BIOGAS DISTRIBUTED GENERATION SYSTEMS EVALUATION AND TECHNOLOGY TRANSFER

NYSERDA PROJECT NO. 6597

Interim Report for May 2001 to May 2005

Prepared for

THE NEW YORK STATE ENERGY RESEARCH AND DEVELOPMENT AUTHORITY

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Introduction

New York State livestock produce over 15 million tons of manure annually. Improper waste management can lead to nutrient runoff, pollution of watersheds, and contamination of groundwater. With new regulations for large concentrated animal feeding operations (CAFOs), farmers are facing increased expenses to properly manage manure and other by-products. Individual farms (mostly larger farms due to economics) and groups of farms are looking at anaerobic digestion as a means of treating manure. The economic viability of anaerobic digestion and its widespread adoption will largely depend on how reliable the system proves to be over time. Reliability of digester systems is of interest not only to dairy producers, but also to buyers of their distributed power and of their solid and liquid byproducts.

The goal of NYSERDA's on-farm distributed generation and composting effort is to help New York State's dairy industry manage by-products effectively, efficiently, and economically, while producing electricity through distributed biogas resources when possible. This on-farm anaerobic digestion monitoring project is being conducted as a support component of NYSERDA's Industrial and Agricultural Waste Management Program. The project focus is to monitor, test, and evaluate anaerobic digestion systems, and disseminate the findings to dairy producers and their advisors so they can make efficient use of biogas for production of electricity and heat.

The objectives of this project are to:

1) Perform initial monitoring of performance and characterization of the system outputs.
2) Develop a greater understanding of the performance of components of the overall digester system (Future testing will be performed for key parameters and components at selected sites.)
3) Build on the results of the baseline monitoring and the shorter-term select testing by identifying and evaluating opportunities for optimizing the anaerobic digester systems. Experimental testing may be performed to assess the potential for promising optimization opportunities.
4) Transfer the findings of the work to participating digester system operators and other farmers, agricultural consultants, equipment designers, digester service businesses, government agencies, and others who can use the project results to optimize the performance of digester systems and increase their energy, environmental and economic benefits.

This report primarily focuses on objectives 1, 2 and 4.

This project provided funding for sampling materials, sample analysis, and recording operational data needed to document and evaluate the performance of five selected digesters for several years. The scope of work for the project included collecting and analyzing data in the areas of: 1) system energy production, farm use, and sale to the grid, 2) manure nutrients that are important for environmental management and field crop utilization, 3) on-farm performance of solid-liquid separators, and 4) selected pathogens that are important for human and animal health. Data collected will be used to identify opportunities for system optimization, and it is anticipated that select optimizations will be tested on collaborating farms as Phase II of this project. The initial work at AA Dairy, one of the five anaerobic digesters monitored by this project, was done in cooperation with the AgSTAR program sponsored by U.S. EPA, DOE, and USDA.

Greater adaptation of anaerobic digesters should occur with documentation of their reliability and knowledge of the important factors to consider when designing and operating these systems. Using dairy manure alone some 15 MW of power could be produced, with greater production possible if optimization opportunities are proven. By reducing odorous gases, digesters can help allow for better timing of recycling manure to cropland resulting in the reduction of runoff of nutrients and pathogens to receiving water bodies and reduced purchases of inorganic fertilizer. Since expensive natural gas is the main feedstock for most nitrogen fertilizers, reducing fertilizer purchases becomes more important for farm profitability as energy prices rise.

Anaerobic Digestion Overview

The anaerobic digestion process biologically converts organic matter (agricultural by-products), in a multi-step process, into biogas. Methane (CH_4) and carbon dioxide (CO_2) are the two predominate gases that make up biogas with concentrations typically in the range of 55 to 68 and 32 to 45 percent, respectively. Biogas also contains trace gases, most notably hydrogen sulfide (H_2S). Biogas can be used as a fuel source for engine-generator sets to produce electricity for on-farm use and sale to the grid or in boilers to make hot water for heating purposes. At this time, most farms also have a flare primarily to burn excess biogas although interest has been shown in determining the carbon credit potentials when flaring biogas. The biomass residue remaining after digestion contains less volatile organic matter so it has fewer odors (Parsons, 1984) and can be recycled as organic nutrients on the farm's land base or sold.

Energy Production

The amount of energy produced by an anaerobic digester depends on many factors including operating temperature (both magnitude and consistency), percent of biologically degradable organic material in the feedstock, and retention time. A rule of thumb is on-farm anaerobic digesters that process dairy manure can produce sufficient energy from ten cows worth of manure to make about one kW of power (Koelsch et al., 1990). The additional food waste to manure greatly increases energy production.

Nutrients

Digester effluent has increased concentrations of ammonia-nitrogen (NH_3-N) and ortho phosphorus (OP) over that of the influent, both of which are readily available for utilization by growing plants. In the case where post-digested effluent is spread on cropland (when crops are not growing) the possibility of NH_3-N and OP mobilizations outside of the plant root zone exists, possibly contributing to eutrophication of receiving surface water bodies and contamination of groundwater sources. For Northeastern U.S. farms to maximize the nutrient value of post-digested manure a minimum of 9-months of storage is needed; at this time the manure storage period is significantly less on most farms. Land application methods of post-digested material, assuming odor control is achieved, can result in reduced application costs. For example, the cost to spray irrigate manure on cropland can be as low as one-quarter of one cent per gallon while tanker spreading can cost as much as two to two and one-half cents per gallon. Spray irrigation of untreated manure that has been stored long-term is generally not acceptable due to odor emissions.

Pathogens

Manure-borne pathogens are a concern to both human and cattle health. Pasteurization, chemical treatment, and separation from the generating source are the primary methods used to kill pathogens. The anaerobic digestion process can be beneficial to both dairy cows and humans through the reduction of pathogens entering the environment, specifically *M. avium paratuberculosis* (Johne's disease) and fecal coliform.

Project Background

The five New York State dairy farms that participated in the initial phase of the project were AA Dairy (AA) in Candor, Dairy Development International (DDI) in Homer, J.J. Farber Farm (FA) in East Jewett, Matlink Farms (ML) in Clymer, and Noblehurst Farms, Inc. (NH) in Linwood. AA, DDI and NH constructed plug flow digesters. The digester at ML was a mixed digester that digested imported food waste pre-blended with dairy manure. (Accepting food waste was a strategy to increase biogas production and collect waste tipping fees both with the goal of increasing revenue generated by the system.) The digester at FA was originally an experimental fixed-film unit implemented with the goal to determine if this type of digester, with a four-day retention time using liquid effluent from a solid-liquid manure separator as a digester feed source, could function in a cold climate and successfully control odor. The primary reason that each farm constructed an anaerobic digester was to reduce odor emissions from the dairy.

Farm Information

Detailed information for each farm participating in the study can be found in the case studies written as part of this project. Included in each case study is the digester system layout, biogas utilization system, combined heat and power (CHP) information, manure handling system description, economic information, system advantages and disadvantages, lessons learned, and farm contact information. A web site link to each case study is provided in the publications section of this report, or they can be found at http://www.manuremanagement.cornell.edu/. The initial case studies for each farm were written in June 2004. A waste treatment flow diagram for AA, DDI, ML and NH is shown in Figure 1 and for FA in Figure 2. Milking center wastewater is not processed by anaerobic digestion at AA, DDI, ML, and NH.

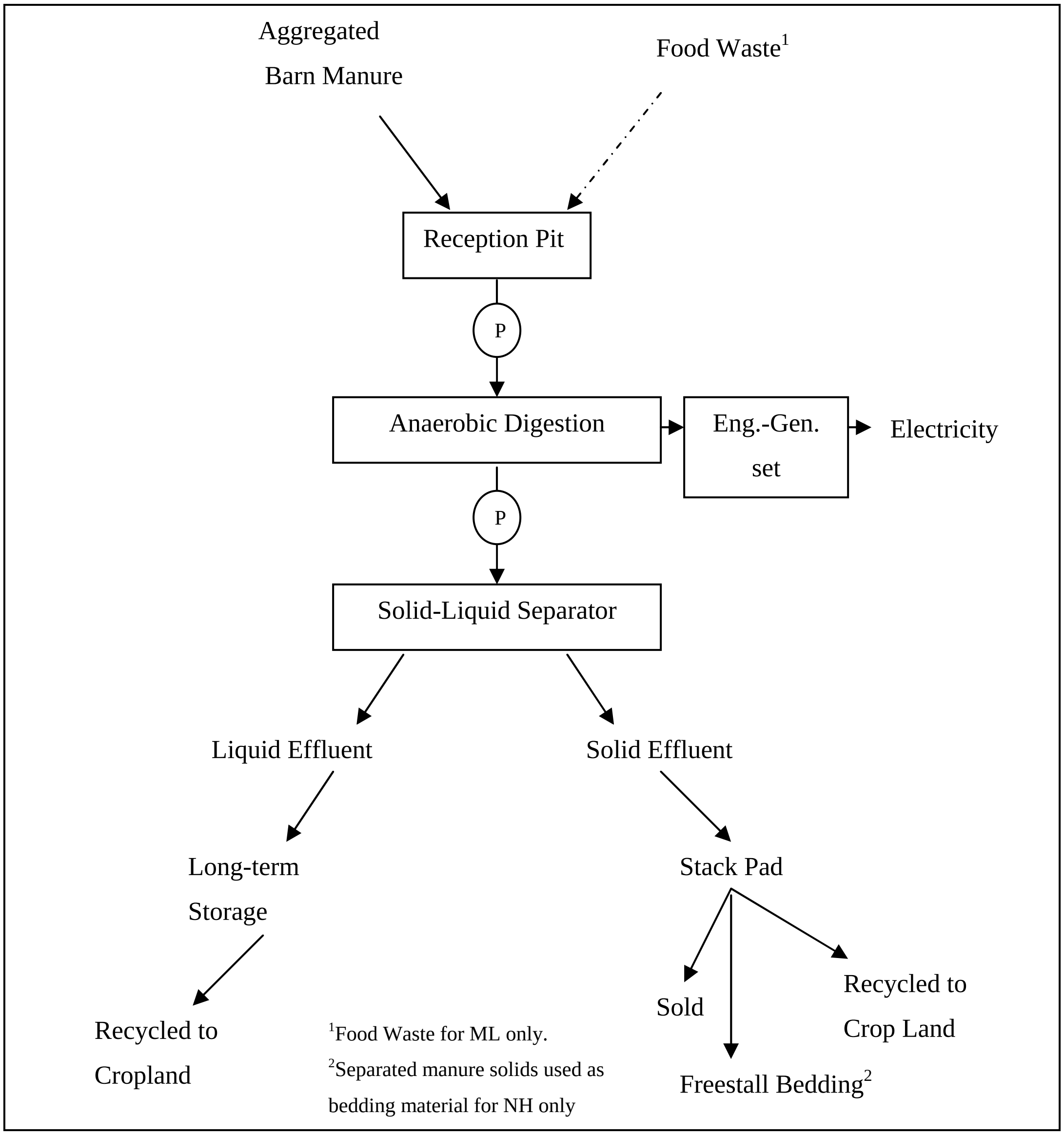

Figure 1. Waste treatment system flow diagram for AA, DDI, ML and NH.

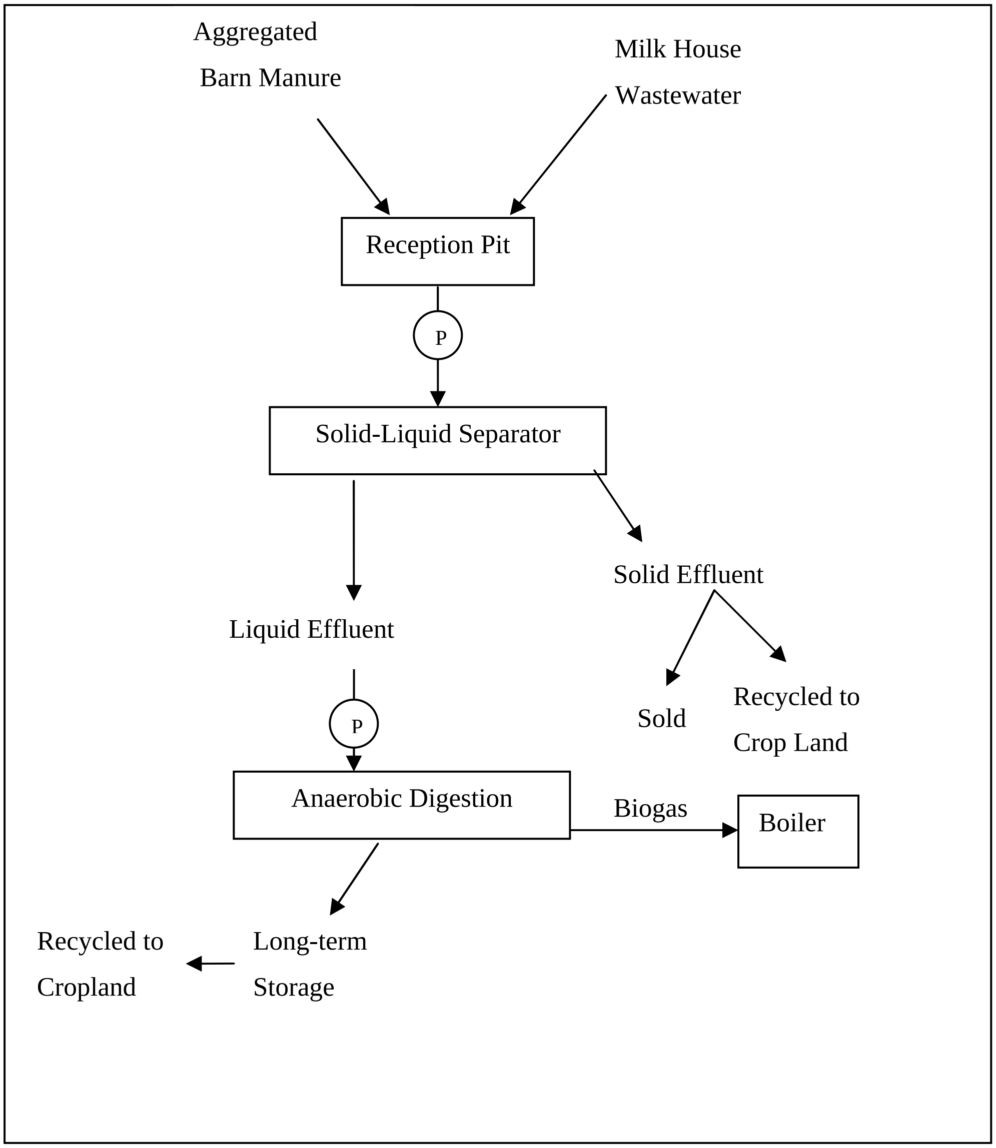

Figure 2. Waste treatment system flow diagram for FA.

Herd Size

The daily number of cows in the herd on test day at each farm, based on data obtained from DHI-202 herd summary records, is shown in Table 1. For DDI and ML, where test data was not available for every month, the rolling average number of cows is shown. Overall, this data cannot be used in equations as independent variables in most cases since it does not accurately represent all waste sources digested.

Table 1. Daily number of cows in the herd on test day for all farms from January 2004 to May 2005.

Month	AA	DDI	FA	ML	NH
January 2004	573	991	105	511	1,303
February 2004	578	991	105	497	1,226
March 2004	560	922	103	497	1,179
April 2004	545	981	104	516	1,186
May 2004	539	972	104	499	1,180
June 2004	528	970	104	499	1,421
July 2004	519	970	113	543	1,431
August 2004	519	947	113	505	1,454
September 2004	525	960	114	505	1,484
October 2004	522	952	117	571	1,492
November 2004	514	956	111	521	1,493
December 2004	512	949	110	521	1,499
January 2005	512	959	113	571	1,516
February 2005	513	952	110	540	1,506
March 2005	510	957	106	540	1,493
April 2005	511	967	105	575	1,481
May 2005	515	957	107	556	1,526

Digester Loading

All five digesters were loaded with a pumping system. A Houle piston pump was used at AA and DDI. At AA, the pump was controlled by a time clock that automatically ran the pump continuously for approximately 4 hours daily while at DDI a countdown timer was used to automatically turn off the pump after it was manually started. The DDI time clock was typically set to run the influent pump continuously for 2-3 hours daily. Centrifugal pumps were used at ML, NH, and FA. At ML, food waste was pumped into a mix tank and mixed with dairy manure four times per day; the resulting mixture was pumped into the digester six times a day. The mix tank impeller agitator ran for 5 minutes twice each day. The digester influent pump at NH was controlled automatically using a float control system. At FA the influent pump was controlled by a time clock set to feed the digester initially 12 then later 24 times daily. Calibration of the influent pumps is discussed later in this report.

Loading Rates

The estimated daily average loading volume for each digester is shown in Table 2. Missing table values represent times when digester influent loading data was not available. The methods used to collect and calculate the average loading rate varied between farms. For AA and DDI, the influent pump calibration data (Table 3), was used in conjunction with the pump daily operating time to obtain the estimated loading volume. For ML and NH, the farm owners provided the estimated daily loading values based on their observations. At FA, the loading volumes were obtained from project data collected under NYSERDA project No. 6249. The estimated daily loading values for AA, DDI, and FA were considered sufficiently accurate to use in equations as values for predictor variables.

Influent volumes for AA and NH are consistent from month to month. The digester influent pump at AA was on a time clock and its settings were not changed. Volumes for NH were estimated by the producer and the estimation did not change throughout the monitoring period.

Pump Calibration

The Houle piston pump used to load the DDI digester was calibrated by measuring the change in manure depth in the manure reception pit every 5 minutes over the period of time to load the digester for a day. Manure reception pit recharge rate subsequent to pumping was measured every 10 minutes for the next two hours. The results of the test are summarized in Table 3.

