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FINAL PROJECT REPORT

ENERGY AND ENVIRONMENTAL PERFORMANCE OF SIX DAIRY DIGESTER SYSTEMS IN CALIFORNIA

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  - Cal Recycle
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PREFACE

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An Economic Analysis of Six Dairy Digester Systems in California is the final report for the Energy, Economic, and Environmental Performance of Dairy Bio-power and Bio-methane Systems project (contract number PIR-08-041) conducted by Summers Consulting, LLC. The information from this project contributes to Energy Research and Development Division's Renewable Energy Technologies Program.

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ABSTRACT

This study examined the performance of six operating dairy digester systems producing biogas for conversion to power and heat in California. A 12-month evaluation was conducted following a standard protocol developed for analyzing these renewable energy production systems. The study tracked attributes of each system including digester feeding, digester performance, biogas production, biogas generator performance and climate change impact.

The study showed that the digester systems treated about 50-80 percent of the manure solids and converted them to biogas at a rate of 2.7 to 4.2 standard cubic feet per pound volatile solids excreted, with a biogas methane content of 60-68 percent. There was potentially 33 billion cubic feet per year of methane that could be generated from California dairy manure using anaerobic digestion technology. Nutrients were conserved in the digestion process and organic bound nitrogen was converted to the more crop available ammonia-nitrogen form at a rate of 34-39 percent for the manure stream. These results meant that manure nutrients were still available for crop production. Biogas power was generated at 21-28 percent efficiency with combined heat and power efficiencies of 42-53 percent using conventional internal combustion engine generator systems. These ranges were consistent with other types of cogeneration but there was room for improvement in optimizing capacity factor and heat utilization. Air emissions from uncontrolled spark ignition engines on biogas were shown to be similar to natural gas and biogas engines with emission control systems that could achieve the most stringent California emissions standards. Dairy facilities with digester systems reduced methane emissions by 61-71 percent over conventional holding pond/flush manure management systems. Widespread adoption of dairy digesters could substantially reduce greenhouse gases from this sector and could generate seven million metric tons per year in potentially valuable carbon credits.

Keywords: anaerobic digester, biogas, cogeneration, renewable energy, dairy manure, atmospheric methane emissions

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EXECUTIVE SUMMARY

Introduction

California is the nation's top dairy producing state with 1.8 million lactating dairy cows plus a support herd that represents about 18 percent of the total United States dairy population. The California dairy industry produces approximately 20 million tons of milk from this dairy herd. A vast amount of dairy manure on the order of 10 million tons of solids is also generated per year in order to produce this large quantity of milk. This manure carries a large amount of nutrients that dairy producers utilize to grow crops. Most dairy producers need to store this manure before applying it to their crops due to the nature of cropping, the capacity of the local land base and the regulations that currently exist in California. This manure can cause environmental impacts in transit from animal housing to the field, including methane emissions, odor emissions and potential water quality impacts.

Anaerobic digestion has been identified as a promising technology for converting dairy manure into renewable energy while potentially mitigating some other impacts of manure management on the ambient environment. Data is limited in both California and the United States regarding the overall energy, economic and environmental performance of biogas digesters. A lack of agreement still exists among regulators, industry, energy development companies and environmental groups regarding the performance and environmental impacts of dairy digesters. Much of this disagreement could be addressed with independent scientific data to account for the form and fate of all constituents as manure moves and is converted through the farm-integrated digester system. This information is critically needed for engineering, permitting, financing and interconnecting this large potential source of renewable power and transportation fuel in California.

Project Purpose

The objective of this research was to evaluate the technical, economic and environmental performance of six working dairy biogas systems for renewable fuel production.

Project Results

The monitoring methodology followed evaluation protocols developed by the United States Environmental Protection Agency (EPA), Association of State Energy Research and Technology Transfer Institutions and the Climate Action Registry and involved the installation and monitoring of continuous automatic sensors along with the collection of periodic samples for composition analysis.

The project focused on dairy facilities with a variety of digester types and modes of operation. The study included covered lagoon, complete mix, and plug flow digester systems. Some digester systems processed only manure, while others processed manure and feedstock from cheese-making facilities and agricultural byproducts. This project included a 12-month field evaluation of different types of manure and solids management technologies, gas conditioning systems, combined heat and power generators, biogas engine emissions controls and other subsystems integral to the performance of the overall energy production systems. Table ES.1 describes the characteristics of the dairy digester facilities evaluated in the study.

Table ES.1: Characteristics of 12-Month Study Dairy Digester Systems.

DAIRY NO.	COWS MILKED	TYPES OF SOLIDS FEED TO DIGESTER SYSTEM	DIGESTER TYPE	DIGESTER VOLUME (GAL)	BIOGAS USE (KILOWATT CAPACITY)	EXTERNAL HEAT UTILIZATION
1	550	1. Recycled Flush Water 2. Fresh Manure	Covered Lagoon	6,400,000	Power (65 kW)	
2	350	1. Recycled Flush Water 2. Fresh Manure 3. Cheese Plant Wastewater	Covered Lagoon	2,500,000	Power (75 kW)	X
3	3,200	1. Fresh Manure 2. Cheese Plant Wastewater	Covered Lagoon	45,000,000	Power (750 kW)	X
4	850	1. Recycled Flush Water 2. Fresh Manure	Mixed Lagoon	3,400,000	Power (212 kW)	
5	1,700	1. Flush Manure Slurry 2. Screened Manure Solids 3. Green Chop Silage	Complete Mix	1,700,000	Power (710 kW)	X
6	2,100	1. Scraped Fresh Manure	Plug Flow	500,000	Power (195 kW)	

All of the digesters in the study were fed raw manure solids while some systems had additional solids input from recycled water and/or other added solids from cheese plant wastewater or green chop silage as shown in Table ES-1. The actual percentage of digester input from these sources measured during the 12-month study is shown for each digester in Table ES.2. The daily volumetric amount of flow and the concentration of the solids was 0.4 percent to 2.1 percent for the flushed lagoon systems and 8.0 percent and 10.5 percent for the high solids digester systems. The total estimated raw manure capture by the digester varied widely from 30 percent to 83 percent and depended on the housing type, collection efficiency, and pre-digestion solids separation. Raw manure capture was calculated from the raw manure solids entering the digester vs. the estimated amount generated by the dairy herd.

Table ES.2: Characteristics of Influent Volumetric and Solids Flow for Each Digester System.

DAIRY NO.	INFLUENT VOLUMETRIC FLOWRATE	TOTAL SOLIDS CONC.	VOLATILE SOLIDS CONC.	INFLUENT VOLATILE SOLIDS FLOW	RAW MANURE VOLATILE SOLIDS	RECYCLE WATER VOLATILE SOLIDS	NON-MANURE VOLATILE SOLIDS	RAW MANURE CAPTURE BY DIGESTER
	(GAL/DAY)	(%)	(% of TS)	(LBS VS/DAY)	(%)	(%)	(%)	(%)
1	129,309	0.9	68.8	6,434	62%	38%	-	34%
2	60,417	1.7	73.8	6,218	54%	43%	3%	43%
3	1,289,992	0.4	75.1	35,989	48%	-	52%	30%
4	696,646	2.1	66.8	80,951	23%	77%	-	83%
5	35,607	10.5	79.5	24,278	64%	-	36%	49%
6	40,849	8.0	79.4	21,605	100%	-	-	55%

The digester systems had temperatures, loading rates and retention times within the design guidelines for these types of systems with the exception of Dairy 4, which had a very short hydraulic retention time and achieved relatively poor digestion. The digesters converted volatile solids to biogas at a rate of 4.9 to 6.3 standard cubic feet (SCF) per pound of volatile solids added for the manure only digesters and 9.2 and 12.9 SCF per pound of volatile solids added for the mixed feed digesters, as shown in Table ES.3. The consumption of volatile solids was from 28 percent to 62 percent and chemical oxygen demand was reduced by 42 percent to 86 percent. All nutrients were shown to be conserved in the digestion process and organic bound nitrogen was converted to the more crop available ammonia-nitrogen form at a rate of 34-39 percent for the manure systems and 125-145 percent for the mixed systems. These results meant that manure nutrients were still available for crop production and that nitrogen was in a more crop available form with the use of anaerobic digester systems.

Table ES.3: Performance Parameters and Conversions for Study Digester Systems.

DAIRY NO.	AVERAGE DIGESTION TEMP.	ORGANIC LOADING RATE	HYDRAULIC RETENTION TIME	SPECIFIC BIOGAS PRODUCED	VOLATILE SOLIDS CONSUMPTION	CHEMICAL OXYGEN DEMAND REDUCTION	AMMONIA-NITROGEN INCREASE
	(DEG F)	(LB VS /1000 CF/DAY)	(DAYS)	(SCF/LB VS Added)	(%)	(%)	(%)
1	67.0	7.5	49.4	5.9	44.4%	63.8%	36.2%
2	80.4	18.6	44.4	6.3	50.2%	44.8%	34.1%
3	80.7	6.0	35.2	12.9	61.7%	86.2%	125.1%
4	62.4	178	4.9	0.6	3.8%	15.6%	-4.6%
5	101.5	107	61.1	9.2	42.4%		144.5%
6	101.1	323	12.7	4.9	28.4%	42.1%	38.8%

Biogas was produced at a consistent rate based on the amount of volatile solids consumed across the study, as shown in Table ES.4. The manure-only digesters produced 14.4 to 18.2 SCF of biogas per pound of volatile solids consumed while the mixed digesters were somewhat higher at 21.4 and 21.9 SCF per pound. These numbers made sense on a mass balance basis as about 16-18 SCF of biogas weighed about one pound. The biogas was consistently 60 to 68 percent methane on average across the study and was slightly lower for the concentrated systems. The amount of hydrogen sulfide in the raw biogas was lowest for the systems with air injection, from 19 to 256 parts per million by volume (ppmv), while the other uncontrolled systems were above 1900 ppmv. The amount of biogas that had to be flared also varied by facility from no flaring to as high as 57 percent and resulted from the matching of the gas production to the generator capacity and from excessive generator downtime.

Table ES.4: Biogas Production and Performance for the Digester Systems in the Study.

DAIRY NO.	TOTAL BIOGAS	SPECIFIC BIOGAS	SPECIFIC BIOGAS	SPECIFIC BIOGAS	METHANE IN BIOGAS	HYDROGEN SULFIDE IN BIOGAS	PERCENT FLARED BIOGAS
	(SCFD)	(SCF/LB VS ADDED)	(SCF/LB VS CONSUMED)	(SCF/LB VS EXCRETED)	(VOL %)	(PPMV)	(%)
1	36,032	5.9	16.4	3.1	66.4	1911	57%
2	32,534	6.3	14.4	4.2	66.6	62	0%
3	449,215	12.9	21.4	7.8	67.6	19	17%
4	44,982	0.6	16.3	2.0	67.8	2380	14%
5	220,244	9.2	21.9	7.0	65.0	256	1%
6	105,158	4.9	18.2	2.7	60.4	4280	19%

The biogas generators operated at capacity factors from 33 percent to 82 percent. Facilities with capacity factors above 80 percent generally had ample biogas production by the digester to keep the generator operating near capacity as shown by the small amount (17-19 percent) of excess gas that had to be flared. The systems with marginal capacity factors between 50-80 percent appeared to not have enough gas to keep the generator near capacity in spite of high engine uptime as seen by their low amount of flaring (less than one percent). The systems with poor capacity factors of less than 50 percent had digester and engine problems that kept the systems from operating well and consistently.

The electrical and recovered heat efficiencies were all in the expected range for engine generator systems. The electrical efficiencies ranged from 21 percent to 28 percent in terms of the biogas lower heating value and heat recovery efficiencies of 21 percent to 27 percent for the facilities that actually utilized the heat. Operation of the generator set below the recommended heat rate due to biogas availability may have reduced the performance of some of the systems.

The specific electrical power output achieved in terms of volatile solids added to the digester of 0.20 to 0.25 kilowatt hour (kWh) per pound of volatile solids added was in the achievable range for a manure-only digester system. Power and heat generation performance are shown in Table ES.5.

Table ES.5: Biogas Power and Heat Generation Performance for Each Dairy Digester Facility.

DAIRY NO.	GENSET CAPACITY	CAPACITY FACTOR	ELECTRICAL EFFICIENCY	HEAT RECOVERY EFFICIENCY	OVERALL CHP EFFICIENCY	SPECIFIC POWER OUTPUT	SPECIFIC HEAT RECOVERY
	(kW)	(%)	(% LHV)	(% LHV)	(% LHV)	(kWh/ LB VS ADDED)	(kWh/ LB VS ADDED)
1	65	40%	25%	33%	58%	0.10	0.12
2	80	68%	21%	21%	42%	0.24	0.22
3	750	82%	24%	24%	48%	0.47	0.42
4	212	33%	27%	38%	66%	0.02	0.03
5	710	57%	26%	27%	53%	0.40	0.43
6	190	80%	28%	25%	53%	0.17	0.14

Raw engine emissions from spark-ignition biogas engines were shown to be similar or lower than the estimated values for natural gas engines. However, emissions controls on stoichiometric and lean burn biogas engines were shown to be able to achieve the most stringent California emissions standards, which was critical for widespread permitting of these facilities.

Dairy facilities with digester systems reduced methane emissions by 61-71 percent over conventional holding pond/flush manure management systems at Dairies 1-5, as shown in Table ES.6. The reduction was only 26 percent for the dry lot/scraped system at Dairy 6. The baseline system was lower in methane emissions because the manure was handled in a dry form. These methane emissions reductions were one of the primary environmental benefits of these systems and could potentially be converted into carbon credits for sale on the nascent carbon market.

Table ES.6: Baseline and Project Methane Emissions From Dairy Facilities (Tonnes/Year).

	DAIRY 1	DAIRY 2	DAIRY 3	DAIRY 4	DAIRY 5	DAIRY 6
Total Modeled Baseline Methane Emissions	***120.4***	***85.7***	***714.9***	***175.5***	***327.9***	***111.7***
Project Methane Emissions from the BCS	19.4	16.2	131.8	37.0	84.8	37.5
Project Methane Emissions from the BCS Effluent Pond	15.3	11.7	90.3	29.3	42.3	45.0
Total Project Methane Emissions	***34.7***	***27.9***	***222.0***	***66.3***	***127.0***	***82.5***
Total Methane Reductions	***85.7***	***57.9***	***492.8***	***109.2***	***200.8***	***29.2***
Percentage Methane Reduction	***71.2%***	***67.5%***	***68.9%***	***62.2%***	***61.3%***	***26.1%***

This study showed that dairy manure digester systems can operate on a consistent basis and produce a substantial amount of energy in the form of biogas for natural gas replacement or in the form of power and heat. It also showed that these digesters have impacts on manure solids management, nutrient management, air emissions and climate change. The potential impact of dairy digester systems being implemented on a wider scale in California with a dairy herd that generated an estimated seven million tons of manure volatile solids annually can be more fully understood based on the results of this study.

