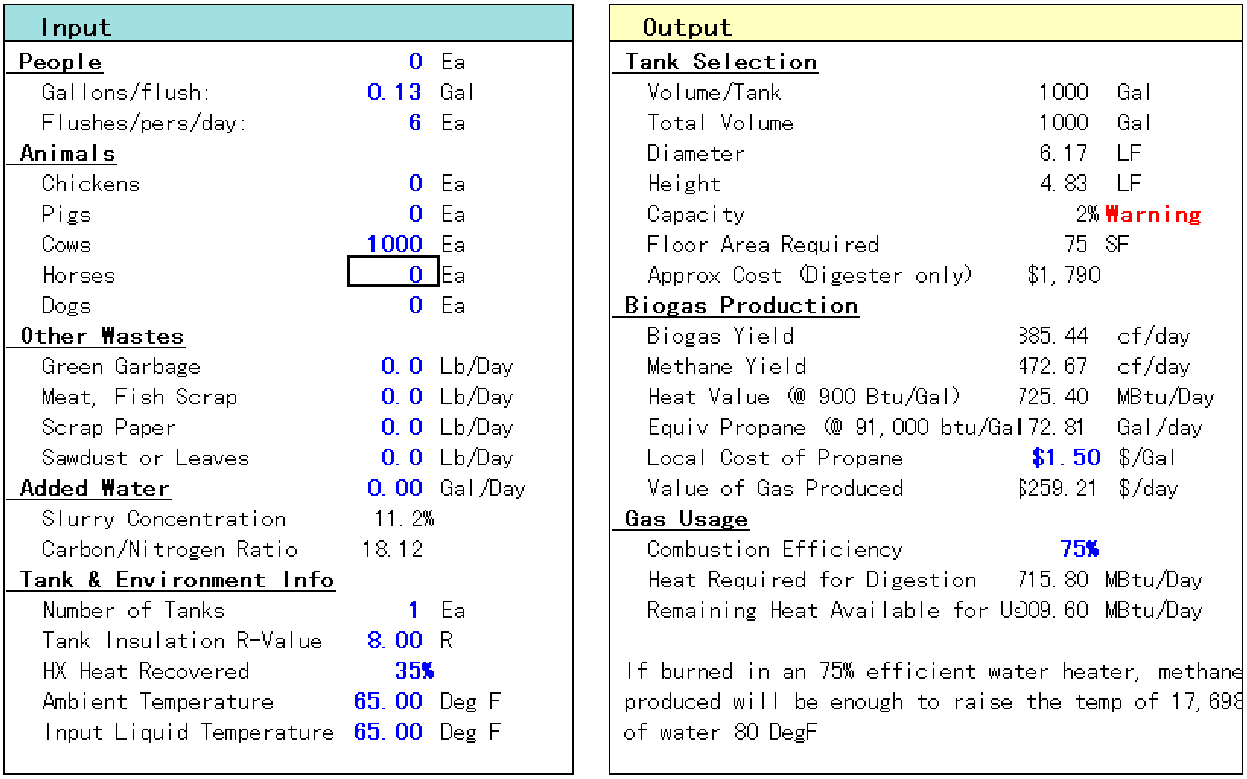


	A	B	C	D	E
19		**On-farm**	**On-farm**	**On-farm**	**On-farm**
20	Waste from farms	Dairy cattle	Other cattle	Fatt'g Pig	Poultry – layers only
21	Cattle	1	1		
22	Pigs			1	1
23	Cattle housed (% in year)	59.00%	50.00%	90.00%	90.00%
24	Quantity of waste (kg/d)	53	29.1	4.5	0.12
25	Quantity of waste (average kg/d)	31	15	4	0
26	Quantity of VS (kgVS/d)	3	3	0	0
27	Quantity of VS (average kgVS/d)	2	1	0	0
28	Total quantity of waste (kg/d)	31	15	4	0
29	Total quantity of waste (kgVS/d)	2	1	0	0
30	Quantity of waste (kg/y)	11,414	5,311	1,478	38
31	Quantity of VS	749	493	161	33
32	Project lifetime (years)	20	20	20	20
33	Utilisation	100.00%	100.00%	100.00%	100.00%
34	Size of digester, m3	131	37	222	???
35	Recovery efficiency	60.00%	60.00%	60.00%	60.00%
36	Methane generation factor (m3/kgVS)	0.24	0.17	0.45	0.45
37	Methane produced from digester (m3/y)	1	50	43	9
38	Methane leakage (overall fugitive)	3.00%	3.00%	3.00%	3.00%
39	Methane leakage (m3/y)	0	2	1	0
40	Net methane produced (m3/y)	0.97	49	42	9
41	Net methane produced (GJ/y)	0	2	2	0
42	Generation efficiency	35.00%	35.00%	35.00%	35.00%
43	Electricity produced (GJ/y)	0	1	1	0
44	Electricity produced (kWh/y)	3	175	151	31

Figure 7: Spreadsheet of the AD Community software

3.2 Kinetic-based Calculators

Kinetic-based calculators are developed using microbial growth models, such as the Lawrence and McCarthy model described earlier. Due to the complexity of AD, kinetic models also have their limitations, but they are useful in that conversion and biogas yield can be calculated for a particular feed, reactor type and HRT. Figure 10 is a web-based kinetic-based calculator from Biorealis Systems, Inc. (http://biorealis.com)**.** It can handle different types of waste, and allows users to manipulate some operating conditions such as water content and temperature. In the output section it provides information about the digester volume, digester cost, CH_4 yield and energy production. However, this software assumes that biogas is utilized only to produce thermal energy. The biggest limitation of this calculator is that the kinetic model used in this calculator is completely hidden from users and therefore it cannot be calibrated for specific types of feed.



Input		
People	0	Ea
Gallons/flush:	0.13	Gal
Flushes/pers/day:	6	Ea
Animals		
Chickens	0	Ea
Pigs	0	Ea
Cows	1000	Ea
Horses	0	Ea
Dogs	0	Ea
Other Wastes		
Green Garbage	0.0	Lb/Day
Meat, Fish Scrap	0.0	Lb/Day
Scrap Paper	0.0	Lb/Day
Sawdust or Leaves	0.0	Lb/Day
Added Water	0.00	Gal/Day
Slurry Concentration	11.2%	
Carbon/Nitrogen Ratio	18.12	
Tank & Environment Info		
Number of Tanks	1	Ea
Tank Insulation R-Value	8.00	R
HX Heat Recovered	35%	
Ambient Temperature	65.00	Deg F
Input Liquid Temperature	65.00	Deg F

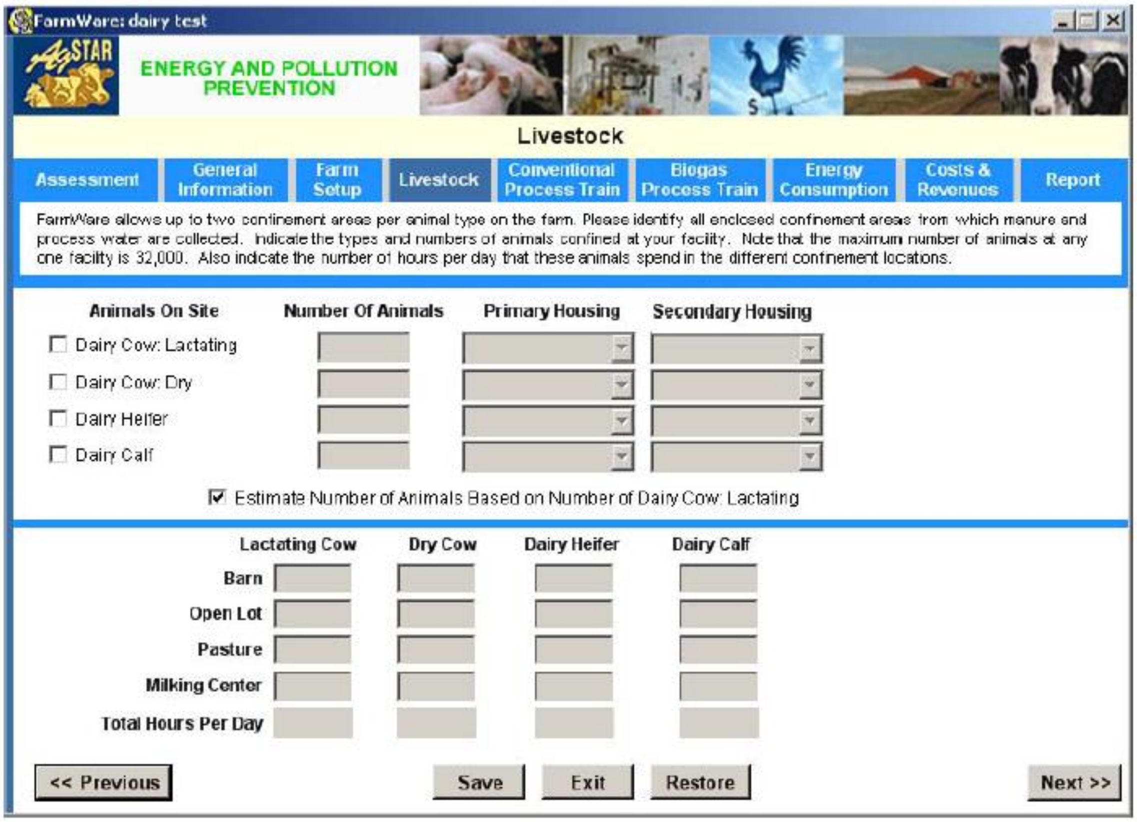
Output		
Tank Selection		
Volume/Tank	1000	Gal
Total Volume	1000	Gal
Diameter	6.17	LF
Height	4.83	LF
Capacity	2%	Warning
Floor Area Required	75	SF
Approx Cost (Digester only)	$1,790	
Biogas Production		
Biogas Yield	385.44	cf/day
Methane Yield	472.67	cf/day
Heat Value (@ 900 Btu/Gal)	725.40	MBtu/Day
Equiv Propane (@ 91,000 btu/Gal	72.81	Gal/day
Local Cost of Propane	$1.50	$/Gal
Value of Gas Produced	$259.21	$/day
Gas Usage		
Combustion Efficiency	75%	
Heat Required for Digestion	715.80	MBtu/Day
Remaining Heat Available for U	309.60	MBtu/Day

If burned in an 75% efficient water heater, methane produced will be enough to raise the temp of 17,69 of water 80 DegF

Figure 8: Calculator from Biorealis Systems, Inc.

A far more advanced AD calculator is FarmWare 3.1 (Figure 11) which was developed only for livestock manure feeds by the U.S. Environmental Protection Agency (USEPA) under its AgStar Program (http://www.epa.gov/agstar/). AgSTAR is an outreach program jointly sponsored by the USEPA, the U.S. Department of Agriculture and the U.S. Department of Energy. The program encourages the use of CH_4 recovery (biogas) technologies at confined animal feeding operations that manage manure as liquids or slurries.

The main advantage of the Farmware is that users can select a wide range of designs for equipment used in the entire process, from pretreatment through post-digestion effluent treatment. This enables users to visualize the detailed layout of the overall process including all the equipment needed. However, Farmware is limited to animal manure as the only feedstock. Since future practice will include addition of off-farm organic wastes so as to improve the biogas yield and economic incentives for AD, FarmWare 3.1 is of limited application for this project. It is projected that typical AD feedstock on BC farms could contain up to 20% (w/wt) of off-farm organic wastes together with animal manure. A minor disadvantage of this software is that it requires local installation, thus compatibility becomes an issue. At the moment, the newest version of FarmWare is compatible with Windows XP, 2000 and 98, but not compatible with Windows VISTA and Apple Macintosh systems. In order to solve this issue, this software requires constant updates with common operating systems.



FarmWare allows up to two confinement areas per animal type on the farm. Please identify all enclosed confinement areas from which manure and process water are collected. Indicate the types and numbers of animals confined at your facility. Note that the maximum number of animals at any one facility is 32,000. Also indicate the number of hours per day that these animals spend in the different confinement locations.

☐ Dairy Cow: Lactating
☐ Dairy Cow: Dry
☐ Dairy Heifer
☐ Dairy Calf

☑ Estimate Number of Animals Based on Number of Dairy Cow: Lactating

Figure 9: FarmWare 3.1 from USEPA

Although the kinetic model and calculations are hidden within the calculator, USEPA provides a user manual with this software **(**http://www.epa.gov/agstar/resources/handbook.html**),** in which it states that the kinetic model used by FarmWare is the Chen and Hashimoto Model. The Lawrence & McCarty model used in this study and the Chen & Hashimoto Model are fairly compatible, as explained previously, but the Lawrence & McCarty model has been applied and verified in more case studies.

4. Development of the New AD Calculator

4.1 Design Rationale

There are several key principles that guided development of the new AD calculator. The calculator software had to be open-source to allow users to view and modify the code. A simple user interface was required for the typical user, such as a farmer, who may not be familiar with computers or AD technologies. Because the calculator must be flexible and extensible to new feedstocks, more advanced users must be able to calibrate or modify model parameters.

In order to achieve these goals, the software was developed using Microsoft Excel 2003. However, for complicated calculations it is not easy for users to find the connections between and the meaning of individual cells. In order to overcome this problem, VBA (visual basic for application) coding was used to create simple graphical user interfaces that guide users through the calculation steps.

As shown in Figure 10, typical users will only see these graphical user interfaces (GUI) constructed with VBA codes. Code running in the background assigns users' inputs to the corresponding cells in the Excel spreadsheets. Once the current spreadsheet calculations are complete, these results are passed back the GUI, which presents the output figures in a more clear and informative way to the user. A major advantage of this approach is that the GUI can check the appropriateness of user inputs for acceptance or rejection. It will inform users of any errors and block its passage onto the spreadsheets, which would otherwise lead to crashing of the program or calculations of misleading results. However, if expert users want to bypass the GUI, they can perform manipulations by accessing the spreadsheet directly. Another advantage of having an Excel-based calculator is that spreadsheets can be viewed in most operating systems. The common operating systems, such as Windows 98, 2000, XP, VISTA and Mac OS X will need to upgrade their Excel program with their systems' updates to ensure that Excel files edited in early version are compatible with the newest version. As a result, compatibility will not be a problem.

Figure 10: VBA interface between users and Excel spreadsheets

4.2 Digester Models

The bacteria growth kinetic model chosen for this project is the Lawrence and McCarty model (Lawrence and McCarty, 1967):

$$\mu = \frac{akS}{K_S + S} - b \tag{8}$$

For digesters without solid recirculation, the values of hydraulic retention time HRT and solids retention time SRT are the same, and the volume of a digester can be calculated by:

$$V = HRT \times v \tag{9}$$

where V is digester volume, and v is the volumetric flow rate of the feed. In order to apply this kinetic model to the CSTR, PF and MPF digesters, the three configurations included in this model, mass balances were performed with the following assumptions:

1. The volumetric flow rate of influent and effluent are considered equal to each other since the density does not change due to the fact that typically 85%~90% of the feed is

water. Also, the mass flow rate of gas produced is much smaller than the total mass of liquid feed and effluent and hence the influent and effluent volumetric flow rates can be considered equal to each other.

2. The inert portion, solids such as sand, of the influent remains unchanged through the process.
3. The biogas produced contains only CH_4 and CO_2. We assume that any water vapour lost with the gases is returned to the digester. Trace amounts of H_2S and other gases are neglected.
4. Aside from biogas, the only products of AD are digestate and ammonium.
5. Phosphorus, potassium and other macro and micro nutrients are not taken into account in the mass balance.

Completely mixed digesters are modelled as a CSTR with volumetric flow, *v*, substrate and digestate concentrations, *S* and *X*, respectively and reactor volume, *V*, labeled as shown in Figure 13. At steady state, the mass balance is:

$$\frac{1}{HRT} = \frac{v}{V} = \frac{1}{X}\left(a\frac{dS}{dt} - bX\right) \tag{10}$$

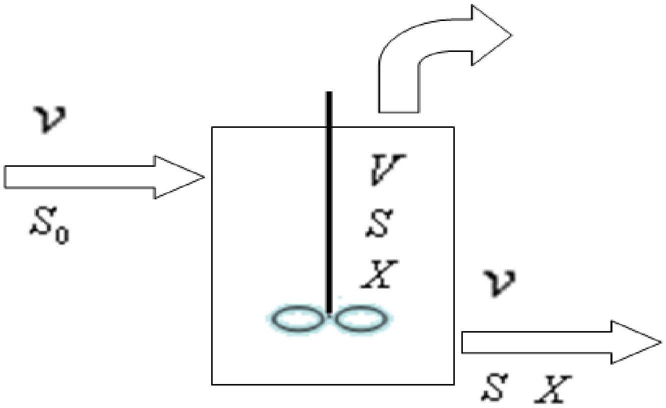


Figure 11. Diagram of CSTR model

Upon substituting the Lawrence and McCarty kinetic model for *dS/dt*, the concentration of un-digested organics inside the digester and hence in the effluent, *S*, can be calculated for a chosen *HRT*, which is a design parameter:

$$S = \frac{Ks(1 + bHRT)}{HRT(ak - b) - 1} \tag{11}$$

Using the value of *S*, the model calculates the amount of organics that have been digested and from this the production rates of biogas, ammonium and digestate:

$$R_i = (S_0 - S) \times v \times yield_i \tag{12}$$

where R_i is production rate (kg/day) and $yield_i$ is the mass of product produced per mass of substrate consumed (kg/kg). The subscript *i* refers to either CH_4, CO_2, ammonium or digestate.

The microbial growth kinetics in an ideal PF digester as shown in Figure 14 is very similar to that for the CSTR. However, in a PF reactor, the concentration of microorganisms and substrate inside the digester changes gradually as materials flow from the entrance to the exit of the digester. In order to adapt the equations developed for CSTR, estimated average values of substrate and microorganisms concentrations are used.

The log mean average S is:

$$S = \frac{S_0 - S_{eff}}{\ln S_0 - \ln S_{eff}} \tag{13}$$

Again, substituting this expression of substrate concentration into the Lawrence and McCarty model, it becomes:

$$\frac{1}{HRT} = \frac{aK(S_0 - S_{eff})}{(S_0 - S_{eff}) + K_s(\ln S_0 - \ln S_{eff})} - b \tag{14}$$

Although an analytical solution for the effluent substrate concentration, S_{eff}, cannot be derived, a numerical solution is obtained via the goal-seek function in Excel. Once the effluent substrate concentration is known, the biogas, ammonia and microorganisms production rates may be estimated using yield coefficients as described before.

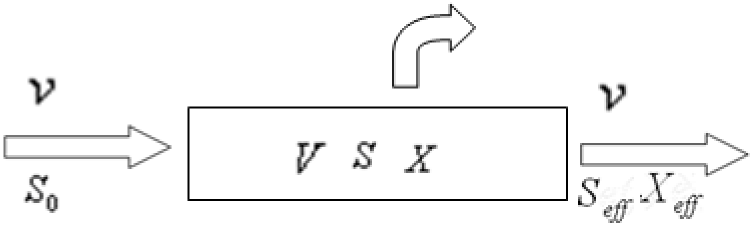


Figure 12. Diagram of PF model

Figure 15 is a simplified illustration of a two-stage MPF digester. The feed spends half of the HRT in the first tank, in which some mixing occurs due to rising biogas bubbles, and then spends the other half of the HRT in the second tank, where some additional mixing takes place also due to rising biogas bubbles.