Future loading calculations will be based on data collected by an ultrasonic level detector or similar device installed on selected farms. Depth to manure level data will be used in combination with the dimensions of the influent and effluent reception tanks to more accurately quantify the daily digester influent values.

Table 2. Estimated digester daily loading (gallons per day) for all farms by month from January 2004 to May 2005.

Month	Substrate	AA[1]	DDI[1]	FA[1]	ML[2,3]	NH[2]
January 2004	Manure	11,055	24,259	709	14,000	18,000
	Other	-	-	-	5,000	-
February 2004	Manure	11,055	28,302	709	12,000	18,000
	Other	-	-	-	14,000	-
March 2004	Manure	11,055	25,000	857	12,000	18,000
	Other	-	-	-	10,000	-
April 2004	Manure	11,055	28,302	896	-	18,000
	Other	-	-	-	-	-
May 2004	Manure	11,055	25,000	1,040	17,000	18,000
	Other	-	-	-	15,000	-
June 2004	Manure	11,055	25,000	1,181	-	18,000
	Other	-	-	-	-	-
July 2004	Manure	11,055	25,000	1,181	13,000	18,000
	Other	-	-	-	4,000	-
August 2004	Manure	11,055	24,259	1,181	15,000	18,000
	Other	-	-	-	15,000	-
September 2004	Manure	11,055	20,000	1,181	15,000	18,000
	Other	-	-	-	12,000	-
October 2004	Manure	11,055	24,000	1,155	15,000	18,000
	Other	-	-	-	12,000	-
November 2004	Manure	11,055	24,000	1,155	22,000	18,000
	Other	-	-	-	7,000	-
December 2004	Manure	11,055	24,500	1,155	15,000	18,000
	Other	-	-	-	10,000	-
January 2005	Manure	11,055	24,259	1,155	14,000	18,000
	Other	-	-	-	3,500	-
February 2005	Manure	11,055	26,280	1,155	12,000	18,000
	Other	-	-	-	6,000	-
March 2005	Manure	11,055	20,793	1,155	15,000	18,000
	Other	-	-	-	10,000	-
April 2005	Manure	11,055	12,129	1,155	15,000	18,000
	Other	-	-	-	12,000	-
May 2005	Manure	11,055	15,000	1,155	15,000	18,000
	Other	-	-	-	13,000	-

[1]Based on pump calibration test data

[2]Estimated values by producer

[3]Manure and food waste combined

Table 3. Results from Houle piston pump calibration at DDI.

Results	
Average pumping (inches/minute)	-0.535
Average filling (inches/minute)	0.071
Average pumping (filling factored in):	-0.606
Total surface area (in^2)	49,662
Average volume pumped out (cubic inches/min)	30,076
Average volume pumped out (gallons/minute)	129.9
Average (gallons/stroke)	43.3

The Houle piston pump at AA is the same make and model tested at DDI and therefore, it was assumed that the pump at AA also displaced 43 gallons/stroke. Rate of delivery (gallons per minute) of the pump at AA was calculated per site conditions at the farm. Site conditions at AA included total pump run time and frequency of stokes per minute.

Digester Design Parameters

An overview of each farm's digester system information is shown in Table 4.

Table 4. Digester system information.

Farm	AA	DDI	FA[5]	NH	ML
Digester type	Plug flow	Plug flow	Fixed-film (originally) Vertical plug flow (currently)	Plug flow (two parallel cells)	Mixed
Design temperature (F)	100	100	100	100	100
Cover material	Soft top (Hypalon 45)	Soft top (Hypalon 45)	Hard top (Precast concrete)	Hard top (Precast and cast-in-place concrete)	Soft top (Hypalon 45)
Construction material	Cast-in-place concrete	Cast-in-place concrete	Precast concrete	Cast-in-place concrete	Cast-in-place concrete
Insulation	4" Styrofoam on walls	4" Styrofoam on walls	4" Styrofoam below-grade 4" Urethane foam above-grade 2" Styrofoam on 80% of top	4" Styrofoam on walls and floor	4" Styrofoam on walls
Influent	Raw manure	Raw manure	Separated liquid manure	Raw manure	Raw manure and food waste[4]
Dimensions (ft) (W,L,H)	30,130,14	30,118,19	10.5 diameter 16 high	50, 120,16 (each cell is 25 wide)	68,78,16
Manure depth (ft)	14	19	12	15	16
Treatment volume (gallons)	408,436	503,139	7,768	673,246	634,826
Estimated hydraulic retention time[3] (days)	37	20	4.8[1] 8.1[2]	37	25
Estimated total loading rate (gpd)	11,000	25,000	1,733-1950[1] 959-1537[2]	18,000	25,000
Biogas utilization	Caterpillar engine with 130 kW generator	Biogas boiler, 2 low BTU Capstone microturbines 30 kW each	Biogas boiler	Caterpillar engine with 130 kW generator	Biogas boiler, food dryer Waukesha engine with 145 kW generator
Stall bedding material	Sawdust	Sawdust	Sawdust and paper waste	Sawdust and digested separated manure solids	Sawdust, digested separated manure solids, and coco shells

[1] For the period 6/2/02 to 4/25/03 when the digester was performing as a fixed-film digester. Pre-treatment of raw manure by solid-liquid separation; liquid effluent digested only.
[2] For the period after 8/21/03 when the digester was performing as a vertical plug flow digester. Pre-treatment of raw manure by solid-liquid separation; liquid effluent digested only.
[3] Total vessel treatment volume / estimated daily loading rate.
[4] Food waste includes by-products from processing milk, grapes, and fish.
[5] This system treated milk house wastewater in the digester.

Testing and Monitoring

Differences in construction schedules, final construction completion dates, and commissioning periods resulted in various monitoring start dates for each digestion system as shown in Table 5.

Table 5. Digester influent/effluent sampling start dates.

Farm	Monitoring Starting Date
AA	May, 2001
DDI	January, 2002
FA	June, 2001
ML	March, 2003
NH	August, 2003

Influent and effluent grab samples were taken monthly in most cases for all digesters monitored. Samples were analyzed in the laboratory for some or all of the following constituents as appropriate: total Kjeldahl nitrogen (TKN), ammonia-nitrogen (NH_3-N), total phosphorous (TP), ortho phosphorous (OP), total potassium (K), copper (Cu), pH, volatile acids calculated and reported as acetic acid (Acetic A), chemical oxygen demand (COD), dissolved COD (DCOD), fecal Coliform (F. Coli.), Johne's disease (MAP), total solids (TS) and total volatile solids (TVS). Organic-nitrogen (ON) was determined by subtracting NH_3-N from TKN. Sampling points for each farm include digester influent and effluent and the two effluent streams from the solid-liquid separator.

The constituents TKN, NH_3-N, ON, TP, OP, and K are important from a crop nutrient management perspective while pH, Acetic A, COD, DCOD, TS, and TVS can be used to evaluate the performance of an anaerobic digester. Quantification of TS and TVS consumed (Minott, 2002) and COD consumed (Metcalf and Eddy, Inc, 2003) by the anaerobic digestion process can be used to predict biogas production. An understanding of the reductions of MAP and F. Coli can be used to quantify the effect of the anaerobic digestion process on overall pathogen reduction.

AA, DDI, ML, and NH each had a digester/engine-generator set performance log sheet that included the following categories: biogas used, biogas flared (where available), energy generated, energy purchased, energy sold, digester heating loop temperature to and from the digester, digester temperature, and, for ML, the number of cows and heifers supplying manure to the digester. Some farms recorded this information daily and others weekly. Data from these logs were entered monthly into Microsoft EXCEL.

The project purchased two portable ultrasonic flow meters, a Dynasonics Model No. TFXP ($6,190) and a Dynasonics Model No. TFXD ($3,382), to measure the heat used to operate the digesters. Portable temperature sensors (Hobo Pro, Onset Computer Corp. ($1,725)) were also purchased to record ambient temperature and digester influent and effluent temperatures. This equipment was shared between farms; it was located at a pair of farms for a month and then relocated to another pair of farms.

Engine parameters recorded by the project were obtained from instrumentation installed by each farm that generated electricity. The instrumentation at AA and ML was purchased from Martin Machinery and at NH from Perennial Energy.

Biogas carbon dioxide concentrations were measured during the same site visits when heat flow equipment was installed. Additionally, digester operators periodically measured and recorded carbon dioxide concentration.

In a combined effort with another NYSERDA funded project with Connected Energy Corp., this project instrumented ML and NH with the equipment shown in Table 6. Future plans include installing similar instrumentation at AA and DDI.

Table 6. Equipment purchased in collaboration with the Connected Energy project.

	AA	DDI	ML	NH
Water flow meter	-	-	Onicon F-1120 (3@$920=$2,760)	Onicon F-1120 (2@$920=$1,840)
Influent pit and digester temperature	-	-	Minco S100479PE18Z3 (5@$125 = $625)	Minco S100479PE18Z3 (1@$125 = $125)
Heating pipe temperature	-	-	Minco S464PBZ6A (6@$48 = $293)	Minco S464PBZ6A (4@$48 =$192)
Ambient temperature	-	-	Minco S414PBZ (1@$45 = $45)	Minco S414PBZ (1@45 = $45)
Gas meter – engine-generator set	Roots 3M175 CTR/SSM B3 ($2,308)	-	Roots 11H175 CTR/SSM B3 ($3,977)	Roots 5M175 CTR/SSM B3 (2@$2,612 = $5,224)
Gas meter – flare	-	-	Fluid Components International (FCI) GF90 ($3,922)	-
CH_4 monitor	-	-	Conspec P2263XP-IR ($900)	-

Monitoring equipment used before the Connected Energy project came on-line and on the farms where the Connected Energy project has not started is shown in Table 7.

Table 7. Equipment used to obtain data.

	AA	DDI	FA	ML	NH
Engine parameters (hrs, kWh)	Equipment purchased from Martin Machinery	-	-	Equipment purchased from Martin Machinery	Equipment purchased from Perennial Energy
Digester heating water flow meter	Dynasonics TFXP, TFXD	Dynasonics TFXP, TFXD	In-line meter from Mitchell Instruments	Dynasonics TFXP, TFXD	Dynasonics TFXP, TFXD Onicon
Digester and reception pit temperature	Onset HOBO, Extech EasyView 10	Onset HOBO, Extech EasyView 10	Omega MDSS41-TC (digester only)	Onset HOBO, Extech EasyView 10	Onset HOBO, Extech EasyView 10
Digester heating pipe temperature	Minco S464PBZ6A	Minco S464PBZ6A	In-line from Mitchell Instruments	Minco S464PBZ6A	Minco S464PBZ6A
Ambient temperature	Onset HOBO	Onset HOBO	Omega MDSS41-TC	Onset HOBO	Onset HOBO
Gas meter – engine-generator set	Roots 3M175 CTR/SSM B3	Roots 3M175 SSM B3	Roots 2M175 SSM B3	Roots 11H175 CTR/SSM B3	Roots 5M175 CTR/SSM B3
Gas meter – flare	-	-	-	Fluid Components International (FCI) GF90 ($3,922)	-
CO_2 measurement	Bacharach Fyrite (0-60%)	Bacharach Fyrite (0-60%)	Bacharach Fyrite (0-60%)	Bacharach Fyrite (0-60%)	Bacharach Fyrite (0-60%)
CH_4 line monitor	-	-	-	Conspec P2263XP-IR	-

Digester Influent and Effluent Sampling Protocol and Analytical Procedures

The following protocol was followed to sample the digester influent, effluent and solid-liquid manure separator effluent streams from project initiation until August 2001 at AA.

1. Label sample containers with date, time, farm, location.
2. Sample from lowest pathogen concentration to highest pathogen concentration; i.e. digester effluent, solid-liquid manure separator streams, and lastly digester influent.
3. Collect separator solid effluent in a clean, 25-gallon Rubbermaid storage container until it is about half full. Mix the contents of the container by hand, and take a sub-sample from the mixed batch and place sample in one 4-oz. sample container.
4. Place the sealed sample container in cooler filled with ice.
5. Use a clean 5-gallon pail to collect separated liquid from the closest discharge pipe available. Fill the pail until it is ¾ full by placing the pail in the separated liquid effluent stream. Mix the contents of the pail. Pour the mixed contents into one 4-oz. sample container.
6. Place in cooler filled with ice.

7. Digester effluent was sampled using a dipper to take ten non-interrupted continuous 16-oz. sub-samples from the overflow of the weir when manure is flowing freely from digester. All 10 samples were combined in a clean 5-gallon pail and mixed thoroughly. A 4-oz. composite sample was taken from the pail and placed on ice.
8. The dipper was thoroughly rinsed with clean water.
9. The dipper was used to take ten non-interrupted continuous 16-oz sub-samples of well-agitated raw manure from the raw manure storage tank. Each sample was combined in a clean 5-gallon pail and mixed thoroughly. A 4-oz. composite sample was taken from the pail and placed on ice.
10. All samples were delivered to the lab within 24 hours.

After August 2001 the sampling protocol was adjusted in an effort to reduce settling in the 5-gallon pails and to reflect a true grab sample protocol. The sampling protocol used after August 2001 for all farms was as follows.

1. Label the sample cups with date, time, farm, location.
2. Sample from lowest pathogen concentration to highest pathogen concentration i.e. the digester effluent before digester influent, and the solid-liquid manure separator effluent streams before the digester. At FA, because the separator was located upstream of the digester, the digester was sampled first, then the solid-liquid manure separator effluent streams, and finally the raw manure pit.
3. If manure was not flowing over the effluent weir, digester effluent samples were collected using a 16-oz. dipper, and transferred to a 4-oz. sample container. Typically, digester effluent samples were collected while the digester was loaded, resulting in flow over the digester effluent weir. Any solids build-up was removed such that digester effluent could flow over the entire weir prior to sampling. A 4-oz sample was obtained by placing a 4-oz. sample container in the digester effluent stream.
4. Separated liquid effluent was sampled by placing the 4-oz. container directly in the stream of the separated liquid effluent.
5. Separated solid samples were taken directly from the separated solid effluent stream. Collected solids were placed directly in a 4-oz. sample container.
6. Raw manure was collected by using a 16-oz. dipper. The dipper was filled completely with well agitated manure. Manure was transferred immediately from the 16-oz. dipper into the 4-oz. sample container.
7. Collected samples were placed in a cooler filled with ice immediately after sample was collection.

When triplicate samples were taken (at FA from March 2004 to December 2004) the sampling procedure above was performed three times.

Laboratory Procedures

Collected samples were analyzed singularly at Certified Environmental Services, Inc. (CES) located in Syracuse, New York for all constituents except Johne's disease (MAP). The testing for MAP was performed at the Cornell Veterinary School Diagnostic Lab. The analytical methods used to determine constituent concentrations are shown in Table 8. All samples were analyzed by the laboratories on an as-received basis.

Table 8. Laboratory analytical methods.

Sampling / Monitoring Parameter	Test Method
Total Solids (TS)	EPA 160.3
Total Volatile Solids (TVS)	EPA 160.4
Total Phosphorous (TP)	EPA 365.3
Ortho Phosphorous (OP)	EPA 365.3
Total Kjeldahl Nitrogen (TKN)	EPA 351.4
Ammonia-Nitrogen (NH_3-N)	SM18 4500F
Organic-Nitrogen (ON)	By subtraction: TKN - NH_3-N
Total Potassium (K)	EPA SW 846 6010
Total Copper (Cu)	SW846 6010
Fecal Coliform (F. Coli.)	SM18 9221E
Johne's Disease (MAP)	Cornell method
Volatile Acid as Acetic Acid (Acetic A)	SM18 5560C
Dissolved COD (DCOD)	SM18 5220B
Chemical Oxygen Demand (COD)	SM18 5220B
pH	SW846 9045

Each sample was analyzed for MAP by the Cornell Diagnostic Laboratory using a procedure they developed and that is recognized as the industry standard method for MAP concentration determination. For the test, 0.15 mL of each sample was diluted in three tubes with 1, 10 and 100 mL of water and the largest MAP population count was reported to give a worst case scenario for the result. Note: MAP concentration is calculated differently by different labs but it is generally reported as cfu/gram (Stabel, 1997; Whitlock, et al., 2000).

CES also had to perform dilutions of the manure samples for several of the analysis they performed. The total solids, total volatile solids, and pH analysis were performed on the samples as received. The TP, OP, TKN, NH_3-N, K, F Coli., Acetic A, DCOD, and COD constituents were determined from a dilution of 40 mL from each sample collected from the digester influents, effluents, and solid-liquid separator influents and liquid effluents with 40 mL of distilled water. These same constituents were determined from 15 grams of each sample collected from the solid effluents from the solid-liquid separators. All diluted samples were blended in a blender prior to analysis.

Project Data

The data and analyses developed to date are as follows.

Digester Influent and Effluent Sampling Results

The values in Tables 9 and 10 are the average (Ave), standard deviation (St. Dev.), 99 percent confidence interval (CI) and the number of samples (n) for the digester influent and effluent samples. A confidence interval for a mean specifies a range of values within which the unknown population parameter, in this case the mean, may lie (Easton and McColl, 2005). An example using Table 9 is as follows. The mean $\log_{10}$ MAP and its associated confidence interval for AA is 3.9±0.1. There is a level of confidence of 99% that the true population mean is in the range of 3.9 – 0.1 and 3.9 + 0.1 or 3.8 to 4.0.

All samples are included in Tables 9 and 10 as reported from the laboratory except for ML calculated influent. ML calculated influent is the weighted average of the food waste and manure lab data multiplied by their associated estimated volumes.