In this study, an average technical potential value of 3.5 SCF of biogas per pound of manure volatile solids excretion with a methane content of 65 percent was shown to be a reasonable expectation for either a well-designed manure-only or mixed digester system in California. This provided an annual technical potential of 33 billion cubic feet of methane or about 33 million British thermal units (MMBTU) of electricity. Conversion of this biogas to power could potentially produce 2.4 million megawatt hours (MWh), assuming 90 percent biogas delivery to the generator and 28 percent efficiency. This would require the installation of about 300 MW of new capacity at a capacity factor of 90 percent. These generator systems would include potential heat production of 2.4 million MWh or eight million MMBTU, but the real technical potential depended on opportunities for thermal integration.

The amount of raw manure volatile solids consumed by the digester would be about 26 percent with an overall manure collection and digestion system performance of 3.5 SCF of biogas per pound of volatile solids excreted at the dairy. This equated to a technical potential to reduce the manure solids by about 1.9 million tons per year when applied to the manure produced in California. For the digested manure streams the chemical oxygen demand (COD) would be reduced on the order of 50 percent, dissolved solids on the order of 25 percent and biomethane potential on the order of 80 percent. The use of a solids separator would result in an additional 40 percent reduction in total solids from the process water stream if implemented before digestion and 30 percent if implemented after digestion.

Manure process water treated with digester systems would have organic nitrogen reduced by about 30 to 40 percent, making these better suited to fertilizing crops in an effective manner. The technical potential would be on the order of 100,000 tons of organic nitrogen converted to ammonia form if manure digesters were employed on an industry-wide scale in California. The study produced no evidence to contradict the assumption that all other nutrients were conserved within digester systems. This could help give confidence to dairy producers and water quality regulators about understanding these systems.

Project Benefits

Industry-wide adoption of biogas-to-power generation systems at the 300 MW capacity discussed above could result in emissions of 1.0 tons per day of oxides of nitrogen and hydrocarbons, 1.5 tons per day of sulfur dioxide, and 8.6 tons per day of carbon monoxide. These emissions would need to be mitigated but they were comparable or better than other best available controls for fuel combustion systems. In addition, the development of this industry could hopefully replace older, higher emissions power generation systems, resulting in a net decrease in pollutant emissions.

Dairies with flush systems represented 95 percent of the industry and were estimated to produce about 0.07 pounds of methane emissions for each pound of manure volatile solids excreted at the facility, which would be reduced to 0.02 by implementing a digester project. The technical potential for digester technology applied at California dairies could reduce the current total methane emissions of 500 thousand tons per year to 140 thousand tons per year or about seven million metric tonnes of potential carbon credits. These methane emissions reductions to the atmosphere represented one of the key ways that dairy digester systems could help improve the environment and could represent a potential revenue source if they could be traded on the nascent carbon market. These additional ways to monetize the benefits of dairy digester systems were needed since revenue from these systems seems to be less than the current operating cost for many of these projects.

CHAPTER 1: Introduction

California has 1.8 million lactating dairy cows plus support herd which represent about 18 percent of total US dairy population (CDFA, 2012). From this dairy herd, California dairy industry produced approximately 20 million tons of milk in 2011. In order to produce this large quantity of milk, a vast amount of dairy manure, on the order of magnitude of 10 million tons of solids is generated per year. This manure carries a large amount of nutrients that dairy producers utilize to grow crops. Due to the nature of cropping, the capacity of the local land base, and the regulations that currently exist in California, most dairy producers need to store this manure for a time period before applying it to their crops. In transit from animal housing to the field, this manure can generate impacts including methane emissions, odor emissions, and potential water quality impacts.

Anaerobic digestion has been identified as a promising technology for converting dairy manure into renewable energy while potentially mitigating some other impacts of manure management on the ambient environment. However, data is limited in both California and the US regarding the overall energy, economic and environmental performance of biogas digesters. A lack of agreement still exists among regulators, industry, energy development companies, and environmental groups regarding the performance and environmental impacts of dairy digesters. Much of this disagreement can be addressed with independent, scientific data to account for the form and fate of all constituents as manure moves and is converted through the farm-integrated digester system. Such information is critically needed for permitting, financing, and interconnecting dairy biogas systems. Expanding the knowledge base related to these systems will also help improve future system design.

In terms of technical and economic performance, there is a need for independent evaluation of dairy digester systems and their components. Many parameters are important to understand effective performance for example manure conversion rates, solids separation efficiencies, power conversion efficiencies, emissions control performance, and maintenance requirements. In addition, the impacts of factors like seasonal climate, cattle feeding regimen, use of mixed digester feedstock, system sizing factors, etc. can be better assessed with a field evaluation. All of these factors, taken with the capital and operating costs of the system and the type of utility contract that can be obtained, determine the overall economic benefit to the dairy production system.

In terms of air emissions, it is generally accepted that the use of anaerobic digesters can reduce the methane generated from manure management (Martin, 2004; CAR, 2007), particularly in liquid flush systems commonly used by dairy facilities in the West. Methane which has a high global warming potential, is converted to carbon dioxide when the biogas is combusted, lowering the impact per pound of carbon in the manure. However, there is also a potential trade-off with emissions of criteria pollutants that contribute to smog formation if the methane is combusted in the power generation system (Ochsner, 2007). In California, new digester facilities have faced emissions control technologies that add cost and complexity to the system.

The performance of these systems is critical to the development of biogas power facilities in California and needs further evaluation.

In terms of water quality, the anaerobic digester converts carbon in the manure biomass into methane and carbon dioxide. This process reduces BOD and pathogens in the effluent but these may not be water quality concerns if manure is properly applied to cropland, as specified in applicable regulations. Previous studies (DPPP, 2009; Martin, 2004) have indicated that anaerobic digestion does not significantly affect nutrient management at a dairy, as nutrients are generally conserved in the digester system. The nutrients initially present in the feedstock remain in the digester effluent. Therefore anaerobic digestion will not mitigate the threat to water quality posed by a dairy that produces more nutrients than needed to fertilize available cropland. However, the form of the nutrients (e.g. ammonia-N vs. organic-N) and the ability to separate nutrients with solids could be important considerations to the manure management strategy at a facility employing an anaerobic digestion system.

In order to improve the knowledge base on these systems, the project team proposes to quantify, through a combination of field and laboratory studies, the technical, economic and environmental performance of California dairy biogas systems including manure and effluent handling, anaerobic digestion, and biogas-to-electricity and biogas-to-fuel generation processes. This will be achieved by monitoring, sampling, and analyzing material flows, monitoring energy consumption and generation, and completing detailed element, mass, energy, and economic balances on six operating dairy digester systems. The team will follow established protocols for conducting this work developed for manure digester systems and distributed generation systems with additional sampling to cover other constituents of interest. The team also proposes to develop empirical models for three common types of dairy digester systems and examine the usefulness of digestibility analyses in predicting the performance of digesters.

CHAPTER 2: Methodology

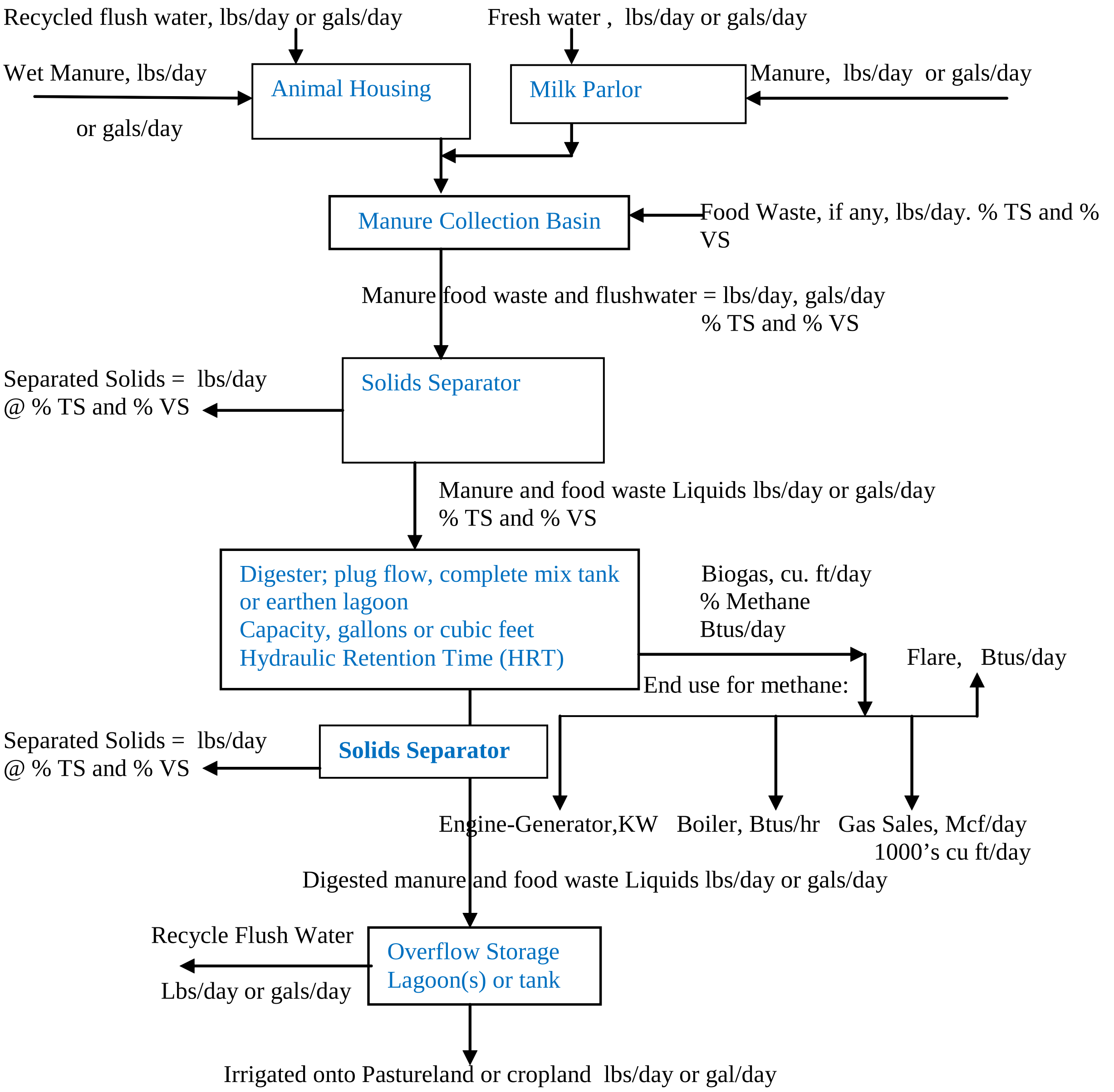
2.1 Technical Approach

The monitoring methodology and system followed protocols developed by the US Environmental Protection Agency (EPA), Association of State Energy Research and Technology Transfer Institutions (ASERTTI), and Climate Action Registry (CAR). The EPA Agstar Program developed "A Protocol for Quantifying and Reporting the Performance of Anaerobic Digestion Systems for Livestock Manures" (Martin, 2007) that gives a method to monitor a digester system at a livestock facility with monitoring points and sampling methodology that was followed by this study. In terms of the biogas engine generator performance, the ASERTTI "Distributed Generation Combined Heat and Power Long Term Monitoring Protocol" (ASERTTI, 2009) provided the methodology for monitoring engine generators by utilizing continuous data collected on gas flow, power generation, and heat recovery. The CAR "Livestock Project Reporting Protocol" (CAR, 2009) was used for determining the methane emissions reductions derived from implementing a digester project at a livestock facility by estimating the emissions from the project compared with the modeled emissions from the prior manure management method at the facility.

Figure 1 shows a typical mass and energy flow diagram an anaerobic digestion system on a dairy facility that includes the manure flow from the animal pens, food waste added, if any, collection system (whether scrape or flush), digester, gas handling system (generator, flare, boiler, or other gas utilization device), effluent storage for the digested manure, and ultimate disposal. A site-specific schematic, like the generic example in Figure 2, was developed as part of the monitoring plan for each of the 6 digesters included in this study. The monitoring layout for each individual facility is shown in the chapter dedicated to that facility. These schematics show the basic layout of the digester systems and the relevant metering points with measurements described in more detail in the tables also included. The site-specific monitoring plans were peer reviewed by the Commission Project Manager and the members of the Project Advisory Committee before the field campaign began.

Continuous sensors were installed at each of the dairy digester facilities monitored pertinent system flows and conditions. This data was recorded in data logger equipment and 15-minute averages were continuously logged and stored on site before periodic downloads by the investigators. These sampling points cover all pertinent manure, biogas, power and process water flows and temperatures. Composition samples (24-hour aggregated) were taken on a monthly basis to establish the mass distribution for each flow of manure, biogas and emissions.

Figure 2.1: Typical Mass and Energy Flow Diagram of Manure Digester System.



The mass and energy flows were demined by measuring volumes, concentrations, and quantities of appropriate parameters as necessary. Automatic data-logging equipment to record these flows along with temperatures and pressures needed for a complete mass and energy balance. This required the installation of new metering equipment and the use of existing on-site metering as determined during the site planning effort. Table 1 shows the types of metering and sensors used for monitoring. Each facility had a site-specific monitoring plan developed with site specific metering points shown in the chapter that describes each system.

All metering equipment was professionally installed following the sensor manufacturers installation and calibration instructions. At the end of the project, the dairy producers were given the option to take over the use of the equipment to continue to collect data or opt for decommissioning by the project team. For automatically logged data, a 15-minute sampling interval was used and the data was monitored remotely using wireless modems allowing for real time monitoring and quality assurance review by the project team.

Figure 2.2: Process Schematic for Generic Dairy Digester Facility with Power and Heat Production.