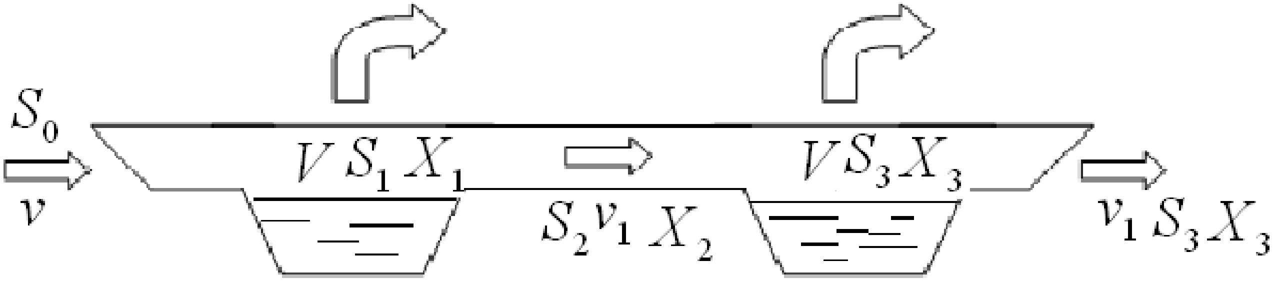


Figure 13: Diagram of MPF model

The two-stage MPF digester was modeled as two CSTRs in series. Therefore, according to the expression developed for a CSTR, the substrate concentration for the first tank is calculated by:

$$S_1 = \frac{K_S(1+0.5bHRT)}{0.5bHRT(ak-b)-1} \tag{15}$$

Experience has shown that the microorganisms experience different growth phases in the two tanks. As shown in Figure 14, the biomass concentration does not increase in tank 2 since the microbes are in the stationary growth phase. Therefore we can make the assumption that X_3 is equal to X_2. Since there is no growth of biomass in tank 2, the substrate consumption is entirely due to bacteria maintenance. As a result, the substrate concentration in digestate (S_3) can be calculated as:

$$S_3 = S_2 - \frac{kX_2HRT}{2} \tag{16}$$

The overall substrate consumption equals $S_o - S_3$, from which biogas production can be calculated as before. In practice, some of the biomass solids in the digestate are recycled back to tank 2, but this constitutes a very low flow rate, which does not affect the calculation of conversion significantly.

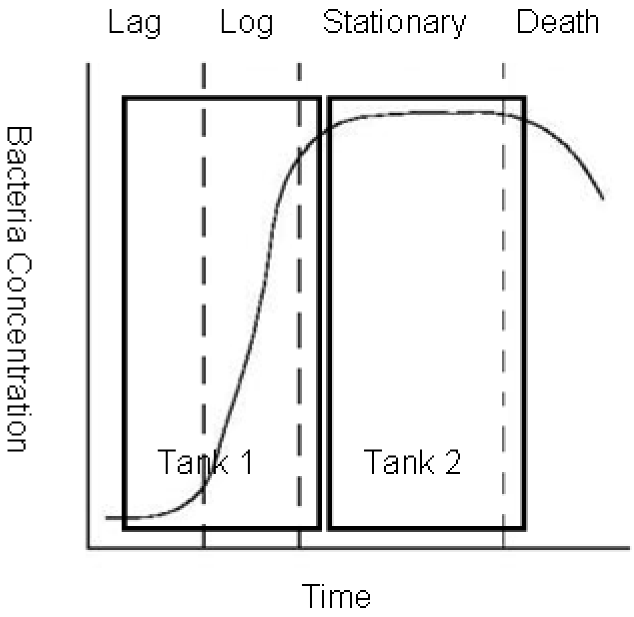


Figure 14. Bacteria growth in a MPF digester

4.3 Biogas Utilization Model

Two options are presented for biogas utilization: cogeneration for heat and power production (CHP) and upgrading to pipeline (natural gas) grade biomethane. An internal combustion engine is used in the former scenario. The overall energy produced through combustion of methane in the biogas is calculated as:

$$E_{combustion} = \dot{m}_{methane} \times \Delta h_{CH_4} \times \eta_{combustion} \tag{17}$$

where $E_{combustion}$ is the energy produced through combustion (kJ/day), $\dot{m}_{\mathrm{methane}}$ is the mass flow rate of CH_4 (kg/day) Δh_{CH_4} is the heat of combustion for CH_4 (kJ/kg) and $\eta_{\mathrm{combustion}}$ is the combustion efficiency (%). In this study, biogas is assumed to be comprised of 60% CH_4 and 40% CO_2 by volume. However, the biogas composition can be adjusted according to a typical range of values.

For the co-generation option, the heat ($E_{thermal}$) and power ($E_{electrical}$) produced are calculated as:

$$E_{thermal} = E_{combustion} \times \eta_{thermal} \tag{18}$$

$$E_{electrical} = E_{combustion} \times \eta_{electrical} \tag{19}$$

Where η_{thermal} is the efficiency of thermal energy or heat recovery (%) and $\eta_{\text{electrical}}$ is the efficiency of electrical energy conversion or power recovery (%). Typically, heat recovery may be assumed to be 50% for small AD systems, and 55-60% for centralized AD systems, whereas power recovery has typical values of 30% and 30-35%, respectively.

Heat is generated for use in the AD process in two ways. Firstly, heating is required ($\mathrm{E}_{\text{heating}}$) to bring the influent's temperature up to the operating temperature. Hence,

$$E_{heating} = Cp_{water} \times \dot{m}_{feed} \times (T_{operate} - T_{feed}) \tag{20}$$

where Cp_{water} is the specific heat capacity of water (kJ/kg$^{\text{o}}$C) (since 85-90% of the feed is water.), $\dot{m}_{\text{feed}}$ is the mass flow rate of influent (kg/day), $T_{operate}$ and T_{feed} are the operating temperature and the influent temperature, respectively ($^{\text{o}}$C). Additional heating is required to counteract losses due to conduction through the wall material and convection from the outside of the digester (E_{loss}) to the ambient environment:

$$E_{loss} = (U_{air}A_{air} + U_{soil}A_{soil})(T_{operate} - T_{ambient}) \tag{21}$$

where U_{air} and U_{soil} are the overall heat transfer coefficients for heat transfer from the digester walls to the surrounding air and soil (kW/m^{2} $^{\text{o}}$C), A_{air} and A_{soil} are the surface areas of the above-ground and underground portions of the digester (m^{2}) and $T_{ambient}$ is the ambient temperature. The net thermal energy available for other heating purposes is:

$$E_{thermal}^{net} = E_{thermal} - E_{heating} - E_{loss} \tag{22}$$

The parasitic electrical load to run the digester, pumps, mixers, compressors and control system are calculated via a utility fraction factor. In the subsequent economic analysis, it is assumed that the facility will buy back market-price electricity from the grid, and this cost is deducted from the annual cash flow of the plant.

The other option for biogas utilization is to upgrade the gas to pipeline-grade CH_4. A small portion of the biogas produced could be used to satisfy the heating requirements of the digester, $E_{thermal,,}$ which comprises of $E_{heating}$ and E_{loss}, as calculated before. The amount of methane in biogas consumed for these heating requirements, is calculated as:

$$\dot{m}_{methane}^{burned} = \frac{E_{thermal}}{\eta_{thermal}\eta_{combustion}\Delta h_{CH_4}} \tag{23}$$

However, farmers usually choose to buy natural gas from the grid to run the heating for the digester because it is less of a premium product and the H_2S will be lower, which makes it easier to pass air emission regulations and receive discharge permits.

The remaining biogas available for upgrading is sent to the CH_4 purification unit. The volume of biogas to be treated, for instance in a pressure-swing adsorption (PSA) unit may be estimated as follows:

$$v_{biogas}^{upgrade} = \frac{\dot{m}_{methane} - \dot{m}_{methane}^{burned}}{\rho_{methane} V\%_{methane}} \tag{24}$$

where ρ_{methane} is the density of CH_4 gas (kg/m^3) and $V\%_{methane}$ is the volume fraction of CH_4 in the biogas (%). As mentioned earlier, biogas is assumed to be comprised of 60% CH_4 and 40% CO_2 by volume, but the values are adjustable.

4.4 Model Calibration and Parameter Estimation

The Lawrence and McCarthy model contains four parameters, *a*, *k*, *Ks* and *b*, which need to be estimated for each different feedstock. The values of these parameters may be obtained from experimental studies. The kinetic parameters can also be calibrated from published data pertinent to operating AD plants; however, one complication of this approach is that each digester uses a different mix of feed. We selected case studies for our calibration where the feed typically consists of a mixture of manure from different animals and other on-farm wastes. Often manure feeds also contain straw and other cellulosic organics used for bedding material. In one case study, 10% by weight of fish farm waste was included in the total feed.

Walford College Farm (CADDET 1997)

Walford College Farm is a 260 hectare mixed farm owned and operated by Walford College near Shrewbury, England. There is a herd of 130 dairy cows and young dairy stock, 160 pigs and beef cattle, which together produce about 3,000 tonnes of manure annually. In 1990, the college decided to introduce an integrated farm slurry management system based on AD. In October 1994, an AD system with an engine-generator and a composting unit at a total construction cost of 133,649 UK pound was commissioned as part of a three-year demonstration project.

The Walford College Farm digester is a 335 m^3 completely-mixed digester sitting above ground. In summer, 12 m^3 of mixed slurry is fed into the digester daily at a hydraulic retention time of 16~20 days. This process yields 450 m^3 of biogas per day, which produces 18.2 kW of electricity for 19.5 hours and enough heat to maintain the digester at a temperature of 35~37℃. The liquid portion of the digestate is passed to a 950 m^3 storage tank and then spread onto the grass fields due to its high nutrient value (2.32 kg nitrogen, 1.32 kg phosphate, and 5.3 kg potash for each cubic meter). The solid portion of the digestate is made into compost for the college’s own use, and for sale to garden centers and other customers.

Linsbod Biogas Reactor in Pucking, Austria (Steffen 2005)

Linsbod Biogas Reactor is a 12-year old farm-scale plant located in Pucking, Austria. Its feedstock is a mixture of poultry manure, poultry bedding and hog manure. The mixture is homogenized to a liquid with a solid content of 10~14%, and is fed into the digester four times a day at 1.5 m^3 per time.

The reactor consists of an outer concrete cylinder 6 m in diameter and 9 m in height and an inner concrete cylinder 3 m in diameter and 11 m in height. The volume between the inner and outer cylinder has an airtight concrete roof and a volume of 270 m^3. As biogas is produced in between the inner and outer cylinder, the pressure builds up until it is strong enough to push biogas into the inner cylinder. This system operates at 35~37℃, and produces 200~300 m^3 of biogas per day with a CH_4 content of 60~65%. Due to the sand in poultry manure, this digester requires sand cleanup every few years.

Davinde Biogas Plant in Denmark (Al Seadi 2000)

Davinde biogas plant, built in 1987, is the first example of a centralized biogas plant established and operated by 11 farmers. The aim of this project is to produce and sell renewable energy from the supplied animal manures and straws supplied by farmers and sell the energy produced. The manures are from 3 pig farms and 3 cattle farms with small amounts of sludge and fish waste from 2 fish processing facilities in the area.

The plant is small scale and rather simple, which keeps operational costs low. The digester is a single 750 m^3 completely-mixed digester operating at mesophilic temperature range (36℃). It treats 28 tons of organic mixture per day (25 tons animal manure and 3 tons alternatives) and produces 0.3 million m^3 of biogas annually.

Table 12 is a summary of the inputs obtained from the three case studies. The digester size varies from 270 m^3 to 1332 m^3, which covers most of the farm-size digesters' volumes. The influent dry material (DM) weight percentage varies from 5.5% to 14%, which is a typical range for wet-digestion. In the Davinde case, the influent DM weight percentage is not given in the report; as a result, the default values within the calculator are used for calibration. The biogas yields at these facilities vary from 25-41 m^3/tonne (w/w) of manure mixture.

Table 13 is a list of some kinetic parameter values that we found through our literature review. Parameter *a* represents the yield of digestate over substrate and its value ranges from 0.04-0.17 g/g (Table 13) for mesophilic AD. The decay rate *b* ranges from 0.02-6.1 1/day, and the maximum rate of substrate utilization *k* can vary widely between 0.77-70.6 g/g.day depending on the nature of the substrate. The value of Ks is an indication of the degradability of the substrate. Simple substrates such as acetate that are rapidly consumed by bacteria have low Ks values (< 400 mg acetate/L). However, more complex substrates such as manure or grass cuttings that need to be broken down into simpler compounds will have much higher Ks values.

There is little information about the Ks values in the literature for many of the substrates that farmers use in their digesters. At an early stage of this project, the substrates "dextrose, bacto-tryptone and bacto-beef extract" which are typically used in lab-scale fermentation studies were thought to be representative of dairy manure characteristics. Later on, further literature search revealed that Barthakur et al. (1991) used the data (Morris 1976; Hashimoto 1982) pertinent to hydrolyzed substrate from the anaerobic fermentation of animal wastes and fitted the data to a one-step Monod-type model which includes a refractory coefficient. We need to synchronize their empirical *Ks* value (approximately 3000 mg/L) with the Lawrence and McCarty model, and in doing so, we determined that a *Ks* value of 6000 mg COD/L would be more representative of dairy manure as feedstock.

Hence, for calibration purposes, the four kinetic parameters were varied over their feasible ranges (Figure 15) to find the best fit to the three case studies mentioned above. Table 14 lists some examples of the parameters in combination that all successfully modeled the case studies to within 10% accuracy. The set of kinetic parameters that is selected for use in the model must include the more realistic Ks value (6000 mg COD/L) as derived and adopted for manure. The other three parameters are then: a = 0.06 g/g, b = 0.026 1/day and k = 1.4 g/g day.

Table 12. General information of selected sites for calibration

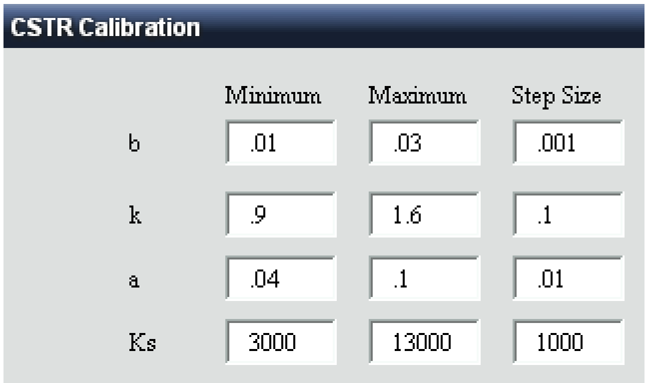
Site	Manure	Digester	HRT	Feed TS	Effluent TS	Biogas production
	m^3/day	m^3	day	% w/w	% w/w	m^3/day
Walford College Summer	12	335	20	14	8.4	450
Walford College Winter	18	335	20	9	5.5	450
Linsbod	6	270	45	12		250[1]
Davinde	33	750	27			882

[1] CH_4 content is 62.5% (v/v)

Table 13. Values of kinetic parameters

Substrate	k , gCOD/gVSS.d	Ks, mg COD/L	a, gVSS/gCOD	b, 1/day	Reference
dextrose, bacto-tryptone, bacto-beef extract	1.07	13000	0.104	0.02	Agardy et al. 1963
long chain fatty acid	0.77-6.67	105-3180	0.04-0.11	0.01-0.015	Pavlostathis and Giraldo-Gomez 1991
carbohydrates	1.33-70.6	22.5-630	0.14-0.17	6.1	
acetate	2.6-11.6	11-421	0.01-0.054	0.004-0.037	
acetate	5.5-12.3	100-207	0.04-0.042	0.01-0.019	Lawrence and McCarty 1967
acetate[1]	n/a	6.0-25.4 mg acetate/L	0.62-3.61 g cell/mol acetate	n/a	Mladenovska and Ahring 2000

[1] This set of parameters was derived from thermophilic AD studies



	Minimum	Maximum	Step Size
b	.01	.03	.001
k	.9	1.6	.1
a	.04	.1	.01
Ks	3000	13000	1000

Figure 15. Calibration range summary

Table 14. Sample calibration results obtained from the calculator

b	k	a	Ks
1/day	g/g day	g/g	mg/L
0.026	1.4	0.06	6000
0.025	1.2	0.06	7000
0.029	1.3	0.07	8000
0.028	1.3	0.07	9000
0.011	1.4	0.05	9000
0.012	1.1	0.06	10000
0.027	1.3	0.06	10000
0.011	1.1	0.06	11000
0.026	1.3	0.06	11000
0.019	1.3	0.08	12000
0.025	1.3	0.07	12000
0.014	1.3	0.06	13000
0.024	1.3	0.07	13000

4.5 Economic Analysis Method

The economic assessment of a sample AD case is done via profitability analysis, which is based on the concept of cash flows. In this study, both before-tax cash flow (BTCF) and after-tax cash flow (ATCF) are calculated. The profitability indicators include simple payback period (PP), discounted payback period (DPP), net present value (NPV) and internal rate of return (IRR).

Following the literature review as summarized earlier, the capital cost of AD system is estimated as a function of maximum power output as follows:

Completely Mixed (CSTR) AD system:

$$Capital = 26920 \times MaximumPowerOutput^{0.7388}$$

Modified plug flow (MPF/PF) AD system:

$$Capital = 7570 \times MaximumPowerOutput^{0.8722}$$

Enahoro and Gloy (2008) at the Department of Applied Economics and Management, Cornell University cited an estimated cost of $788,405 for a MPF system by FarmWare 3.1 (USEPA AgStar Program, 2006) in their report on economic analysis of AD systems for a 1000-cows case study. They also presented an estimated cost of $940,250 using a more flexible model in which the parameters were developed from a wider range of resources. For the same number of animals, our estimated cost was $735,571.

The annual operating cost includes labor, maintenance, and insurance. It is calculated as a fraction (f_{OC}) of the capital cost of the plant:

$$OC = Capital \times f_{OC} \tag{25}$$

In this study, f_{OC} is assumed to be 5%. Utility cost (for electricity purchased) to operate the digester, pumps and other equipment, and financial cost are considered as additional cost items.

Assuming a portion of the capital investment requires debt financing, annual cash outflows would then include operating and maintenance (O&M) costs, corporate taxes payable, and financial cost (loan/debt repayments). Annual production period cash flows are assumed equal, unless further capital investment is incurred in certain years.