The data shows that the food wastes imported to ML varied in constituent concentration when compared to the farm's manure. As would be expected, the concentration of F. Coli was much less in food waste compared to manure. The concentrations of Acetic A, TKN, and ON were very similar for the food wastes and manure while the food waste concentration of NH_3-N, TP, OP, and K were lower than manure. From a comprehensive nutrient management plan (CNMP) perspective, a unit of food waste contained overall less nutrients by mass compared to a unit of manure on this farm. (Note: a recent analysis of a food waste sample collected from a cheese plant had a TP concentration about four times greater than cow manure.) Average food waste concentrations for DCOD, COD, TS, and TVS were 16, 46, 50, and 53 percent, respectively greater than the ML manure average values. These comparatively higher concentrations provided more biogas production potential for food wastes mixed with manure than just manure alone. Overall, the addition of food wastes added more biogas production potential per unit volume and less nutrients of concern with respect to the farm's CNMP than adding more cow manure alone.

Table 9. Digester influent constituent concentrations for all farms.

Constituent	Statistic	AA[A]	DDI[B]	FA Fixed-Film[1,C]	FA Vertical Plug Flow[1,D]	ML Manure[E]	ML Food Waste[F]	ML Calculated Influent	NH[G]
Log_{10} MAP (cfu/gram)	Ave	3.9	3.3	-	-	3.1	-	3.0	3.6
	St. Dev.	0.5	0.6	-	-	0.8	-	0.8	0.4
	CI	0.1	0.4	-	-	0.6	-	0.6	0.3
	n	65	17	-	-	13	-	13	11
Log_{10} F. Coli. (mpn/gram)	Ave	6.1	5.9	5.5	5.9	5.5	1.0	5.4	6.0
	St. Dev.	0.8	0.9	0.7	0.5	0.6	1.1	0.6	0.6
	CI	0.2	0.5	0.5	0.2	0.3	0.6	0.3	0.3
	n	73	27	12	46	24	23	24	19
Acetic A (mg/kg)	Ave	3,273	3,688	-	2,799	3,382	3,654	3,623	2,881
	St. Dev.	1,368	1,005	-	799	1,174	2,035	1,277	1,021
	CI	536	402	-	217	451	798	671	437
	n	25	24	-	52	26	25	24	21
DCOD (mg/l)	Ave	24,331	22,797	22,463	23,583	38,712	46,335	39,111	23,508
	St. Dev.	8,315	7,877	4,656	6,453	11,624	22,330	11,956	11,021
	CI	1,894	3,028	2,866	2,582	4,650	8,934	6566	4,714
	n	74	26	10	24	24	24	22	21
COD (mg/kg)	Ave	125,875	103,496	54,028	57,184	171,761	364,169	200,756	78,586
	St. Dev.	174,622	66,317	4,439	11,284	82,745	206,665	103,487	28,638
	CI	39,520	25,014	2,623	3,097	32,435	82,682	55583	12,248
	n	75	27	11	51	25	24	23	21
TKN (mg/kg)	Ave	4,782	3,682	3,898	3,718	3,366	3,086	3,174	4,075
	St. Dev.	1,275	641	722	584	984	1,118	877	974
	CI	289	238	365	163	386	447	471	416
	n	75	28	15	49	25	24	23	21
NH_3-N (mg/kg)	Ave	1,876	1,866	2,140	2,226	1,296	571	1,177	1,944
	St. Dev.	474	423	345	330	558	234	438	634
	CI	107	157	175	90	214	92	230	271
	n	75	28	15	52	26	25	24	21
ON (mg/kg)	Ave	2,908	1,815	1,758	1,485	2,095	2,392	1,944	2,130
	St. Dev.	1,167	613	679	505	643	1,212	698	923
	CI	264	227	344	141	252	475	367	395
	n	75	28	15	49	25	25	24	21
TP (mg/kg)	Ave	803	561	659	517	570	446	534	503
	St. Dev.	241	105	100	94	189	168	143	148
	CI	55	39	51	26	73	66	75	63
	n	75	28	15	52	26	25	24	21
OP (mg/kg)	Ave	457	298	382	313	329	198	296	242
	St. Dev.	132	92	62	56	137	119	90	80
	CI	30	34	31	15	53	47	47	34
	n	75	28	15	52	26	25	24	21
K (mg/kg)	Ave	1,927	2,425	-	2,756	2,756	931	2,742	2,374
	St. Dev.	299	341	-	638	875	1,165	909	422
	CI	169	193	-	232	458	633	649	239
	n	12	12	-	29	14	13	13	12
TS (percent)	Ave	11.15	9.81	4.96	5.36	13.06	26.1	15.5	10.4
	St. Dev.	1.24	1.55	0.42	0.65	4.16	18.7	8.21	2.29
	CI	0.28	0.58	0.21	0.18	1.60	7.34	4.31	0.98
	n	75	28	15	52	26	25	24	21
TVS (percent)	Ave	9.44	8.21	3.37	3.75	11.73	25.21	14.31	7.72
	St. Dev.	1.05	1.40	0.39	0.52	4.19	18.8	8.33	1.91
	CI	0.24	0.52	0.20	0.14	1.61	7.37	4.38	0.82
	n	75	28	15	52	26	25	24	21
Cu (mg/kg)	Ave	16.08	50	-	-	12	2.82	7.00	15.7
	St. Dev.	8.95	19	-	-	11	0.73	2.68	6.2
	CI	3.92	18	-	-	10	0.64	3.45	6.08
	n	20	4	-	-	5	5	4	4
pH (Std. units)	Ave	7.24	7.48	7.34	7.35	5.43	3.65	5.36	7.42
	St. Dev.	0.32	0.47	0.18	0.27	0.96	0.77	0.83	0.39
	CI	0.07	0.18	0.9	0.07	0.37	0.30	0.44	0.17
	n	75	28	15	52	26	25	24	21

[1]The influent for digester at FA is the same as the separator liquid effluent. [A]AA was sampled monthly from 5/2001 – 6/2002 and 7/2003 – 4/2005. [B]DDI was sampled monthly from 1/2002 – 8/2002 and 7/2003 – 4/2005. [C]FA fixed-film was sampled monthly from 11/2001 – 4/2003. [D]FA vertical plug flow was sampled monthly, and for some periods more intensively, from 8/2003 – 9/2004 and one sample during 12/2004. [E]ML manure was sampled monthly from 3/2003 – 4/2005. [F]ML food waste was sampled monthly from 3/2003 – 4/2005. [G]NH was sampled monthly from 8/2003 – 4/2005.

Table 10. Digester effluent constituent concentrations for all farms.

Constituent	Statistic	AA[A]	DDI[B]	FA Fixed-Film[C]	FA Vertical Plug Flow[D]	ML[E]	NH Digester Cell 1[F]	NH Digester Cell 2[G]
Log (MAP) (cfu/gram)	Ave	1.8	1.5	-	-	2.0	1.7	2.0
	St. Dev.	0.6	0.3	-	-	0.5	0.4	0.4
	CI	0.2	0.2	-	-	0.4	0.4	0.4
	N	59	15	-	-	11	9	8
Log (F. Coli.) (mpn/gram)	Ave	3.1	3.5	3.8	4.4	3.4	3.5	3.8
	St. Dev.	0.7	0.9	0.9	0.8	0.6	0.7	0.5
	CI	0.2	0.5	0.6	0.3	0.3	0.4	0.3
	N	70	24	15	43	22	17	17
Acetic A (mg/kg)	Ave	871	1,658	929	1,077	469	569	589
	St. Dev.	1,582	1,416	484	775	273	270	395
	CI	620	566	274	213	105	115	169
	N	25	24	12	51	26	21	21
DCOD (mg/l)	Ave	16,053	17,711	16,411	19,577	13,244	20,211	18,168
	St. Dev.	6,555	7,520	3,838	5,736	7,257	8,060	5,869
	CI	1,494	2,890	2,379	2,295	2,903	3,447	21
	N	74	26	10	24	24	21	2510
COD (mg/kg)	Ave	88,993	88,232	45,309	46,669	63,070	63,107	63,067
	St. Dev.	76,921	12,620	13,764	44,224	12,516	17,272	17,846
	CI	17,409	47,760	8,134	12,137	4,906	7,387	7,633
	N	75	27	11	51	25	21	21
TKN (mg/kg)	Ave	5,145	3,717	3,830	3,854	3,263	4,203	4,001
	St. Dev.	1,292	928	737	575	513	869	829
	CI	292	344	373	161	201	372	355
	N	75	28	15	49	25	21	21
NH_3-N (mg/kg)	Ave	2,588	2,294	2,439	2,636	1,326	2,516	2,329
	St. Dev.	421	454	314	357	381	464	515
	CI	95	168	159	100	146	199	220
	N	75	28	15	49	26	21	21
ON (mg/kg)	Ave	2,556	1,815	1,391	1,218	1,921	1,687	1,672
	St. Dev.	1,292	613	790	564	421	749	681
	CI	292	227	400	158	165	321	291
	N	75	28	15	49	25	21	21
TP (mg/kg)	Ave	811	556	627	487	553	518	514
	St. Dev.	220	126	94	116	122	102	92
	CI	50	47	48	32	47	44	39
	N	75	28	15	51	26	21	21
OP (mg/kg)	Ave	534	325	440	360	290	310	290
	St. Dev.	122	84	61	83	89	40	56
	CI	28	31	31	23	34	17	24
	N	75	28	15	51	26	21	21
K (mg/kg)	Ave	2,216	2,530	-	2,650	2,592	2,363	2,499
	St. Dev.	401	342	-	628	590	580	500
	CI	227	194	-	225	309	328	283
	N	12	12	-	30	14	12	12
TS (percent)	Ave	8.08	7.25	3.99	4.62	5.60	8.52	8.20
	St. Dev.	1.08	1.56	0.54	1.12	0.74	1.31	1.57
	CI	0.24	0.58	0.27	0.31	0.29	0.56	0.67
	N	75	28	15	51	26	21	21
TVS (percent)	Ave	6.43	5.81	2.60	2.89	4.35	6.51	6.26
	St. Dev.	0.91	1.47	0.45	0.33	0.51	1.22	1.39
	CI	0.21	0.55	0.23	0.09	0.20	0.52	0.60
	N	75	28	15	51	26	21	21
Cu (mg/kg)	Ave	31	74	-	-	15.4	15.3	20.75
	St. Dev.	14	12	-	-	3.51	6.15	4.86
	CI	6.4	12	-	-	3.07	6.03	4.76
	N	20	4	-	-	5	4	4
pH (Std. units)	Ave	7.90	7.68	7.72	7.86	7.60	7.74	7.75
	St. Dev.	0.10	0.23	0.10	0.12	0.13	0.18	0.14
	CI	0.02	0.08	0.05	0.03	0.05	0.08	0.06
	N	75	28	15	51	26	21	21

[A]AA was sampled monthly from 5/2001 – 6/2002 and 7/2003 – 4/2005. [B]DDI was sampled monthly from 1/2002 – 8/2002 and 7/2003 – 4/2005. [C]FA fixed-film was sampled monthly from 11/2001 – 4/2003. [D]FA vertical plug flow was sampled monthly, and for some periods more intensively, from 8/2003 – 9/2004 and one sample during 12/2004. [E]ML manure was sampled monthly from 3/2003 – 4/2005. [F]NH Cell 1 waste was sampled monthly from 8/2003 – 4/2005. [G]NH Cell 2 was sampled monthly from 8/2003 – 4/2005.

Effect of Anaerobic Digestion on Constituents

The percent change of all constituents between digester influent and digester effluent was calculated using Equation 1 with results shown in Table 11. The average value for each constituent at each farm shown in Tables 9 and 10 were used in Equation 1.

Equation 1.

$$\text{Percent change} = \left(\frac{[\text{influent}] - [\text{effluent}]}{[\text{influent}]} \right) * 100$$

A negative value indicates an increase in the constituent concentration as a result of the digestion process while a positive value represents a constituent concentration reduction. A paired two-tailed student's T-test was used to determine if the digester influent and effluent constituent concentration values are equal or not, and shaded table cells indicates those values found to be statistically different at the 99 percent confidence interval (CI) while those cells not shaded were not found to be statistically different at the 95 percent CI.

A graphical representation of Table 11 values are shown in Figures 3 and 4. The constituents related to manure solids and pathogens (TS, TVS, Acetic A, DCOD, COD, MAP, and F. Coli.) are shown in Figure 3 while those related to manure nutrients (TKN, NH_3-N, ON, TP, OP, and K) are shown in Figure 4.

As expected to occur, a consistent reduction for TS, TVS, ON, Acetic A, DCOD, COD, MAP and F. Coli was shown to exist due to the anaerobic digestion process. Organic matter, represented by TS, TVS, Acetic A (indirectly), DCOD, and COD was consumed by operative microorganism during the anaerobic digestion process to make biogas. (Since plug flow digesters also inherently function as sedimentation tanks, a reduction of organic matter can occur due to the sedimentation process as well.) The two pathogens, MAP and F. Coli, were subject to consistent heating for a time frame that in theory equals the estimated digester hydraulic retention time; this, combined with the time they were away from the host appears to be the two governing reasons for their significant reduction. Particle short circuiting of the digestion system that inherently takes place for ML (due to the mixing system) did not adversely affect the concentration reductions of the pathogens based on comparisons made to the other digester performances.

Table 11. Percent change in constituent concentration during anaerobic digestion for each farm.[1,2]

Constituent	AA[A]	DDI[B]	FA Fixed- Film[C]	FA Vertical Plug Flow[D]	ML[E]	NH Digester Cell 1[F]	NH Digester Cell 2[G]
TS	27.5	26.2	19.6	15.1	63.9	18.1	21.2
TVS	31.9	29.3	22.8	22.8	69.6	15.5	18.8
TKN	-7.5	-1.0	1.7	-3.7	-2.8	-3.15	1.81
NH_3-N	-37.9	-22.9	-14.0	-17.7	-12.7	-29.4	-19.7
ON	12.1	21.6	20.9	17.9	1.2	20.8	21.5
TP	-0.93	0.9	4.9	5.79	-3.6	-3.10	-2.26
OP	-16.7	-9.0	-15.2	-15.0	2.0	-28.0	-19.7
K	-14.9	-4.3	-	3.86	5.5	0.47	-5.26
Acetic A	73.3	55.0	66.8	61.5	87.1	80.2	79.5
DCOD	34.0	22.3	26.9	17.0	66.1	14.0	22.7
COD	29.3	14.7	16.1	18.3	68.6	19.7	19.7
MAP	98.7	99.1	-	-	94.8	98.7	98.1
F. Coli.	99.9	99.7	80.7	96.3	98.4	99.5	99.5

[1]Positive table values represent a reduction in constituent concentration while negative values represent an increase in the constituent concentration. [2]Shaded table cells indicates those values found to be statistically different at the 99 percent confidence interval (CI) while those cells not shaded were not found to be statistically different at the 95 percent CI.
[A]AA was sampled monthly from 5/2001 – 6/2002 and 7/2003 – 4/2005. [B]DDI was sampled monthly from 1/2002 – 8/2002 and 7/2003 – 4/2005. [C]FA fixed-film was sampled monthly from 11/2001 – 4/2003. [D]FA vertical plug flow was sampled monthly, and for some periods more intensively, from 8/2003 – 9/2004 and one sample during 12/2004. [E]ML manure was sampled monthly from 3/2003 – 4/2005. [F]NH Cell 1 was sampled monthly from 8/2003 – 4/2005. [G]NH Cell 2 was sampled monthly from 8/2003 – 4/2005.

Conversely, there was a noticeable increase in NH_3-N and OP concentrations during the anaerobic digestion process. The conditions present in an anaerobic digester were favorable for the mineralization of ON (as indicated by its concentration reduction) to NH_3-N and for a shift of some organic P to OP. Increases in NH_3-N and OP concentration both need to be accounted for in each farm's comprehensive nutrient management plan (CNMP).

There should be an insignificant change in concentration of TKN, TP, and K due to the anaerobic digestion process since biogas does not appreciably contain the elements N, P, or K. However for TKN, the data vary from a 4 percent decrease to an 8 percent increase; this could be the result of settling of some TKN in the digesters (for the cases where there were decreases), sampling variation, and/or laboratory error. Relatively little concentration change existed for TP from influent to effluent, as expected for all digesters. Influent/effluent potassium concentration showed little change for all digesters.

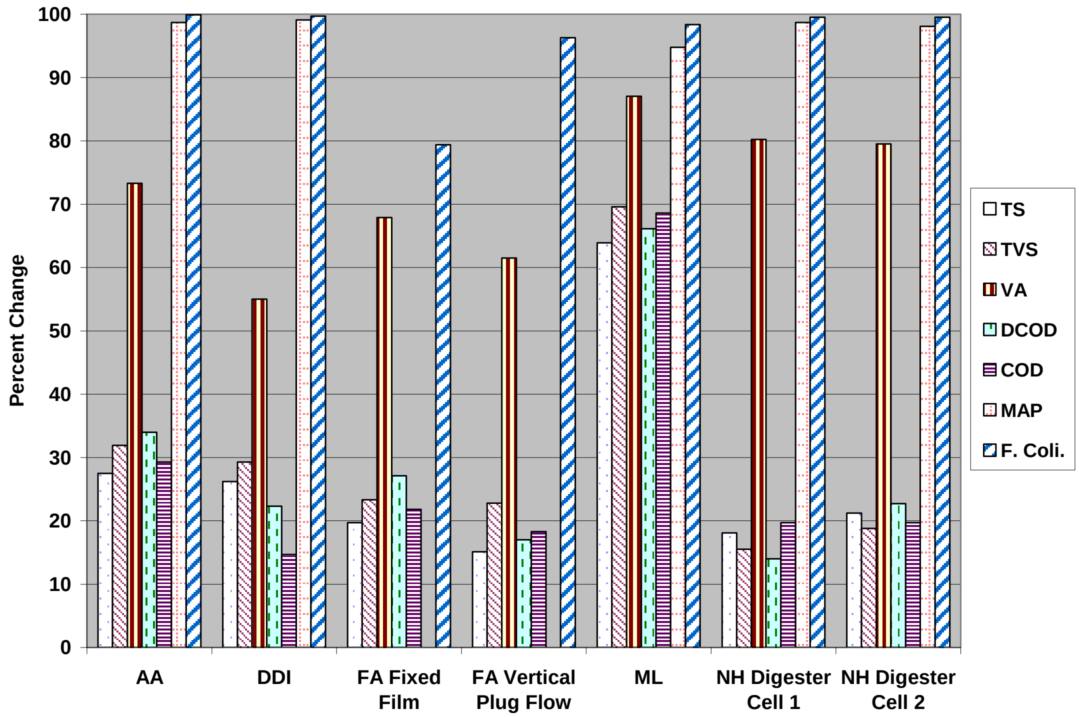

Figure 3. Percent change in constituent concentration during anaerobic digestion for each farm.