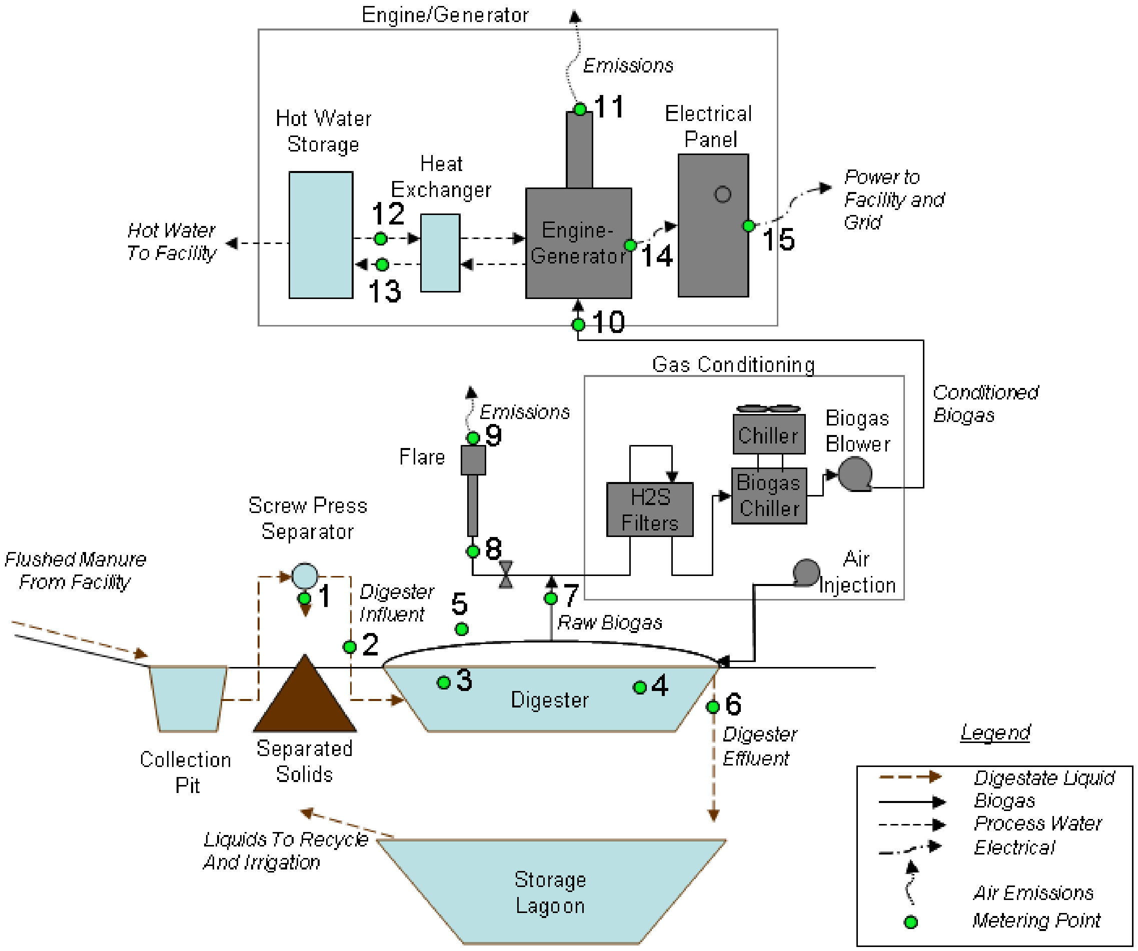


Table 2.1: Typical Continuous Metering Data and Sensors Utilized at the Facilities.

Description	Eng. Units	Sensor or Instrument
Power Output	kWh/int	Power meter or utility meter
Process Water Flow	gpm	Turbine flowmeter
Biogas Flow	cf/h	Thermal mass flow meter
Exhaust Gas Flow	cf/h	Estimated from gas flow and O2 concentration
Influent/Effluent Flow	cf/h	Ultrasonic flowmeter
Manure Solids Flow	Lb/day	Monthly volume/weight over 24-hr period
Temperature	°F	Thermocouple

The composition of the various flows within the system were determined at the locations described for each dairy digester facility and shown generically in Figure 2. This required periodic sampling at each of the six project sites which included monthly and quarterly procedures that were followed for a 12-month period. These sampling procedures are more fully described in Appendix A – Tables 5 and 6.

For the liquid influent and effluent to the digester system, the constituents in Appendix A - Table 1 will be monitored on a monthly basis to determine the impact of the digestion on these factors. Aggregate samples were collected with automatic wastewater samplers over a 24 hour period where practicable but many facilities required a manually collected sample because of intermittent feeding and other system complexities. The sample collection process was tailored to the system at each facility to try to ensure a representative sample of the digester influent and effluent, but at minimum involved the aggregation of at least 5 samples over a flush period to derive each analyzed sample. Co-digestion systems required samples of manure and co-digestate added to the system. Samples were delivered via courier to a certified laboratory facility where samples will be analyzed by analytical methods described in Methods for Chemical Analysis of Water and Wastes, EPA-600/4-79-020 (U.S. Environmental Protection Agency, 1983) or Standard Methods for the Examination of Water and Wastewater, 21st edition (American Public Health Association, 2005). Randomized duplicates were used as a periodic check on laboratory repeatability.

Herd size and herd management information were also collected. Number of cows on the manure system, maturity and average weight of the cows, and housing management patterns were recorded on a monthly basis working with the dairy manager.

In addition to the analytical tests described above, quarterly samples of the influent and effluent from each of the digesters were analyzed to determining Biochemical Methane Potential (BMP) in the project team laboratory facility. BMP analysis is an efficient and economical method for evaluating the rate and extent of biomass conversion to methane under anaerobic conditions. Angelidaki et. al. 2009 describes the BMP method and the means to insure repeatable results utilized by this study.

Prior to BMP trial setup, the influent and effluent samples were characterized for total solids (TS), and volatile solids (VS). Then, an aliquot of each sample were placed in a serum bottle with anaerobic inoculum. Because the digester effluent should be high in anaerobic bacteria population, it was run without additional innoculum and was used for innoculating the influent samples. The sealed serum bottles were placed in a shaker bath and incubated under mesophilic (35°C) conditions for 30 days. Each assay was performed in triplicate. Biogas production was monitored daily using a displacement method and methane content is measured weekly by supplying a syringe sample to a gas sensor. At end of trial, sample solids characterization, cumulative biogas production, and methane content was analyzed and reported. These BMP assays can be used to determine potential anaerobic process efficiency and amount of a specific biomass that could be converted to methane.

On a quarterly basis, the solids separated from the liquid manure either before the digester (as in the case of covered lagoons) or after the digester (as in the case of plug flow or complete mix systems) will be analyzed according to the analyses in Appendix A - Table 2.

In addition to the liquid and solids flows in the system, the composition of the produced biogas is required to complete the mass and energy balance. This was sampled at each site on a monthly basis using a calibrated handheld analyzer. The unit was field calibrated before each use using a standard reference gas. Appendix A – Table 3 shows the gases that were analyzed in the field. In addition, higher heating value of the gas was determined from the quantity of methane in the gas sample. The parameters for the raw and conditioned biogas were determined to look at the effectiveness of upgrading equipment.

Another source of constituent losses to the environment important to mass balance and environmental performance of the manure-to-energy system is the combustion engine generator utilized at digester facilities to convert the combustible biogas to electricity. To test these systems, a portable emissions analyzer was utilized to measure the trace emission from the generator set. Appendix A - Table 4 shows the important constituents that were be measured by this system. These measurements will correspond to recommended procedures for emissions measurement from stationary internal combustion engines as specified in San Joaquin Valley Air Pollution Control District Rule 4702. To get the mass flow, the total exhaust flow is estimated by knowing the fuel flow to the generator set and the measured air to fuel ratio via the oxygen measurement in the exhaust.

Emissions from the biogas engines were determined during the digester testing campaign. A portable emissions analyzer (Testo 350XL, #01034445) was used for direct sampling of the exhaust stack (Figure 11). This instrument is accepted by the San Joaquin Valley Air Pollution Control District for in-field engine testing and is recognized for testing with US EPA methods CTM-030 and CTM-034. The unit employs electrochemical sensors for measuring O_2, NO, NO_2, CO, and SO_2, and hydrocarbons (as methane) and the sampling probe also measures stack temperature. The gas concentrations, temperature, and various other combustion parameters are also calculated and stored on the internal data logger.

The instrument was pre-calibrated at the factory immediately prior to use in the field and was re-calibrated every two weeks during the facility testing and re-checked at the end of testing. All calibration gases were NIST traceable and the factory calibration levels and instrument performance are shown on Appendix A – Table A.4. The instrument remained stable with little drift for O_2, NO_x, CO, and SO_2 during multi-day testing. However the hydrocarbon sensor did was not always show stability and required frequent check. Also, the zero for the O_2 sensor was not properly set during some sampling runs, but the data was corrected post sampling for a couple of runs.

The sampling approach was to conduct three fifteen minute runs (with 5 minute purge) at each facility to characterize the pollutant concentrations in the stack. The probe was generally inserted at least two diameters into the end of the stack for sampling. A few facilities had a sampling port in the stack that facilitated sampling. Gas concentrations were recorded once per minute for a total of fifteen samples for each fifteen minute average. All data was printed for a paper record and also downloaded to a PC for analysis.

In order to convert concentrations to rate of emission (in lb/MMBtu), the following formula was used from EPA Method 19 as followed in Source Test Guidelines from the San Joaquin Valley Air District, 2002.

$$E = \frac{C_p M}{385 * 10^6} F \frac{20.9}{(20.9 - \%O_2)}$$

where E is the emissions rate (lb/MMBTU), Cp is the dry concentration of the pollutant (ppm), M is the molecular weight of the pollutant, 385 is the standard volume of air at 68°F and 1 atm (dry SCF/lb), F is the oxygen based f-factor for the fuel (dry SCF/MMBTU), %O2 is the dry concentration of oxygen (%), and 20.9 is the concentration of oxygen in air (%). The emissions formula estimates the total amount of exhaust plus any excess air (as determined by the oxygen concentration in the stack) expected for complete combustion of a million BTU's of biogas and multiplies it by the mass concentration of the pollutant. The use of this formula is an approximation, but it avoids the need to measure flow rate in a narrow, turbulent stack which can lead to larger errors. The emissions rates for these engines can be directly compared to other engine emissions factors in the literature.

The F factor is the ratio of the gas volume of the products of combustion to the heat content of the fuel. F includes all components of combustion less water. It can be calculated using the following equation knowing the mass concentrations of hydrogen, carbon, sulfur, nitrogen and oxygen and the higher heating value (BTU/lb) of the fuel:

$$F = \frac{10^6[3.64 * (\%H) + 1.53 * (\%C) + 0.57 * (\%S) + 0.14 * (\%N) - 0.46 * (\%O)]}{HHV}$$

For example, using the formula above, pure methane has an F value of 8600 dry SCF/MMBTU. Biogas with 65 percent methane content and 35 percent carbon dioxide content by volume has an F value of 9120 dry SCF/MMBTU. This value changes less than 2 percent for all of the measured biogas compositions, so this F value for biogas was used for all of the calculations in this study.

The heat rate for each generator (in MMBTU/kWh) was also computed using the fuel flow, heat content, and kW output of the generator. Multiplying the emissions rate per unit of heat input above by the emissions rates per unit of power production can be calculated (lb/kWh).

2.2 Analysis

A key step in the process is monitoring and verifying the quality of the data that is collected using standard quality assurance procedures outlined in the methodology that was followed by this study. Data includes process and flow data collected continuously on a 15-min interval and compositional data that are generated on a monthly basis. Once data is verified, it was processed into a spreadsheet model for the mass and energy flows within the digester system. Pertinent system performance outputs were calculated like electrical efficiency, thermal efficiency, carbon conversion efficiency, methane emissions reduction, nutrient conversion, etc. Summary data analysis will be generated on a monthly basis for each system in the study.

Data was also used to develop various empirical models of the digester performance and models for estimating conversions within the digester system. The methane production data for the digesters will be analyzed for its fit with the model utilized by Farmware 3.0 program in the AgSTAR Handbook (2006). This document uses the model as developed by Chen and Hashimoto (1978) to describe the kinetics of methane fermentation:

$$Y_v = \frac{B_0 * VS}{\Theta}\left[1 - \left(\frac{K}{\theta\mu_m - 1 + K}\right)\right] \qquad (1)$$

Where:

Y_v = volumetric methane production, L CH_4 per influent volume/day

VS = influent total volatile solids (TVS) concentration, grams per influent volume/day

B_0 = ultimate methane yield, L/g TVS added as θ approaches infinity

θ= retention time, days

μ_m = maximum specific microbial growth rate, days^{-1}

K = kinetic parameter, dimensionless.

Equation 1 is a modification of the Contois model, a model that Chen and Hashimoto suggest has the advantages of and generally avoids the disadvantages of the more widely used Monod model. Chen and Hashimoto defined the relationship between μ_m and temperature, T (°C), for temperatures between 20 °C and 60 °C based on the analysis of data from several sources as follows:

$$\mu_m = 0.013\,T - 0.129 \qquad (2)$$

Equation 3 describes the relationship between K and VS for dairy manures.

$$K_{dairy} = 0.8 + 0.016 \exp(0.06 * VS) \qquad (3)$$

Where: VS = influent total volatile solids concentration per influent volume, kg/m^3

K_{dairy} less than or equal to 1.64

Other similar kinetic models may be used to determine the conversion of nitrogen compounds or other conversions of interest within the system.

The BMP analysis will also be used to determine how well these measurements can predict the actual performance of the digester system. The actual methane production is expected to be some fraction of the BMP and it is possible that this relationship will vary by system type, HRT, temperature, pH, volatile solids content, feed mixture, and other factors. An important part of the study will be to determine the usefulness of BMP analysis in predicting performance of different types of digester systems, a potentially useful tool for future design. BMP will be compared with chemical digestion methods to determine if these can be appropriate surrogates for BMP applicable to manure and mixed digester feeds.

2.3 Economic Analysis

A critical part of the project is to evaluate the overall economic performance of the digester systems to better understand the market for these renewable energy technologies. A major problem that exists that is hindering the growth of manure digestion is the lack of good public information and data on both the technical performance and the capital and operating costs of successful dairy digester projects. The proposed work under this proposal also collected this information using fully operational manure digesters in California and builds on recent studies completed on the use of dairy digesters (Hurley, 2006; Sustainable Conservation, 2009). Details of the research plan and results for the economic study are provided in a companion report to this study.

2.4 Participant Facilities

The project team secured participants in this study with a variety of digester systems and modes of operation. Initial site visits were conducted and monitoring plans have been developed that are specific to each particular site. The team has sought systems with the following differences in operation type: (1) small (<500 cows) and large (>2000 cows) systems; (2) both pure manure and mixed feed digesters, (2) covered lagoon, complete mix, and plug flow systems; (3) electricity production and pipeline gas production. Table 5 shows some characteristics of facilities selected for the study. Note that Dairy 0 was dropped from the study due to the business closing before a year of performance data could be collected.

The group includes the only facility in California operating a gas cleanup system for pipeline quality gas and includes the only on-farm complete mix digester system, new technologies which need further analysis for their potential in California. In addition there are different strategies and technologies for solids handling, sulfur gas control, and exhaust emissions control that are employed by these facilities that were evaluated as part of the project. The specifics for each facility, the results of the data collection, and the analysis of the performance are shown in the following chapters.

Table 2.2: Characteristics of Participant Facilities.