Annual debt repayment (A) is a lumped sum including principal (P) and interest. Its calculation involves the capital recovery factor, $[i\ (1 + i)^n] / [(1 + i)^n - 1]$, where *i* is the loan interest rate, and *n* is the loan period, such that

$$A = P\ [i\ (1 + i)^n] / [(1 + i)^n - 1] \tag{26}$$

In Canada, debt interest payments and depreciation charges constitute allowable tax deductions. Depreciation is calculated using the Declining Balance Depreciation (DBD) method, applying an appropriate federal capital cost allowance (CCA) rate. Thus, knowing the taxable income (TI), the annual tax payable is calculated as:

$$Tax = Taxable\ income \times Tax\ rate \tag{27}$$

The tax rate is a combination of federal tax rate and provincial (BC) tax rate. Different deductions are allowed for small businesses versus large corporations in order to reduce the taxes payable.

The annual cash inflows would primarily be revenue, which consists of two parts, the sales of electricity (or CH_4), and the savings from heating, fertilizers and bedding materials. Biogas is not the only useful product from AD process. The solid portion of the digestate can be further processed to become compost or used as bedding materials for livestock. For composting purposes, it may be beneficial to have a slightly longer HRT (30 days) that further breaks down the solids. On the other hand, if the solids are used as bedding materials, it may be better to have a slightly shorter HRT (25 days) that soften but not necessarily break down the fibers in the influent.

The annual before-tax cash flow (BTCF) is:

$$BTCF = Revenue - Operating\ cost - Cost\ of\ purchased\ electricity \tag{28}$$

If taxable income (TI) is defined as:

$$TI = BTCF - Depreciation\ charges - Interest\ payment \tag{29}$$

Then the annual after-tax cash flow (ATCF) is:

$$ATCF = BTCF - Tax - Financial\ cost \tag{30}$$

Net present value (NPV) of the project is the sum of the present values of the annual cash flows, which are computed with the MARR (minimum acceptable rate of return) specified. In this study, MARR is assumed to be 10%.

The smallest value of N (number of years of operation) that yields a non-negative net present value is the discounted payback period (DPP), which measures the time required to recover the initial investment from the discounted production cash flows. Simple payback period (PP) is similar to DPP, except that the time value of money due to MARR is not taken into consideration.

Finally, the internal rate of return (IRR) is computed as the break-even interest rate or discount rate, i, that makes NPV of a project equal to 0, such that:

$$\Sigma\,[CF_t / (1 + i)^t] = 0 \qquad \text{for } t = 0 \text{ to } N \tag{31}$$

In general, a project is economically viable if its net present value is positive or its internal rate of return is greater than MARR.

Economic analysis was applied to the predictive case study and the results are presented in Section 6 of this report.

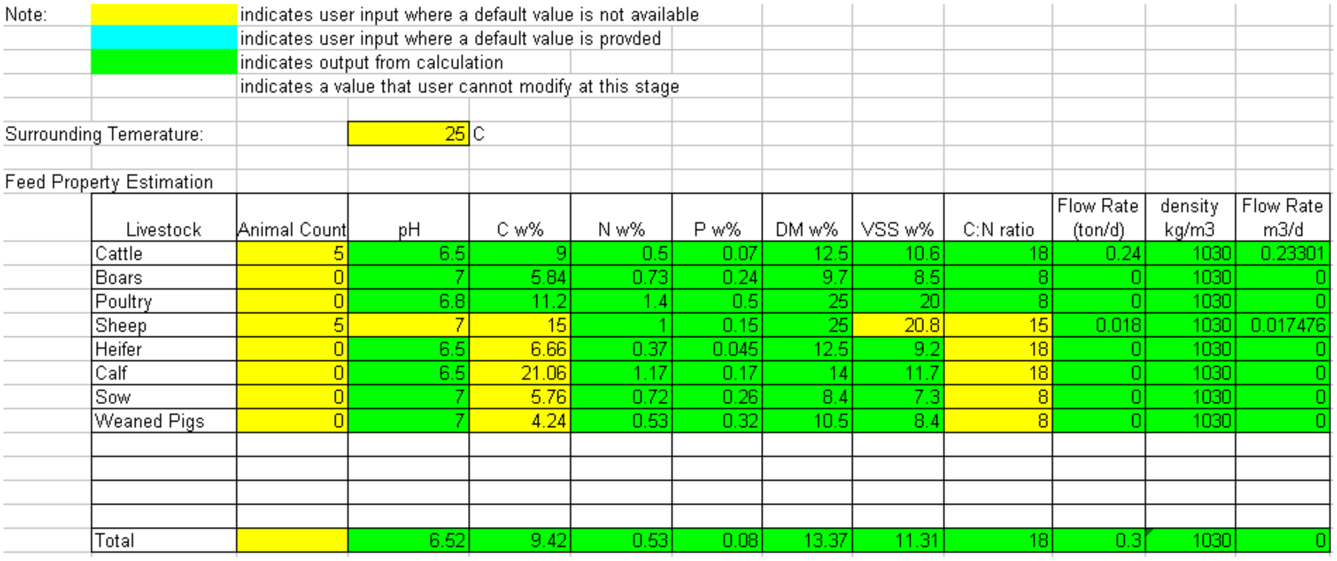
4.6 Interface Design

The calculator developed consists of three groups of files: supplementary files, Excel spreadsheets and graphical user interfaces (GUIs). As shown in Figure 17, the supplementary files are documentation files in the Help folder and in the Image folder are the GUI images used by the Visual Basic VBA program. These files can also be accessed directly as word files and image files.

Figure 16: Files included in the calculator

The MS Excel spreadsheets and the VBA code for the GUI are combined in the calculator itself as a Microsoft Excel file: CalculatorDevelope1020. The spreadsheets are used to store data and perform calculations. As shown in Figure 18, there are nine spreadsheets in total. Spreadsheet “Start” contains the macro to initiate the calculator when the MS Excel file is first accessed. As a result, users will not see the spreadsheets when the calculator is running. Spreadsheet “Feed” and “Rate” are used to store users’ inputs on feed properties and kinetic parameters. Spreadsheet “CSTR”, “PlugFlow” and “MPF” contain calculations for their corresponding type of digester. Spreadsheet “Energy Balance” contains calculations on co-generation and biogas upgrading. Spreadsheet “Econ” contains calculations for economical analysis. Finally, spreadsheet “Calibration” is used to help user select optimal kinetic parameters from their own experimental data.

Figure 17: A list of spreadsheets used in the calculator



Note:
🟨 indicates user input where a default value is not available
🟦 indicates user input where a default value is provded
🟩 indicates output from calculation
⬜ indicates a value that user cannot modify at this stage

Surrounding Temerature: 25 C

Feed Property Estimation

Livestock	Animal Count	pH	C w%	N w%	P w%	DM w%	VSS w%	C:N ratio	Flow Rate (ton/d)	density kg/m3	Flow Rate m3/d
Cattle	5	6.5	9	0.5	0.07	12.5	10.6	18	0.24	1030	0.23301
Boars	0	7	5.84	0.73	0.24	9.7	8.5	8	0	1030	0
Poultry	0	6.8	11.2	1.4	0.5	25	20	8	0	1030	0
Sheep	5	7	15	1	0.15	25	20.8	15	0.018	1030	0.017476
Heifer	0	6.5	6.66	0.37	0.045	12.5	9.2	18	0	1030	0
Calf	0	6.5	21.06	1.17	0.17	14	11.7	18	0	1030	0
Sow	0	7	5.76	0.72	0.26	8.4	7.3	8	0	1030	0
Weaned Pigs	0	7	4.24	0.53	0.32	10.5	8.4	8	0	1030	0
Total		6.52	9.42	0.53	0.08	13.37	11.31	18	0.3	1030	0

Figure 18: Colour-coding of spreadsheet cells

Figure 19 is the screenshot of part of Spreadsheet “Feed”. As indicated in the spreadsheet, yellow cells contain users’ inputs and green cells are calculated results. The part shown in Figure 19 is used specifically for inputting feed properties by supplying the head-counts of each livestock available at the farm site. Once the numbers are entered, using default manure property data, all the properties for each manure type and the final combined feed are calculated.

There are many GUIs provided used in this calculator. The general links between each interface are shown in Figure 20. The diamonds indicate a selector interface where a user must select only one of the several possible following interfaces. The rectangles indicate a standard interface where certain inputs or outputs are requested or given. The black line indicates standard design mode. The red and green lines indicate calibration mode and quick-start mode. Sometimes the red and green lines merge with the black lines. This means that the upcoming interface is shared by different modes. At the end of "Calibration" and "Results" interface, there is an option to go back to the "Mode Selection" interface to start a new simulation. A more detailed demonstration of each interface and how they are connected can be viewed in Appendix A: A Case Study Using AD Calculator.

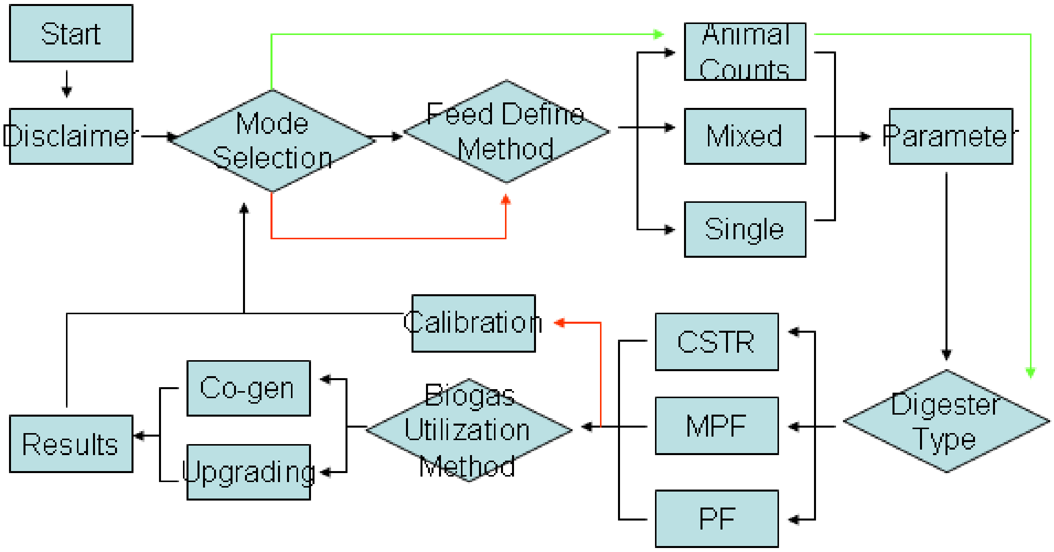


Figure 19: Interface organization diagram

4.7 Error Handling

There are two types of errors that may rise during the application of this software. The first type of error is an input error. If invalid data are input into the spreadsheet, they may cause calculation errors such as no-value (a character is used as a number in an equation) or divide-by-zero (the denominator of an equation is 0). Therefore, before users can go to the next interface, all inputs of the current interface are checked for these errors. Other error checks include those for missing input values, input format check and input value check. The *missing input error check* will, for example, interrupt the program and give a warning if a user forgot to input the amount of animals on the farm site. The *input format check* detects any inputs that are not in the correct format. For example, this check will interrupt the program and give a warning if a user enters a word instead of a number for the desired digester HRT. The *input value check* is only available for some inputs. For example, if a user enters a combustion efficiency over 100%, this check will provide a warning. On the other hand, if a user enters the wrong ambient temperature, 250^{o}C instead of 25^{o}C, there is no built-in checking to detect this error, since this type of error is very unlikely to cause serious calculation errors that may crash the program. However, in all of the GUIs, "default" buttons are available to help users restore all inputs to their default values.

The second type of error is fatal error that causes the program or Excel to crash. Some unforeseen events may lead to this type of error, but it is not clear how to prevent these events from occurring. Several mechanisms are adapted for this project to improve the stability of the software. The first mechanism is to hide the spreadsheet while interfaces are running. Therefore, users cannot modify the same cell in two different ways, which may lead to inconsistency. The second mechanism is to only allow users to turn off the program at certain GUI. This prevents data from a previous case study over-writing the current case. Finally, if all these fail and a fatal error does occur, the program will terminate its current application without saving any of the user inputs.

5. Verification of the Calculator

In order to test the stability, performance and accuracy of the calculator software, several case studies were conducted. Each case involves an operating digester for which sufficient information has been published in the literature. The calculator predicts the performance of the digester by inputting feed information for each case. These results are compared with the reported biogas production rate and digester volume. A more detailed guide of how to use the calculator to run a simulation can be viewed in Appendix B: Demonstration Case Study Using AD Calculator.

5.1 Baldwin Dairy

Baldwin Dairy is located in Baldwin, Kansas. It has a herd size of 1,050 cows, which produces about 113 m3 of manure and wastewater at about 8% total solids content. Initially, this site did not have an engine; it only used some biogas to heat the process and flares the remaining biogas. In 2008, this farm reached an agreement to supply biogas to a nearby farm and a greenhouse complex for heating through pipeline. The AD system is a MPF digester designed by a local company in Wisconsin, Bob Komro. The designed operating temperature is between 35-37^{o}C and the designed HRT is about 21 days (Kramer and Krom 2008a).

Table 15: Baldwin Dairy case study – key inputs and outputs

	Digester type	Temperature, ^{o}C	# cows	HRT, d	Total solids, %	Biogas, m^{3}/day
Reported	MPF	35-37	1050	21	8	3681
Predicted	MPF	35	1050	21	8	3063

The information obtained for this case study and the calculator’s predicted results are shown in Table 15. Since most of the required inputs (number of cows, HRT, influent TS%) are reported, it is relatively easy to run the simulation. The final biogas production rate is in good agreement with the reported value. However, since this site does not have a co-generation engine set, heat and electricity production rates cannot be compared.

5.2 Bell Farm

This case is for swine manure. It is included in the study as a demonstration when default values need to be assumed for some key input parameters. Bell Farms has 5000 sows and is located in Thayer, Iowa. The digester developed by RCM Digesters/RCM International Inc. started to produce biogas in 1999. During the first six months of operation, the total biogas produced was 64250 m^3 and the system was virtually trouble free. Its 80 kW co-generation engine operated 77% of the time, and annually produced about $46,600 worth of electricity at $0.09 per kWh (Moser 2003). The calculator kinetic parameters were calibrated for the mesophilic temperature range (~35^{o}C). The reported operating temperature for the Bell Farm digester is within the mesophilic range also and so we assumed that this still applies.

Table 16: Bell Farms case study – key inputs and outputs

	Digester type	Temperature, ^{o}C	# sows	HRT, d	Total solids, %	Biogas, m^3/day
Reported	CSTR	37	5000	n/a	n/a	357
Predicted	CSTR	35	5000	26	8	302-654

The HRT used for simulation is a common and default value for CSTR, and the total solids content is the default value for sow manure. As shown in Table 16, the reported biogas production rate falls within the range of predicted biogas production rates. This range of values corresponds to the wider range of biogas yields for pig manure in the literature versus that of cattle manure (Table 3), despite the fact that the kinetic constants (including yield) used in the simulation were derived from the latter.

5.3 Deere Ridge Dairy

Deere Ridge Dairy with a herd size of 850 is located in Nelsonville Ohio. The average total solids content of the collected manure is about 8~9%. This site uses a 140 kW Caterpillar net engine generator to produce electricity, which is sold to Alliant Energy. The captured heat from the engine is used for heating the digester, milk parlor and facility water. The AD system is a U-shaped, concrete MPF digester designed by GHD, Inc. The design temperature is within mesophilic range, and the design HRT is 22 days. Passive mixing is done by recirculation of biogas at the bottom of the digester (Kramer and Krom 2008a).

Table 17: Deere Ridge Dairy case study – key inputs and outputs

	Digester type	Temperature, ^{o}C	# cows	HRT, d	Total solids, %	Electricity, kW
Reported	MPF	Mesophilic	850	22	8-9	<140
Predicted	MPF	35	850	22	8.5	<172

The information obtained for this case and the calculator’s predicted results are shown in Table 17. In this case, the estimated electricity production rate is ~20% higher than the actual amount. This is mostly because the biogas yield used in the simulation is the default value, which is calibrated for a mixed feed with less than 20% of off-farm organic wastes and over 80% of animal manure.

5.4 Stencil Farm

Stencil Farm is located in Denmark. It has a herd size of around 1300, but only between 700 and 1000 heads regularly send manure to the digester. As a result, the volume and the total solids content vary depending on which barn the manure came from. The AD system at Stencil Farm is a below grade, concrete, straight plug-flow system designed by RCM Digesters, Inc. This system operates at around 37 ^{o}C with a designed total solid of 9 to 12 percent. (Kramer and Krom 2008b)

Table 18: Stencil Farm case study – key inputs and outputs

	Digester type	Temperature, ^{o}C	# cows	HRT, d	Total solids, %	Electricity, kW
Reported	PF	37	700-1000	n/a	9-12	<123
Predicted	PF	37	850	25	10.5	<117

The information obtained for this site and the calculator's predicted results are shown in Table 18. For the simulation, both the herd size and the total solids content values were assumed to be the average values of the site's records. The HRT was unknown, hence the typical value of 25 days was used. The site's reported and the calculator's estimated values of electricity production rate are in good agreement.

5.5 Five Star Dairy

Five Star Dairy is located in Elk Mound, Wisconsin with a herd size of 850. According to an agreement between the dairy operation and Microgy, Inc., Microgy would install the digester in 2000 with no cash outlay from the dairy owner, and the owner would pay off the debt through biogas sales to Dairyland Power, which provides the generator. This Microgy AD system is an above-ground, carbon-steel CSTR digester. It has a design HRT of 20 d, and operates at 52 ^{o}C. In addition to the dairy wastes on site, this system also treats off-farm food wastes at approximately 10% of the total feed (Environmental Law & Policy Center 2009).

Table 19: Five Star Dairy case study - key inputs and outputs

	Digester type	Temperature, ^{o}C	# cows	HRT, d	Total solids, %	Electricity, kW
Reported	CSTR	Thermophilic	850	20.	n/a	<775
Predicted	CSTR	35	850	28	10	<133

The information obtained for this site and the calculator's results are shown in Table 19. The digester on this site is operating at thermophilic temperature range. Since the calculator kinetic constants are only for mesophilic temperatures, we ran the model with a longer residence time corresponding to almost 80% conversion. This was done assuming that a similar conversion occurs in the thermophilic digester. The solids content is not given in the report, hence 10% is assumed because it is close to the default manure total solids (~12.5%) and the possibility of dilution due to wet manure collection. Nevertheless, the difference of electricity production between the reported and estimated values is large. However, in the previous two cases (Deere Ridge Dairy and Stencil Farm), wastes from 850 cattle only require 140 kW and 123 kW engine respectively, which are reasonably close to the predicted 133 kW. Therefore we do not believe that the larger power output is due to thermophilic conditions, rather, from our literature review, it was noticed that AD processes from Microgy Inc. include oversized engines. Therefore, it is possible that the biogas production from this site requires a 775 kW engine with future expansion taken into consideration.