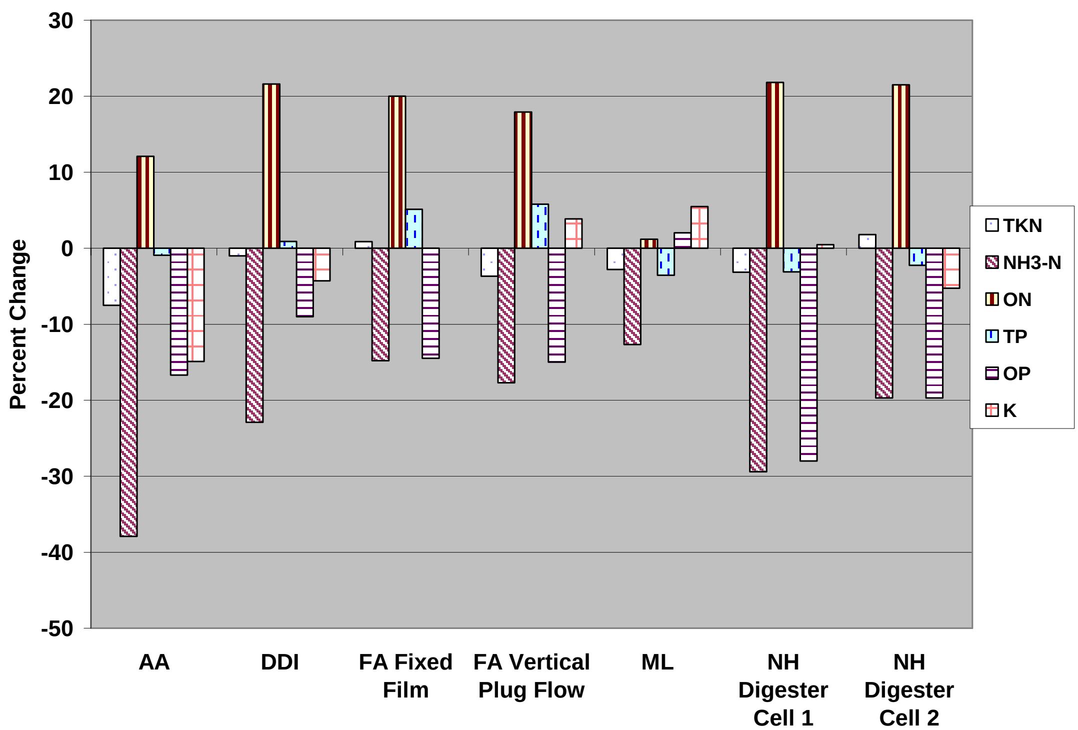

Figure 4. Percent change in constituent concentration during anaerobic digestion for each farm.

The effect of each digester's hydraulic retention time (HRT) on the percent change in constituent concentration was normalized by dividing the values in Table 11 by the estimated HRT (Table 4); results are shown in Table 12. Graphical representation of Table 12 values for TS, TVS, Acetic A, DCOD, COD, MAP, and F. Coli. are shown in Figure 5 while values for TKN, NH_3-N, ON, TP, OP, and K are shown in Figure 6.

Table 12. Percent change in constituent concentration per unit treatment volume for all digesters.[1,2]

Constituent	AA[A]	DDI[B]	FA Fixed Film[C]	FA Vertical Plug Flow[D]	ML[E]	NH Digester Cell 1[F]	NH Digester Cell 2[G]
TS	0.74	1.31	4.90	2.32	2.55	0.49	0.57
TVS	0.86	1.47	5.70	3.51	2.78	0.42	0.51
TKN	-0.20	-0.05	0.43	-0.57	-0.11	-0.09	0.05
NH_3-N	-1.02	-1.15	-3.50	-2.72	-0.51	-0.79	-0.53
ON	0.33	1.08	5.23	2.75	0.05	0.56	0.58
TP	-0.03	0.05	1.23	0.89	-0.14	-0.08	-0.06
OP	-0.45	-0.45	-3.80	-2.31	0.08	-0.76	-0.53
K	-0.40	-0.22	-	0.59	0.22	0.01	-0.14
Acetic A	1.98	2.75	16.70	9.46	3.48	2.17	2.15
DCOD	0.92	1.12	6.73	2.62	2.65	0.38	0.61
COD	0.79	0.74	4.03	2.82	2.74	0.53	0.53
MAP	2.67	4.96	-	-	3.79	2.67	2.65
F. Coli.	2.70	4.99	20.18	14.82	3.93	2.69	2.69

[1] Positive table values represent a reduction in constituent concentration while negative values represent an increase in the constituent concentration. [2]Shaded table cells indicates those values found to be statistically different at the 99 percent confidence interval (CI) while those cells not shaded were not found to be statistically different at the 95 percent CI.
[A]AA was sampled monthly from 5/2001 – 6/2002 and 7/2003 – 4/2005. [B]DDI was sampled monthly from 1/2002 – 8/2002 and 7/2003 – 4/2005. [C]FA fixed-film was sampled monthly from 11/2001 – 4/2003. [D]FA vertical plug flow was sampled monthly, and for some periods more intensively, from 8/2003 – 9/2004 and one sample during 12/2004. [E]ML manure was sampled monthly from 3/2003 – 4/2005. [F]NH Cell 1 was sampled monthly from 8/2003 – 4/2005. [G]NH Cell 2 was sampled monthly from 8/2003 – 4/2005.

Results shown in Table 12 represent the daily efficiency of each digester design to reduce or increase each constituent. As expected the digester with the highest surface area per treatment volume (FA, fixed film) had the highest efficiency to reduce or increase each constituent. In several cases FA (vertical plug flow digester) had the second highest efficiencies. At ML the mixed digester processing food waste was not as efficient as the FA digester; however, it did perform better than the plug flow digesters at DDI, AA, and NH. The general trends mentioned in the previous sentences are supported by the data in that the highest TVS reduction per unit volume occurred at FA (fixed-film) followed by FA (plug flow), ML, DDI, AA, and finally NH. The pathogen reduction trend was nearly identical as exhibited by TS and TVS. Digesters with longer HRT's were less efficient at reducing TS, TVS, and pathogen concentrations per unit volume. The Acetic A unit reductions were similar to TS, TVS, except at NH, DDI, and AA.

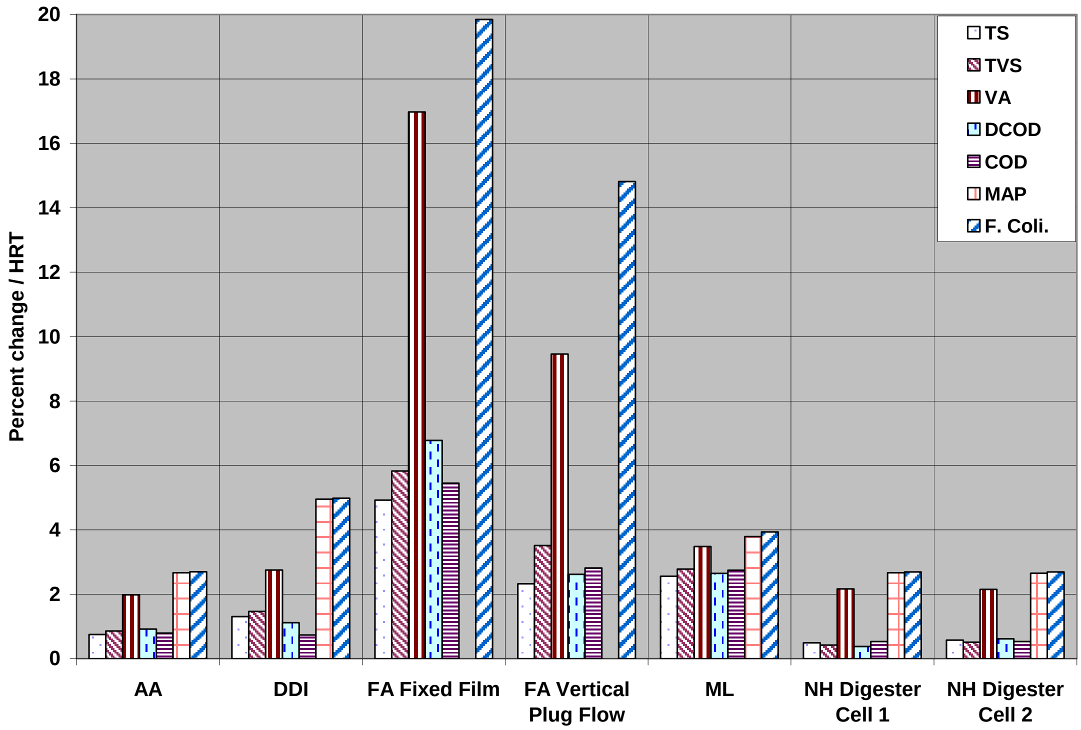

Figure 5. Graphical representation of normalized Table 12 values for TS, TVS, Acetic A, DCOD, COD, MAP, and F. Coli.

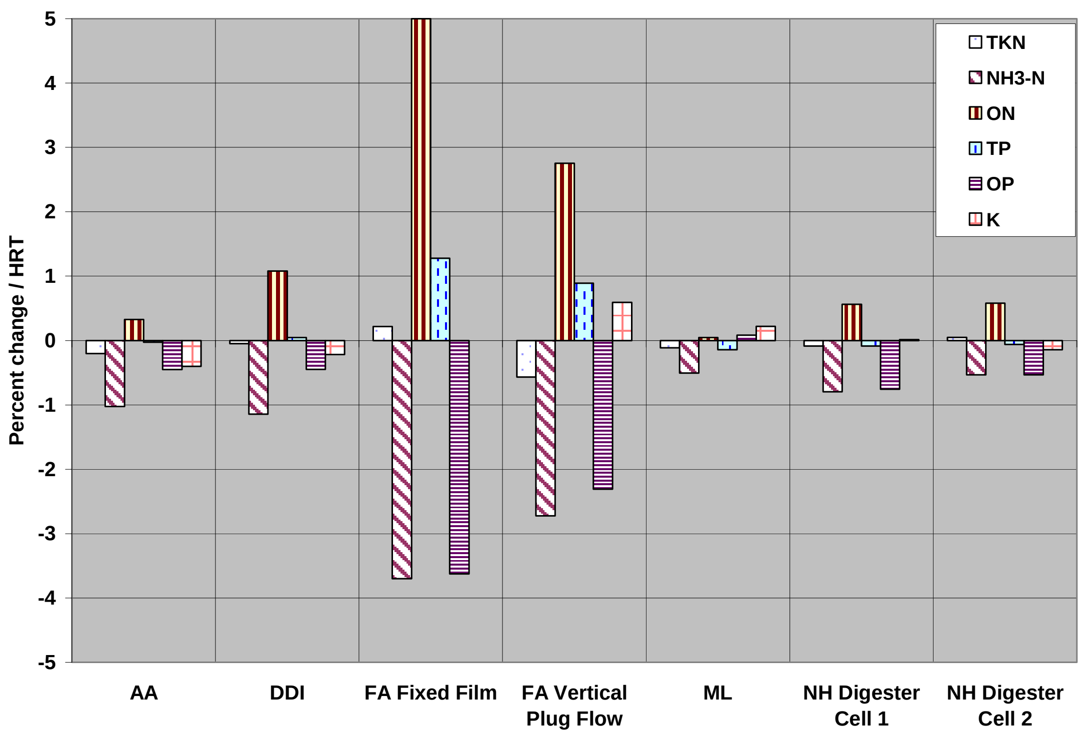

Figure 6. Graphical representation of normalized Table 12 values for TKN, NH_3-N, ON, TP, OP, and K.

Mechanical Solid-Liquid Separator Sampling Results

All anaerobic digester treatment systems included a screw-press solid-liquid separator. A separator processed digester effluent at AA, DDI (infrequently), ML, and NH and raw manure at FA where the liquid effluent was subsequently fed to the digester. AA used two FAN separators during the study: Model No. PSS 1-520 and Model No. PSS 2-520, both with a 0.5 mm screen. FA also used a FAN separator, Model No. PSS 2-520 with a 0.75 mm screen. A Vincent separator (Model No. K2-10) with a 2.25 mm screen was used at ML while model No. KP-10 was used at NH.

Separator influent and effluents were sampled monthly, with increased frequency for AA-1 during the 14-month period from May 2001 to June 2002. The average (Ave), standard deviation (St. Dev.), 99 percent confidence interval (CI), and number of samples (n) for the solid-liquid separator influent stream, liquid effluent stream, and solid effluent stream are shown in Tables 13, 14 and 15, respectively. The two columns for AA (AA-1 and AA-2) represent the two different separators that the farm used over the course of the sampling. All available data from NH digester cell 1 and cell 2 during the entire study were averaged to determine the influent concentration of the constituents for the NH separator. Operation of the separator at DDI was infrequent and therefore was not sampled as part of this project.

The nutrient concentrations in the solid effluent stream varied more than the liquid effluent stream. TP and OP were consistently higher in concentration for all farms except for FA; K was consistently lower for all farms.

Separator influent and effluent estimated mass flow rates are shown in Table 16 for AA, ML, and FA. The separator installation at FA allowed the influent flow rate to be measured directly while the installations at AA and ML did not; influent flow rate was calculated by performing a system mass balance where the separator liquid influent is equal to the sum of the measurements of the separator liquid and solid effluent streams. Mass flow data for FA was obtained from Ludington (2006). Mass flow data at NH was not obtained and therefore this farm was included in this analysis.

Table 13. Solid-liquid separator influent constituent concentrations for AA, FA, ML, and NH.

Constituent	Statistic	AA-1[A]	AA-2[B]	FA[C]	ML[D]	NH[E]
Log_{10} MAP (cfu/gram)	Ave	1.8	1.8	-	2.0	1.8
	St. Dev.	0.5	0.5	-	0.5	0.3
	CI	0.2	0.5	-	0.4	0.2
	n	48	7	-	11	11
Log_{10} F. Coli. (mpn/gram)	Ave	3.0	3.5	6.0	3.4	3.6
	St. Dev.	0.8	0.3	0.6	0.6	0.5
	CI	0.5	0.3	0.3	0.3	0.2
	n	52	11	27	22	19
DCOD (mg/l)	Ave	15,937	17,350	27,957	13,244	19,242
	St. Dev.	5,193	5,667	19,380	7,257	6,653
	CI	1,385	3,513	10,535	2,903	2,916
	n	54	10	13	24	20
COD (mg/kg)	Ave	87,025	66,555	89,370	63,070	61,714
	St. Dev.	25,436	11,567	40,857	12,516	10,221
	CI	6,784	6,835	16,697	4,906	4,479
	n	54	11	23	25	20
TKN (mg/kg)	Ave	5,445	4,292	3,944	3,263	4,029
	St. Dev.	1,232	1,457	617	513	776
	CI	329	861	233	201	340
	n	54	11	27	25	20
NH_3-N (mg/kg)	Ave	2,683	2,231	2,253	1,326	2,414
	St. Dev.	408	373	425	381	470
	CI	109	220	160	146	206
	n	54	11	27	26	20
ON (mg/kg)	Ave	2,762	2,061	1,691	1,921	1,616
	St. Dev.	1,288	1,490	654	421	629
	CI	343	880	247	165	276
	n	54	11	27	25	20
TP (mg/kg)	Ave	908	552	649	553	508
	St. Dev.	163	124	170	122	79
	CI	43	73	64	47	35
	n	54	11	27	26	20
OP (mg/kg)	Ave	583	397	363	290	300
	St. Dev.	86	71	61	89	44
	CI	23	42	23	34	19
	n	54	11	27	26	20
K (mg/kg)	Ave	-	2,234	-	2,592	2,435
	St. Dev.	-	523	-	590	500
	CI	-	388	-	309	295
	n	-	7	-	14	11
TS (percent)	Ave	8.37	7.40	9.96	5.60	8.25
	St. Dev.	1.08	0.77	1.38	0.74	1.21
	CI	0.29	0.45	0.27	0.29	0.53
	n	54	11	27	26	20
TVS (percent)	Ave	6.61	5.93	7.97	4.35	6.28
	St. Dev.	0.96	0.65	1.18	0.51	1.09
	CI	0.26	0.39	0.44	0.20	0.48
	n	54	11	27	26	20
pH (Std. units)	Ave	7.92	7.83	7.45	7.60	7.74
	St. Dev.	0.09	0.09	0.25	0.13	0.13
	CI	0.02	0.05	0.09	0.05	0.06
	n	54	11	27	26	20

[A]AA-1 was sampled monthly from 5/2001 – 6/2002 [B]AA-2 was sampled monthly from 1/2004 – 11/2004. [C]FA was sampled monthly from 11/2001 – 12/2003. [D]ML manure was sampled monthly from 3/2003 – 4/2005. [E]NH was sampled monthly from 10/2004 – 2/2005.

Table 14. Solid-liquid separator liquid effluent constituent concentrations for AA, FA, ML and NH.