Dairy No.	Cows Milked	Feedstock Type	Digester Type	Digester Volume (gal)	Biogas Use
0	5200	Recycled Flush Manure	Covered Lagoon	25,000,000	Pipeline Gas (250,000 CFD)
1	550	Recycled Flush Manure	Covered Lagoon	6,400,000	Power (65 kW)
2	350	Recycled Flush Manure & Cheese Plant WW	Covered Lagoon	2,500,000	Power (75 kW) Heat Recovery
3	3,200	Flush Manure & Cheese Plant WW	Covered Lagoon	45,000,000	Power (750 kW) Heat Recovery
4	850	Recycled Flush Manure	Mixed Lagoon	3,400,000	Power (212 kW) Heat Recovery
5	1,700	Concentrated Flush Manure & Silage	Complete Mix	1,700,000	Power (710 kW) Heat Recovery
6	2,100	Scraped Manure	Plug Flow	500,000	Power (195 kW) Heat Recovery

2.5 Limitations of the Study

There are a few major limitations to this study that need to be understood. First, most of the operations that were studied are still very much in the experimental stages of the technology. Two of the dairies started operation of their digesters in 2004, two came on-line in 2008, and two were operational in 2009. During the three years of this study and during the 12-month data collection period specifically analyzed, changes have occurred at each dairy in order to improve the operation. Some of the changes have been substantial including one dairy that added a third engine to exploit additional gas production. Also, since these operations were first adopters, some of the start-up issues have been substantial. Two facilities had significant amounts of downtime during the data collection period.

A caveat that should be observed is that these dairy operations are not necessarily at a point where they have become consistent in there operating and maintenance because they are still in a learning mode. It was not feasible in this study to ascertain the impact of operations and maintenance on actual performance, as the data gives the actual resulting performance only.

CHAPTER 3:
Dairy 1 Results

3.1 Dairy 1 Background Information

Dairy 1 is a dairy farm located in the Northern California Central Valley. The dairy facility installed an anaerobic digester system in 2009 to manage the manure and wastewater that is generated from the facility and produce renewable power for the dairy and farming operations and selling any excess power to the local municipal utility district.

The digester is an earthen lagoon digester with a volume of 6.4 million gallons located adjacent to the freestall dairy barns at the facility (Figure 1). Flushed manure from the dairy is collected daily in a pit prior to being pumped across a screen separator to remove large solids and directly into the digester. The cover system maintains anaerobic conditions, providing for natural microbial action to convert the organic matter in the manure into methane-rich biogas. During active production, an estimated 30,000 cubic feet per day of biogas should be produced based on about 7,000 lbs per day of manure solids being flushed into the digester system. The gas production could be lower in the winter months due to low digester temperatures. The effluent from the digester lagoon overflows to an effluent storage pond. Liquid effluent is utilized for recycle manure flushing and for crop irrigation. A custom-engineered HDPE system encloses the covered lagoon, Figure 1, captures the biogas, and channels to a gas cleanup system and co-generation system located adjacent to the digester. The gas first passes through a hydrogen sulfide gas bio-scrubber unit, shown in Figure 2, where it is filtered to remove hydrogen sulfide, conditioned for moisture and particulate removal, and is pumped to be delivered to the prime mover located adjacent to the conditioning skid. The fuel is delivered to the 65 kW synchronous generator system which had been operated on an intermittent basis primarily due to problems with the system and gas handling skid. Based on the estimated biogas production of the digester system and a generator efficiency of 25 percent, this generator should be producing about 40,000 kWh per month or a Capacity Factor of approximately 85 percent.

The digester pumps, generator, and other miscellaneous loads were added to a 3-phase, 480 volt electrical service at the farm (the existing electrical service at the farm was unaffected). The system utilizes a 65 kW packaged gas engine-generator (Figure 2 & 3). This 65 kW unit has been designed to use lower heat content biogas. The gas piping, controls and power distribution have been housed in a metal building as shown in the figures below. Table 1 gives some the descriptions of the primary sub-systems making up the Dairy 1 manure digester system.

Figure 3.1: Covered Earthen Lagoon Digester at Dairy 1.

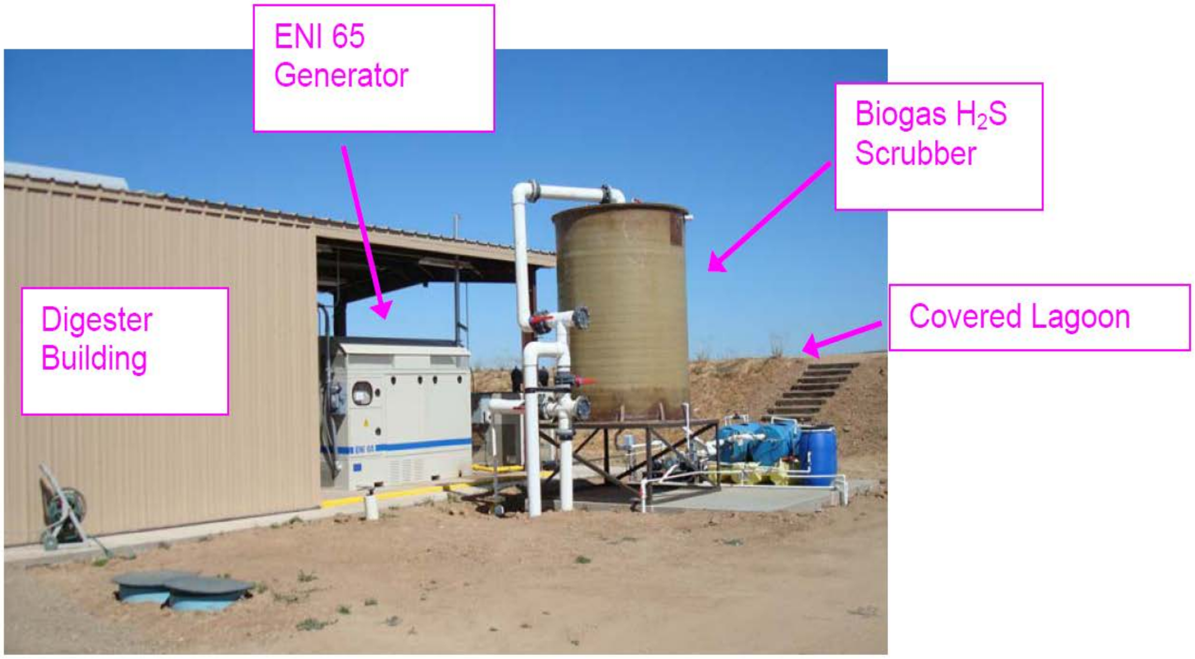


Figure 3.2: Equipment Layout at the Dairy 1 Digester System.

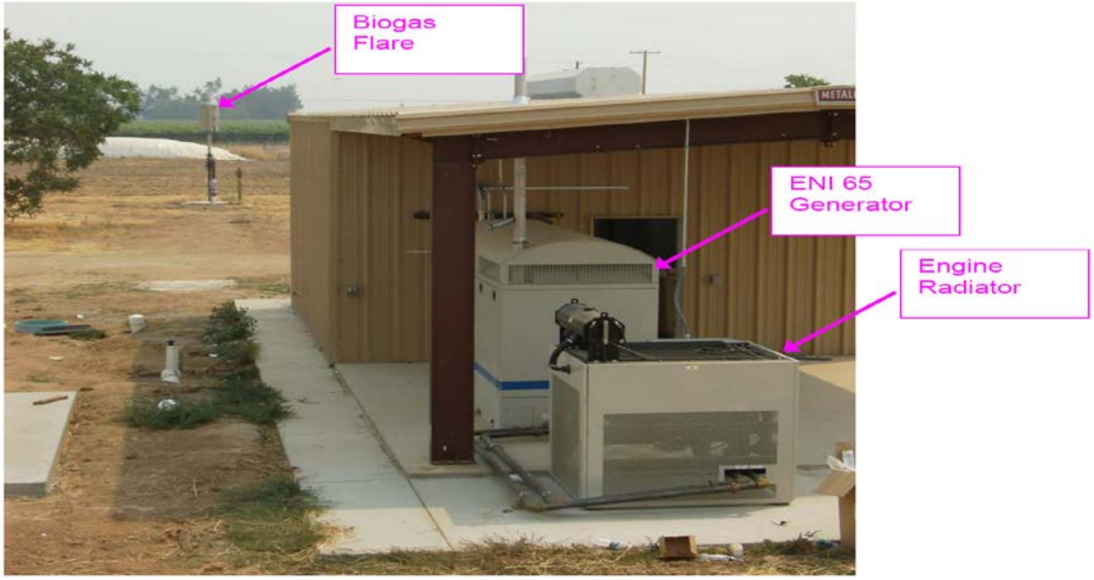


Figure 3.3: Location of Engine and Flare Equipment at Dairy 1 Digester.

The flare is activated to burn excess biogas that cannot be used by the engine to produce electricity. For the data collection period the flare was frequently activated so that about 50 percent of the gas was burned in the flare. When the engine-generator was shut off for maintenance, the biogas continuously flared and the rate was tuned manually by the amount of cover inflation. The large amount of gas under the cover could be subsequently utilized by the engine-generator. The cover had sufficient storage so that several days of gas production could be safely collected.

The Figure 4 schematic shows the overall biogas and power generation systems. The annual average mass and energy flows are given in the process flow diagram in Figure XX. All the biogas from the digester was used in the engine-generator of the flare. The hot water leaving the engine jacket was cooled in the radiator. This heat could have been captured and used in the parlor house for preheating wash-down water as well as other hot water needs of the facility but these operations are distant from the generator and digester and have not been implemented.

Table 3.1: Dairy 1 Digester System Description.

Digester	Earthen lagoon – 6,400,000 gallon capacity Unheated HDPE cover Fibrous solids separation using inclined screen
Engine-Generator	65 kW output on biogas 480 VAC, 3 phase 28% LHV electrical reported by manufacturer
Biogas Treatment	H2S scrubber, biologically activated tower
Heat Rejection	Air-cooled radiator

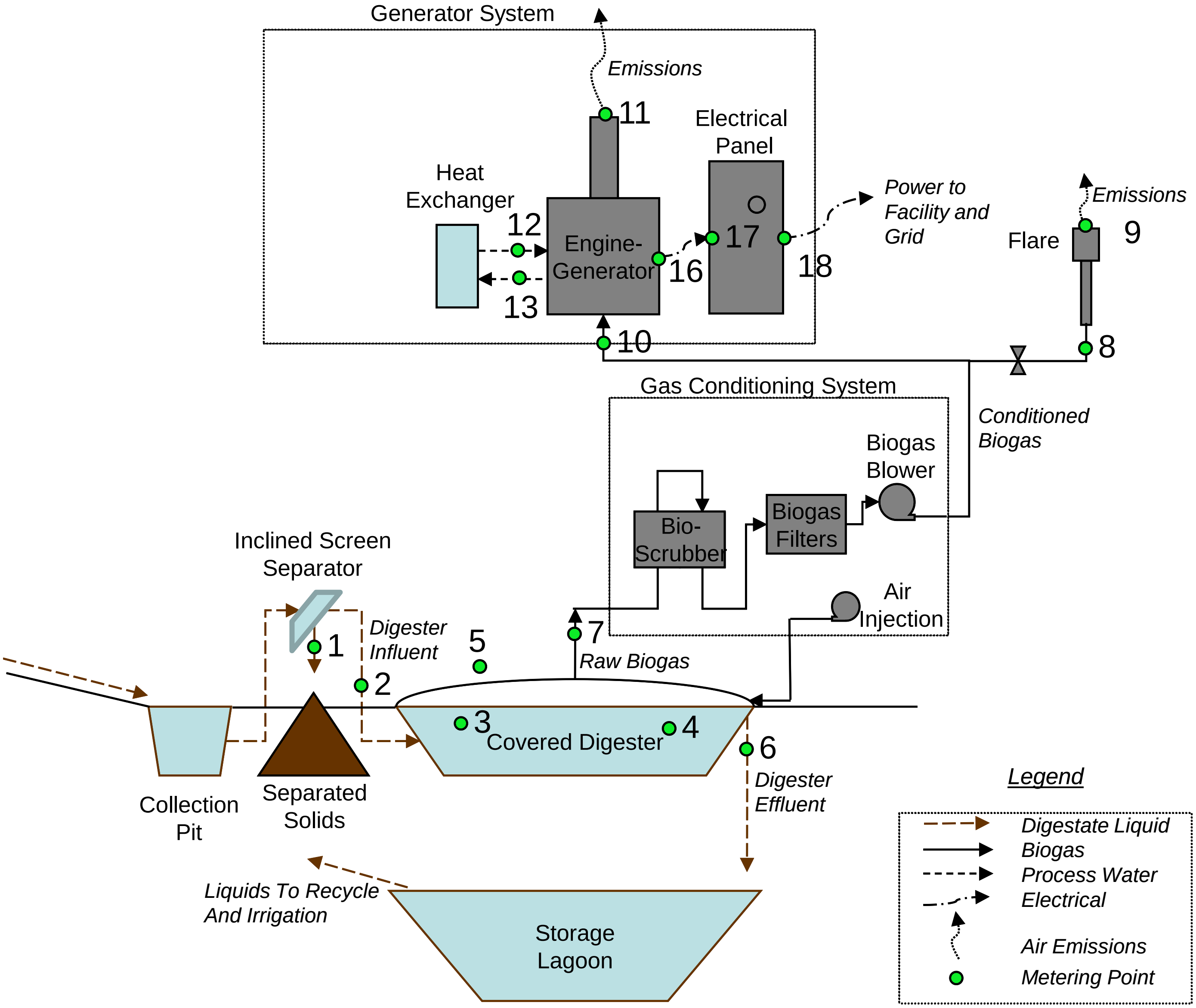


Figure 3.4: Schematic of Biogas System With Metering Points.

3.2 Dairy 1 Materials and Methods

The monitoring methodology and system followed protocols developed by ASERTTI, Climate Action Registry, and US EPA. Continuous sensors will monitored pertinent system flows and conditions including those shown in Table 2. This data was recorded in data logger equipment and 15-minute averages were continuously logged and stored on site before periodic downloads by the investigators. Sampling locations are shown on the schematic in Figure 4. These sampling points cover all pertinent manure, biogas, power and process water flows and temperatures. Composition samples (24-hour aggregated) were taken on a monthly basis to establish the mass distribution for each flow of manure, biogas and emissions.

The monitoring system supplied by Summers Consulting adapted on existing metering systems that were installed by the local utility. The system was configured to capture the data points listed in Table 2. The sensors were automatically sampled at 1-minute intervals and averaged or summed into 15-minute data as appropriate. The PLC-based system provided the investigators access to the time-stamped 15-minute data via the internet. The on-site controller has the ability to store and retain several hundred days of 15-minute data in the event that communications are lost.

The electrical output of the engine-generator (WGO) was measured with a power transducer already installed in the engine control panel. A utility-supplied power meter also indicated the amount of power that was exported (WGT) by the engine. The net power exported to the grid was also supplied by the PG&E supplied metering (WNT).

The biogas delivered to the engine (FGE) was measured by a Sage gas flow meter (hot-wire probe) that determined the mass flow in standard cubic feet per minute (scfm). The biogas flow to the flare (FGF) was not measured since for the duration of the project no biogas was allowed to flow to the flare. The total biogas flow (FGT)was therefore equal to is FGE. From the biogas and power measurements the engine efficiency was calculated using the measured gas composition data. The gas flows also allowed for an estimate of emissions from the engine (FEE) using standard combustion assumptions and monthly measurement of exhaust composition.