5.6 Four dairy farms in Vermont, USA

Demonstration case studies were then extended to four dairy farms in Vermont that have installed GHD Inc.'s modified plug flow AD systems in 2006/2007. Since actual manure characteristics were unknown, default values were used for all kinetic parameters and feed characteristics. Hydraulic retention time (HRT) was assumed to be 22 days for MPF reactor, operating at 35^{o}C. Manure generation rate was assumed to be 0.055 m^3/cow.day (per ASAE Standards, 2008) with total solids (TS) or dry matter content of 12.5%, to be diluted to 10%. Moreover, addition of off-farm wastes was not considered. Comparison was made between calculated results and data reported by Tucker (2008) in terms of power production, as shown in Table 20. The predicted and actual power productions differ by 7-33%.

Table 20. Four Vermont Dairy Farms case study – predicted versus reported power production

	#cows	Predicted CH_4 generation t/d	Reported power production x 10^6 kWh/yr	Predicted power production x 10^6 kWh/yr
Blue Spruce Farm	950	0.9	1.30	1.94
Pleasant Valley Farm	1500	1.5	3.20	2.62
Green Mountain Farm	1100	1.1	1.80	1.93
Montagne Farm	680	0.7	1.40	1.19

6. Predictive Case Study

A fictitious 450-cows dairy farm located in the Fraser Valley was used for performing overall technical and economic feasibility analyses, so as to assess project viability. Fresh cow manure is considered an ideal feedstock for AD since it has a balanced carbon-to-nitrogen ratio, a good buffering capacity and is rich in anaerobic bacteria (Electrigaz Inc., 2007 and 2008). Calculations were performed for CSTR and MPF, with different HRTs. In scenario #1, off-farm food waste is not included in the influent (feedstock) to the digester. Then, simulation is extended to scenario #2, with food waste added to the feedstock, resulting in a mixture of 80% dairy manure and 20% food waste. In the simulation, the 20% food waste is further broken down into 15% non-greasy food waste and 5% fats oil and grease (FOG). Inputs and assumptions used in the calculator are summarized as follows:

- Without food waste, manure/slurry generation is 25 m^3/d (or, equivalent to 0.055 m^3/cow.d); TS 12.5% w.b. The manure will be diluted from TS 12.5% to TS 10.0% (w.b.) to obtain the following digester influent characteristics:

pH	N, % d.b.	P, % d.b.	TS, % w.b.	VS, % d.b.	Feed rate, tonne/d
6.5	4.0	0.6	10.00	84.8	25

- Digester operating temperature: 35°C (mesophilic)
- Average annual ambient temperature: 13.8°C
- Digester configuration: Diameter-to-length ratio is 1.5:5.0
- With food waste, the mixture has an original volume of 31 m^3/d or tonnes/d, and again diluted to TS 10%, resulting in an influent feed rate of 39 tonnes/d.

For co-generation

- Heat recovery efficiency: 50%
- Power or electricity recovery efficiency: 40%
- Combustion or engine efficiency: 90%
- Utility fraction: 5%

For biogas upgrading to utility grade CH_4

- Heat recovery efficiency: 70%

Predicted AD system performance results are summarized in Tables 21 and 22 for the two scenarios: dairy manure with food waste and dairy manure without food waste, respectively.

The computed results indicate that, among all configurations involved in the simulations (CSTR with HRT of 25, 28 and 30 days; MPF with HRT of 20, 22 and 25 days), a MPF system with HRT of 25 days has the best system performance. With mixed waste (80% dairy manure and 20% food waste), the CH_4 production rate is 0.91 tonnes/day, leading to power production of 212 kW, which is equivalent to 0.47 kW/cow. The corresponding biogas yield is 58 m^3/tonne feed (wet basis). Percent volatile solids reduction is also the highest, at 80%. When compared to the digestion of dairy manure alone, expected biogas yield would be doubled, whereas power production would be greater by 2.5 times.

Table 21. Computed AD system performance for the 450 cows predictive case study (mixed waste – 80% dairy manure and 20% food waste)

	CSTR			MPF		
	HRT 25 d	HRT 28 d	HRT 30 d	HRT 20 d	HRT 22 d	HRT 25 d
Digester volume, m^3 (with 30% over-design factor)	1261	1412	1513	1009	1110	1261
Biogas production						
CH4 production, tonne/d	0.39	0.71	0.80	0.64	0.74	0.91
CO_2 production, tonne/d	0.71	1.30	1.46	1.17	1.36	1.68
Biogas yield, m^3/tonne feed	24.4	44.9	50.3	40.3	46.8	57.8
Co-generation						
Heat production, 10^6 kWh/y	0.658	1.459	1.665	1.310	1.558	1.981
Power production, 10^6 kWh/y	0.774	1.424	1.595	1.279	1.485	1.833
kW	89.6	164.8	184.6	148.1	171.8	212.1
kW/cow	0.199	0.366	0.410	0.329	0.382	0.471
Power purchased, 10^6 kWh/y	0.029	0.053	0.060	0.048	0.056	0.069
Biogas upgrading						
Purified CH4, m^3/d	415	886	1007	798	943	1192
Power purchased, 10^6 kWh/y	0.096	0.197	0.223	0.177	0.209	0.262
Effluent						
TS, % w.b.	7.38	5.04	4.40	5.61	4.85	3.52
VS, % d.b.	77.7	66.6	61.5	70.1	65.1	51.4
VS reduction, %	33.7	62.1	69.7	55.9	64.9	80.1

Table 22. Computed AD system performance for the 450 cows predictive case study (100% dairy manure)

	CSTR			MPF		
	HRT 25 d	HRT 28 d	HRT 30 d	HRT 20 d	HRT 22 d	HRT 25 d
Digester volume, m^3 (with 30% over-design factor)	813	910	975	650	715	813
Biogas production						
CH_4 production, tonne/d	0.07	0.23	0.28	0.26	0.30	0.37
CO_2 production, tonne/d	0.14	0.43	0.51	0.48	0.55	0.68
Biogas yield, m^3/tonne feed	7.30	22.9	23.0	25.4	29.5	36.4
Co-generation						
Heat production, 10^6 kWh/y	< 0	0.363	0.462	0.450	0.548	0.716
Power production, 10^6 kWh/y	0.149	0.469	0.553	0.519	0.603	0.744
kW	17.3	54.2	64.0	60.1	69.8	86.1
kW/cow	0.04	0.120	0.142	0.134	0.155	0.191
Power purchased, 10^6 kWh/y	0.006	0.018	0.021	0.020	0.023	0.028
Biogas upgrading						
Purified CH4, m^3/d	2.48	232	290	283	340	439
Power purchased, 10^6 kWh/y	0.006	0.055	0.068	0.065	0.078	0.099
Effluent						
TS, % w.b.	8.73	5.93	5.17	5.51	4.75	3.43
VS, % d.b.	76.9	65.3	60.0	62.6	56.4	39.1
VS reduction, %	16.8	52.9	62.4	58.6	68.1	84.1

By comparison, Electrigaz Technologies Inc. (2007) presented a case study regarding biogas energy potential in their report. The fictitious feedstock comprises 30 t/d cow slurry (7% TS) and 20% by weight or 6.3 t/d fats oil and grease (FOG, 15% TS). Assuming biogas yield of 15.7 m^3/tonne and 347.8 m^3/tonne for manure and FOG respectively, the overall biogas yield was estimated to be 58.7 m^3/tonne feed. The estimated power production was 293 kW, assuming power recovery efficiency of 40%. Their estimates follow the coefficient-based calculations, without consideration of kinetics, but possibly include a correction factor for non-complete conversion of VS (biodegradable organic matter) to biogas. In a follow-up report (Electrigaz Technologies Inc. 2008), the feedstock comprises 88 t/d cow slurry (10% TS) and 24% by weight of food waste (11 tonnes/d, 23% TS) and FOG (10 tonnes/d, 36% TS). Assuming biogas yields of 22.4, 71.7 and 361 m^3/tonne for manure, food waste and FOG respectively, the overall biogas yield was again estimated to be 58.2 m^3/tonne feed. This amount of biogas is equivalent to 250 m^3/h, which could power a 500 kW co-generation plant, and it is also deemed to be the minimum biogas production rate to justify a biogas upgrading plant. It shall be noted that the estimated results are dependant on the various key assumptions, including biogas yield and power recovery efficiency. It is also worth to note that both Electrigaz examples are based on complete mix systems and much of the source data would be from private companies like Schmack and PlanET.

One important parameter that will affect system performance is the electricity recovery efficiency. If it should be 35% rather than the 40% assumed, calculations show that the power generation would be reduced by approximately 10%. Also, statistics from a recent survey (Rogstrand, 2009) on dairy manure with samples from some 50 farms in the Lower Fraser Valley indicated that on average, the manure has TS 6.6% (wet basis) with a pH of 8.0; also, N and P contents are 0.25% and 0.048% (wet basis) respectively. These are equivalent to 3.7% and 0.73% (dry basis) respectively, which are close to the afore-mentioned assumptions in our analysis. Upon inputting these alternative values to the calculator, the power produced was found to vary from 0.04-0.09 kW/cow for a MPF system, and 0.12-0.20 kW/cow for a CSTR system. When compared to 10% TS for manure and 40% electricity recovery efficiency, the decrease in estimated power production is more significant for CSTR.

In order to properly use the calculator developed through this project, it is important to understand the impacts of HRT (a user input) on biogas production and the biogas plant's economic analysis. As shown in the substrate concentration calculation (Eqn. 11) through the Lawrence and McCarty model:

$$S = \frac{Ks(1 + bHRT)}{HRT(ak - b) - 1}$$

HRT has direct effects on the biogas production rate and the effluent's substrate concentration. For the calibrated parameters,

$$S = 6000 \times \frac{0.026HRT + 1}{0.058HRT - 1}$$

As HRT increases, the effluent's substrate concentration decreases, which stabilizes after 35-40 days. This suggests that a longer HRT will have the highest biogas yield per ton of organic wastes. However, as the biogas yield increases, the co-generation engine size also needs to increase, thus leading to a higher capital cost. Hence, HRT needs to be optimized for economic feasibility; the choice of HRT has to be a value that produces reasonable amount of biogas but does not lead to a very high capital cost. Through literature review for MPF/PF and CSTR digesters, a reasonable HRT is between 25 and 30 days for treating feedstock that is primarily livestock manure. In the case of feedstock primarily made up of food waste and other organic municipal wastes, a reasonable HRT is between 10 and 15 days.

Economic analyses were then conducted using the regression equations established for capital cost estimate in Section 4.5 of this report. Results are summarized in Table 23.

The major assumptions used in the economic analysis include the following:

- Project life (period of analysis): 10 years *
- 70:30 equity/debt financing structure
- Loan compound interest rate: 6% per annum
- Minimum acceptable rate of return MARR: 10%
- Electricity purchased at 5 cents/kWh and sold at 9 cents/kWh
- Sales revenue is only due to power generated
- No revenue from gate fees nor expenses related to the treatment of off-farm wastes
- No revenue from carbon credits or government grants/incentives
- Revenue due to biogas upgrading, processing of digestate to compost, and fiber recovery are not considered in this example
- Tax rate: 13.5% (federal and provincial rates for small business)
- No investment tax credits from SR&ED activities
- Capital cost allowance (CCA rate, Class 43.1 Income Tax Act) for depreciable assets: 30% (for high efficiency AD co-generation systems, this rate is increased to 50% after the first year

* Typical digester life 20+ years, generator 5-10 years, but the period of analysis is chosen to match the longest possible life of the generator. This is in line with the method used by Enahoro and Gloy (2008) in their study.

All of the above parameters are in the form of user inputs to the calculator and they are adjustable.

Table 23. Results of economic analyses for the 450 cows predictive case study (mixed waste – 80% dairy manure and 20% food waste)

	CSTR		MPF	
	HRT 28 d	HRT 30 d	HRT 20 d	HRT 25 d
Co-generation				
Power production, 10^6 kWh/y	1.424	1.595	1.279	1.833
kW	164.8	184.6	148.1	212.1
Revenue				
Electricity sale, $/yr	128,160	143,550	115,110	164,970
Costs				
Capital cost, $	1,169,270	1,271,507	591,908	809,664
$/kW	7,095	6,888	3,997	3,817
Operating cost, $/yr	63,141	68,661	31,963	43,722
Utility cost, $/yr	2,650	3,000	2,400	3,450
Cash flows				
Before-tax cash flow BTCF, $/yr	60,779	70,089	79,307	115,728
After-tax cash flow ATCF, $/yr*	13,120	18,262	55,181	87,726
Profitability indicators				
Based on BTCF				
Net present value NPV, $	-420,682	-432,918	85,295	161,192
Internal rate of return IRR, %	3	2	14	16
Simple payback period PP, yr	~ 20	~ 20	5.5	5
Based on ATCF				
Net present value NPV, $	-729,172	-769,986	-92,145	-81,996
Internal rate of return IRR, %	--	--	4.5	6.5
Simple payback period PP, yr	--	--	8.5	7.5

* ATCF values vary from year to year. However, its values are constant during the earlier years when tax payable is zero

Results derived from the economic analysis of the 450-cows predictive case study for mixed waste (80% dairy manure and 20% food waste) suggest that MPF systems are less expensive than CSTR systems. The capital cost of a CSTR system is around $7,000/kW whereas that for a MPF system is around $4,000/kW. These values fall within the reported range of capital costs of a biogas electricity generating plant (Navaratnasamy et al. 2008). For co-generation, if the selling price of the electricity is at 9 cents per kWh, none of the configurations investigated are economically feasible based on after-tax cash flows, since for all cases, net present values are negative. However, if economic feasibility is based on before-tax cash flow, then the net present values associated with MPF systems having HRT of 20-25 days are positive, and hence the internal rates of return are greater than MARR of 10%. Under these circumstances, simple payback period of 5-6 years is achievable. If the selling price of the electricity can be increased to 14 cents per kWh, a CSTR digester with 30 days HRT would have a positive net present value and a simple payback period of 6 years, based on before-tax cash flow, but its net present value is still negative based on after-tax cash flow. A MPF digester is projected to perform even better economically, with internal rates of return around 15%, based on before-tax cash flow.

A comparison was made with results generated by applying the correlations (Eqns. 4 and 5) developed by USEPA AgStar Program (2009). In their estimate, the capital cost of a MPF system is greater than a CSTR system by 50%. For a selling price of 9 cents per kWh power produced, and on the basis of before-tax cash flow, a MPF system with HRT of 25 days has a positive NPV (which coincides with an IRR of 12% and a simple payback period of 6 years); however, its profitability is less than a CSTR system with HRT = 28-30 days. In general, these results are in opposite trend to the economic analysis results derived from our correlations (Eqns.6 and 7), with respect to CSTR versus MPF systems. Despite the opposite predictions, both sets of correlations have identified the case of a MPF system with HRT = 25 days to have the best techno-economic performance. Again, after-tax cash flows do not favor the installation of AD systems under the assumptions made in the economic analysis.

7. Conclusions

AD is one solution to waste management in the Lower Fraser Valley and other parts of BC. It will help to reduce GHG emissions while at the same time providing an alternative source of energy. Based on the availability of wastes in the Valley, potentially 30 MW of energy can be generated with the added benefits of reduced odour, GHG emissions and soil and water contamination from artificial fertilizers. Therefore, there is the incentive to educate local farm owners about AD technologies and to enable them to estimate the benefits of adopting AD on their farms. Thus, the objective of this project was to produce a "user-friendly" calculator that can be used by farmers to determine the costs and benefits associated with AD.

The calculator is based on a kinetic model; the Lawrence and McCarty model (Kumar et al 2007). Default parameters for manure as feedstock are included in the software; however, users can input custom parameters for other types of feedstock. The user can input different feed types and select from the most common bioreactor configurations. Model output provides estimations of biogas production rate, the energy produced and the capital cost of adopting AD technology. In order to produce a calculator compatible with both PC and Apple Macintosh computers and to have an accessible algorithm, this software is constructed on Microsoft Excel spreadsheets with simple user interfaces coded via VBA. Therefore, this software is more flexible and adaptable than most existing AD calculators that we could access freely.

Although some laboratory experimental work has been done on AD of various types of feedstock, we found few reported values for the Lawrence and McCarthy Model parameters for farm-site feedstocks. At present, the kinetic parameter values of the calculator are suitable for manure alone or mixture of manure (80% w/w) and food waste (20% w/w) as feedstock. The kinetic parameters have been calibrated with operating data for several AD plants processing manure alone. Therefore, results provided by this calculator should be considered as the average values that best represent the performance and capital cost of biogas plants specified by users during the simulation. The intent of this software is to show users how beneficial and how much it would cost to adapt AD technology with fairly accurate and realistic values, which means that in some cases, it will not be feasible or beneficial to apply AD technology. This software would provide useful information for the preliminary design of an AD system though it must be fine-tuned if it is to be used in the final design stage of a project.

In addition to being a simple-to-use tool for most farmers, the calculator can be used by more sophisticated users. The algorithms, parameters (with their default values) and logics of all the calculation involved can be viewed and modified on the spreadsheet. This was designed for people with the knowledge of more accurate and site-specific data or a specific idea of a new digester configuration. Either they can modify some parameter values via the GUI or directly in the appropriate cells in the spreadsheet to improve the performance of the calculator. So far, to our knowledge, there has been no kinetic-based AD technology simulation program that allows users to view all the details and calculations behind the user interfaces.

Through this project, a MPF system with HRT of 25 days has the best system performance. With mixed waste (80% dairy manure and 20% food waste), the CH_4 production rate is 0.62 ton/day, leading to power production of 108 kW, which is equivalent to 0.24 kW/cow. The corresponding biogas yield is 39 m^3/tonne feed (wet basis). Percent volatile solids reduction is also the highest, at 80%, among all configurations simulated. Economic analysis results indicated that for co-generation purposes, if selling price of the electricity is at 9 cents per kWh, and economic feasibility is based on before-tax cash flow, then the net present values associated with MPF systems having HRT of 20 to 25 days are positive, and the internal rates of return are greater than a 10% minimum acceptable rate of return. Therefore, MPF digester was found to be the most suitable and profitable AD system for on-farm digestion of animal wastes.

It should be noted from the simulations performed that the capital cost of a typical farm-size biogas plant is still a burden to most farm owners. Support and incentives from government departments, such as grants, permits or co-ownership with energy companies, are extremely important to encourage farm owners to upgrade their current manure management systems to a more eco-friendly technology.

8. Recommendations for Future Work

Since experimental work was not part of this project, all the data used for calibration and testing were obtained from reports, articles and websites gathered during literature review. There is a paucity of experimental data for many feed types. In the future, if feeds other than manure alone or manure with 20% food waste are to be considered, then new kinetic parameters can either be input into the model or calibrated using that feature of the model, if data are available. Experimental data or data from more representative facilities in BC or elsewhere are needed for feedstocks such as food waste, yard waste and non-manure agricultural wastes, to allow for calibration of a more accurate calculator applicable to model mixed feedstocks.

Depending on the recalcitrance of the organic feed material, the hydrolytic, acidogenic, acetogenic or methanogenic step may be rate controlling. If feeds that contain mostly difficult to degrade cellulosic substances are digested, then the first-order hydrolysis process will be the slowest step. When organics consisting of more soluble carbon compounds such as food waste are digested, methanogenesis will be rate controlling. Therefore, the overall model may have to include different kinetic models.