Constituent	Statistic	AA-1[A]	AA-2[B]	FA[C]	ML[D]	NH[E]
Log_{10} MAP (cfu/gram)	Ave	1.5	1.6	-	1.8	-
	St. Dev.	0.6	1.0	-	0.6	-
	CI	0.2	1.2	-	0.5	-
	n	34	4	-	10	-
Log_{10} F. Coli. (mpn/gram)	Ave	2.5	3.7	5.6	3.2	3.3
	St. Dev.	0.9	0.4	0.6	0.6	0.8
	CI	0.2	0.4	0.3	0.3	1.1
	n	54	9	25	23	4
DCOD (mg/l)	Ave	16,114	-	22,129	21,170	-
	St. Dev.	8,142	-	6,037	10,118	-
	CI	2,192	-	2,523	8,868	-
	n	53	-	22	5	-
COD (mg/kg)	Ave	57,275	36,670	52,209	82,669	42,440
	St. Dev.	14,504	13,742	8,907	91,099	7,324
	CI	3,905	8,517	3,640	35,710	6,420
	n	53	10	23	25	5
TKN (mg/kg)	Ave	4,918	4,166	3,906	3,071	3,931
	St. Dev.	1,468	1,428	679	485	625
	CI	399	885	256	190	548
	n	52	10	27	25	5
NH_3-N (mg/kg)	Ave	2,525	2,280	2,245	1,256	2,450
	St. Dev.	631	660	350	374	519
	CI	170	409	132	144	455
	n	53	10	27	26	5
ON (mg/kg)	Ave	2,394	1,886	1,661	1,697	1,481
	St. Dev.	1,293	1,185	576	620	231
	CI	351	735	217	238	203
	n	52	10	27	26	5
TP (mg/kg)	Ave	798	477	595	523	471
	St. Dev.	165	99	117	109	50
	CI	44	61	44	42	44
	n	53	10	27	26	5
OP (mg/kg)	Ave	545	320	346	279	301
	St. Dev.	129	81	76	101	50
	CI	35	50	29	39	44
	n	53	10	27	26	5
K (mg/kg)	Ave	-	2,098	-	2,472	2,707
	St. Dev.	-	308	-	573	262
	CI	-	246	-	300	230
	n	-	6	-	14	5
TS (percent)	Ave	5.13	4.06	4.93	5.13	4.90
	St. Dev.	0.83	0.55	0.73	0.77	0.24
	CI	0.22	0.34	0.28	0.30	0.21
	n	53	10	27	26	5
TVS (percent)	Ave	3.61	2.81	3.33	3.99	3.29
	St. Dev.	0.54	0.37	0.59	0.75	0.20
	CI	0.15	0.23	0.22	0.29	0.18
	n	53	10	27	26	5
pH (Std. units)	Ave	7.86	7.76	7.38	6.58	7.83
	St. Dev.	0.18	0.06	0.21	0.63	0.10
	CI	0.05	0.04	0.08	0.24	0.09
	n	53	10	27	26	5

[A]AA-1 was sampled monthly from 5/2001 – 6/2002 [B]AA-2 was sampled monthly from 1/2004 – 11/2004. [C]FA was sampled monthly from 11/2001 – 12/2003. [D]ML manure was sampled monthly from 3/2003 – 4/2005. [E]NH was sampled monthly from 10/2004 – 2/2005.

Table 15. Solid-liquid separator solid effluent constituent concentrations for AA, FA, ML, and NH.

Constituent	Statistic	AA-1[A]	AA-2[B]	FA[C]	ML[D]	NH[E]
Log_{10} MAP (cfu/gram)	Ave	1.5	1.6	-	1.4	-
	St. Dev.	0.5	0.9	-	0.3	-
	CI	0.4	1.3	-	0.4	-
	n	13	3	-	6	-
Log_{10} F. Coli. (mpn/gram)	Ave	2.1	3.5	5.3	3.3	3.0
	St. Dev.	0.7	0.2	0.7	0.7	0.5
	CI	0.3	0.2	0.3	0.4	0.7
	n	50	10	27	22	3
DCOD (mg/l)	Ave	15,772	-	19,013	17,651	-
	St. Dev.	3,997	-	6,639	8,212	-
	CI	1,086	-	3,757	7,198	-
	n	52	-	12	5	-
COD (mg/kg)	Ave	157,327	111,900	141,978	208,397	127,360
	St. Dev.	104,089	34,739	70,009	77,308	78,660
	CI	28,291	21,531	28,611	30,304	68,947
	n	52	10	23	25	5
TKN (mg/kg)	Ave	6,237	4,520	3,429	4,877	4,444
	St. Dev.	1,717	1,325	566	1,499	756
	CI	467	821	213	588	683
	n	52	10	27	25	5
NH_3-N (mg/kg)	Ave	2,574	1,956	1,641	1,274	2,180
	St. Dev.	379	380	376	498	599
	CI	103	236	142	191	525
	n	52	10	27	26	5
ON (mg/kg)	Ave	3,664	2,564	1,787	3,583	2,265
	St. Dev.	1,737	1,324	504	1,399	723
	CI	472	765	190	548	634
	n	52	10	27	25	5
TP (mg/kg)	Ave	1,253	818	559	964	892
	St. Dev.	299	269	158	296	101
	CI	91	167	60	114	89
	n	52	10	27	26	5
OP (mg/kg)	Ave	667	420	298	514	563
	St. Dev.	158	107	81	189	36
	CI	43	66	31	73	31
	n	52	10	27	26	5
K (mg/kg)	Ave	-	1,845	-	1,966	2,241
	St. Dev.	-	158	-	578	547
	CI	-	127	-	303	479
	n	-	6	-	14	5
TS (percent)	Ave	23.9	23.7	25.3	28.1	37.4
	St. Dev.	2.05	1.42	2.98	5.64	2.15
	CI	0.56	0.88	1.12	2.17	1.89
	n	52	10	27	26	5
TVS (percent)	Ave	21.2	21.3	22.1	25.96	33.4
	St. Dev.	1.98	1.48	2.84	5.65	2.04
	CI	0.54	0.92	1.07	2.17	1.79
	n	52	10	27	26	5
pH (Std. units)	Ave	8.49	8.42	8.10	6.55	8.83
	St. Dev.	0.14	0.13	0.25	0.91	0.09
	CI	0.04	0.08	0.09	0.35	0.08
	n	52	10	27	26	5

[A]AA-1 was sampled monthly from 5/2001 – 6/2002 [B]AA-2 was sampled monthly from 1/2004 – 11/2004. [C]FA was sampled monthly from 11/2001 – 12/2003. [D]ML manure was sampled monthly from 3/2003 – 4/2005. [E]NH was sampled monthly from 10/2004 – 2/2005.

Table 16. Average mass flow rate (lbs/min and ft^3/min) for four solid-liquid manure separators.

Separator Influent Flow Rate							
	AA-1[1]	**AA-2**[1]	**ML**	**FA**			
(lbs/min)	202	321	456	411[A]			
(Ft^3/min)				6.6			
Separated Liquid Effluent Flow Rate							
	AA-1	**AA-2**	**ML**	**FA**			
(lbs/min)	172±22.4	271±54.5	454±28.4	318±100[B]			
(Ft^3/min)	2.7±0.35	4.3±0.87	7.3±0.45	5.1±1.6			
Separated Solid Effluent Flow Rate							
	AA-1	**AA-2**	**ML**	**FA**			
(lbs/min)	31.8±6.8	50.0±9.67	3.35±1.09	114±11.7[C]			
(Ft^3/min)	1.25±0.20	1.75±0.31	0.19±0.09	2.86±0.77[D]			
n	27	6	4	[A]6	[B]5	[C]3	[D]4

[1]Two different FAN separators were used by the farm.
Superscripts a - d correspond to the sample size (n) of the chart associated with each flow rate and confidence interval.

Solid-liquid Separation Efficiency

Equations 2 and 3, presented by Burns and Moody (2003), were used to quantify the efficiency of each solid-liquid manure separator monitored. Equation 2 was used to calculate the percent of the constituents partitioned to the liquid stream while Equation 3 was used to calculate the percent of constituents partitioned to the solid stream. Average data for each constituent shown in Tables 13, 14, and 15 were used as values for the independent variables and the results are shown in Table 17.

Equation 2.

$$\text{Eff. } (\%)_{Capture} \text{ liquids} = M_L(\%_{Const}) / M_{in}(\%_{Const})$$

Equation 3.

$$\text{Eff. } (\%)_{Capture} \text{ solids} = M_S(\%_{Const}) / M_{in}(\%_{Const})$$

Where:

Eff. $(\%)_{Capture}$ = the separator's efficiency in capturing constituents in each effluent stream

M_{in} = mass of the influent

M_L = mass of the separated liquid

M_S = mass of the separated solids

$\%_{Const}$ = constituent concentration of the constituent as a percent of material mass

Table 17. Percent efficiency of capture for nutrients and solids for AA, FA, and ML.

Separated Liquid Effluent									
Constituent		**AA-1**[1]		**AA-2**[1]		**ML**		**FA**	
TKN		75.8		80.0		94.0		76.6	
NH_3-N		81.3		87.5		93.3		77.1	
ON		69.3		72.5		94.5		76.0	
TP		74.1		76.7		96.5		71.0	
OP		77.8		68.9		97.8		73.8	
TS		51.8		46.1		93.8		38.3	
TVS		46.3		39.9		95.6		32.3	
K		-		78.7		93.2		-	
n	n_K	29	-	10	6	19	7	27	-
Separated Solid Effluent									
Constituent		**AA-1**[1]		**AA-2**[2]		**ML**		**FA**	
TKN		16.8		16.0		1.2		24.1	
NH_3-N		14.5		13.8		0.7		20.2	
ON		19.6		18.2		1.5		29.3	
TP		20.1		24.3		1.2		23.9	
OP		17.5		16.7		1.2		22.8	
TS		46.5		49.6		3.9		70.5	
TVS		52.5		55.7		4.7		76.9	
K		-		12.7		0.5		-	
n	n_K	29	-	10	6	19	7	27	-

[1]Two different FAN separators were used by the farm.

The efficiencies in Table 17 indicate that all separators, regardless of farm specific affects on separator performance, captured no more than 25 percent of the TKN and TP in the solid stream effluent. The FAN separator at FA, as predicted based on the influent material being raw manure, had the highest TS capture efficiency in the solid stream effluent with 70.5 percent. Farm ML had the lowest TS reclamation efficiency at 3.9 percent; this may be explained by the low TS concentration in the separator influent, comparatively higher TS consumed by the anaerobic digester, and the larger screen size used in the separator, and may not reflect on the overall design, installation, or maintenance of the separator.

Manure Storage Sampling Results

The long-term storages at AA and ML were sampled for all constituents. The long-term storages were sampled vertically at 4'and 8' below the manure surface and at the bottom (12' for AA and 10' for ML) and horizontally at each end and the center of the storage. Data were averaged and are shown in Table 18. Samples from the long-term storage were also obtained as the storage was being emptied at ML and are included in the analysis.

Table 18. Average concentration of constituents in the long-term storage for AA and ML.

Constituent	Statistic	AA	ML
Log_{10} MAP (cfu/gram)	Ave	1.1	2.1
	St. Dev.	0.2	0.3
	CI	0.2	0.3
	n	7	9
Log_{10} F. Coli. (mpn/gram)	Ave	3.5	3.4
	St. Dev.	0.8	0.3
	CI	0.4	0.3
	n	27	10
DCOD (mg/l)	Ave	30,680	14,779
	St. Dev.	14,033	5,740
	CI	5,293	3,248
	n	27	12
COD (mg/kg)	Ave	12,952	29,707
	St. Dev.	6,713	9,786
	CI	2,532	4,952
	n	27	15
TKN (mg/kg)	Ave	2,564	1,972
	St. Dev.	614	366
	CI	232	185
	n	27	15
NH_3-N (mg/kg)	Ave	1,552	1,031
	St. Dev.	665	122
	CI	251	62
	n	27	15
ON (mg/kg)	Ave	1,012	942
	St. Dev.	595	280
	CI	224	142
	n	27	15
TP (mg/kg)	Ave	457	335
	St. Dev.	190	93
	CI	72	48
	n	27	14
OP (mg/kg)	Ave	360	208
	St. Dev.	156	61
	CI	60	32
	n	26	14
K (mg/kg)	Ave	-	-
	St. Dev.	-	-
	CI	-	-
	n	-	-
TS (percent)	Ave	2.84	2.83
	St. Dev.	1.02	0.51
	CI	0.38	0.26
	n	27	15
TVS (percent)	Ave	1.86	2.04
	St. Dev.	0.79	0.41
	CI	0.30	0.21
	n	27	15
pH (Std. units)	Ave	7.57	7.32
	St. Dev.	0.10	0.07
	CI	0.04	0.04
	n	27	15

Anaerobic Digester Biogas Production

The total monthly metered biogas data shown in Table 19 were obtained from the farm log sheets and monthly farm visits. Roots brand gas meters were used to meter biogas (see Tables 6 and 7); they were not compensated for temperature or pressure. For every 1.0 inch of water (WC) above atmospheric at the gas meter, the lower heating value (LHV), Btu per ft^3 of biogas measured, will increase by approximately 0.25 percent. For every degree F increase in temperature above 32 F, the LHV, Btu per ft^3 of biogas measured, will decrease by 0.25 percent (Ludington, 2005).

For DDI, ML, and NH the total monthly metered biogas was not necessarily the total biogas produced for the month; there were biogas streams that were not measured on these farms. All biogas produced at AA was metered prior to use by the engine-generator set. DDI used biogas to fire a boiler and any excess biogas was flared. FA burned all biogas generated in a biogas-fired boiler and excess heat was dispersed to the ambient with a heat dump radiator-fan unit. ML used biogas to fire an engine-generator set, a biogas boiler, occasionally a six million Btu biogas food dryer, and to boil maple sap for syrup production during the spring season; excess biogas was flared. From January 2005 – May 2005 the table values for ML are divided into two rows. The top row represents biogas used by the engine-generator set, and the bottom row represents total metered biogas production for the month. NH used biogas to fire an engine-generator set and the excess was flared. Blank cells in Table 19 represent times when meter readings were not available.

Table 19. Total monthly metered biogas (ft^3) for all farms from January 2004 to May 2005.

Month	AA	DDI	FA	ML[A]	NH
January 2004	1,310,900	1,139,100	27,145	2,248,604	-
February 2004	1,361,700	1,115,700	14,948	2,083,013	-
March 2004	846,500	883,900	36,855	2,333,516	-
April 2004	1,455,100	937,800	37,999	2,309,184	1,623,683
May 2004	-	581,500	61,789	2,381,176	1,965,919
June 2004	-	710,700	26,573	2,521,927	1,592,215
July 2004	-	589,900	22,673	2,366,446	415,500
August 2004	856,600	577,600	54,922	2,504,337	1,437,838
September 2004	1,363,000	653,379	13,647	2,031,481	518,500
October 2004	1,264,100	1,132,400	19,400	2,756,856	1,898,735
November 2004	701,000	912,300	54,354	2,176,922	1,995,126
December 2004	884,400	1,242,700	52,010	2,416,991	1,196,800
January 2005	396,700	134,000	44,183	2,303,292 6,517,740	1,619,800
February 2005	-	134,050	26,256	2,110,320 6,384,959	1,546,200
March 2005	872,300	3,101	61,829	2,160,402 9,383,185	1,533,003
April 2005	1,029,800	350,000	63,696	2,323,522 8,605,361	1,714,197
May 2005	1,198,500	350,000	70,183	2,443,672 8,373,584	1,561,994

[A]January 2005 – May 2005 are divided into two rows. The top row represents biogas used by the engine-generator set, and the bottom row represents total metered biogas production for the month.

The average, range, and standard deviation for the data in Table 19 is shown in Table 20. ML produced the greatest amount of biogas; increased biogas production is attributed to the addition of food waste to the digester.

Table 20. Average, range, and standard deviation of total monthly metered biogas for all farms from January 2004 – May 2005.

Farm	AA	DDI	FA	ML	NH
Average	1,041,585	673,419	40,025	3,964,428	1,472,822
Range	396,700 1,455,100	3,101 1,242,700	13,647 70,183	2,031,481 9,383,185	415,500 1,995,126
Standard Deviation	313,727	386,110	18,792	2,676,995	475,334
No. Months	13	17	15	17	14

Biogas Volume: Measured vs. Calculated

The amount of methane one gram of anaerobically digested COD will produce is 0.40 liters at a temperature of 35C (Metcalf and Eddy, Inc., 2003). Minott (2002) developed a TS/VS predictive equation that assumed one gram of anaerobically digested biologically degradable VS yielded 0.5 liter of methane.

These two prediction equations were used with project data for AA as follows. Biogas production was predicted by converting the average manure volume in Table 2 from gallons to grams. The resulting mass value was then multiplied by the influent and effluent concentration of COD and TVS respectively. Accounting for the plug flow nature at AA, the difference of effluent and previous month's influent mass for both COD and TVS was used to predict methane production. Predicted methane production was then divided by 0.6 (or multiplied by 1.4) to account for carbon dioxide content in biogas.

Predicted biogas production, based on COD and TS/VS, and measured biogas production for AA are shown in Figure 7. The breaks in the measured production line are when the gas meter was malfunctioning. As previously mentioned in the report, COD concentration varied greatly, and the plot of the predicted biogas production reflects this accordingly. When the effluent COD concentration was greater than the influent COD concentration the equation predicts negative gas production. When all the COD data was used in the predictive equation, the lower limit of biogas production was 13,581 ft^3/day, the mean was 35,334ft^3/day, and the upper limit was 57,087 ft^3/day. When all the TVS data was used in the predictive equation, the lower limit of biogas production was 41,695 ft^3/day, the mean was 42,111 ft^3/day, and the upper limit was 42,320 ft^3/day. AA's actual biogas production ranged from 30,000 - 60,000 ft^3/day and averaged 43,731ft^3/day.