The digester temperatures (TMI, TME, TD1 and TD2) were measured by thermocouples at the influent and effluent pipes and placed in the two vent pipes on the cover of the digester. The ambient temperature (TAO) was recorded to understand how digester performance varied with weather conditions.

The flow of manure into the digester (FMI) was measured with a clamp-on ultrasonic flow meter. It was assumed that influent and effluent liquid water flow were approximately balanced, therefore FMO is estimated to be equal to FMI. The flow of manure solids (FMS) was measured monthly by weighing the solids separated by the screw press over a 24-hour period.

The thermal output rejected from the engine jacket to the radiator was determined from the coolant water flow and temperature difference data (FC, TCI, TCO).

The parasitic power consumption of various components in the system were determined by power readings with a hand-held meter capable of measuring true power. The sum of all parasitic loads not accounted for in the net metering was compared with the power generated by the system.

Table 3.2: Monitoring Points on the Dairy 1 Digester System. Locations Shown in Figure 4.

Loc #	Data Point	Description	Eng. Units	Sensor or Instrument	Typical Range
1	FMS	Flow of Manure Solids	lb/day	Monthly weight est.	4000-7000
	CMS	Composition of Manure Solids	% by wt.	Quarterly samples	20-25% TS
2	FMI	Flow of Manure, Influent to Digester	Gal/day	Ultrasonic Flowmeter	50,000-200,000
	TMI	Temperature of Manure, Influent to Digester	°F	Type-K TC, 6 in probe	50-80
	CMI	Composition of Manure, Influent to Digester	mg/l	Monthly samples, 24h	7,100-11,600 TS
3	TD1	Temperature of Digester at Vent Valve 1	°F	Type-K TC, 72 in depth	67-80
4	TD2	Temperature of Digester at Vent Valve 2	°F	Type-K TC, 72 in depth	65-80
5	TAO	Temperature of Ambient Out	°F	Type-K TC, near digester	45-95
6	FME	Flow of Manure, Effluent from Digester	Gal/day	Estimated from FMI	=FMI
	TME	Temperature of Manure, Effluent from Digester	°F	Type-K TC, 6 in probe	50-84
	CME	Composition of Manure, Effluent from Digester	mg/l	Monthly samples, 24h	5,300-7,600 TS
7	FGT	Flow of Gas Total (Raw Biogas)	SCF/day	Estimated from FGE & FGF	26,000 – 52,000
	CGT	Composition of Gas Total (Raw Biogas)	% by vol.	Monthly analysis	65-72% CH4
8	FGF	Flow of Gas to Flare (Raw Biogas)	SCF/day	Sage Prime SIP	0 – 48,000
	CGF	Composition of Gas to Flare (Raw Biogas)	% by vol.	Monthly analysis	65-72% CH4
9	FEF	Flow of Emissions from Flare	SCF/day	Estimated from FGF	0-55,000
	CEF	Composition of Emissions from Flare	% or ppm	Monthly analysis	NA
10	FGE	Flow of Gas to Engine (Conditioned Biogas)	SCF/day	Sage Prime SIP	0-35,000
	CGF	Composition of Gas to Engine (Conditioned)	% by vol.	Monthly analysis	65-72% CH4
11	FEE	Flow of Emissions from Engine	SCF/day	Estimated from FGE and CEF	0 – 55,000
	CEE	Composition of Emissions from Engine	% or ppm	Monthly analysis	0-3% O2
12	TCI	Temperature of Coolant, Inlet to Engine, (Jacket and Exhaust Coolant)	°F	Type-K TC, 6 in probe	142-190
	FC	Flow of Coolant	GPM	Onicon Flowmeter	0-28
13	TCO	Temperature of Coolant, Outlet of Engine (Between Jacket and Exhaust)	°F	Type-K TC, 6 in probe	177-207
16	WGO	Watts of Generator Output (Power at Generator)	kW	Gen power meter	0-55
17	WGT	Watts of Generator Total (Power at Utility Meter)	kW	Utility meter - pulse	0-50
18	WNT	Watts of Net Total (Power after Parasitic Loads)	kW	Utility meter - pulse	0-50

The composition of the manure influent and effluent was measured on a monthly basis by taking representative samples at the dairy and subsequently sent overnight for laboratory analysis for the components described in Appendix A. Samples were prepared using an aggregate of five grab samples collected during the manure flushing cycle. Because of the inherent problems with using a sample from a single day to represent the composition for an entire month, a smoothing function that included the prior and subsequent month results was used to represent the reported monthly composition. The amount of solids removed by the separator was also estimated on a monthly basis by estimating the pile volume and collection period. Solids were also laboratory analyzed on a quarterly basis for the components described in Appendix A.

The composition of the biogas was measured using a GEM™2000 Portable Gas Analyzer from Landtec on a monthly basis. This sampling included raw and conditioned biogas. The portable Landtec meter was used to determine the percentage of CH_4, CO_2, O_2, H_2S and balance gas on a monthly basis. The emissions from the engine were measured using a Testo 350XL portable analyzer. The metering equipment was calibrated on a routine basis and the estimated accuracy is shown in Appendix A.

Periodic samples of the influent to and effluent from the digester was subjected to a Biochemical Methane Potential (BMP) analysis in a specially-designed apparatus in the Summers Consulting laboratory. BMP analysis is an efficient and economical method for evaluating the rate and extent of biomass conversion to methane under anaerobic conditions. The effluent BMP shows the remaining methane production potential after digestion and provides an estimate of the potential methane produced in a liquid storage pond after digestion.

Annual greenhouse gas emissions reductions were also estimated using the Climate Action Registry Livestock Protocol. This protocol uses a particular methodology to estimate the baseline emissions or emissions from the manure management system without the digester and compares these with estimated emissions from the digester system.

3.3 Dairy 1 Results and Analysis

The following sections summarize the monitoring results of this year-long monitoring campaign and provide annual operational factors including digester feeding, digester performance, biogas production, biogas generator performance, and climate change impact. The digester monitoring system for Dairy 1 was designed in 2011 and installation was completed in late 2011. However, the gas and generator performance data was available from the utility installed data collection system back to the start of the digester in 2009 and some of this data was used to compute the generator set performance because the generator usage was more frequent in the earlier timeframe while 2011 and 2012 were plagued with generator downtime. The monthly sampling was initiated in late 2011 and completed in 2012. The actual cow and heifer numbers during the data collection period are shown in Table 3 along with the estimated daily manure production as predicted by typical estimation method from ASABE.

Table 3.3: Dairy Herd Size Characteristics and Estimated Manure Production at Dairy 1.

DAIRY HERD			ESTIMATED MANURE PRODUCTION	
	HEAD (#)	WEIGHT (LB/HEAD)	VOLATILE SOLIDS (LB/HEAD/DAY)	TOTAL VOLATILE SOLIDS (LB/DAY)
Milk Cows	550	1499	17.0	9,350
Dry Cows	50	1507	9.2	460
Heifers	250	897	7.1	1,775
			Total Manure Volatile Solids	11,585

3.3.1 Digester Feeding

The rate of influent feeding of the digester averaged 129,000 gallons per day over the entire year, with little observed monthly variation. This is likely due to a timed flush cycle at the facility and the fact that a rainwater collection system that diverts water away from the manure system has been installed. The influent flowmeter had some problems during extended time periods during the measurement campaign so the average number of gallons per day was applied to the entire year to calculate solids flows. This average represents a flush system flow of 11 gallons per pound of manure volatile solids excreted per day.

The results for the monthly solids composition of the influent mixture is shown in Figure 5. Total solids concentration ranged from 7,4000 to 11,500 milligrams per liter with an average of 8,600 milligrams per liter. Volatile solids ranged from 4,300 to 8,000 milligrams per liter with an average of 6,000 milligrams per liter. The volatile solids were consistently 65 to 73 percent of the total solids. The variability seen in these samples can also be attributed to variable system flows and the limitations of taking a single aggregated grab sample to represent an entire month of flow. The aggregation of all of the samples taken over the year is a better representation of the typical influent composition and for comparison with effluent samples. Table 4 shows the annual average and standard deviation for all of the samples taken over the year for constituents of the influent.

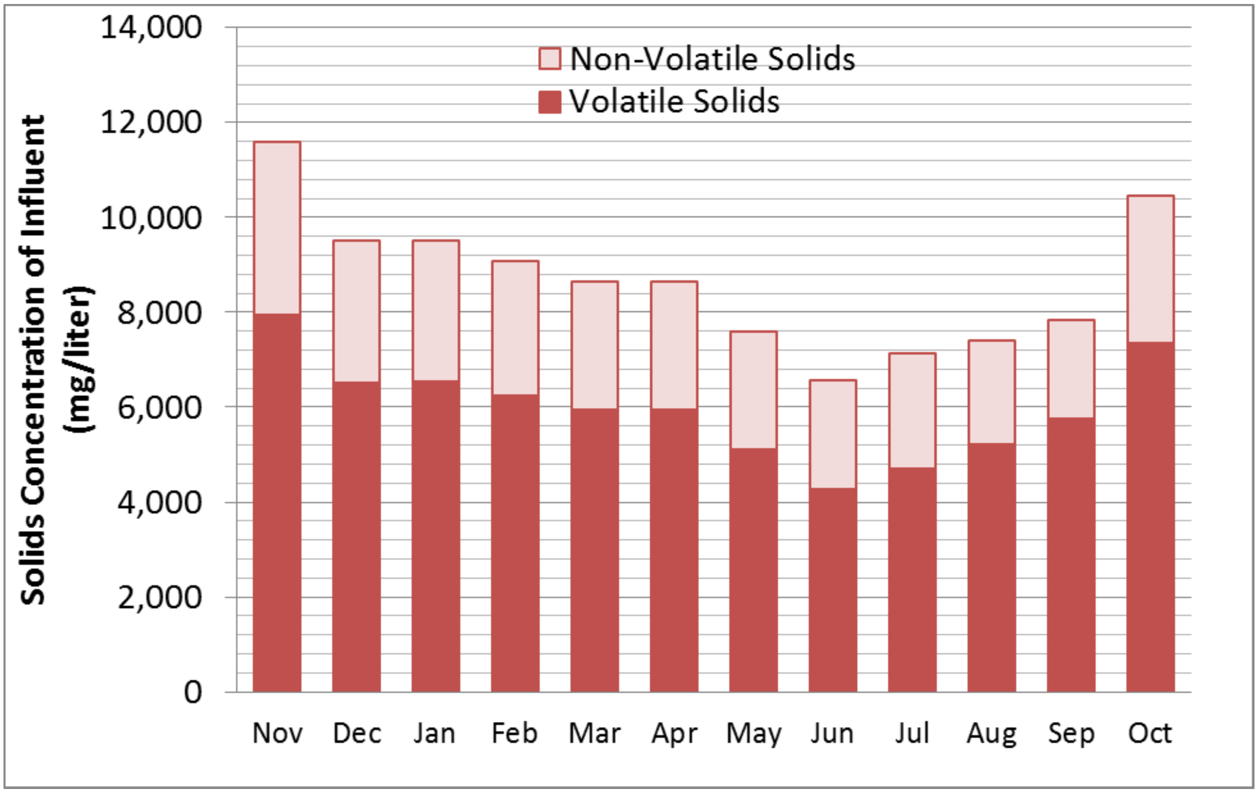


Figure 3.5: Total Solids Concentration of Digester Influent With Volatile and Non-Volatile Fractions.

Using pile size estimates and monthly moisture and density samples, it was determined that about 40 percent of the total solids in the manure stream or about 6,200 pounds of total solids per day were removed by the solid separator before the digestion process. These separated solids can be valuable as a composted bed material or for use in farming or horticultural soil amendment. Table 5 shows the typical composition of these separated solids. Additional information on the flows of liquids and solids throughout the dairy facility are shown in the section below on Mass and Energy Balance.

Table 3.4: Composition of Various Constituents of the Digester Influent. Average and Standard Deviation of the Monthly Samples Taken Over the Study Year.

Analyte	Units	Method	Average	St Dev
Total Solids	mg/L	SM 2540B	8,553	2,844
Volatile Solids	mg/L	EPA 160.4	5,904	1,961
Total Dissolved Solids	mg/L	SM 2540 C	4,211	395
Chemical Oxygen Demand	mg/L	SM 5220D	8,587	5,291
Specific Conductance	µS/cm	SM 2540B	7.0	1.7
Ammonia-N	mg/L	SM 4500	384	137
Ammonium-N	mg/L	SM 4500G	11.2	9.6
Nitrate-Nitrogen	mg/L	EPA 300.0	0.4	0.5
Total Nitrogen	mg/L	EPA 351.2	848	314
Total Phosphorus	mg/L	SM 4500P B	134	65
Total Potassium	mg/L	SM 3120 B	633	243
Total Sulfur	mg/L	SM 3120 B	123	77
Total Clorine	mg/L	SM 3120 B	249	32
Total Calcium	mg/L	SM 3120 B	201	17
Total Magnesium	mg/L	SM 3120 B	135	14
Total Sodium	mg/L	SM 3120 B	232	27

Table 3.5: Composition of Various Constituents of the Separated Solids. Average and Standard Deviation of the Quarterly Samples Taken Over the Study Year.

Analyte	Units	TMECC Method	Average	St Dev
Dry Matter (eq TS)	Wt %	03.09-A	20.82	0.11
Organic Matter (eq VS)	Wt %	05.07-A	18.83	0.11
Total Nitrogen	Wt %	04.02-D	0.310	0.028
Total Phosphorus	Wt %	04.03-A	0.060	0.014
Total Potassium	Wt %	04.04-A	0.105	0.007
Sodium	Wt %	04.05-Na	0.035	0.007
Calcium	Wt %	04.05-Ca	0.205	0.064
Magnesium	Wt %	04.05-Mg	0.080	0.014
Iron	mg/kg	04.05-Fe	226	14
Copper	mg/kg	04.07-Cu	11.3	3.7
Manganese	mg/kg	04.05-Mn	19.7	0.0

Analyte	Units	TMECC Method	Average	St Dev
Zinc	mg/kg	04.05-Zn	14.5	2.9
Sulfur	Wt %	04.05-S	0.045	0.007

3.3.2 Digester Performance

The digester was fed a daily dose of liquid consisting of mostly recycled solids and a small amount of fresh manure solids, throughout the study period. The average amount was 129,000 gallons per day with 0.87 percent solids although there was some variability due to real variations in operations and due to the measurement limitations discussed above. The measured loading of the digester can be seen in Table 6 – Digester Feeding.

Table 3.6: Digester Influent Feeding and Performance Parameters.