Although reasonable system performance results were obtained from the calculator, further fine-tuning of the simulation model is required to arrive at more accurate results. Capital cost data reported in the literature are quite uncertain and this requires coordinated efforts to establish a reliable database for further work on economic analysis.

The economic analysis should be extended to estimate the profitability of biogas utilization via a biogas upgrading system. The relevant module in the calculator has been configured to take in key parameters such as capital and operating costs once the data and information are available.

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APPENDICES

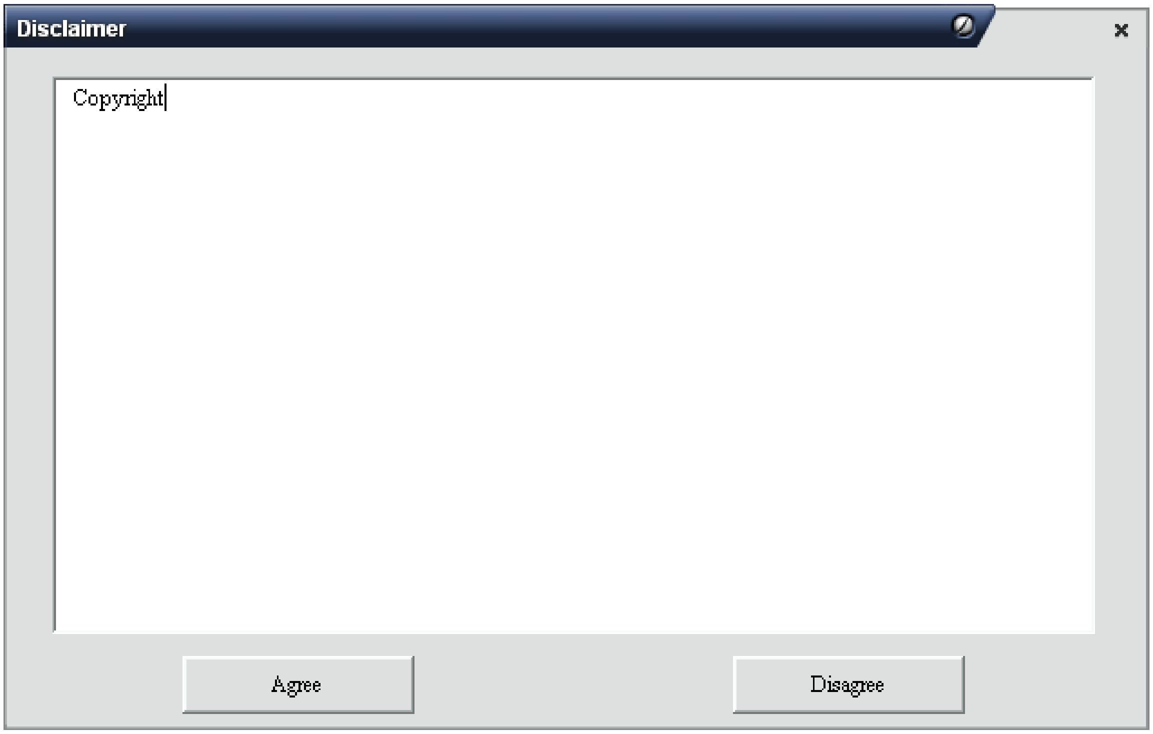
Appendix A

Case Study using the AD Calculator

This case study is done for the Baldwin Dairy case shown in 6.0 Case Studies. The given information are: 1,050 cattle, 8% total solid in feed, 35-37 ^{o}C operating temperature, MPF digester, 21 days HRT and the biogas production rate of 3,681 m^3/day.

The first interface is shown in Figure A1. Users can choose “Start” to continue or “Quit” to terminate the current application. Figure A2 is the following interface, which is a disclaimer. Although the information has not been filled yet, users must select agree to continue.

Figure A1: Welcome interface



Copyright

Figure A2: Disclaimer interface

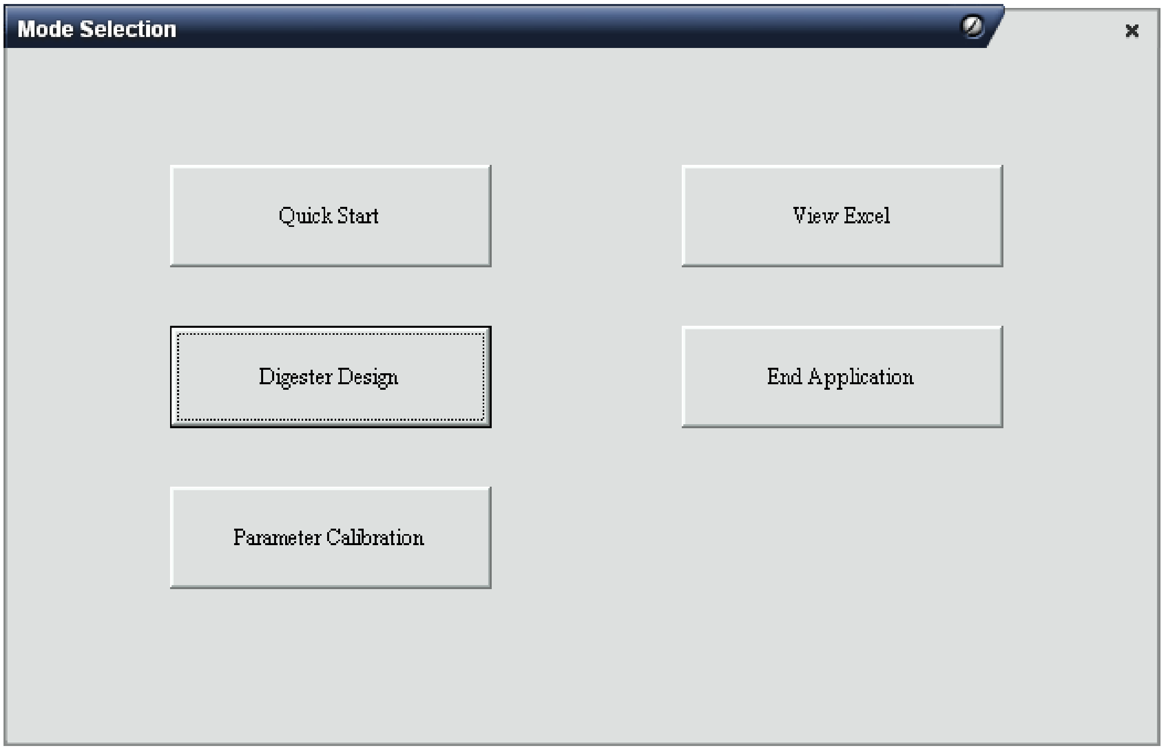
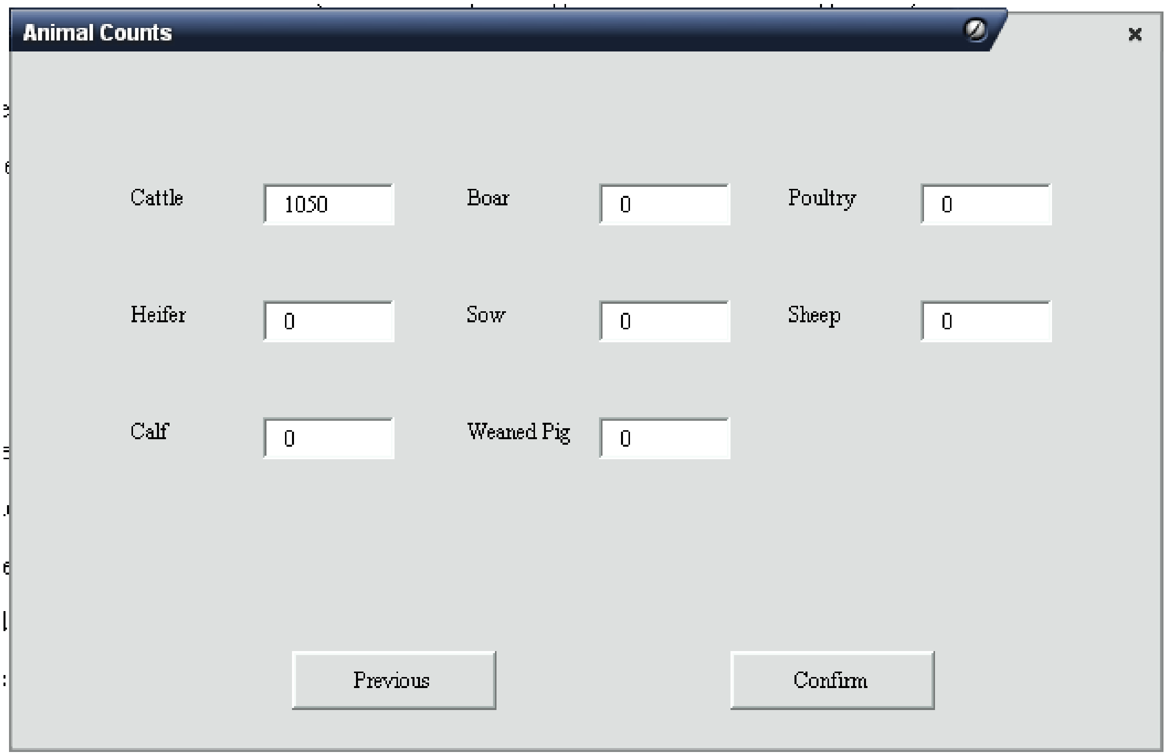


Figure A3: Mode interface

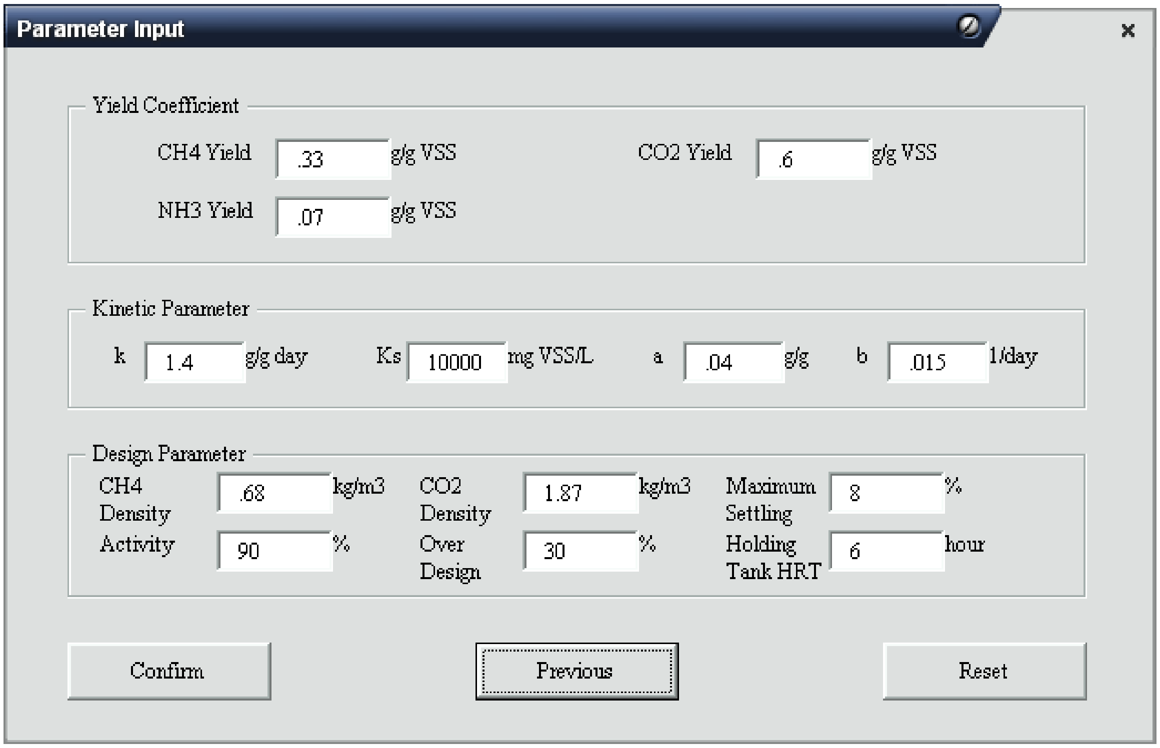
Figure A3 is the mode selector (interface sequencing can be viewed in Figure 11). In this case study, since the only feed information we know is the herd size, we can select “Digester Design” then select “Input via Animal Count” or just select “Quick Start” here. Either way will bring us to the interface show in Figure A4.



Cattle 1050
Boar 0
Poultry 0
Heifer 0
Sow 0
Sheep 0
Calf 0
Weaned Pig 0

Figure A4: Input via Animal Count

After entering 1,050 cattle, press confirm to continue or press previous to go back to the previous interface. Figure A5, thenext interface, is parameter input. Users can modify any of the parameters used for this simulation, and they can also press “Reset” to restore the parameters to their default value. In this case, since we are not given any information on the parameters, we will use the default parameters and press “Confirm” to continue.



Yield Coefficient

CH4 Yield .33 g/g VSS

CO2 Yield .6 g/g VSS

NH3 Yield .07 g/g VSS

Kinetic Parameter

k 1.4 g/g day

Ks 10000 mg VSS/L

a .04 g/g

b .015 1/day

Design Parameter

CH4 Density .68 kg/m3

CO2 Density 1.87 kg/m3

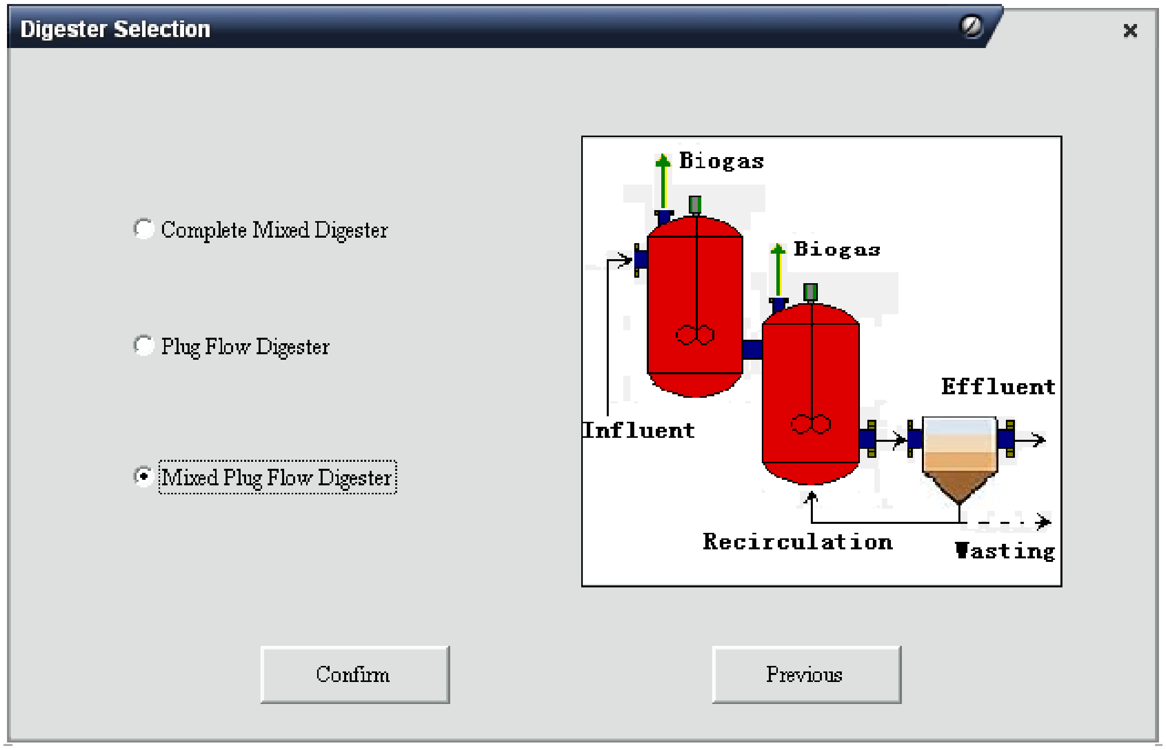
Maximum Settling 8 %

Activity 90 %

Over Design 30 %

Holding Tank HRT 6 hour

Figure A5: Parameter input



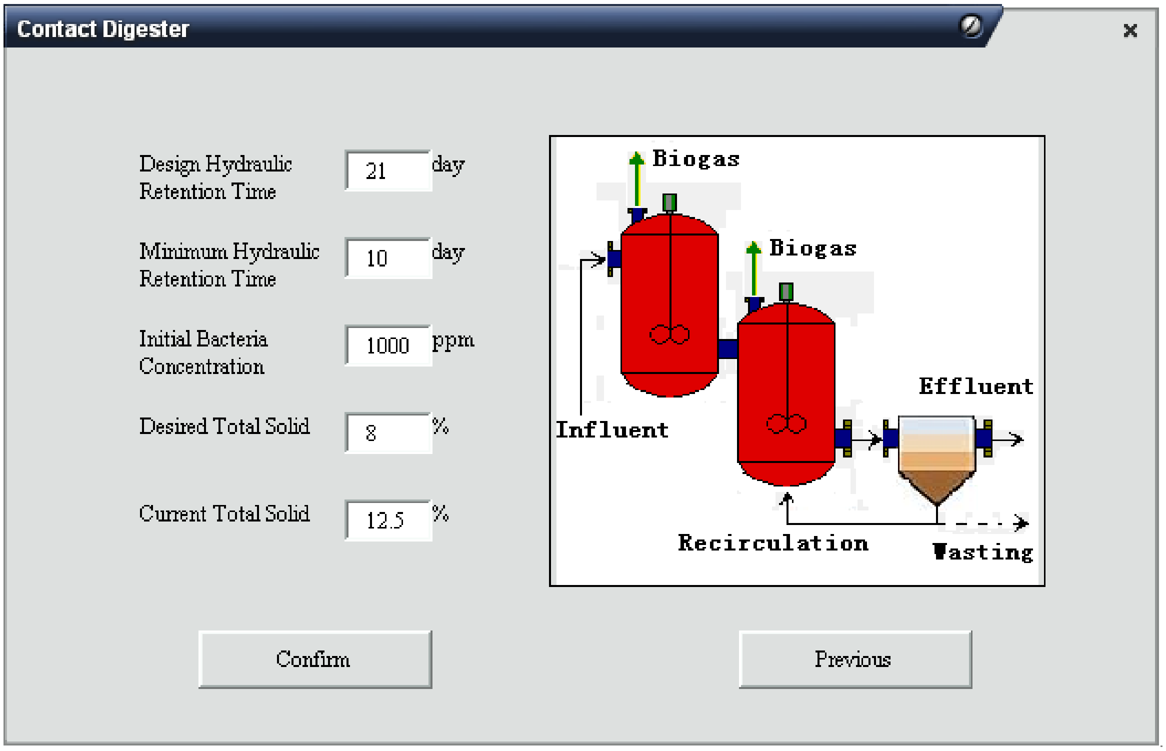
○ Complete Mixed Digester

○ Plug Flow Digester

● Mixed Plug Flow Digester

Figure A6: Digester selection

Figure A6 is the digester selection interface. In this case, we select “Mixed Plug Flow Digester” then press “Confirm” to continue. The interface shown in Figure A7 is the design interface for mixed plug flow digester. In here, users can modify the designed HRT, initial bacteria concentration and desired total solid. In this case, we will modify the design HRT to 21 days and desired total solid to 8% according to the information given, then press “Confirm” to continue.