The average daily biogas production for AA, and FA was divided by the average daily weight of VS consumed by the digester to compare each digester's efficiency in production of biogas. Biogas produced per pound of volatile solids consumed was not calculated for DDI and, NH as the total biogas measured in Table 19 was not necessarily total biogas produced. Biogas flow to the flare at DDI and NH was not measured. Biogas produced per pound of volatile solids consumed was not calculated for ML as average daily weight of VS consumed could not be reliably calculated with the data collected.

Table 21. Biogas produced per pound of volatile solids consumed (ft^3/lb.)

Farm	AA	FA
Average	16.2	15.3
Standard Deviation	7.6	8.1
No. Samples	23	12

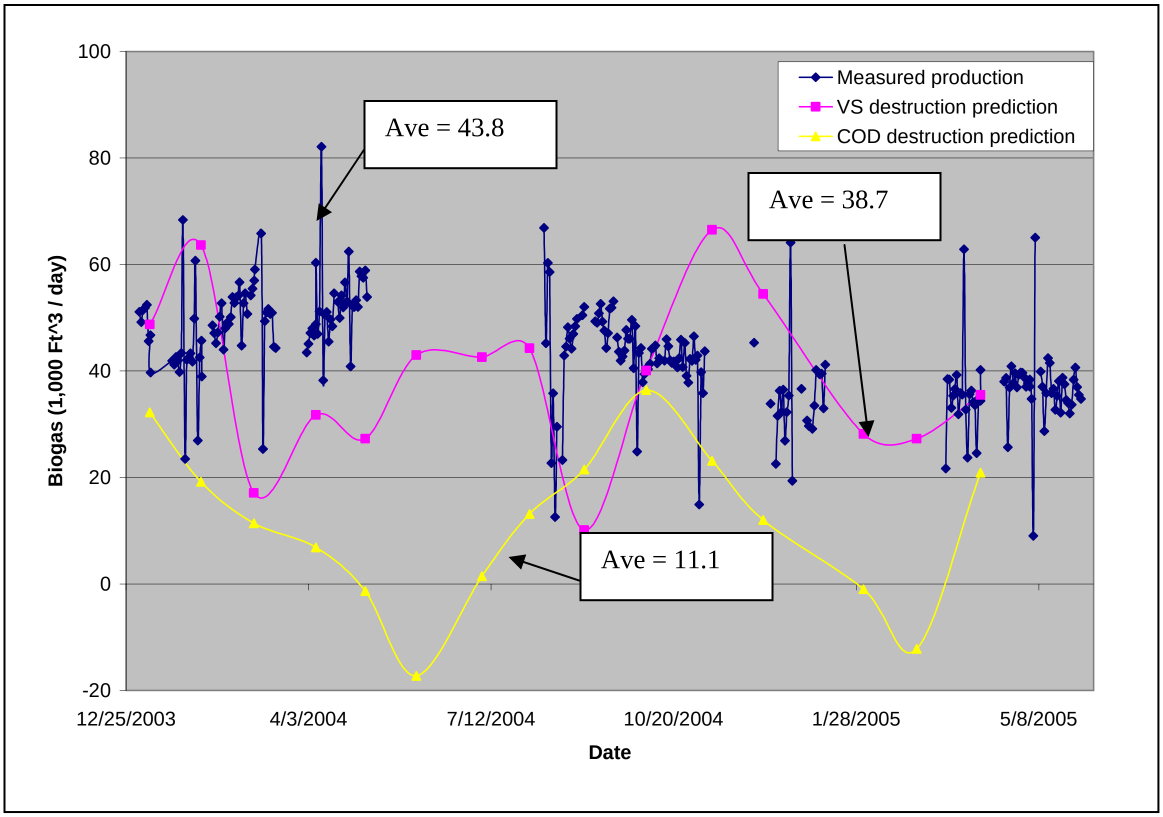

Figure 7. Measured and calculated biogas (based on prediction equations with COD and VS destroyed as predictor variables) for AA.

Biogas CO_2 Content

The biogas carbon dioxide concentration was measured using a Bacharach, Inc. FYRITE gas analyzer. The analyzer measured the concentration of biogas CO_2 in a range of 0 - 60 percent. The biogas was tested by the farm or the researchers during farm visits, and the recorded values are shown in Table 22. The results show that concentration of CO_2 in biogas range from 30 to 40 percent. The readings at DDI over 40 percent starting in March 2005 were due to the unintended over heating of the digester to 120°F in February of 2005.

Table 22. Average biogas CO_2 content, percent.

Month		AA	DDI	FA	ML	NH
January 2004	% CO_2	38	34	32	30	40
	n	1	7	1	1	1
February 2004	% CO_2	38	34	32	30	37
	n	1	20	1	1	2
March 2004	% CO_2	38	34	33	30	40
	n	1	23	2	1	1
April 2004	% CO_2	38	33	33	-	40
	n	1	24	2	-	1
May 2004	% CO_2	38	32	32	26	-
	n	1	20	2	1	-
June 2004	% CO_2	38	33	31	34	40
	n	1	19	1	3	14
July 2004	% CO_2	38	33	-	33	-
	n	2	19	-	1	-
August 2004	% CO_2	36	33	31	31	-
	n	1	12	2	2	-
September 2004	% CO_2	34	33	30	-	36
	n	1	18	2	-	1
October 2004	% CO_2	36	33	32	-	-
	n	1	1	1	-	-
November 2004	% CO_2	34	33	-	-	32
	n	1	14	-	-	1
December 2004	% CO_2	36	33	34	33	38
	n	1	10	1	2	1
January 2005	% CO_2	38	33	-	34	-
	n	1	6	-	1	-
February 2005	% CO_2	34	37	-	-	-
	n	1	6	-	-	-
March 2005	% CO_2	36	45	30	33	38
	n	1	22	1	10	1
April 2005	% CO_2	40	50	32	31	-
	n	1	7	1	1	-
May 2005	% CO_2	34	44	32	30	38
	n	1	13	1	11	1

The average CO_2 concentration over the monitoring period was 34.5, 35.4, 31.8, 31.5, and 39 percent for AA, DDI, FA, ML, and NH respectively. The methane (CH_4) concentration was approximated by subtracting the percent CO_2 concentration from 100. Therefore, the estimated CH_4 concentrations were 65.5, 64.6, 68.1, 68.5, and 61 percent respectively for AA, DDI, FA, ML, and NH. ML had the lowest percentage of CO_2 (highest calculated CH_4 content) perhaps resulting from the mixing action and/or addition of food waste to the raw manure prior to digestion.

Electrical Energy Generated On-Farm from Biogas

The estimated electrical energy generated, purchased, sold, displaced, and used by each farm is shown in Tables 23a and 23b. Electricity production sold by DDI to Niagara Mohawk to date was 100 kWh; this is not shown in the table. Displaced energy was the energy sold subtracted from the energy produced. Farm utilization was calculated by adding the energy displaced and the energy purchased. For example, for AA in January of 2004, the displaced energy was 26,251 kWh (31,851 kWh – 5,600 kWh) and the farm utilization was 30,411 kWh (26,251 kWh + 4,160 kWh). Energy generated at AA, ML, and NH was obtained every farm visit from the Watt-hour meter included as part of the engine-generator set control panel instrumentation. Energy purchased and sold was obtained from the Niagara Mohawk or NYSEG meter at AA, FA, and NH. Energy purchased by DDI was retrieved from the Niagara Mohawk energy check website; the 15-minute interval power data was summed for every month. Energy purchased and sold at ML was obtained from spreadsheet files containing 15-minute power data developed by Niagara Mohawk and supplied by the farm. Blank table values represent times when data was unavailable.

Table 23a. Estimated and actual monthly energy generated, purchased, sold, displaced, and utilized for all farms from January 2004 to July 2004.

Month	Energy (kWh)	AA[1]	DDI[2]	FA[1]	ML[2]	NH[1]
January 2004	Produced	31,851	0	N/A	99,842	35,472
	Purchased	4,160	56,047	1,798	993	23,841
	Sold	5,600	0	N/A	46,511	8,897
	Displaced	26,251	0	N/A	53,331	26,575
	Farm utilization	30,411	56,047	1,798	54,324	50,416
February 2004	Produced	34,833	0	N/A	92,679	29,001
	Purchased	5,920	57,095	1,876	730	18,842
	Sold	10,960	0	N/A	43,800	2,005
	Displaced	23,873	0	N/A	48,879	26,996
	Farm utilization	29,793	57,095	1,876	49,609	45,838
March 2004	Produced	22,174	0	N/A	100,497	38,458
	Purchased	11,920	58,368	1,426	3,477	21,755
	Sold	8,400	0	N/A	45,234	3,278
	Displaced	13,774	0	N/A	55,263	35,180
	Farm utilization	25,694	58,368	1,426	58,740	56,935
April 2004	Produced	51,483	0	N/A	94,693	55,633
	Purchased	400	45,671	1,080	6,585	4,355
	Sold	26,640	0	N/A	39,307	11,902
	Displaced	24,843	0	N/A	55,386	43,731
	Farm utilization	25,243	45,671	1,080	61,971	48,086
May 2004	Produced	56,245	0	N/A	96,938	74,377
	Purchased	2,320	65,804	1,147	3,104	9,841
	Sold	22,720	0	N/A	39,869	17,134
	Displaced	33,525	0	N/A	57,069	57,243
	Farm utilization	35,845	65,804	1,147	60,173	67,084
June 2004	Produced	53,102	0	N/A	96,739	55,755
	Purchased	2,720	-	1,080	2,249	25,110
	Sold	18,800	0	N/A	25,212	7,110
	Displaced	34,302	0	N/A	71,527	48,645
	Farm utilization	37,022	-	1,080	73,776	73,755
July 2004	Produced	15,160	0	N/A	71,709	14,558
	Purchased	10,400	61,886	1,147	2,657	68,392
	Sold	8,560	0	N/A	27,436	168
	Displaced	6,600	0	N/A	44,246	14,390
	Farm utilization	17,000	61,886	1,147	46,903	82,782

[1]Estimated based on an average daily power reading for the month.
[2]Actual average daily power reading for the month.

Table 23b. Estimated and actual monthly energy generated, purchased, sold, displaced, and utilized for all farms from August 2004 to May 2005.

Month	Energy (kWh)	AA[1]	DDI[2]	FA[1]	ML[2]	NH[1]
August 2004	Produced	24,497	0	N/A	91,699	49,206
	Purchased	18,240	62,744	1,085	6,555	43,317
	Sold	10,800	0	N/A	22,256	1,166
	Displaced	13,697	0	N/A	69,443	48,040
	Farm utilization	31,937	62,744	1,085	75,998	91,357
September 2004	Produced	39,900	0	N/A	83,369	18,267
	Purchased	2,160	59,872	1,110	3,430	60,637
	Sold	13,600	0	N/A	25,330	71
	Displaced	26,300	0	N/A	58,039	18,196
	Farm utilization	28,460	59,872	1,110	61,469	78,833
October 2004	Produced	35,123	0	N/A	94,941	77,119
	Purchased	960	60,457	961	42,038	7,045
	Sold	11,520	0	N/A	2,162	17,021
	Displaced	23,603	0	N/A	52,903	60,098
	Farm utilization	23,663	60,457	961	55,065	67,143
November 2004	Produced	14,015	0	N/A	92,313	85,893
	Purchased	14,960	57,682	930	3,513	1,551
	Sold	2,960	0	N/A	38,968	22,749
	Displaced	11,055	0	N/A	53,345	63,114
	Farm utilization	26,015	57,682	930	56,858	64,665
December 2004	Produced	8,206	0	N/A	103,569	47,750
	Purchased	15,120	62,948	961	3,897	19,422
	Sold	800	0	N/A	43,559	10,798
	Displaced	7,406	0	N/A	60,010	36,952
	Farm utilization	22,526	62,948	961	63,907	56,374
January 2005	Produced	954	0	-	93,469	54,836
	Purchased	19,040	60,172	-	2,473	21,337
	Sold	80	0	-	36,801	8,462
	Displaced	874	0	-	56,668	46,374
	Farm utilization	19,914	60,172	-	59,141	67,711
February 2005	Produced	0	0	-	80,522	70,317
	Purchased	19,360	54,114	-	1,875	10,816
	Sold	0	0	-	31,551	8,656
	Displaced	0	0	-	48,971	61,661
	Farm utilization	19,360	54,114	-	50,846	72,477
March 2005	Produced	21,967	0	-	93,576	56,598
	Purchased	7,120	62,631	-	1,925	11,072
	Sold	6,480	0	-	43,987	4,048
	Displaced	15,487	0	-	49,589	52,550
	Farm utilization	22,607	62,631	-	51,514	63,622
April 2005	Produced	30,684	0	-	94,807	75,370
	Purchased	1,440	54,291	-	963	15,104
	Sold	9,280	0	-	48,364	7,040
	Displaced	21,404	0	-	46,443	68,330
	Farm utilization	22,844	54,291	-	47,406	83,434
May 2005	Produced	33,809	0	-	99,119	61,061
	Purchased	2,240	52,632	-	819	35,712
	Sold	9,600	0	-	38,801	3,807
	Displaced	24,209	0	-	60,318	57,254
	Farm utilization	26,449	52,632	-	61,137	92,966

[1]Estimated based on an average daily power reading for the month.
[2]Actual average daily power reading for the month.

Monthly energy generated, purchased, sold, displaced, and utilized by AA from January 2004 to May 2005 is shown graphically in Figure 8.

Monthly energy surplus/deficit ratios for AA, ML, and NH were calculated using data from Tables 23a and 23b. The energy surplus and/or deficit ratio was calculated using Equation 4. The results are shown graphically in Figure 9.

Equation 4.

$$\text{Energy Surplus/Deficit Ratio} = \frac{\text{Gen - Set Production (kWh)}}{\text{Farm Utilization (kWh)}}$$

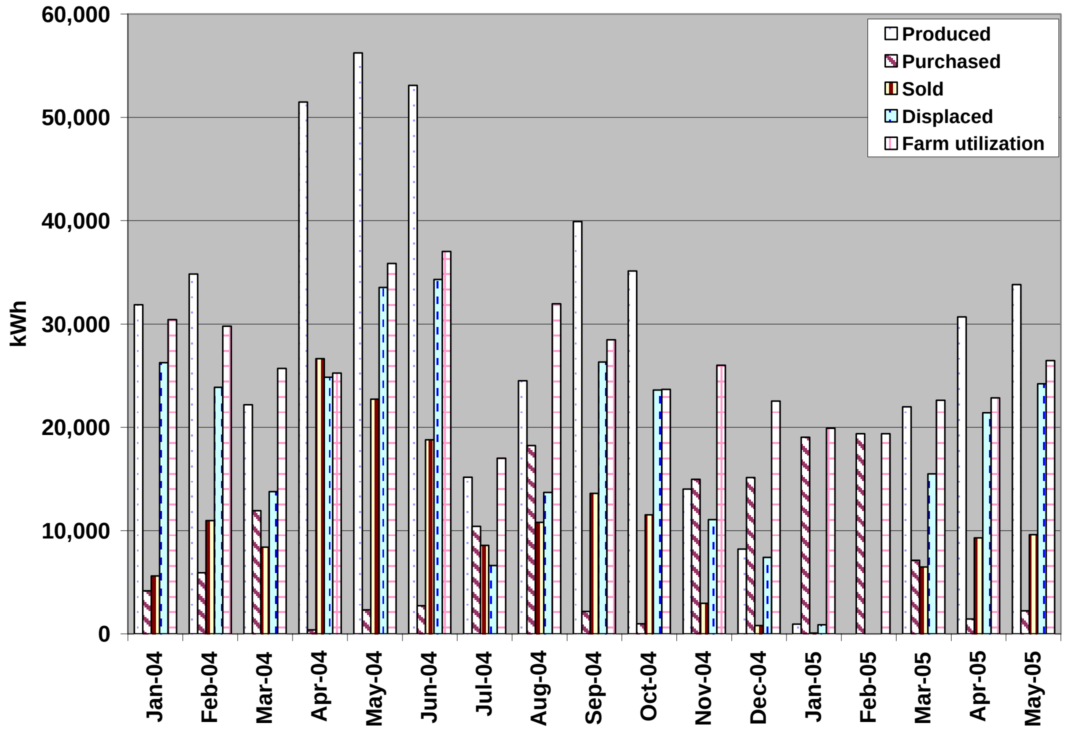

Figure 8. Monthly energy generated, purchased, sold and utilized for AA from January 2004 to May 2005.

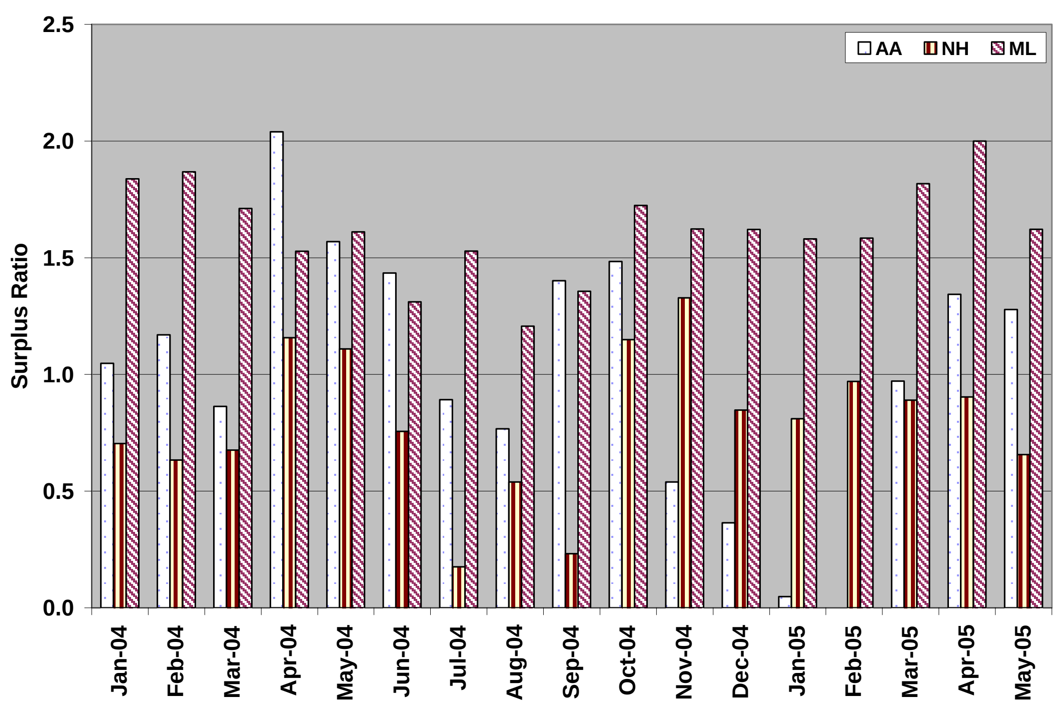

Figure 9. Electrical energy surplus deficit ratios for AA, ML, and NH from January 2004 to May 2005.