	DIGESTER FEEDING				DIGESTER PERFORMANCE			
MONTH	INFLUENT FLOWRATE	TOTAL SOLIDS CONC.	VOLATILE SOLIDS CONC.	INFLUENT VOLATILE SOLIDS	AVERAGE DIGESTER TEMP	ORGANIC LOADING RATE	HYDRAULIC RETENTION TIME	VOLATALE SOLIDS CONSUMPTION
(MM)	(GAL/DAY)	(%)	(% TS)	(LBS /DAY)	(DEG F)	(LB VS /1000 CF/DAY)	(DAY)	(%)
01	129,309	1.16	68.7	8,576	66.1	10.0	49.4	62.8
02	129,309	0.95	68.5	7,037	57.6	8.2	49.4	50.7
03	129,309	0.95	68.9	7,063	57.6	8.3	49.4	49.0
04	129,309	0.91	68.9	6,743	54.9	7.9	49.4	47.2
05	129,309	0.86	68.9	6,423	54.9	7.5	49.4	47.2
06	129,309	0.86	68.9	6,423	61.6	7.5	49.4	47.2
07	129,309	0.76	67.1	5,498	67.4	6.4	49.4	31.5
08	129,309	0.66	65.3	4,614	72.5	5.4	49.4	15.8
09	129,309	0.71	65.8	5,066	79.9	5.9	49.4	29.6
10	129,309	0.74	70.4	5,630	80.6	6.6	49.4	44.5
11	129,309	0.78	73.3	6,194	78.1	7.3	49.4	48.5
12	129,309	1.04	70.5	7,938	72.3	9.3	49.4	59.2
AVE	129,309	0.87	68.8	6,434	67.0	7.5	49.4	44.4

The influent volatile solids averaged 6,400 pounds per day. These volatile solids were generated from an estimated 8,600 lbs per day and 2,500 lbs per day of volatile solids from fresh manure and recycled flush water respectively with the removal of 4,600 lbs per day over the solids separator. Compared with the estimated volatile solids excretion of 11,600 pounds per day for this dairy herd, the fresh manure solids equate to an estimated manure capture of 75 percent by the flush system. This seems like a reasonable result given that the animals are confined in the free-stall area most of the year at this facility.

The digester appeared to maintain stable anaerobic digestion throughout the study as evidenced by the consistent volatile solids consumption observed averaging 44.4 percent. The average daily organic loading rate of 7.5 pounds of volatile solids per thousand cubic feet is close to the recommended loading rate of 10 pounds of volatile solids per thousand cubic feet[1]. The 49 day average hydraulic retention time exceeds the recommended HRT of 40 to 45 days for this type of unheated, unmixed lagoon digester. The measured digester temperatures varied from 55 to 80°F on a seasonal basis but these temperatures are sufficient to maintain mesohpillic anaerobic activity. All of these performance factors calculated for each month of the study period are shown in Table 6 – Digester Performance.

Consumption, conversion, and accumulation of the wastewater constituents within the digestion system are of interest and were analyzed by looking at the difference between the influent and effluent compositions (Table 7). Statistical analysis was applied to the data observations to determine if there was a statistically significant difference between the influent and the effluent compositions. A two-tailed pair-wise Student's T-test was applied to the data sets for the influent and effluent composition. The null hypothesis is rejected for alpha was less than 0.05, meaning that for p-values less than 0.05, we conclude that there is a statistically significant difference between the influent and the effluent composition and that there is statistical evidence supporting the conclusion that conversion occurred within the digester.

The observed averages for composition of influent and effluent are shown in Table 7 along with the percentage difference observed with a bold negative value meaning a reduced concentration after digestion and a bold positive value meaning an increased concentration. The differences that are statistically significant are shown in bold including Total Solids, Volatile Solids, Chemical Oxygen Demand, Ammonia-Nitrogen, Sulfur, and Calcium. Solids and Oxygen Demand are reduced and Ammonia-Nitrogen is increased as is expected to occur in the digestion process. Sulfur reduction is also expected because sulfur leaves the digester in the form of hydrogen sulfide in the biogas. There is no physical explanation for a small increase in Calcium concentration during the digestion process. This could have been an anomaly as it was not seen in any of the other five digester systems that were tested.

All other constituents do not show statistically significant differences (non-bold results) between influent and effluent. These results do not contradict the assumption that nutrients are conserved in the digestate during anaerobic process while volatile solids are consumed, although they may be converted in form. For example, although ammonia nitrogen increases during the digestion process, the total nitrogen difference between inlet and outlet of the digester was not statistically significant.

The mass and energy flow diagram in Figure 13 illustrates how water and solids and energy are transported and converted in the system. While the conversion within the digester was small, the results still show fairly good closure on mass and energy balances for the system.

Table 3.7: Differences Between Influent and Effluent Compositions Observed During the Study Period.

Analyte	Units	Method	Influent	Effluent	Difference	P-Value[2]
Total Solids	mg/L	SM 2540B	**8553**	**5979**	**-30.1%**	**0.0415**
Volatile Solids	mg/L	EPA 160.4	**5904**	**3140**	**-44.4%**	**0.0202**
Total Dissolved Solids	mg/L	SM 2540 C	4211	4120	-2.2%	0.6182
Chemical Oxygen Demand	mg/L	SM 5220D	**8587**	**3108**	**-63.8%**	**0.0194**
Specific Conductance	µS/cm	SM 2540B	**7.0**	**8.7**	**24.2%**	**0.0176**
Ammonia-N	mg/L	SM 4500	**384**	**522**	**36.2%**	**0.0266**
Ammonium-N	mg/L	SM 4500G	11.2	5.8	-48.1%	0.2165
Nitrate-Nitrogen	mg/L	EPA 300.0	0.41	1.57	279.3%	0.1926
Total Nitrogen	mg/L	EPA 351.2	848	691	-18.6%	0.2252
Total Phosphorus	mg/L	SM 4500PB	134	93	-31.0%	0.1433
Total Potassium	mg/L	SM 3120 B	633	632	-0.1%	0.9968
Total Sulfur	mg/L	SM 3120 B	**123**	**70**	**-42.9%**	**0.0049**
Total Clorine	mg/L	SM 3120 B	249	302	21.1%	0.1875
Total Calcium	mg/L	SM 3120 B	**201**	**237**	**17.9%**	**0.0033**
Total Magnesium	mg/L	SM 3120 B	135	178	31.9%	0.0566
Total Sodium	mg/L	SM 3120 B	232	278	20.1%	0.1664

3.3.3 Biogas Production

The measured daily biogas production varied from 28,000 to 52,000 cubic feet per day with an average of 36,000 as shown in Table 8 and Figure 10. A large portion of the gas was flared (57 percent) due to frequent engine downtime. There was also a continuous gas bleed to the flare due to flow problems with the engine intake that prevented utilizing all of the gas in the engine generator.

The average specific biogas production for both added and consumed volatile solids are estimated in Table 8. The average value of 5.9 cubic feet per pound of volatile solids added is near the reported yields of 6 to 8 cubic feet per pound from successful and stable dairy manure digesters. The average value of 16.3 cubic feet per pound of volatile solids consumed is consistent from a mass balance perspective because 15 cubic feet of biogas weighs about one pound. The observed biogas production per pound of volatile solids excreted by the herd was 3.1 cubic feet (or about 0.21 pounds per pound VS excreted) which can be compared with other dairy digester systems as a performance metric.

The composition of the biogas was monitored throughout the study during monthly sampling and analysis. These observations are shown in Figure 11. The methane content ranged from 58-72 percent of the biogas (66.4 percent average). The balance of the gas is primarily carbon dioxide (32.8 percent average), the other major gas product of anaerobic digestion. There was

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[2] P-Values generated from a Paired Two-Tailed Student's T-Test for the difference between influent and effluent data sets with alpha = 0.05. Statistically significant differences are shown in bold.

an amount of nitrogen (0.7 percent average) and oxygen (0.1 percent average) in the gas attributed to air added by the biofiltration system. Gas samples were analyzed before and after the biofilter system show the difference. The hydrogen sulfide content of the biogas was observed to average 3,300 parts per million by volume before the biofilter and 1,900 parts per million after for an average reduction effectiveness of 43 percent although this varied quite a bit by month as shown in Figure 12. These sulfur levels in the filtered biogas are still quite high for a gas engine. The biofilter was not nearly as effective at reducing hydrogen sulfide as an air injection that has since been implemented at this facility.

Table 3.8: Biogas Production Parameters Observed From the Digester System.

	BIOGAS PRODUCTION					
MONTH	TOTAL BIOGAS*	SPECIFIC BIOGAS	SPECIFIC BIOGAS	SPECIFIC BIOGAS	METHANE	PERCENT FLARED BIOGAS
(MM)	(SCFD)	(SCF/LB VS ADDED)	(SCF/LB VS CONSUMED)	(SCF/LB VS EXCRETED)	(VOL %)	(%)
01	32,145	3.7	6.0	2.8	72.9	43%
02	26,466	3.8	7.4	2.3	74.2	18%
03	29,286	4.1	8.5	2.5	72.2	41%
04	35,324	5.2	11.1	3.0	71.0	24%
05	36,049	5.6	11.9	3.1	65.3	64%
06	42,025	6.5	13.8	3.6	61.9	35%
07	27,807	5.1	16.1	2.4	60.2	49%
08	35,979	7.8	49.5	3.1	58.5	75%
09	52,161	10.3	34.8	4.5	61.3	85%
10	47,658	8.5	19.0	4.1	67.0	78%
11	34,951	5.6	11.6	3.0	65.3	95%
12	32,528	4.1	6.9	2.8	67.5	81%
AVE	36,032	5.9	16.4	3.1	66.4	57%

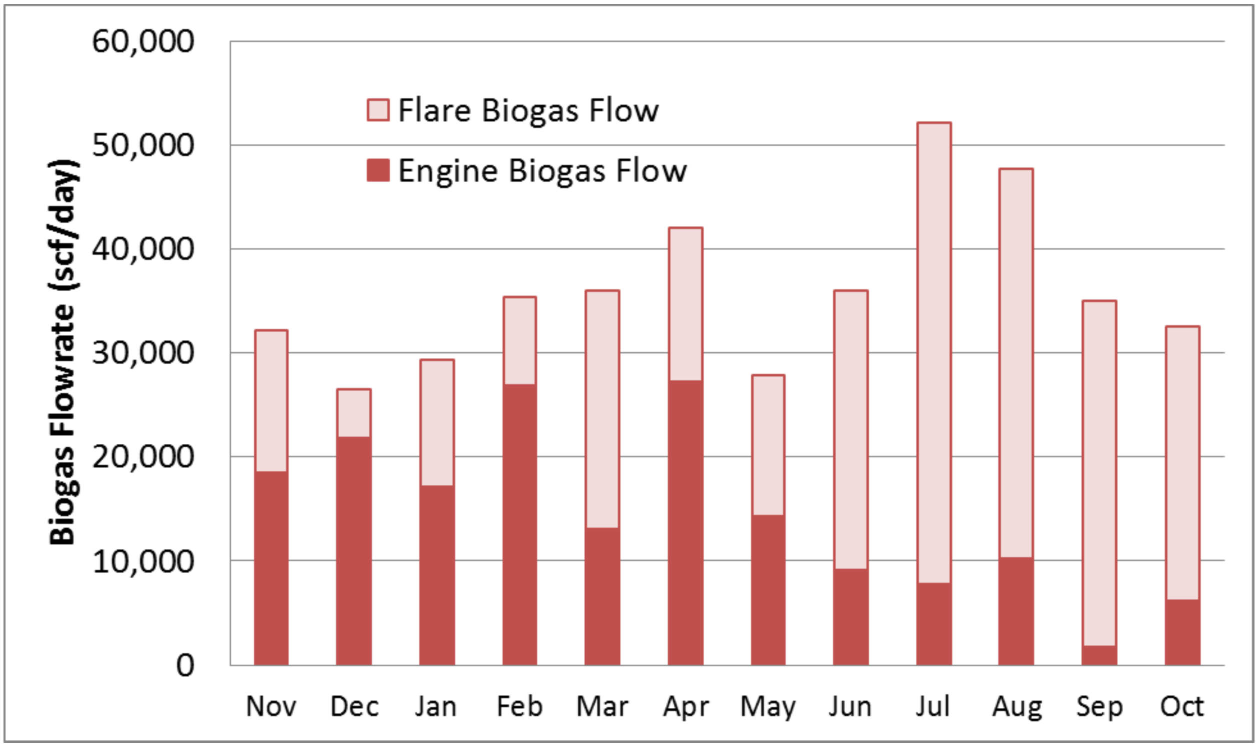

Figure 3.6: Average Daily Biogas Flowrate by Month From the Digester System.

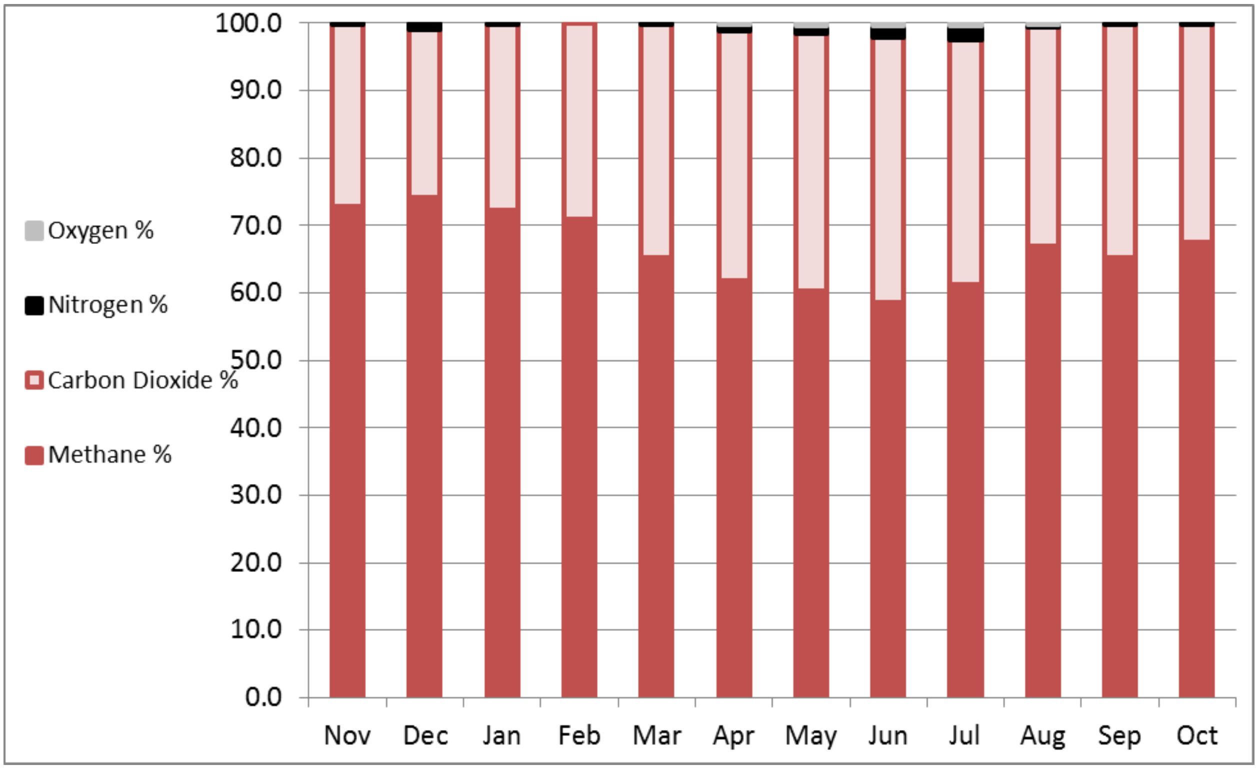

Figure 3.7: Biogas Composition Observed During the Study.