Design Hydraulic Retention Time 21 day

Minimum Hydraulic Retention Time 10 day

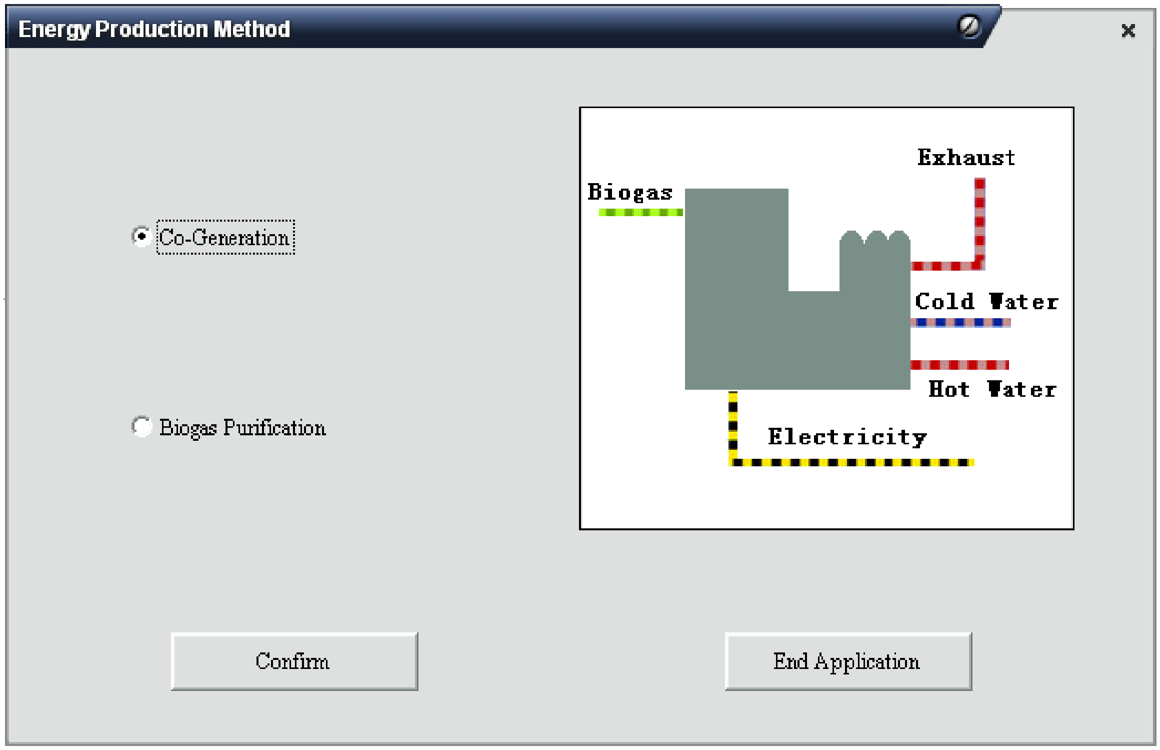
Initial Bacteria Concentration 1000 ppm

Desired Total Solid 8 %

Current Total Solid 12.5 %

Figure A7: MPF interface

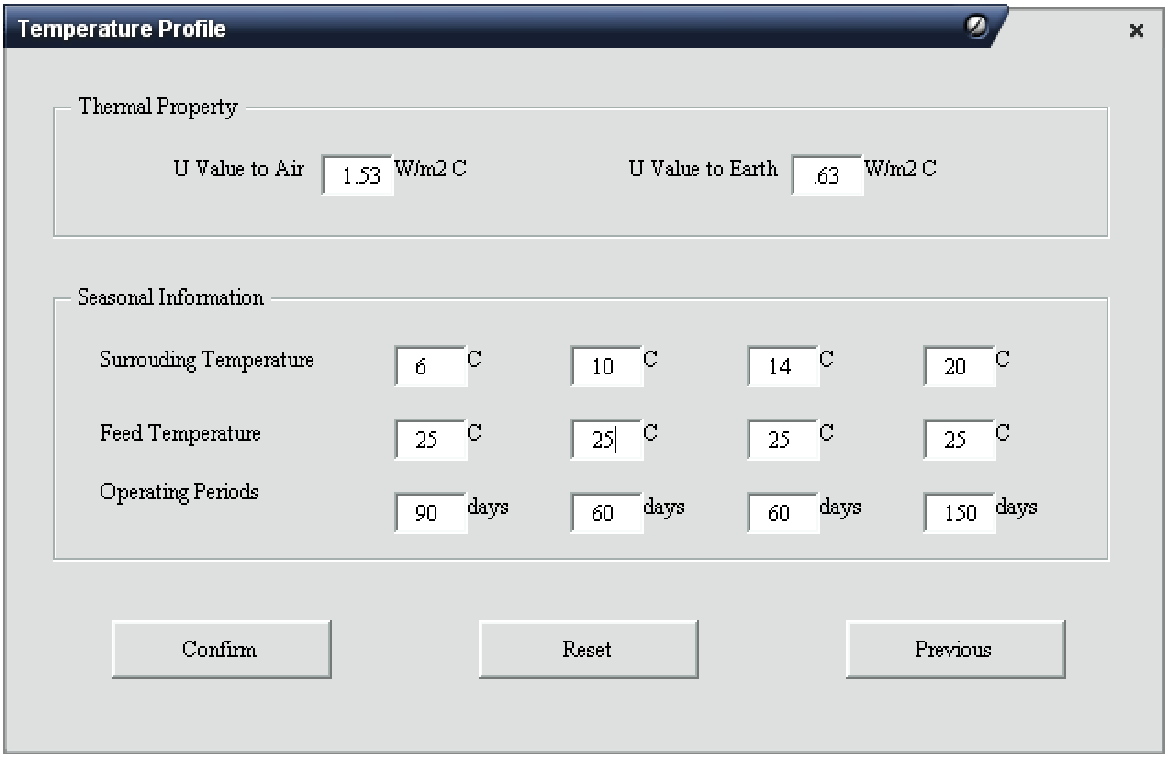
In the energy production method or biogas utilization method interface, we will select co-generation, even though this particular site does not have either co-generation or biogas purification on site. Figure A9 shows the thermal parameters used for co-generation energy production. The yearly temperature profile is only for the Lower Mainland, BC. Users in other region must adjust the values accordingly.



● Co-Generation

○ Biogas Purification

Figure A8: Energy production method



Thermal Property

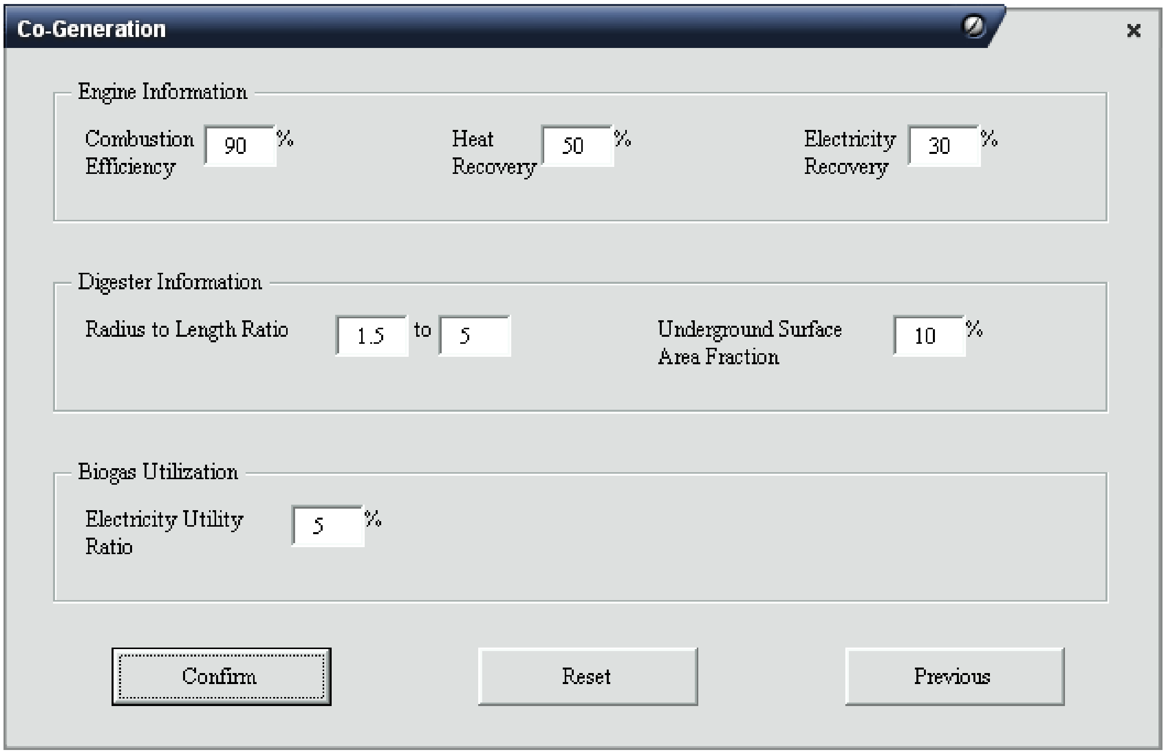
U Value to Air 1.53 W/m2 C

U Value to Earth .63 W/m2 C

Seasonal Information

Surrouding Temperature	6 C	10 C	14 C	20 C
Feed Temperature	25 C	25 C	25 C	25 C
Operating Periods	90 days	60 days	60 days	150 days

Figure A9: Thermal parameters interface



Engine Information

Combustion Efficiency: 90 %

Heat Recovery: 50 %

Electricity Recovery: 30 %

Digester Information

Radius to Length Ratio: 1.5 to 5

Underground Surface Area Fraction: 10 %

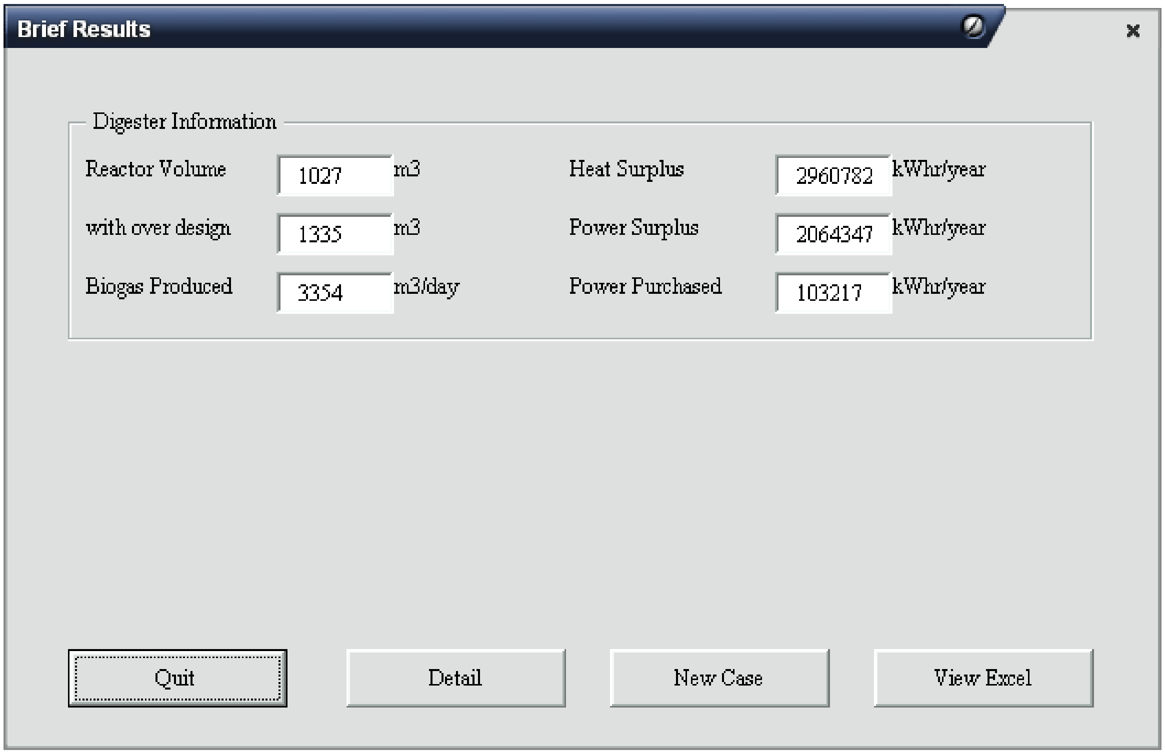
Biogas Utilization

Electricity Utility Ratio: 5 %

Figure A10: Co-generation parameters interface

Figure A10 shows the parameters involved for performing the energy balance for co-generation. Depends on the dimension and position of the digester, users can adjust the radius to length ratio and the underground surface area fraction of the digester. The electricity utility covers the entire electricity requirement by the digestion systems, such as pumping, sensors, mixing, etc.

Figure A11 shows the final results, in this case, the biogas production rate is 4,081 m^3/day (this compares to the reported value 3,681 m^3/day). Users can press “Detail” to export the whole simulation into another spreadsheet for later viewing or press “View Excel” to view the current case in spreadsheet without the interfaces. Users can also start a new case by selecting “New Case” or terminate the current application by selecting “Quit”