If the energy surplus deficit ratio in Figure 9 is equal to one the farm produced as much electricity as it used for the month. If the ratio is less than one the farm produced less energy than it used for the month, and if the ratio is equal to zero the farm did not produce any energy for the month. If the ratio is equal to two the farm produced twice as much electricity as it used.

Biogas production at ML was consistently greater than could be utilized by the farm's engine-generator set. Subsequently, large amounts of energy were lost by the farm to the atmosphere by flaring excess biogas. The maximum electrical energy surplus ratios that could be developed for ML based on total measured biogas production, engine-generator set efficiency, and engine down time is shown in Figure 10.

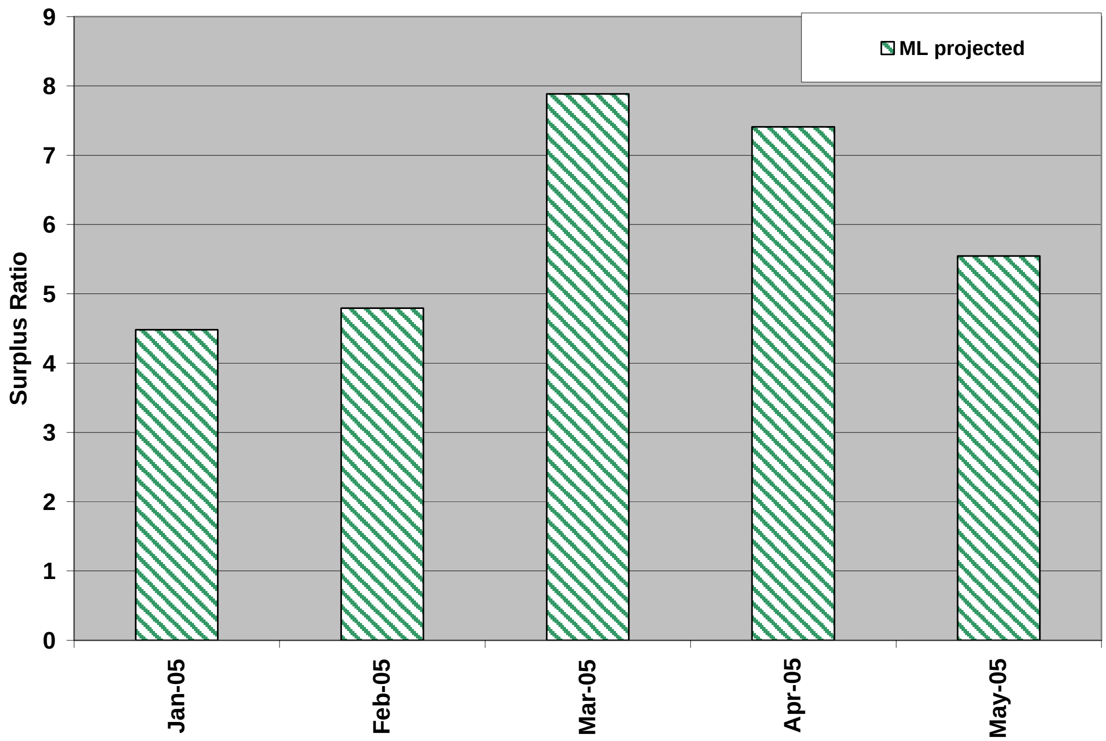

Figure 10. Electrical energy surplus projected ratios for ML based on measured biogas production.

If ML had more engine-generators almost eight times more energy could be produced by the farm than was required for farm use.

Capacity Factor

The monthly capacity factor for the engine-generator sets at AA, ML and NH was calculated using Equation 5 and with input values from Tables 23a and 23b. The results are shown in Table 24.

Equation 5.

$$\text{Capacity factor} = \frac{\text{electrical energy produced monthly (kWh)}}{\text{hours in month} * \text{generator max power output (kW)}}$$

Table 24. Capacity factor for each month for AA, ML and NH.

	AA	ML	NH
January 2004	0.329	0.925	0.367
February 2004	0.399	0.951	0.332
March 2004	0.229	0.932	0.398
April 2004	0.550	0.907	0.594
May 2004	0.582	0.899	0.769
June 2004	0.567	0.927	0.596
July 2004	0.157	0.665	0.151
August 2004	0.253	0.850	0.509
September 2004	0.426	0.799	0.195
October 2004	0.363	0.889	0.797
November 2004	0.150	0.884	0.918
December 2004	0.085	0.960	0.494
January 2005	0.010	0.866	0.567
February 2005	0.0	0.826	0.805
March 2005	0.227	0.867	0.585
April 2005	0.328	0.908	0.805
May 2005	0.350	0.919	0.631

A capacity factor that approaches unity is desired. Low monthly capacity factors at AA are the result of an engine-generator sized for a digester processing manure from 1,000 cows, while the digester at AA only processed manure from 550 cows. NH had low monthly capacity factors as a result of the engine controls frequently shutting the engine down due to low biogas pressure. Higher capacity factors at ML may be a result of the digester consistently producing more biogas than the engine required.

Capacity factor values shown in Table 24 are shown graphically in Figure 11.

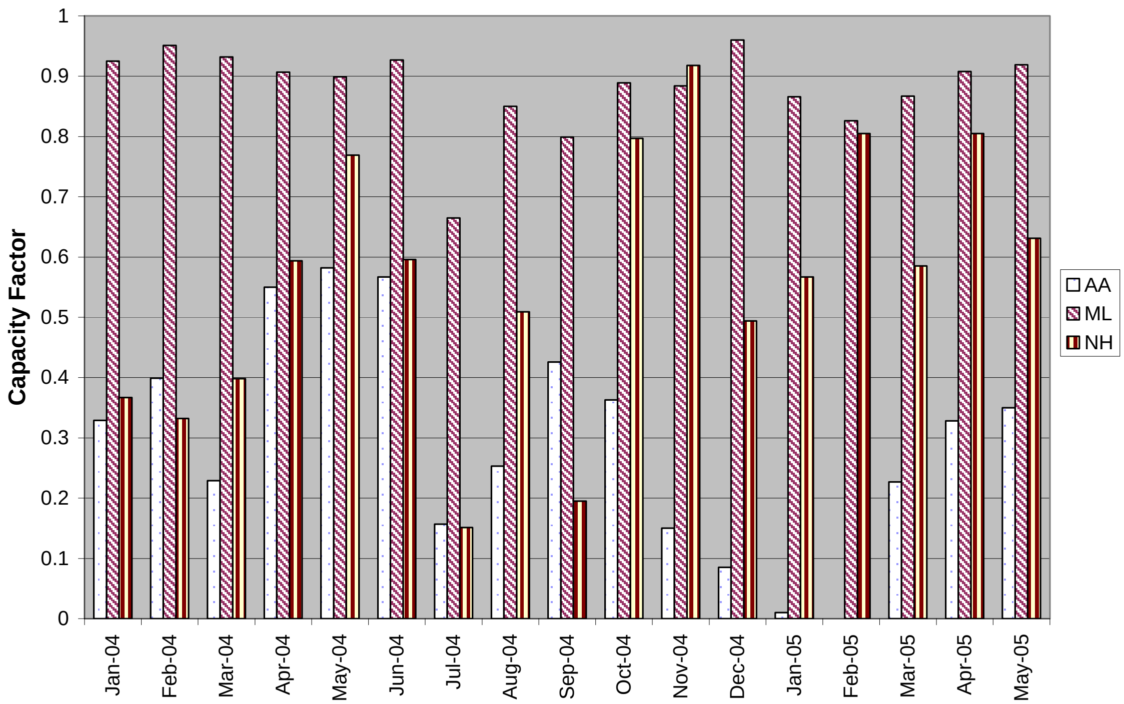

Figure 11. Capacity factor for AA, ML, and NH from January 2004 to May 2005.

Biogas to Electricity

The calculated volume of biogas, in cubic feet, needed to generate one kWh of energy was determined by using Equation 6.

Equation 6.

$$\text{Biogas volume per kWh} = \frac{\text{Biogas}\,(\text{ft}^3)}{\text{Energy Produced}\,(\text{kWh})}$$

The electric production efficiency for the engine-generator sets at AA, ML, and NH was calculated by using Equation 7 (adapted from ETV, 2005).

Equation 7.

$$\text{Elect. Efficiency}\quad(\%) = \frac{\text{Electrical Energy Produced (kWh)}}{\left(\text{Biogas }(\text{ft}^3)\right)\times\left(\text{Assumed LHV} = \dfrac{650\text{ Btu}}{\text{ft}^3}\right)\times\left(0.0002929\ \dfrac{\text{kWh}}{\text{Btu}}\right)}$$

Table 25 shows the outputs from Equations 6 and 7.

Table 25. Biogas (ft^3) used per energy produced (kWh) and engine-generator set efficiency (percent) by month from January 2004 to May 2005.

Month	Units	AA	ML	NH
January 2004	ft^3 / kWh	41.2	22.5	-
	%	15.1	27.6	-
February 2004	ft^3 / kWh	39.0	22.5	-
	%	15.9	27.6	-
March 2004	ft^3 / kWh	38.2	23.2	-
	%	16.3	26.7	-
April 2004	ft^3 / kWh	28.3	24.4	29.2
	%	22.0	25.5	21.3
May 2004	ft^3 / kWh	-	24.6	26.4
	%	-	25.3	23.5
June 2004	ft^3 / kWh	-	26.1	28.6
	%	-	23.8	21.7
July 2004	ft^3 / kWh	-	33.0	28.5
	%	-	18.8	21.7
August 2004	ft^3 / kWh	34.9	27.3	29.2
	%	17.8	22.7	21.2
September 2004	ft^3 / kWh	34.2	24.4	30.3
	%	18.2	25.5	21.9
October 2004	ft^3 / kWh	36.0	29.0	24.6
	%	17.2	21.4	25.2
November 2004	ft^3 / kWh	50.0[1]	23.6	23.2
	%	12.4[1]	26.3	26.7
December 2004	ft^3 / kWh	103[1]	23.3	25.1
	%	5.8[1]	26.6	24.8
January 2005	ft^3 / kWh	416[1]	24.6	29.5
	%	1.5[1]	25.2	21.0
February 2005	ft^3 / kWh	-	26.2	22.0
	%	-	23.7	28.2
March 2005	ft^3 / kWh	39.7	23.1	27.1
	%	15.6	26.9	22.9
April 2005	ft^3 / kWh	33.6	24.5	22.7
	%	18.5	25.3	27.3
May 2005	ft^3 / kWh	35.4	24.7	25.6
	%	17.5	25.2	24.3

[1]During this time the engine was run for multiple hours for heat reclamation only (no power generation) skewing the results.

Average biogas volume (ft^3) used per energy produced (kWh) were 36.1, 25.1, and 26.6 for AA, ML, and NH respectively. Average engine-generator set electrical production efficiency over the data collection period was 17.4, 24.9, and 23.7 for AA, ML, and NH respectively. Biogas volume (ft^3) per kWh generated is shown in Figure 12.

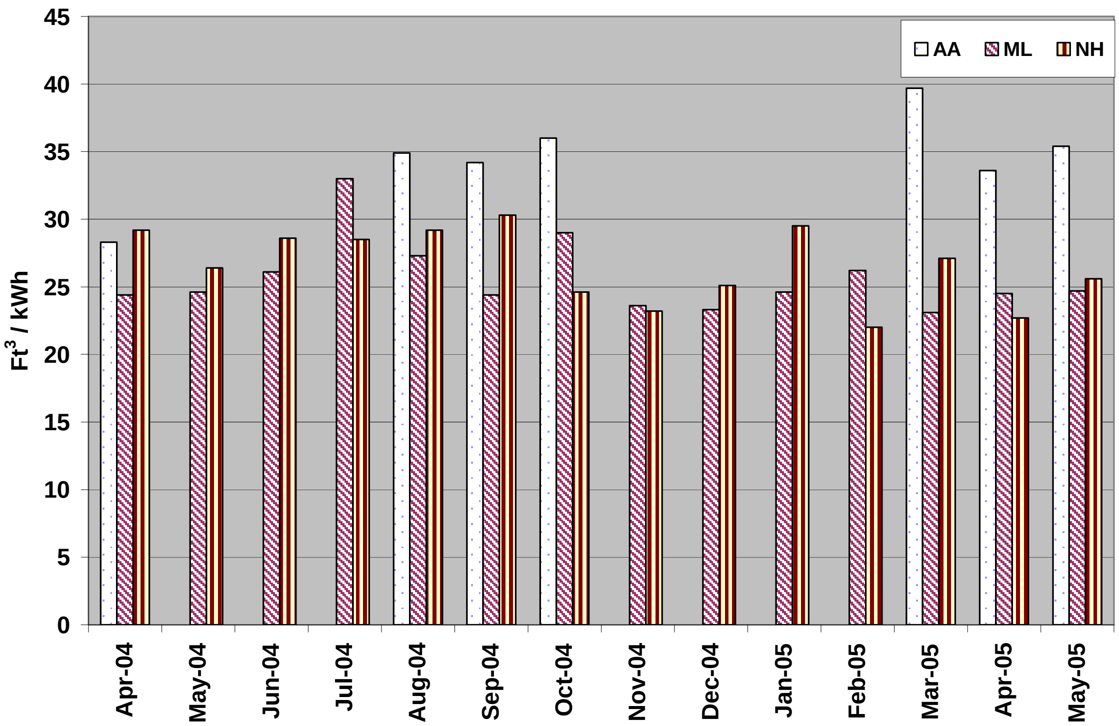

Figure 12. Biogas volume (ft^3) utilized at AA, ML, and NH for each kWh generated from April 2004 to May 2005.

The inverse of Equation 6, multiplied by 1,000 was used to calculate the values shown in Table 26.

Table 26. Energy (kWh) per cubic foot of biogas used, multiplied by 1,000.

Month	AA	ML	NH
January 2004	24.3	44.4	-
February 2004	25.6	44.4	-
March 2004	26.2	43.1	-
April 2004	35.3	41.0	34.2
May 2004	-	40.7	37.9
June 2004	-	38.3	35.0
July 2004	-	30.3	35.1
August 2004	28.7	36.6	34.2
September 2004	29.2	41.0	33.0
October 2004	27.8	34.5	40.7
November 2004	20.0	42.4	43.1
December 2004	1.0	42.9	39.8
January 2005	0.2	40.7	33.9
February 2005	-	38.2	45.5
March 2005	25.2	43.3	36.9
April 2005	29.8	40.8	44.1
May 2005	28.2	40.5	39.1

Digester Heating

The estimated average heat each digester used per month is shown in Table 27. Portable Btu meters were used at AA, DDI, and NH to collect data. FA had permanent Btu meters installed previous to January 2004. ML had permanent flow meters and temperature sensors (to calculate Btu's) installed after November 2004. The design of the portable and permanent Btu meters and the design of the digester heating systems precluded the placement of the meters immediately adjacent to the digesters. Therefore, the Btu meters were located in the building that housed the digester heating system. For AA, ML, and NH meter placement was in the engine-generator room while for FA and DDI meter placement was in the boiler room. The meter placement resulted in data that included heat losses to the ground from the hot water heating loop circulation lines between the heat source and the digesters, in addition to heat needed to maintain the temperature of the digester. The monthly heating values for FA were lower than the other digesters because of the comparatively small size of the FA digester. Technical difficulties prevented the use of the portable Btu meters at ML previous to the installation of the permanent equipment installation in November of 2004. All values for ML were obtained after November of 2004 from the Connected Energy website. The project only purchased two portable meters; therefore, some of the missing data in the table is due to a shortage of equipment. Other missing data is due to equipment malfunction.

Table 27. Estimated average daily heat (Btu's) for each digester by month from January 2004 to May 2005.

Month	AA	DDI	FA	ML	NH
January 2004	-	8,797,164	346,687	-	-
February 2004	-	-	402,734	-	5,230,922
March 2004	-	10,510,108	377,233	-	7,935,071
April 2004	-	-	379,931	-	5,620,650
May 2004	4,343,550	9,291,609	421,000	-	-
June 2004	2,824,426	-	402,667	-	2,506,352
July 2004	-	10,340,241	306,667	-	-
August 2004	3,072,456	-	342,364	-	-
September 2004	-	11,655,611	113,900	-	-
October 2004	-	9,051,238	384,370	-	-
November 2004	-	14,022,398	534,300	10,315,000	-
December 2004	-	-	552,387	13,055,000	12,306,600
January 2005	-	-	561,387	11,893,000	-
February 2005	5,403,250	18,298,679[1]	534,429	10,724,000	-
March 2005	-	-	537,032	11,035,000	8,394,192
April 2005	6,923,788	5,115,637	517,233	10,056,000	-
May 2005	-	6,053,634	532,871	9,193,000	11,447,568

[1]Digester was inadvertently heated to 120°F.