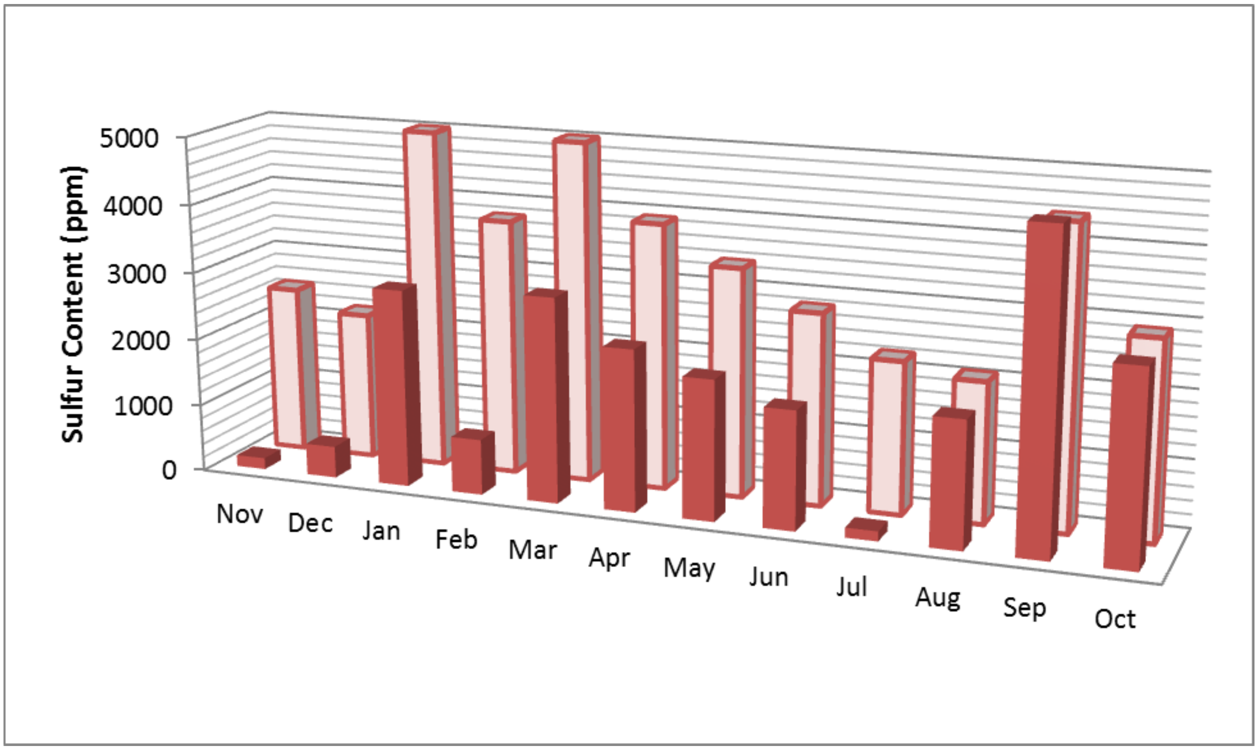

Figure 3.8: Hydrogen Sulfide Concentration in the Biogas Observed With No Control (Light, Back) and After Bio-Filtration (Dark, Front).

Biological methane potential (BMP) was also examined for the digester influent feed to compare the methane production at ideal mesophillic conditions with actual performance of the digester system. In addition, the biomethane potential of the digester effluent was quantified to determine what additional biogas production potential remains after the digestion process. Using the standard BMP test, average biogas production was 5.1 standard cubic feet (SCF) per pound of volatile solids added for the digester feed which was actually slightly lower than the estimated digester performance of 5.9 SCF per pound of volatile solids added. This indicates that the digester was quite good at generating the full potential in the manure. The biological methane potential was determined to be 3.4 SCF per pound of volatile solids added. The methane potential of the digester effluent was 0.13 SCF per pound of volatile solids showing methane potential for the effluent to be only 4 percent that of the digester feed, another indication that this system delivered very complete anaerobic digestion of the manure.

3.3.4 Biogas Generator Performance

The biomass combined heat and power generator performance was observed including the power and heat utilization from the 65 kW engine generator set. Table 9 shows the results. After a small amount of parasitic load from the gas pump and engine skid, the electrical power output was an average of only 26 kilowatts over the 12 month period. The recoverable heat from the engine radiator was monitored at 31 kilowatts which is equivalent to about 1.3 Therms per hour. It should be noted that this heat was not utilized but could have been converted to hot water for other energy use.

Table 3.9: Engine Generator Performance Observed During the Study.

	BIOGAS CHP PERFORMANCE							
MONTH	ELECTRICAL POWER OUTPUT	SPECIFIC POWER OUTPUT	AVERAGE HEAT RECOVERY	SPECIFIC HEAT RECOVERY	CAPACITY FACTOR*	ELECTRICAL EFFICIENCY	HEAT EFFICIENCY	OVERALL CHP EFFICIENCY
(MM)	(kW)	(kWh/LB VS ADDED)	(kW)	(kWh/LB VS ADDED)	(%)	(% LHV)	(% LHV)	(% LHV)
01	35	0.097	32	0.089	53%	23%	21%	45%
02	39	0.134	43	0.145	61%	22%	24%	46%
03	31	0.105	36	0.121	48%	23%	26%	48%
04	49	0.173	52	0.184	75%	23%	24%	47%
05	24	0.088	24	0.090	36%	25%	25%	50%
06	49	0.183	55	0.206	76%	26%	30%	56%
07	26	0.112	34	0.149	40%	27%	36%	63%
08	17	0.086	23	0.118	25%	28%	38%	66%
09	14	0.067	22	0.105	22%	27%	42%	68%
10	19	0.079	24	0.103	28%	24%	32%	56%
11	3	0.012	4	0.017	5%	25%	35%	60%
12	11	0.034	29	0.089	17%	24%	64%	88%
AVE	26	0.098	31	0.118	40%	25%	33%	58%

* Note: Heat recovered from engine was rejected via radiator. Heat not recovered for other use.

The system was run at a 40 percent capacity factor during the study period. The actual online time for the engine generator was about 60 percent so the system was consistently operated at only 40-70 percent of the nameplate biogas capacity, partly because of problems with the gas intake and throttle system. At this low set point, it is possible the engine performed at a lower efficiency than is possible when the system is run near its capacity. The electrical efficiency of the system was observed to be 25 percent with a recoverable heat efficiency of 33 percent from the jacket water for an overall combined-heat and power efficiency of 58 percent, on a lower heating value basis.

3.3.5 Mass and Energy Flows

The process flows throughout the manure handling system are shown in Table 10 below. It can be seen where volumes of liquids and masses of water, solids, and volatile solids (VS) are added and removed from the manure collection and handling system at the dairy. The estimated average daily amounts of recycled flush water and fresh collected manure make up the total dairy manure flush composition. An inclined screen separator removes an estimated 40 percent of these solids leaving the digester influent with the remaining solids. The digester then converts 44 percent of the volatile solids to produce biogas, further reducing the solids loading of the process water now dominated by mostly non-digestible solids. The final liquid remaining after the process goes to a storage pond to be recycled for flushing to irrigate feed crop land around the dairy. Figure 13 is a graphical representation of the average mass, solids, and energy balances for the Dairy 1 Digester system, based on the data collection and analysis from the study.

Table 3.10: Daily Process Volume and Mass Flows.

Process Water/ Solids Stream	Liquid Volume (gal/day)	Total Mass (lbs/day)	Solids Conc. (%)	VS Conc. (%TS)	Water Mass (lbs/day)	Solids Mass (lbs/day)	VS Mass (lbs/day)	Solids Removal (%)	VS Removal (%)
Fresh Water	9,000	75,100	0.00	0.0	75,100	0	0		
Recycle Water	113,200	944,300	0.50	55.2	939,800	4,500	2,500		
Collected Manure	10,700	88,900	12.45	78.0	77,800	11,100	8,600		
Total Flush	132,900	1,108,200	1.40	71.4	1,092,700	15,600	11,100		
Screen Separator	-	29,800	20.80	75.0	23,600	6,200	4,600	39.8%	41.8%
Influent	129,300	1,078,400	0.87	68.8	1,069,100	9,300	6,400		
Effluent	129,000	1,075,600	0.60	55.2	1,069,100	6,500	3,600	30.6%	44.4%

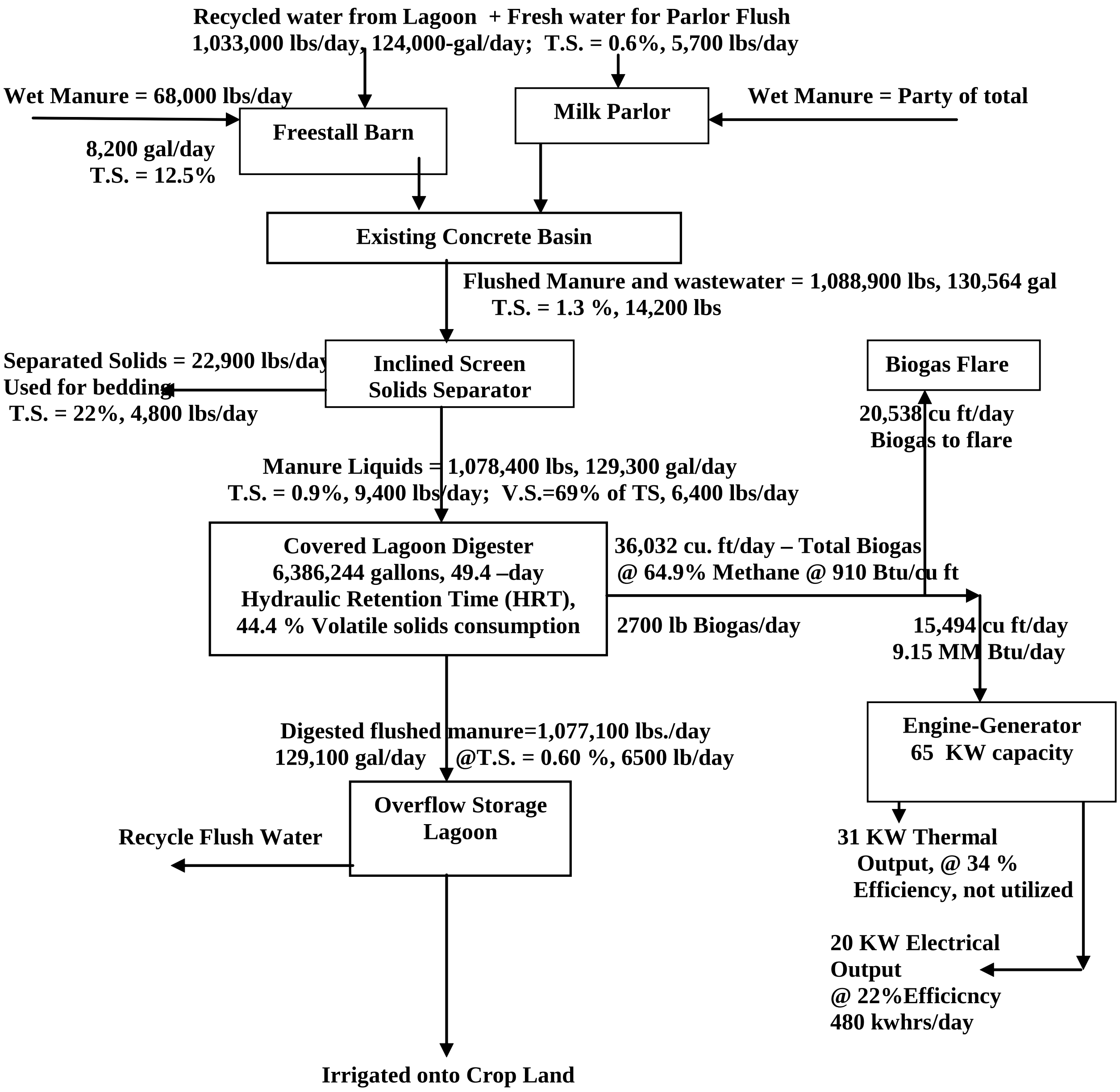

Figure 3.9: Average Mass and Energy Flow Diagram With Daily Flows For Dairy and Digester System.

3.3.6 Climate Change Impact

Using the data collected from the study, the Climate Action Registry Livestock Protocol was used to compute the amount greenhouse gas emissions reductions that have resulted from the digester project. The protocol provides a methodology for quantifying the baseline greenhouse gas emissions and comparing those with the emissions estimated to still be generated from the digester system or biogas control system (BCS) as the digester system is called by the Registry. The baseline emissions are the methane emissions that would have occurred from decomposition of manure in a lagoon storage system if the digester was not constructed. The project emissions are from un-burned methane from the engine and digester leakage and/or venting and methane generated in the effluent storage pond. The difference between the baseline and project emissions are a conservative estimate of the climate impact of the digester system. The results are shown in Table 11.

The total methane reductions are available to the facility as carbon credits through a verification process with the registry. Carbon credits represent a potential source of revenue depending on the value of the credits in the marketplace. Note that there is also a cost in establishing these credits (including monitoring system installation costs, data collection costs, and third-party reporting and verification) and this has been seen to potentially be prohibitive for some small projects.

The results show that the baseline methane emissions of the facility are about 120 tonnes (metric tons or 1000 kg) per year. The project methane emissions of the facility are estimated to be 20 tonnes from the BCS and 15 tonnes from the effluent storage pond or 35 tonnes total. The difference is 86 tonnes of methane for a total reduction of almost 1800 tonnes of carbon dioxide equivalents to the atmosphere which is equivalent to 3.3 tonnes of carbon dioxide per year per lactating cow at the facility. This represents a 71 percent reduction in greenhouse gas emissions associated with manure management at the facility. Note that this is not the 156 tonnes of methane that is actually destroyed by the engine and flare each year but better represents the climate impact of the digester project than the actual methane destruction.

Table 3.11: Climate Modeling Results for Digester Project Including Estimated Methane Reductions.

	Tonnes CH4 Per Year	***Tonnes CO2e Per Year***
Total Modeled Baseline Methane Emissions	***120.4***	***2527***
Project Methane Emissions from the BCS	19.4	408
Project Methane Emissions from Effluent Pond	15.3	320
Total Project Methane Emissions	***34.7***	***728***
Total Methane Reductions	***85.7***	***1799***
Methane Destroyed in the BCS	156.0	3275

3.4 Dairy 1 Conclusions

The project generated results for the annual performance of a hybrid mixed lagoon dairy digester system coupled with a cogeneration system for conversion of biogas into power and heat. The following conclusions provide normalized results so that the study of this system can be compared with other digester systems in terms of overall characteristic performance.