Brief Results

Digester Information

Reactor Volume 1027 m3

with over design 1335 m3

Biogas Produced 3354 m3/day

Heat Surplus 2960782 kWhr/year

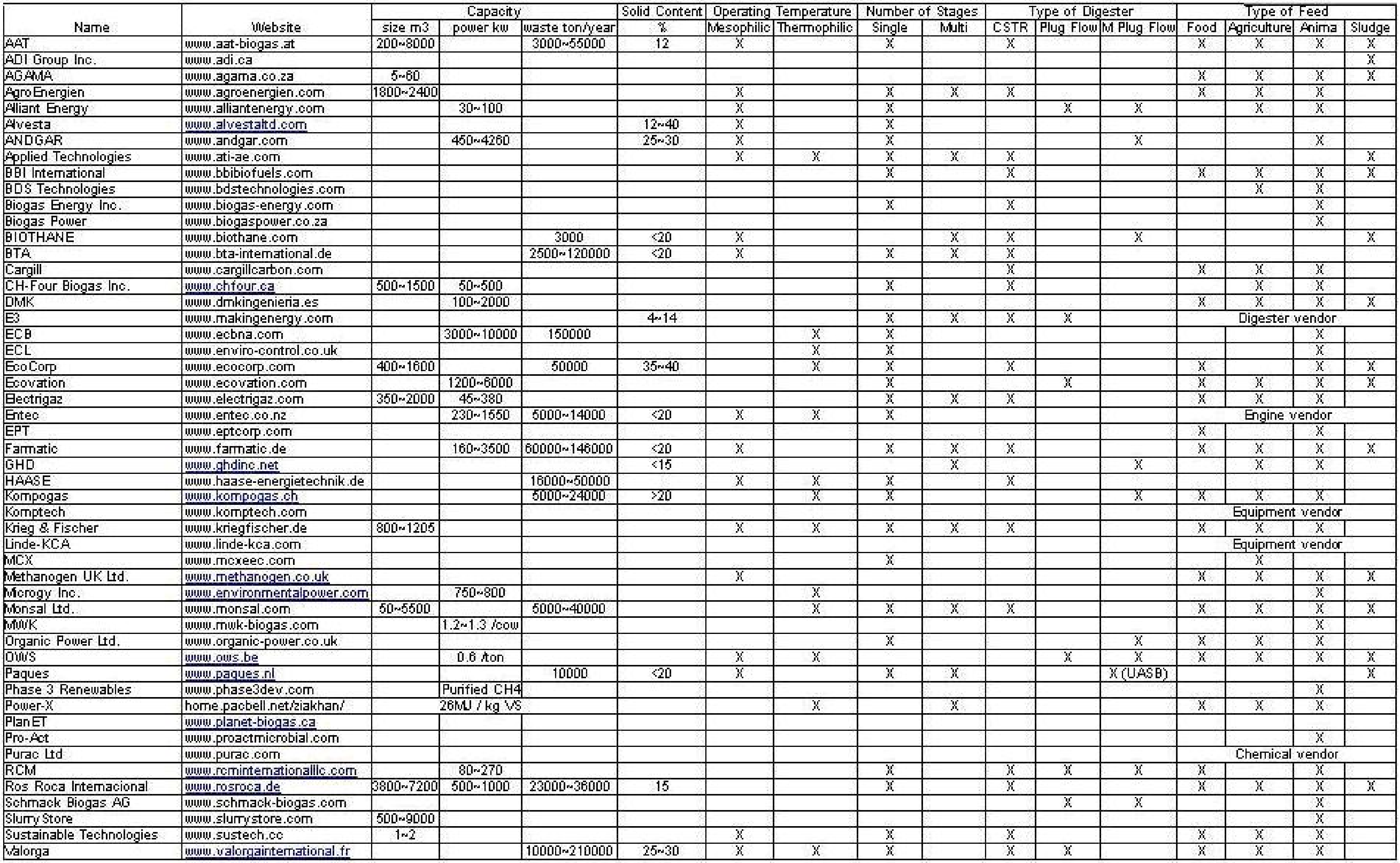
Power Surplus 2064347 kWhr/year

Power Purchased 103217 kWhr/year

Figure A11: Brief outputs interface

Appendix B

Table B1. List of AD Technology Suppliers



Name	Website	Capacity			Solid Content	Operating Temperature		Number of Stages		Type of Digester			Type of Feed			
		size m3	power kw	waste ton/year	%	Mesophilic	Thermophilic	Single	Multi	CSTR	Plug Flow	M Plug Flow	Food	Agriculture	Anima	Sludge
AAT	www.aat-biogas.at	200~8000		3000~55000	12	X		X		X			X	X	X	X
ADI Group Inc.	www.adi.ca															X
AGAMA	www.agama.co.za	5~60											X	X	X	X
AgroEnergien	www.agroenergien.com	1800~2400				X		X	X	X			X	X	X	
Alliant Energy	www.alliantenergy.com		30~100			X		X			X	X		X	X	
Alvesta	www.alvestaltd.com				12~40	X		X								
ANDGAR	www.andgar.com		450~4260		25~30	X		X				X			X	
Applied Technologies	www.ati-ae.com					X	X	X	X	X						X
BBI International	www.bbibiofuels.com							X		X			X	X	X	X
BDS Technologies	www.bdstechnologies.com													X	X	
Biogas Energy Inc.	www.biogas-energy.com							X		X					X	
Biogas Power	www.biogaspower.co.za														X	
BIOTHANE	www.biothane.com			3000	<20	X			X	X		X				X
BTA	www.bta-international.de			2500~120000	<20	X		X	X	X						
Cargill	www.cargillcarbon.com									X			X	X	X	
CH-Four Biogas Inc.	www.chfour.ca	500~1500	50~500					X		X				X	X	
DMK	www.dmkingenieria.es		100~2000										X	X	X	X
E3	www.makingenergy.com				4~14			X	X	X	X		Digester vendor			
ECB	www.ecbna.com		3000~10000	150000			X	X							X	
ECL	www.enviro-control.co.uk						X	X							X	
EcoCorp	www.ecocorp.com	400~1600		50000	35~40		X	X		X			X		X	X
Ecovation	www.ecovation.com		1200~6000					X			X		X	X	X	X
Electrigaz	www.electrigaz.com	350~2000	45~380					X	X	X			X	X	X	
Entec	www.entec.co.nz		230~1550	5000~14000	<20	X	X	X					Engine vendor			
EPT	www.eptcorp.com												X		X	
Farmatic	www.farmatic.de		160~3500	60000~146000	<20	X		X	X	X			X	X	X	X
GHD	www.ghdinc.net				<15				X			X		X	X	
HAASE	www.haase-energietechnik.de			16000~50000		X	X	X		X						
Kompogas	www.kompogas.ch			5000~24000	>20		X	X				X	X	X	X	
Komptech	www.komptech.com												Equipment vendor			
Krieg & Fischer	www.kriegfischer.de	800~1205				X	X	X	X	X			X	X	X	
Linde-KCA	www.linde-kca.com												Equipment vendor			
MCX	www.mcxeec.com							X						X		
Methanogen UK Ltd.	www.methanogen.co.uk					X							X	X	X	X
Microgy Inc.	www.environmentalpower.com		750~800				X								X	
Monsal Ltd.	www.monsal.com	50~5500		5000~40000			X	X	X	X			X	X	X	X
MWK	www.mwk-biogas.com		1.2~1.3 /cow												X	
Organic Power Ltd.	www.organic-power.co.uk							X				X	X	X	X	
OWS	www.ows.be		0.6 /ton			X	X				X	X	X	X	X	X
Paques	www.paques.nl			10000	<20	X		X	X			X (UASB)				X
Phase 3 Renewables	www.phase3dev.com		Purified CH4												X	
Power-X	home.pacbell.net/ziakhan/		26MJ / kg VS				X		X				X	X	X	
PlanET	www.planet-biogas.ca															
Pro-Act	www.proactmicrobial.com														X	
Purac Ltd	www.purac.com												Chemical vendor			
RCM	www.rcminternationalllc.com		80~270					X		X	X	X	X		X	
Ros Roca Internacional	www.rosroca.de	3800~7200	500~1000	23000~36000	15			X		X			X	X	X	X
Schmack Biogas AG	www.schmack-biogas.com										X	X			X	
Slurry Store	www.slurrystore.com	500~9000													X	
Sustainable Technologies	www.sustech.cc	1~2				X		X		X			X	X	X	
Valorga	www.valorgainternational.fr			10000~210000	25~30	X	X	X		X	X		X	X	X	

Table B2. On-farm AD systems in the US (USEPA AgStar website, accessed May 2009)

Farm/Project Name and Location		**Digester Type**	**Status**	**Year**	**Animal**	**# animals**	**Biogas End Use(s)**	**Power (kW)**	**System Designer**
Blakes Landing Dairy	CA	Covered Lagoon	O	2004	Dairy	362	Electricity	75	Williams Engineering Assoc
Cal Poly Dairy	CA	Covered Lagoon	O	1998	Dairy	175	Electricity	30	RCM International, Inc.
CAL-Denier Dairy	CA	Covered Lagoon	O	2008	Dairy	900	Electricity	65	RCM International, Inc.
Castelanelli Bros. Dairy	CA	Covered Lagoon	O	2004	Dairy	3,214	Electricity	180	RCM International, Inc.
CottonWood Dairy	CA	Covered Lagoon	O	2004	Dairy	2,808	Cogeneration; Boiler/Furnace Fuel	700	Williams Engineering Assoc
Fiscalini Farms	CA	Complete Mix	O	2008	Dairy	2,513	Cogeneration	720	Biogas Energy, Inc. (Biogas Nord System)
Hilarides Dairy	CA	Covered Lagoon	O	2008	Dairy	1,500	Electricity; Vehicle Fuel	750	Sharp Energy; Phase 3 Renewables
Inland Empire Utilities Agency - Reg Plant 5	CA	Horizontal Plug Flow	O	2003	Dairy	3,225	Electricity	1,500	IEUA
Langerwerf Dairy	CA	Horizontal Plug Flow	O	1982	Dairy	700	Cogeneration	40	RCM International, Inc.
Lourenco Dairy	CA	Covered Lagoon	O	2007	Dairy	2,640	Electricity	150	Sharp Energy
Meadowbrook Dairy	CA	Horizontal Plug Flow	O	2004	Dairy	2,000	Electricity	160	RCM International, Inc.
Strauss Family Dairy	CA	Covered Lagoon	O	2004	Dairy	200	Cogeneration	25	
Van Ommering Dairy	CA	Horizontal Plug Flow	O	2004	Dairy	624		130	RCM International, Inc.
Vintage Dairy	CA	Covered Lagoon	O	2008	Dairy	5,000	Pipeline Gas		BioEnergy Solutions
Cushman Dairy	CT	Complete Mix	O	1997	Dairy	600	Electricity	80	Agri-Biosystems, Inc.
Freund Farm	CT	Horizontal Plug Flow	O	1997	Dairy	200	Boiler/Furnace Fuel		RCM International, Inc.
Suwannee Farms	FL	Mixed Plug Flow	O	2009	Beef				GHD, Inc.
University of Florida	FL	Fixed Film	O	2000	Dairy	250		30	
Wright Whitty Davis Farms, Inc.	GA	Mixed Plug Flow	O	2006	Dairy	1,135	Electricity; Boiler/Furnace Fuel	200	GHD, Inc.
Amana Farms, Inc.	IA	Mixed Plug Flow	O	2008	Beef	4,000	Cogeneration	2,600	GHD, Inc.
Boland Farm	IA	Covered Lagoon	O	1998	Swine	3,000			RCM International, Inc.
Top Deck Holsteins	IA	Horizontal Plug Flow	O	2002	Dairy	700	Cogeneration	130	Ray Crammond
Bettencourt's Dry Creek	ID	Horizontal Plug Flow	O	2008	Dairy	10,000	Cogeneration	2,250	GHD, Inc. and Andgar

Dairy									
Dean Foods Big Sky Dairy	ID	Modified Plug Flow	O	2008	Dairy	4,700	Cogeneration	1,500	GHD, Inc. (Design) and Andgar (Installation)
Apex Pork	IL	Covered Lagoon	O	1998	Swine	8,900	Cogeneration	40	RCM International, Inc.
Hillcrest Dairy (Formerly New Horizons)	IL	Horizontal Plug Flow	O	2002	Dairy	1,400	Cogeneration	270	RCM International, Inc.
Hunter Haven Farms, Inc.	IL	Mixed Plug Flow	O	2005	Dairy	650	Cogeneration	140	GHD, Inc.
Scheidairy Farms	IL	Unknown	O	2005	Dairy	650	Electricity	120	GHD, Inc.
Bos Dairy	IN	Mixed Plug Flow	O	2005	Dairy	3,600	Electricity	1,050	GHD, Inc.
Fair Oaks Dairy - Digester 1	IN	Vertical Plug Flow	O	2004	Dairy	3,500	Electricity	750	Dennis Burke, Environmental Energy Corporation
Fair Oaks Dairy - Digester 2	IN	Mixed Plug Flow	O	2008	Dairy	10,500	Flared Full Time		GHD, Inc.
Herrema Dairy	IN	Mixed Plug Flow	O	2002	Dairy	3,750	Cogeneration	800	GHD, Inc.
Hidden View	IN	Mixed Plug Flow	O	2007	Dairy	3,500	Flared Full Time	950	GHD, Inc.
Windy Ridge Dairy	IN	Mixed Plug Flow	O	2006	Dairy	7,000	Flared Full Time		GHD, Inc.
USDA-Beltsville ARS facility, Unmixed Tank	MD	Complete Mix	O	1994	Dairy	150		15	Agway
den Dulk	MI	Complete Mix	O	2007	Dairy	1,000	Cogeneration		Grand Valley State University; Entect Biogas GmbH Austria
Geerlings Hillside Farms Overisel Hog Facility	MI	Complete Mix	O	2008	Swine	16,000	Electricity; Boiler/Furnace Fuel	130	Phase 3 Developments & Investments
Green Meadows Dairy	MI	Complete Mix	O	2007	Dairy	3,200		800	Michigan State University; Biogas Nord
Scenic View Dairy - Fennville	MI	Complete Mix	O	2006	Dairy	3,650	Cogeneration; Pipeline Gas	700	Phase 3 & Biogas Direct, LLC (Biogas-Nord)
Scenic View Dairy - Freeport	MI	Complete Mix	O	2008	Dairy	3,050	Electricity; Boiler/Furnace Fuel	1,600	Phase 3 Developments, Inc.
Willow Point Dairy	MI	Mixed Plug Flow	O	2007	Dairy	2,750	Flared Full Time		GHD, Inc.
Haubenschild Dairy	MN	Horizontal Plug Flow	O	1999	Dairy	900	Cogeneration; Electricity	155	RCM International, Inc.

Jer-Lindy Farms	MN	Unknown	O	2008	Dairy	290	Cogeneration	37	Genex Farm Systems and Andigen
Northern Plains Dairy	MN	Horizontal Plug Flow	O	2003	Dairy	3,000	Cogeneration	260	RCM International, Inc.
Riverview Dairy	MN	Mixed Plug Flow	O	2009	Dairy	6,500			GHD, Inc.
West River Dairy	MN	Mixed Plug Flow	O	2009	Dairy	5,000			GHD, Inc.
Brinson Farms	MS	Complete Mix	O	2005	Broiler	270,000	Cogeneration; Boiler/Furnace Fuel	75	
Piney Woods School	MS	Covered Lagoon	O	1998	Swine	145		5	RCM International, Inc. and ICF, Inc.
Huls Dairy	MT	Induced Blanket Reactor	O	2008	Dairy	350	Electricity; Boiler/Furnace Fuel	50	Andigen
Barham Farms	NC	Covered Lagoon	O	1997	Swine	4,000	Boiler/Furnace Fuel		RCM International, Inc.
Butler Farms	NC	Covered Lagoon	O	2008	Swine	8,280	Flared Full Time		Environmental Fabrics, Inc.
Darrell Smith Farm	NC	Complete Mix	O	1983	Caged layer	70,000		80	Bio-Gas of Colorado; A.O. Smith Harvestore
Murphy Brown LLC - Kenansville Farm #2539	NC	Partial Cover Lagoon	O	2008	Swine	10,500	Boiler/Furnace Fuel		Environmental Fabrics, Inc.
Vestal Farm	NC	Covered Lagoon	O	2003	Swine	9,792	Cogeneration; Boiler/Furnace Fuel	30	Cavanaugh and Associates
Danny Kluthe Farm	NE	Complete Mix	O	2005	Swine	8,000	Cogeneration	80	RCM International, Inc.
AA Dairy	NY	Horizontal Plug Flow	O	1998	Dairy	600	Cogeneration	130	RCM International, Inc.
Cayuga Regional Digester Bioenergy Enterprise	NY	Complete Mix	O	2007	Dairy	1,255	Cogeneration	625	Eco Technology Solutions LLC; GBU Germany and Sterns & Wheeler (NY)
Corwin Duck Farm	NY	Complete Mix	O	2006	Duck	800,000	Electricity		Applied Technologies, Inc.
EL-VI Farms	NY	Horizontal Plug Flow	O	2004	Dairy	1,500	Boiler/Furnace Fuel		Ted Peck; Stanley A. Weeks, LLC
Emerling Farms	NY	Horizontal Plug Flow	O	2006	Dairy	1,200	Cogeneration	230	RCM International, Inc.
New Hope View Farm	NY	Horizontal Plug Flow	O	2001	Dairy	850	Cogeneration; Boiler/Furnace Fuel	70	RCM International, Inc.
Noblehurst Farms	NY	Horizontal Plug Flow	O	2003	Dairy	1,300	Cogeneration	130	Cow Power

Patterson Farm	NY	Complete Mix	O	2005	Dairy	1,760	Cogeneration	250	RCM International, Inc.
Ridgeline Farm	NY	Complete Mix	O	2001	Dairy	525	Cogeneration	130	RCM International, Inc.
Sheland Farms	NY	Complete Mix	O	2007	Dairy	555	Cogeneration	125	Siemens; Stearns & Wheeler; Stanley A. Weeks, LLC
Sunny Knoll Farm	NY	Horizontal Plug Flow	O	2006	Dairy	2,220	Cogeneration	230	RCM International, Inc.
Sunnyside Farms	NY	Mixed Plug Flow	O	2009	Dairy	6,100	Cogeneration	1,600	GHD, Inc.
SUNY at Morrisville	NY	Horizontal Plug Flow	O	2007	Dairy	505	Cogeneration	50	David Palmer at Cow Power, Inc.; Tiry Engineering
Twin Birch Dairy	NY	Horizontal Plug Flow	O	2003	Dairy	1,900	Cogeneration; Boiler/Furnace Fuel	120	Anaerobics
Seaboard Foods Wakefield Farm	OK	Permeable Cover Lagoon	O	2002	Swine	26,500			
Bernie Faber Dairy (Portland General System)	OR	Complete Mix	O	2002	Dairy	350	Cogeneration	35	Portland General Electric
Tillamook_1 (2 digesters)	OR	Horizontal Plug Flow	O	2003	Dairy	2,000	Cogeneration	250	RCM International, Inc.
Tillamook_2 (last 2 digesters)	OR	Horizontal Plug Flow	O	2008	Dairy	2,000	Cogeneration	300	RCM International, Inc.
Breinig	PA	Horizontal Plug Flow	O	1983	Caged layer	350,000	Cogeneration	150	Bert Waybright
Brendle’s Egg Farm	PA	Horizontal Plug Flow	O	1985	Caged layer	72,000	Cogeneration	65	Bert and Dick Waybright
Brookside Dairy	PA	Horizontal Plug Flow	O	2006	Dairy	400	Cogeneration	85	Team Ag & Jim Resh Engineering
Brubaker Farms	PA	Complete Mix	O	2007	Dairy	900	Cogeneration	160	RCM International, Inc. & Team Ag
David High	PA	Vertical Plug Flow	O	1998	Swine	1,200	Cogeneration	22	Orgo Systems
Dovan Farms	PA	Horizontal Plug Flow	O	2006	Dairy	400	Cogeneration	100	Environomics & RCM International, Inc.
Four Winds Farm	PA	Horizontal Plug Flow	O	2006	Dairy	650	Cogeneration	140	Environomics & RCM International, Inc.
Hillcrest Saylors Farm	PA	Horizontal Plug Flow	O	2007	Dairy	1,150	Cogeneration	130	Team Ag

Mains Farm	PA	Complete Mix	O	2006	Dairy	600	Cogeneration	90	EMG Intl Inc.
Mason Dixon Farms	PA	Horizontal Plug Flow	O	1979	Dairy	2,300	Cogeneration	600	Dick & Bert Waybright
Oregon Dairy Farm	PA	Horizontal Plug Flow	O	1983	Dairy	250	Cogeneration	45	Bert Waybright
Penn England Farm	PA	Complete Mix	O	2006	Dairy	800	Cogeneration	130	Team Ag & RCM International, Inc.
Pine Hurst Acres	PA	Complete Mix	O	2004	Swine	4,400		47	PSU & Schick Enterprises
Reinford Farms	PA	Complete Mix	O	2007	Dairy	800	Cogeneration	130	RCM International, Inc.
Rocky Knoll Swine Farm	PA	Horizontal Plug Flow	O	1985	Swine	1,000	Cogeneration	130	Environomics & RCM International, Inc.
Schrack Farms	PA	Horizontal Plug Flow	O	2006	Dairy	1,430	Cogeneration	200	Environomics & RCM International, Inc.
Wanner's Pride-N-Joy Farm	PA	Complete Mix	O	2007	Dairy	400	Cogeneration	160	RCM International, Inc. & Team Ag
Zimmerman Farm	PA	Complete Mix	O	2007	Beef/ Poultry	1,000; 120,000	Cogeneration	100	DGW & Associates
Midwest Dairy Institute	SD	Unknown	O	2006	Dairy	2,400	Electricity; Boiler/Furnace Fuel	375	
Broumley Dairy Farm	TX	Covered Lagoon	O	2008	Dairy	980	Cogeneration		Cascade Earth Sciences
Huckabay Ridge / Microgy	TX	Complete Mix	O	2008	Dairy	10,000	Pipeline Gas		Microgy
Premium Standard 1	TX	Unknown	O	2002	Swine	108,000		2,000	
Premium Standard 2	TX	Unknown	O	2002	Swine	10,000		160	
Circle Four Farms	UT	Covered Lagoon	O	2005	Swine	194,000			
Wadeland Dairy	UT	Induced Blanket Reactor	O	2004	Dairy	1,200	Cogeneration	150	USDA, DOE, Utah State University, Andigen
Martin Farms	VA	Covered Lagoon	O	1994	Swine	3,000		25	RCM International, Inc.; AgriWaste Technology
Blue Spruce Farm, Inc.	VT	Mixed Plug Flow	O	2005	Dairy	1,100	Electricity	240	GHD, Inc.
Foster Brothers Farms	VT	Horizontal Plug Flow	O	1982	Dairy	340	Electricity	85	Hadley and Bennett
Gervais Family Farm	VT	Mixed Plug Flow	O	2009	Dairy	1,000	Electricity	200	GHD, Inc.
Green Mountain Dairy, LLC	VT	Mixed Plug Flow	O	2007	Dairy	1,050	Cogeneration	300	GHD, Inc.
Maxwell Farm /	VT	Mixed Plug Flow	O	2008	Dairy	750	Electricity	225	GHD, Inc.