The estimated average daily heat (Btu's) required per unit treatment volume (gallons) for each digester was calculated by dividing Table 27 values by the treatment volume (gallons) shown in Table 4. The results are shown in Table 28.

Table 28. Estimated average daily heat demand per treatment volume (Btu's/gallon) for each digester from January 2004 to May 2005.

Month	AA	DDI	FA	ML	NH
January 2004	-	17.4	44.6	-	-
February 2004	-	-	51.8	-	8.2
March 2004	-	20.8	48.6	-	12.5
April 2004	-	-	48.9	-	8.9
May 2004	10.6	18.4	54.2	-	-
June 2004	6.9	-	51.8	-	3.9
July 2004	-	20.5	39.5	-	-
August 2004	7.5	-	44.1	-	-
September 2004	-	23.1	14.6	-	-
October 2004	-	17.9	49.4	-	-
November 2004	-	27.8	68.7	16.2	-
December 2004	-	-	71.1	20.6	19.4
January 2005	-	-	72.2	18.7	-
February 2005	13.2	36.3	68.7	16.9	-
March 2005	-	-	69.1	17.4	13.2
April 2005	16.9	10.1	66.5	15.8	
May 2005	-	12.0	68.5	14.5	18.0

Data shown in Table 28 are shown graphically in Figure 13.

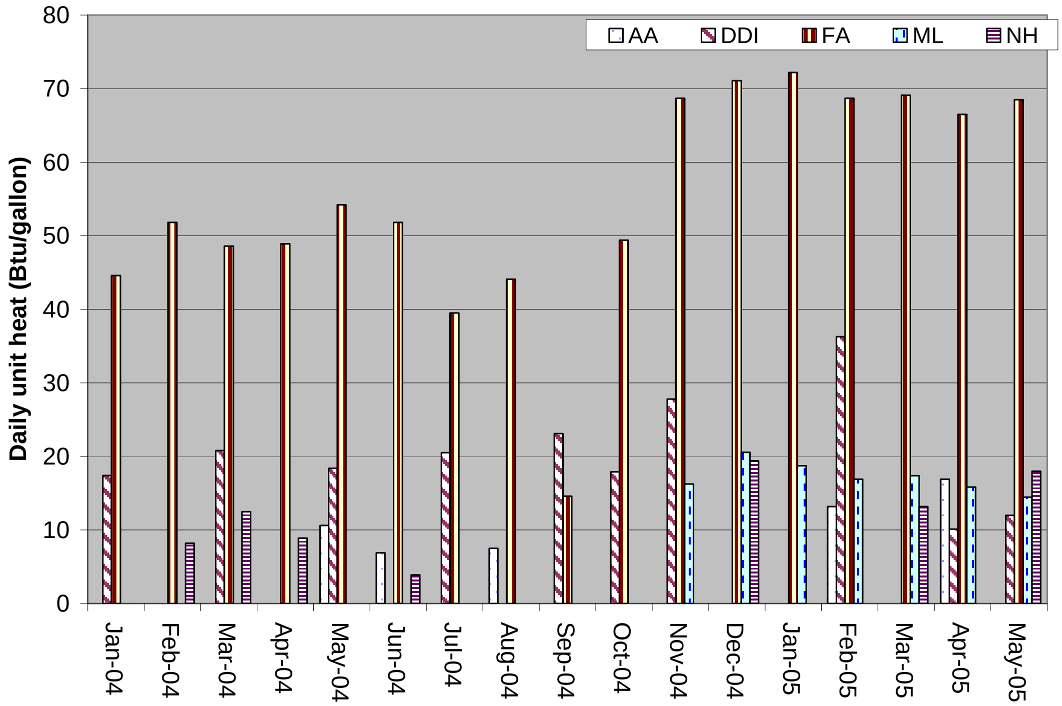

Figure 13. Estimated average daily heat demand per treatment volume (Btu/gallon) for all farms.

For each month with data, FA had the highest heating demand per unit of treatment volume. High heat demand at FA is likely a result of the low retention time associated with the design. In contrast, in most months NH had the lowest heating demand per treatment volume. This digester was fully below-grade and was well insulated with rigid insulation covered by a layer of soil.

The estimated daily heat (Btu's) per estimated daily influent volume (gallons) for AA,DDI, and ML is shown in Table 29. The values were calculated by dividing the estimated daily heating values in Table 27 by the estimated daily loading rate (gallons) shown in Table 2.

Table 29. Estimated heat (Btu's) per estimated daily influent volume (gallons) for AA, DDI, and FA from January 2004 to May 2005.

Month	AA	DDI	FA
January 2004	-	363	489
February 2004	-	-	-
March 2004	-	420	440
April 2004	-	-	424
May 2004	393	372	405
June 2004	255	-	341
July 2004	-	414	260
August 2004	278	-	290
September 2004	-	583	96
October 2004	-	377	333
November 2004	-	584	463
December 2004	-	-	478
January 2005	-	-	486
February 2005	489	696	463
March 2005	-	-	465
April 2005	626	422	448
May 2005	-	404	461

Data in Table 29 is shown graphically in Figure 14.

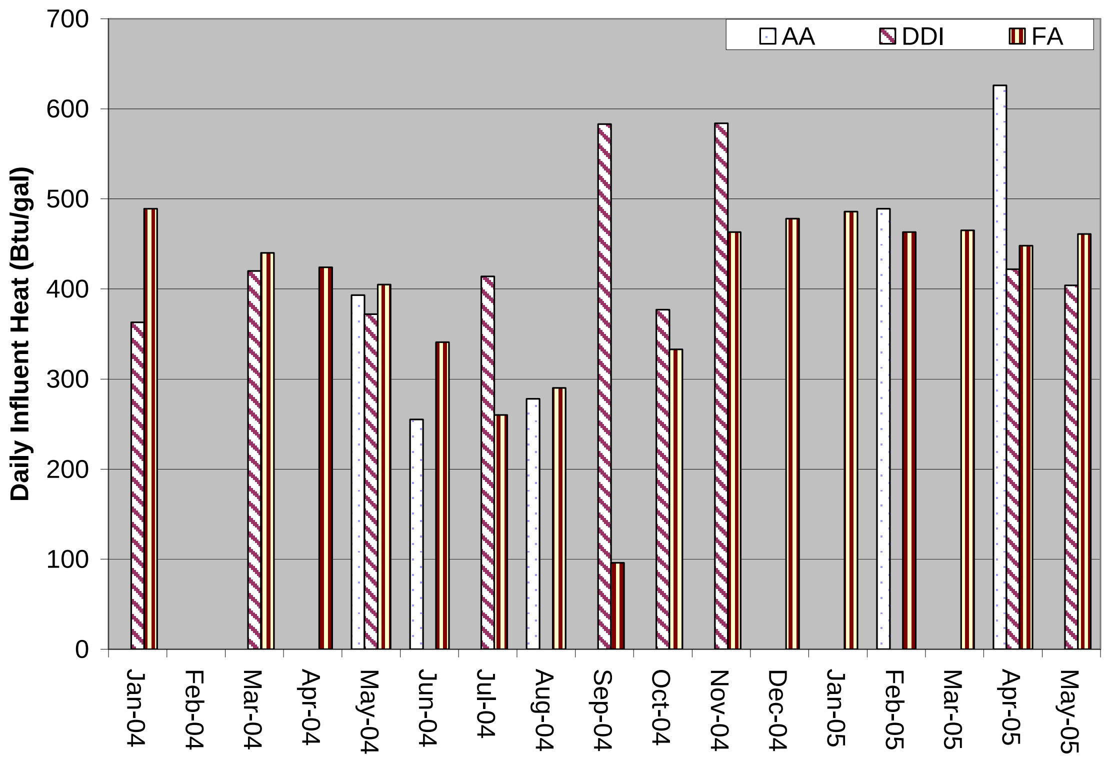

Figure 14. Estimated heat per daily influent volume (Btu's/gal) for all AA, DDI, and FA.

Anaerobic Digester System Economics

A complete economic analysis is needed for anaerobic digester systems so a producer can make an informed business decision regarding their use. Producers who make a capital investment in an anaerobic digester need to understand the economics of the system. The capital, estimated operating costs, and estimated total annual costs for the five farms are shown in Table 30. The available data for the capital costs shown have not been adjusted to reflect the grant funds each farm received.

Table 30. Predicted net annual cost or benefit for the five digester systems (Wright et al., 2004).

	Farm				
	AA	**DDI**	**NH**	**ML**	**FA**
Number of Cows	500	850	1,100	725	100
Capital Costs					
Digester Set	$192,000	$442,200	$339,400	$298,149	$80,183
Separator Set	$50,000	$89,000	$61,000	$61,689	$44,013
Gas Utilization Equipment	$61,000	$138,200[4]	$287,300	$130,431	$13,135
Total Capital Cost	$303,000	$669,400	$687,700	$490,269	$137,331
Total Capital Cost Per Cow	$606	$788	$625	$676	$1,373
Annual Projected Capital Cost	$25,468	$52,978	$63,274	$49,016	$13,396
Annual Projected Capital Cost Per Cow	$51	$62	$58	$68	$134
Total Predicted Annual Cost[1]	$37,540	$79,317	$103,960	$70,880	$21,497
Total Predicted Annual Cost Per Cow[1]	$75	$93	$95	$96	$215
Total Predicted Annual Revenues	$56,445	$60,400[3]	$77,680	$287,685	$10,900
Total Predicted Annual Revenues Per Cow	$113	$71[3]	$71	$397	$109
Total Predicted Annual Cost or Benefit[1, 2]	$18,906	-$18,917[2, 3]	-$26,280[2]	$216,805	-$10,597[2]
Total Predicted Annual Benefit Per Cow[1, 2]	$38	-$22[2, 3]	-$24[2]	$299	-$106[2]

[1] Does not include system electrical use.

[2] Negative numbers mean the farm incurs a net loss from the digester system.

[3] The electrical savings for DDI assumes the price of electricity is 10 cents/kW. This farm actually incurs a lower cost due to a specific business initiative. Since this is not typical of most dairy farms, the higher price is used.

[4] This cost assumes the microturbines were purchased new.

The values shown for the digester set include capital costs, as applicable by farm, such as site preparation, digester structure and cover, influent/effluent, circulate, mixture, and feed pumps, biogas boilers, heat exchangers, hot water tanks, and other auxiliary equipment. The separator set includes the capital cost of the separator system, separator building, and interim storage. The gas utilization set includes the capital costs, as applicable by farm, of microturbines, engine/generator sets, electrical switch gear, engine building, biogas flare, coolant pumps, heat radiator, solids dryer, electrical engineer consulting fee, any initial engine-generator set rebuild costs, and other gas utilization equipment.

Annual projected capital cost is calculated as the foregone interest, which is estimated to be five percent of the average investment value of the capital plus the annual capital straight-line depreciation cost. When calculating the annual capital straight-line depreciation, varying useful lives are used according to the expected life of the piece of equipment in the system. The digesters, solid digester covers, buildings, separators, boilers, heat exchangers, microturbines, variable speed drives, and piston pumps are estimated to have a useful life of 20 years. The flexible digester covers, mixing, coolant, and circulating pumps, flares, heat dump radiators, and new engine-generator sets are estimated to have a useful life of 10 years. Engine-generator sets that were acquired used, or had to be rebuilt upon purchase, are estimated to have a useful life of seven years. The pH and CO_2 meters, centrifugal, effluent, separator, and food waste feed pumps are estimated to have a useful life of five years. Also, certain components of the system are projected to have a salvage value at the end of their useful life. The salvage value of such equipment is calculated as 10 percent of the capital cost, or initial investment, for that particular component.

The total estimated annual cost for each digester system is the sum of the estimated annual capital cost and the estimated annual operating costs for each component. Estimated annual operating costs were estimated based on any annual repairs on the equipment and facilities plus the cost of management, labor, and insurance, but do not include electrical cost to operate the system. Total estimated annual revenues were calculated as an addition of heat savings, electricity savings (only for the non-parasitic power) and sales, profits on solids, tipping fees, bedding, hot water, and composting. They do not include any odor control benefits.

The capital and estimated annual cost and revenue calculations do not include any costs/revenues from manure storage, spreading, or electrical cost to run the system. Manure storage costs, not shown here, varied significantly from farm-to-farm depending on whether earth, concrete, or metal were used as construction materials. The benefit of being able to use treated manure on cropland previously unavailable for manure use (due to odor problems) was also not considered in this analysis.

Total capital costs vary because each digester is specifically designed for each farm. DDI had microturbines, FA doesn't generate electricity, and the three others used internal combustion engine-generator sets. AA's capital cost is less than its electricity-generating counterparts because it was built in June of 1998.

The total annual cost or benefit calculation is considered to be the cost the farm pays for odor control when the value is less than zero. ML had a comparatively high annual economic benefit because of the annual tipping fee received. Total annual cost per cow is not correlated with the total number of cows, again showing that site-specific systems have highly variable costs.

It is anticipated that some of the economic data will be used to calculate digester performance indices as part of phase II of the project.

Digester Performance Indices

The following performance indices were developed as a proposed means to quantify the performance of anaerobic digestion and gas utilization on dairy farms. Data needed for the calculations can be obtained from a combination of Connect Energy monitoring, individual equipment monitoring, logs kept by the farm, and laboratory analysis of biogas samples. Values for select indices are anticipated to be calculated under phase II of the project.

General

1. **Biogas Production Rating;** Biogas produced (ft^3 or Btu's[1]) / Influent volume (ft^3); measure of efficiency of digester in converting biologically degradable solids to biogas. Note: on farms where accurate total solid (TS) reduction or volatile fatty acids (VFA) reduction data is available, this would be used in lieu of volume.

2. **AD System Energy Production Efficiency;** [System parasitic energy (kWh) + Supplemental energy added (Btu's)] / Heat value of utilized biogas produced (Btu's[1]); measure of the overall energy efficiency of the AD system.

3. **Combined Heat and Power Efficiency;** [Electrical power produced + Heat recovered] / Biogas energy value.

4. **Overall Parasitic Heat Rating;** Total heat (Btu's) / Influent volume (gal or ft^3); influent heat required per unit volume calculated on a daily, monthly, or yearly basis. Higher rating values will occur for systems with cold or frozen manure, less insulation, and/or more exposure.

5. **AD Parasitic Heat Rating;** Maintenance heat (Btu's) / Total treatment volume (gal or ft^3); values will be higher for cold climates and/or digesters with less insulation. Not applicable for digesters without a maintenance heating system.

6. **AD Unit Insulation Rating;** Maintenance heat (Btu's) / Ave. daily ambient temperature (F); correlation between heat required and ambient temperature, measure of the thermal efficiency of the digestion vessel. Not applicable for digesters without a maintenance heating system.

Electrical Energy Generation

1. **Engine-Generator Set Electrical Efficiency;** Electrical energy generated (kWh) / Biogas consumed by engine (ft^3 or Btu's[1]); measure of engine-generator set energy conversion efficiency.

2. **AD System Electrical Energy Efficiency;** [Energy generated by generator (kWh) - AD system parasitic energy (kWh)] / Energy generated by generator (kWh); measure of the efficiency of the system to produce net electrical energy.

Heat Energy Recovery

1. **AD Heat Energy Rating;** Total heat used (Btu's) / total heat produced (Btu's); measure of the efficiency of utilizing heat of combustion.

2. **Heat Recovery Efficiency;** Heat recovered (Btu's) / [Biogas energy (Btu's) – Electrical power produced (kWh)].

Economics

1. **System Total Annual Cost (TAC);** Annual cost for odor control if no heat is utilized or electricity produced.

2. **Annual Overall Electrical Generation Cost Rating;** Total Annual Cost of the AD system ($) / Annual electrical energy produced (kWh); measure of the unit cost of the electrical energy produced on-farm annually.

3. **Annual Electrical Energy Generation Cost Rating;** TAC of Eng.-gen. system ($) /Annual energy generated (kWh); the annual unit cost of the electrical energy generation system.

4. **Annual Heat Recovery Cost Rating;** TAC of the heat recovery system ($) / Annual captured heat (Btu's); the annual unit cost to capture engine combustion heat.

5. **Annual Heat Generation Cost Rating;** TAC of boiler equipment ($) / Annual heat produced (Btu's); the annual unit cost of producing heat by biogas combustion in a boiler.

6. **Annual System CHP Cost Rating;** [Value of electrical energy produced + Value of Heat Recovered] / TAC of system.

7. **Annual Wasted Energy Rating;** Heat or biogas dumped reported as an equivalent of heating oil (or diesel, kerosene etc.)

[1]Energy content of biogas generated by the AD can be calculated by the product of the measured gas produced multiplied by 1) either an assumed energy density of the gas or 2) using data developed based on gas sampling. Currently, no gas sampling is being performed.

Future Work

Potential Optimization Strategies

The follow optimization strategies have been identified for consideration. Select optimization strategies will tested on farms based on the appropriateness and interest by the farm owner.

1. Manure inputs
   Loading rate; feed; bedding; water content
2. Add materials to digester influent
   Micronutrients; specialty microbes; fats or other energy sources
3. Change mixing times and/or frequency for mixed digesters
4. Change digester temperature
5. Use a portion of digester effluent to inoculate digester influent

Odor Quantification

Odor logs completed by the farm and/or ambient air sample analysis by a olfactory panel are two ways that quantification of odor control as a result of the anaerobic digestion process may be implemented in future project work.

Project Data

Raw data associated with this project is maintained on file at the Cornell Biological and Environmental Engineering department and is available by written request.

Publications to Date Supported by Project Work

1. Anaerobic Digester at AA Dairy: Case Study. Available from: http://www.manuremanagement.cornell.edu/Docs/AA%20Case%20Study%20draft%20(6-11-04).htm

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