Neighborhood Energy, LLC									
Montagne Farm	VT	Mixed Plug Flow	O	2007	Dairy	1,200	Cogeneration	300	GHD, Inc.
Pleasant Valley Farms - Berkshire Cow Power, LLC	VT	Mixed Plug Flow	O	2006	Dairy	1,950	Cogeneration	600	GHD, Inc.
G DeRuyter & Sons Dairy	WA	Flush System Plug Flow	O	2007	Dairy	3,500	Cogeneration	1,200	GHD, Inc.
Qualco Energy/Quil Ceda Power Corp.	WA	Horizontal Plug Flow	O	2008	Dairy	2,000	Cogeneration	450	GHD, Inc. and Andgar
Vander Haak Dairy	WA	Mixed Plug Flow	O	2005	Dairy	750	Cogeneration	450	GHD, Inc., and Andgar Corp.
Baldwin Dairy	WI	Modified Mixed Plug Flow	O	2006	Dairy	1,050	Flared Full Time	200	Komro International, LLC
Central Sands Dairy, LLC	WI	Mixed Plug Flow	O	2008	Dairy	3,500	Electricity	1,200	GHD, Inc.
Clover Hill Dairy, LLC	WI	Mixed Plug Flow	O	2007	Dairy	1,250	Cogeneration	300	GHD, Inc.
Crave Brothers Dairy Farm / Clear Horizons LLC	WI	Complete Mix	O	2007	Dairy	800	Cogeneration	230	Clear Horizons, LLC
Double S Dairy	WI	Mixed Plug Flow	O	2004	Dairy	1,100	Cogeneration	200	GHD, Inc.
Emerald Dairy	WI	Mixed Plug Flow	O	2006	Dairy	1,600	Pipeline Gas		GHD, Inc.
Five Star Dairy Farm	WI	Complete Mix	O	2005	Dairy	850	Cogeneration	775	Microgy
Gordondale Farms	WI	Mixed Plug Flow	O	2002	Dairy	850	Cogeneration	140	GHD, Inc.
Green Valley Farm	WI	Complete Mix	O	2007	Dairy	2,100	Cogeneration	600	Biogas Direct, LLC
Grotequt Dairy Farm, Inc.	WI	Mixed Plug Flow	O	2009	Dairy	2,400	Cogeneration	600	GHD, Inc.
Holsum Dairy - Elm Road	WI	Mixed Plug Flow	O	2007	Dairy	4,000	Cogeneration	1,200	GHD, Inc.
Holsum Dairy - Irish Road	WI	Mixed Plug Flow	O	2004	Dairy	4,000	Cogeneration	700	GHD, Inc.
Lake Breeze Dairy	WI	Mixed Plug Flow	O	2006	Dairy	2,550	Cogeneration	600	GHD, Inc.
Maple Leaf Farms	WI	Complete Mix	O	1988	Duck	500,000	Electricity	200	Applied Technologies, Inc.
Norm-E-Lane, Inc. (NEL)	WI	Mixed Plug Flow	O	2008	Dairy	2,000	Cogeneration	500	GHD, Inc.
Norswiss Farms	WI	Complete Mix	O	2006	Dairy	1,180	Cogeneration		Microgy
Pagels Ponderosa Dairy	WI	Mixed Plug Flow	O	2009	Dairy	4,000	Electricity	800	GHD, Inc.
Quantum Dairy	WI	Mixed Plug Flow	O	2005	Dairy	1,700	Cogeneration	300	GHD, Inc.
Statz Brothers, Inc.	WI	Mixed Plug Flow	O	2009	Dairy	2,000	Cogeneration	600	GHD, Inc.
Stencil Farm	WI	Horizontal Plug Flow	O	2002	Dairy	1,000	Cogeneration	123	RCM International, Inc.

Suring Community Dairy	WI	Complete Mix	O	2005	Dairy	810	Cogeneration	250	American Biogas Company,
Tinedale Farms	WI	Complete Mix	O	2003	Dairy	2,400			Steve Dvorack
Vir-Clar Farms	WI	Complete Mix	O	2004	Dairy	1,200	Cogeneration	350	Biogas Direct, LLC
Wild Rose Dairy	WI	Complete Mix	O	2005	Dairy	880	Cogeneration	750	Microgy
Wyoming Premium Farms 1	WY	Complete Mix	O	2003	Swine	5,000	Electricity	80	RCM International, Inc.
Wyoming Premium Farms 2	WY	Complete Mix	O	2004	Swine	18,000	Electricity	160	RCM International, Inc.
Inland Empire Utilities Agency - Phase II	CA	Complete Mix	C	2008	Dairy	6,450	Electricity	1,500	IEUA
Tollenaar Holsteins Dairy	CA	Complete Mix	C	2008	Dairy	1,895	Cogeneration; Boiler/Furnace Fuel	250	RCM International, Inc.
Bison Renewable Energy - Cornerstone AD	IA	Unknown	C	2008	Swine/Cattle		Pipeline Gas		Bison Renewable Energy, HCI Construction
Double A Dairy	ID	Mixed Plug Flow	C	2009	Dairy	14,400			GHD, Inc.
Westpoint Dairy	ID	Unknown	C	2007	Dairy		Pipeline Gas		Intrepid Technology and Resources Inc.
Tradition Dairy	IL	Mixed Plug Flow	C	2009	Dairy	5,000			GHD, Inc.
JBS Swift / Microgy	NE	Complete Mix	C	2008	Beef	6,000	Boiler/Furnace Fuel		Benham Construction (Contractors to Microgy)
Aurora Ridge Dairy	NY	Mixed Plug Flow	C		Dairy	1,800		135	GHD, Inc.
Boxler Dairy	NY	Mixed Plug Flow	C	2009	Dairy				GHD, Inc.
Bridgewater Dairy, LLC	OH	Mixed Plug Flow	C	2007	Dairy	3,900	Cogeneration	800	GHD, Inc.
Harrison Ethanol	OH	Horizontal Plug Flow	C	2008	Dairy	2,000		1,500	
Wenning Poultry Farm	OH	Mixed Plug Flow	C	2008	Layers	750,000	Cogeneration	600	GHD, Inc.
Threemile Canyon Farms	OR	Fixed Film	C	2009	Dairy	1,200	Cogeneration		J-U-B
Cove Area Regional Digester	PA	Unknown	C	2010	Dairy				Herbert, Rowland & Grubic
Cnossen Project - Microgy	TX	Complete Mix	C	2009	Dairy	10,000	Pipeline Gas		Microgy
Panda Ethanol - Hereford	TX	Unknown	C	2008	Beef				
Rio Leche Project - Microgy	TX	Complete Mix	C	2009	Dairy	10,000	Pipeline Gas		Microgy
Westminster Farms	VT	Mixed Plug Flow	C		Dairy	750	Cogeneration	225	GHD, Inc.
Farm Power Northwest,	WA		C	2009	Dairy	1,500	Electricity		GHD, Inc.

LLC									
Bach Digester, LLC	WI	Mixed Plug Flow	C	2009	Dairy	1,250	Electricity		GHD, Inc.
Maple Leaf West	WI	Mixed Plug Flow	C		Dairy	4,000	Cogeneration	1,200	GHD, Inc.
Volm Farms	WI	Mixed Plug Flow	C	2009	Dairy				GHD, Inc.
Bar 20 Dairy 2 - Microgy	CA	Complete Mix	P		Dairy	19,100	Pipeline Gas		Microgy
Superior Cattle Feeders	CA	Complete Mix	P		Dairy	45,000		2,000	
Fort St. Vrain - Microgy	CO	Unknown	P		Dairy		Pipeline Gas		Microgy
Hamilton Farm	IA	Horizontal Plug Flow	P		Dairy	450		50	
Jeff Elm Farm	IA	Horizontal Plug Flow	P		Swine	33,000		650	
Naser Farm	IA	Horizontal Plug Flow	P		Dairy	1,000		100	
Beukers Dairy	ID	Complete Mix	P		Dairy	3,000	Cogeneration	350	
Hunter Haven Farms, Inc.	IL	Mixed Plug Flow	P	2008	Dairy	850	Cogeneration	130	GHD, Inc.
Bio Town Ag, Inc.	IN	Mixed Plug Flow	P	2008	Swine/ Cattle	5,400	Cogeneration	600	GHD, Inc.
Kilby's Inc.	MD	Covered Lagoon	P	2008	Dairy	536	Cogeneration	80	
Rainbow Valley Farm	ME	Horizontal Plug Flow	P		Dairy		Cogeneration		
Novi Energy Digester	MI	Unknown	P	2008	Swine	12,000			Novi Energy
Swisslane Dairy	MI	Complete Mix	P	2008	Dairy	1,770			Phase 3
VREBA-Hoff Dairy (I & II)	MI	Mixed Plug Flow	P		Dairy	3,500	Cogeneration; Boiler/Furnace Fuel	700	GHD, Inc.
West Michigan Renewables LLC	MI	Unknown	P	2008	Swine				
Daley Farms LLP	MN	Unknown	P	2006	Dairy	950	Pipeline Gas	775	GHD, Inc.
Diamond K Dairy/Ponderosa Dairies	MN	Complete Mix	P		Dairy	2,100	Cogeneration	261	RCM International, Inc.
Durst Brothers Dairy	MN	Unknown	P		Dairy			300	
Rick Neuvirth Farm	MN	Unknown	P		Swine				
Ripley Dairy	MN	Horizontal Plug Flow	P		Dairy	300		400	
Westland Dairy	MN	Horizontal Plug Flow	P	2005	Dairy	1,100	Cogeneration	133	
Curtin Dairy Farm	NY	Horizontal Plug Flow	P		Dairy	2,000		260	Cow Power; Hadley and Bennett

Energy Co-opportunity	NY	Complete Mix	P		Dairy	3,000		800	
Greenwood Dairy Farm	NY	Complete Mix	P	2009	Dairy	2,300	Electricity	400	RCM International, Inc.
Herrington Farms Inc.	NY	Complete Mix	P		Dairy	580	Cogeneration	150	Saratoga Biogas; Greenman-Pedersen, Inc.
Marks Farms	NY	Complete Mix	P		Dairy	4,000		1,000	Cyclus Envirosystems
North Harbor Dairy LLC	NY	Horizontal Plug Flow	P	2008	Dairy	500	Cogeneration	80	Unknown
Perry Community Digester	NY	Complete Mix	P	2008	Dairy	1,500	Electricity	600	ECOTS (generation); GBU (digester)
Roach Dairy Farm	NY	Horizontal Plug Flow	P	2009	Dairy	1,600	Electricity	300	
Spruce Haven Farm	NY	Complete Mix	P		Dairy	3,000		4,000	
True Farms	NY	Horizontal Plug Flow	P		Dairy	974		140	
Walker Farms LLC	NY	Complete Mix	P	2009	Dairy	1,350	Cogeneration	225	RCM International, Inc.
Zuber Farms	NY	Complete Mix	P	2009	Dairy	1,550	Electricity	300	RCM International, Inc.
Central Ethanol	OH	Horizontal Plug Flow	P		Dairy	12,000		1,500	
Pike Ethanol	OH	Horizontal Plug Flow	P		Dairy	12,000		1,500	
Schmack BioEnergy, LLC	OH	Complete Mix	P						
Beaver Ridge Farm	PA	Complete Mix	P	2008	Swine	3,000	Cogeneration	130	DGW & Associates
Bishcroft Farm	PA	Unknown	P		Dairy	500	Flared Full Time		
Bortnick Dairy	PA	Complete Mix	P	2007	Dairy	1,950	Cogeneration	400	
Klejka Dairy	PA	Horizontal Plug Flow	P		Dairy	650	Cogeneration	85	
Kulp Family Farm	PA	Horizontal Plug Flow	P		Dairy	1,150	Electricity	200	
Mathis Farm	PA	Complete Mix	P	2008	Swine		Cogeneration	15	DGW & Associates
Pennwood Farms	PA	Horizontal Plug Flow	P		Dairy	500	Electricity	50	
Star Rock Farm	PA	Horizontal Plug Flow	P		Dairy	950	Cogeneration	100	Team Ag
Terczak Farm	PA	Unknown	P	2006	Veal				
Turner County Dairy	SD	Mixed Plug Flow	P		Dairy	1,650	Cogeneration	600	GHD, Inc.
Mission Project - Microgy	TX	Complete Mix	P	2009	Dairy	10,000	Pipeline Gas		Microgy
Panda Ethanol - Sherman Plant	TX	Unknown	P		Cattle				
Still Meadow Dairy	TX	Horizontal Plug Flow	P	2008	Dairy	5,000	Cogeneration	1,200	GHD, Inc. (Design); Andgar Corp. (installation)
Chaput Family Farms	VT	Complete Mix	P	2009	Dairy	1,600	Cogeneration	300	RCM International, Inc.

Newmont Farm, LLC	VT	Mixed Plug Flow	P	2007	Dairy	935	Cogeneration	200	GHD, Inc.
Burr Oak Hills Dairy	WI	Mixed Plug Flow	P	2009	Dairy	450		90	GHD, Inc.
Dairy Dreams	WI	Horizontal Plug Flow	P		Dairy	1,400		560	Weltech
Dairyland Farm	WI	Mixed Plug Flow	P	2008	Dairy	2,200	Cogeneration; Boiler/Furnace Fuel	600	GHD, Inc.
DIC-Wisco Farms	WI	Mixed Plug Flow	P	2008	Dairy	1,200	ditto	300	GHD, Inc.
Ducat Farms	WI	Mixed Plug Flow	P	2008	Dairy	2,100	Cogeneration	600	GHD, Inc.
Four Cubs Farm	WI	Mixed Plug Flow	P	2008	Dairy	500	Cogeneration; Boiler/Furnace Fuel	130	GHD, Inc.
Hilltop Dairy	WI	Complete Mix	P		Dairy	850	Cogeneration	250	Biopower LLC; WELtec Biopower; Ambico, Inc.
Majestic View Dairy, LLC	WI	Unknown	P		Dairy			225	
Moriarty Farm	WI	Horizontal Plug Flow	P		Dairy	1,000		120	
Redtail Farms	WI	Mixed Plug Flow	P		Dairy	800	Cogeneration; Boiler/Furnace Fuel	160	GHD, Inc.
Schopf's Hilltop Dairy	WI	Mixed Plug Flow	P	2008	Dairy	650		130	GHD, Inc.
Son-Bow Farms	WI	Mixed Plug Flow	P		Dairy	1,200	Ditto	240	GHD, Inc.
Trillium Hill Farm	WI	Mixed Plug Flow	P		Dairy	550	Ditto	110	GHD, Inc.
Weiss Family Farms	WI	Mixed Plug Flow	P	2008	Dairy	1,000	Cogeneration; Boiler/Furnace Fuel	300	GHD, Inc.
Eden-Vale Dairy	CA	Horizontal Plug Flow	S	2006	Dairy	1,100	Cogeneration	180	RCM International, Inc.
IEUA - Reg Plant 1	CA	Complete Mix	S	2003	Dairy				IEUA
Koetsier Dairy	CA	Horizontal Plug Flow	S	2005	Dairy	2,000	Electricity	135	RCM International, Inc.
Royal Farms Digester 1	CA	Covered Lagoon	S	1982	Swine	7,500	Cogeneration	75	Sharp Energy
Royal Farms Digester 2	CA	Covered Lagoon	S	1985	Swine	7,500	Cogeneration	100	Sharp Energy
St. Anthony Farm	CA	Covered Lagoon	S	2007	Dairy	240	Cogeneration	80	
Colorado Pork	CO	Complete Mix	S	1999	Swine	6,300	Cogeneration	115	
Futura Dairy-Waubeek	IA	Horizontal Plug Flow	S	2002	Dairy	380		50	
McCabe Farms	IA	Unknown	S	1972	Swine	1,150	Flared Full Time		Harold McCabe

Swine USA, Bell Farms	IA	Complete Mix	S	2001	Swine	5,000		60	
Thaler Farm	IA	Complete Mix	S	1999	Swine	5,000	Electricity		RCM International, Inc.
Whitesides Dairy	ID	Complete Mix	S	2004	Dairy	2,900	Pipeline Gas		Intrepid Technology and Resources Inc.
Fairgrove Farms, Inc.	MI	Horizontal Plug Flow	S	1981	Dairy	720		85	
Harris Farm	NC	Fixed Film	S	2003	Swine	12,000		125	AgriClean
Genesis Ethanol Closed-Loop Plant / E3 BioFuels	NE	Complete Mix	S	2007	Beef	28,000	Boiler/Furnace Fuel		E3 Biofuels
Cooperstown Holstein	NY	Complete Mix	S	1985	Dairy	270	Cogeneration	65	A.O. Smith Harvestore
Farber Farm/NYC Watershed Ag Council (WAC)	NY	Fixed Film	S	2001	Dairy	100	Boiler/Furnace Fuel	15	Stanley A. Weeks, LLC
Craven Dairy Farms	OR	Horizontal Plug Flow	S	1997	Dairy	1,000	Electricity	130	RCM International, Inc.
Kirk Carrell Dairy	TX	Horizontal Plug Flow	S	1998	Dairy	455	Cogeneration	60	Cady Engler, Texas A&M
Emerald Dairy	WI	Covered Lagoon	S	1995	Dairy	1,600	Flared Full Time		
Ravenna Dairy	MI	Complete Mix	S		Dairy				
Bidart Dairy II	CA	Horizontal Plug Flow	S		Dairy	7,200		1,000	
Guepard Energy LLC	CA	Unknown	S		Beef		Electricity; Boiler/Furnace Fuel	1,250	
Harmony Farms	CA	Covered Lagoon	S		Dairy	1,050		120	
Plane View Dairy	CA	Complete Mix	S		Dairy	1,100		100	
Van Warmerdam Dairy	CA	Covered Lagoon	S		Dairy	1,550	Cogeneration; Boiler/Furnace Fuel	135	RCM International, Inc.
Little Pine Dairy	MN	Complete Mix	S		Dairy	1,400		160	
Allenwaite Farms Inc.	NY	Complete Mix	S		Dairy	800	Cogeneration	196	RCM International, Inc.
Hardie Farms	NY	Horizontal Plug Flow	S		Dairy	1,400	Cogeneration; Boiler/Furnace Fuel	125	DL-tech, Inc.
Porterdale Dairy	NY	Horizontal Plug Flow	S		Dairy	2,950	Ditto	312	RCM International, Inc.
Spring Valley Dairy	NY	Manure Activation	S		Dairy	236		25	Dubara Company, Inc.

		System							
Graywood Farms	PA	Horizontal Plug Flow	S		Dairy	800	Electricity	160	Team Ag
Huntsman Farm	PA	Unknown	S		Dairy	500	Electricity	50	
Manbeck Farm	PA	Complete Mix	S		Swine	2,200		40	
Monte Edgin Farm	PA	Unknown	S		Swine				
Pleasant View	PA	Complete Mix	S		Dairy	1,000	Cogeneration	300	Team Ag/RCM International
Red Knob Farm	PA	Fixed Film	S		Dairy	850	Cogeneration	160	EMG Intl Inc.
Robbins Farm	PA	Vertical Plug Flow	S		Dairy	300	Cogeneration	50	
Skyline Farm	PA	Horizontal Plug Flow	S		Dairy	460		60	
Boucher Farm	VT	Unknown	S		Dairy	250	Electricity		
Deer Flats Farm/Hulett Farm Biogas Project	VT	Complete Mix	S		Dairy	275	Cogeneration	500	Bruckner, Inc.
Nelson Farms, Inc.	VT	Horizontal Plug Flow	S		Dairy	975			
Bach Digester, LLC	WI	Unknown	S		Dairy	1,475	Electricity;Boiler/Furnace Fuel		Microgy
Bonde Acres Dairy	WI	Mixed Plug Flow	S		Dairy	150	Boiler/Furnace Fuel	50	GHD, Inc.
CADC Renewable Energy, LLC	WI	Complete Mix	S		Dairy	3,000		400	
Omro Dairy	WI	Horizontal Plug Flow	S		Dairy	1,000	Electricity	200	
Tidy View Dairy	WI	Horizontal Plug Flow	S		Dairy	2,100		200	

O: Operational
C: Construction
P: Planned
S: Shutdown or cancelled