DIGESTER FEEDING: The digester influent feed came from recycled flush water containing solids and fresh manure solids that had the large fibrous solids removed by an inclined screen separator. The dairy flush contained about 75 percent of the volatile solids estimated to be generated by the dairy herd, and these only made up about 78 percent of the solids in the flushed manure water. After removal of 40 percent of the solids over the separator, the influent had an average total solids concentration of 0.87 percent which consisted of 69 percent volatile solids. The digester was only fed with fresh and recycled manure solids with a more detailed constituent analysis shown in Table 4.

DIGESTER PERFORMANCE: The project results demonstrate that the un-heated covered lagoon digester having a long hydraulic retention time and low organic loading rate has the capability to maintain stable anaerobic digestion. The digester showed consistent volatile solids reduction and gas production over the year. The average hydraulic retention time was 49 days with an organic loading rate of 7.5 pounds of volatile solids per thousand cubic feet per day. Average digester temperature was 67°F with seasonal variation over the year. The study showed that the digester reduced total solids by 30 percent, volatile solids by 44 percent, chemical oxygen demand by 64 percent, and sulfur by 49 percent during the digestion process. Ammonia nitrogen increased by 36 percent. There were no other statistically significant changes to the digestate composition within the digester system as shown in Table 7.

BIOGAS PRODUCTION: The digester produced an average of 5.9 cubic feet of biogas per pound of volatile solids added which also equated to 16.4 cubic feet per pound of volatile solids consumed. The composition of the biogas was consistently high in methane at an average of 66.4 percent, but also consisted of 31.8 percent carbon dioxide, 0.7 percent nitrogen, and 0.1 percent oxygen. Hydrogen sulfide content in the biogas was lowered 43 percent by a biofilter system but was still fairly high with an average of 1,900 ppmv.

BIOGAS GENERATOR PERFORMANCE: The engine-generator for this project operated at a capacity factor of 40 percent although the actual engine online time was 60 percent. The electrical efficiency averaged 25 percent and the rejected heat efficiency was 33 percent for a total recoverable energy efficiency of 58 percent expressed on a lower heating value basis. The actual efficiency might have been increased by running the generator closer to capacity and increasing the heat utilization.

CLIMATE CHANGE IMPACT: Utilizing the methodology developed for predicting livestock emissions reductions using digesters, it is estimated that the baseline and digester project emissions of methane are 120 and 35 tonnes per year respectively, for a total reduction due to the installation and operation of the digester of 71 percent. This is equates to 1800 tonnes of carbon dioxide equivalents per year that could potentially be traded as carbon credits which is about 3.3 tonnes per lactating cow at the dairy.

CHAPTER 4: Dairy 2 Results

4.1 Dairy 2 Background

Dairy 2 is an organic dairy farm located in coastal Northern California. The dairy is adjacent to a farmstead cheese plant that produces blue cheese and other cheese products from the milk produced at the dairy. The facility installed an anaerobic digester system in 2008 to manage the manure and wastewater that is generated from the facility and produce renewable power and heat for the facility.

The digester is a 32,000-square foot covered lagoon digester located adjacent to the freestall dairy barns. Flushed manure from the 300-cow dairy along with a small amount of daily wastewater from the cheese plant collects in a concrete pit prior to being pumped through a screw press solids separator, Figure 1, where the fibrous solids are removed and composted for use as bedding and fertilizer. The manure liquids then flow by gravity into the 2.5 million-gallon lagoon resulting in about a 40 day hydraulic retention time. This covered lagoon, Figure 2, is maintained under anaerobic conditions, and provides favorable conditions for natural microbial action to convert the organic matter in the manure and cheese plant wastewater into methane-rich biogas. The effluent from this covered lagoon overflows to a lined storage lagoon, Figure 3, and provides valuable fertilizer for the dairy’s pastures. A custom-engineered HDPE system encloses the covered lagoon, captures the biogas, and channels it into a pipeline where it is transported to the new 80-KW co-generation system located adjacent to the dairy parlor and cheese plant. The system was retrofitted in 2009 with an air injection system to reduce hydrogen sulfide in the raw biogas to below 50 ppm.

After the digester, the biogas first passes through the gas conditioning unit, Figure 4, where it is filtered to remove any residual hydrogen sulfide, dried with a chiller-type gas drier, is lightly compressed to be delivered to the prime mover located up the hill near the milking parlor and cheese plant. The fuel is delivered to a synchronous generator system which operates approximately 24 hours per day. The system uses an engine-generator that can produce up to 75 kW on biogas. The generator is quieted by a special acoustic shielding, Figure 5. The electricity generated provides a substantial portion of the electrical requirements of the dairy milking center and the cheese plant through a net metering interconnection agreement with Pacific Gas & Electric Company. The heat from the generator engine and exhaust system is captured via heat exchanger, Figure 6 and used to produce hot water for the parlor and cheese plant. The actual electricity and heat produced by the system during one year will be presented in this report along with other performance factors.

Figure 4.1: Screw Press Solids Separator.

Figure 4.2: Covered Lagoon Digester.

Figure 4.3: Lined Overflow Lagoon.

Figure 4.4: Gas Handling Skid.

Figure 4.5: 75-KW Engine-Generator System.

Figure 4.6: Heat Exchanger (Left) Next To Engine.

Table 4.1: Dairy 2 Digester System Description.

Digester	Covered lagoon digester, 2.5 Million gal capacity Unheated and unmixed HDPE cover Fibrous solids separation before digestion
Engine-Generator	Martin Machinery MMG-80 with M.A.N. Engine 80 kW capacity on natural gas/ 75 kW on biogas 240 VAC, 3 phase Manufacturer estimated 36.3% LHV shaft efficiency
Biogas Treatment	Air injection system under digester cover Carbon canister-type H2S scavenger Biogas chiller for "dewatering"
Heat Recovery	Preheat hot water for milk parlor and cheese plant Back-up radiator system Both engine jacket and exhaust heat recovery

The flare is normally off so that biogas can be used by the engine to produce electricity. For the year –long data collection period the flare was never activated so that 100 percent of the gas was burned in the engine-generator. When the engine-generator was shut off for maintenance, the gas was stored under the cover and subsequently utilized by the engine-generator. The cover had sufficient storage so that several days of gas production could be safely collected.

The Figure 7 schematic shows the overall biogas and power generation systems. The annual average mass and energy flows are given in the process flow diagram in Figure 13. All the biogas from the digester was used in the engine-generator. The hot water leaving the engine jacket and exhaust was used to provide useful heating in the parlor house for preheating wash-down water as well as heat water for the cheese making process.

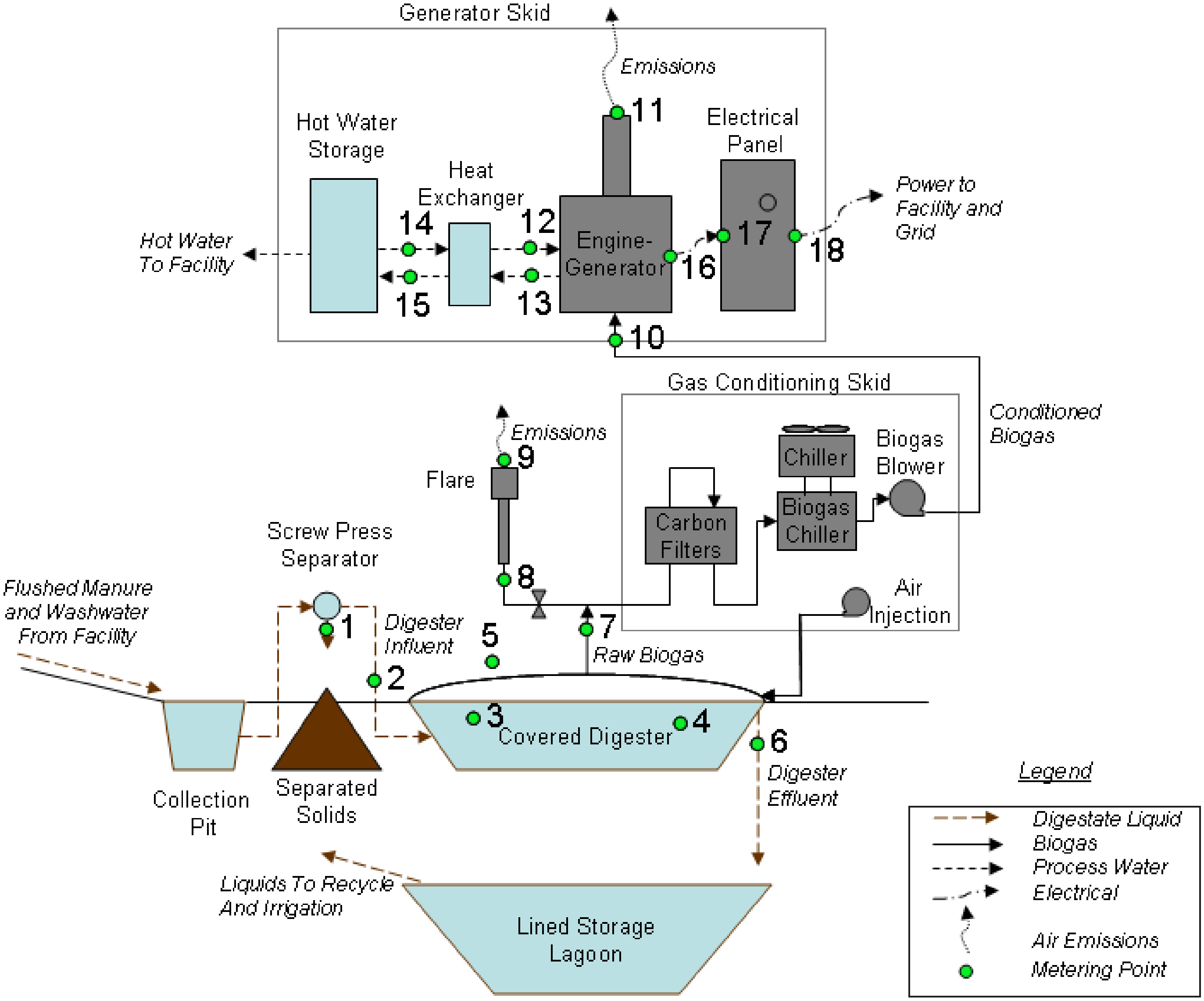

Figure 4.7: Schematic of Biogas System With Metering Points.

4.2 Dairy 2 Materials and Methods

The monitoring methodology and system followed protocols developed by ASERTTI, Climate Action Registry, and US EPA. Continuous sensors monitored pertinent system flows and conditions including those shown in Table 2. This data was recorded in data logger equipment and 15-minute averages were continuously logged and stored on site before periodic downloads by the investigators. Sampling locations are shown on the schematic in Figure 7. These sampling points cover all pertinent manure, biogas, power and process water flows and temperatures. Composition samples (24-hour aggregated) were taken on a monthly basis to establish the mass distribution for each flow of manure, biogas and emissions.

The monitoring system supplied by Summers Consulting was configured to capture the data points listed in Table 2. The sensors were automatically sampled at 1-minute intervals and averaged or summed into 15-minute data as appropriate. The PLC-based system provided the investigators access to the time-stamped 15-minute data via the internet. The on-site controller has the ability to store and retain several hundred days of 15-minute data in the event that communications are lost.

The electrical output of the engine-generator (WGO) was measured with a Gen-Tec power transducer already installed in the engine control panel. A PG&E-supplied power meter also indicated the amount of power that was exported (WGT) by the engine. The net power exported to the grid was also supplied by the PG&E supplied metering (WNT).

The biogas delivered to the engine (FGE) was measured by a Sage gas flow meter (hot-wire probe) that determined the mass flow in standard cubic feet per minute (scfm). The biogas flow to the flare (FGF) was not measured since for the duration of the project no biogas was allowed to flow to the flare. The total biogas flow (FGT)was therefore equal to is FGE. From the biogas and power measurements the engine efficiency was calculated using the measured gas composition data. The gas flows also allowed for an estimate of emissions from the engine (FEE) using standard combustion assumptions and monthly measurement of exhaust composition.

The digester temperatures (TMI, TME, TD1 and TD2) were measured by thermocouples at the influent and effluent pipes and placed in the two vent pipes on the cover of the digester. The ambient temperature (TAO) was recorded to understand how digester performance varied with weather conditions.

Table 4.2: Monitoring Points on the Dairy 2 Digester System. Monitoring Locations Shown on Figure 7.

Loc #	Data Point	Description	Eng. Units	Sensor or Instrument	Typical Range
1	FMS	Flow of Manure Solids	lb/day	Monthly weight est.	4000-7000
	CMS	Composition of Manure Solids	% by wt.	Quarterly samples	20-25% TS
2	FMI	Flow of Manure, Influent to Digester	Gal/day	Ultrasonic Flowmeter	50,000-200,000
	TMI	Temperature of Manure, Influent to Digester	°F	Type-K TC, 6 in probe	50-80
	CMI	Composition of Manure, Influent to Digester	mg/l	Monthly samples, 24h	7,400-20,400 TS
3	TD1	Temperature of Digester at Vent Valve 1	°F	Type-K TC, 72 in depth	67-80
4	TD2	Temperature of Digester at Vent Valve 2	°F	Type-K TC, 72 in depth	65-80
5	TAO	Temperature of Ambient Out	°F	Type-K TC, near digester	45-95
6	FME	Flow of Manure, Effluent from Digester	Gal/day	Estimated from FMI	=FMI
	TME	Temperature of Manure, Effluent from Digester	°F	Type-K TC, 6 in probe	50-84
	CME	Composition of Manure, Effluent from Digester	mg/l	Monthly samples, 24h	5,200-19,300 TS
7	FGT	Flow of Gas Total (Raw Biogas)	SCF/day	Estimated from FGE & FGF	=FGE+FGF
	CGT	Composition of Gas Total (Raw Biogas)	% by vol.	Monthly analysis	65-72% CH4
8	FGF	Flow of Gas to Flare (Raw Biogas)	SCF/day	Sage Prime SIP	0
	CGF	Composition of Gas to Flare (Raw Biogas)	% by vol.	Monthly analysis	65-72% CH4
9	FEF	Flow of Emissions from Flare	SCF/day	Estimated from FGF	0
	CEF	Composition of Emissions from Flare	% or ppm	Monthly analysis	NA
10	FGE	Flow of Gas to Engine (Conditioned Biogas)	SCF/day	Sage Prime SIP	15,000-35,000
	CGF	Composition of Gas to Engine (Conditioned)	% by vol.	Monthly analysis	65-72% CH4
11	FEE	Flow of Emissions from Engine	SCF/day	Estimated from FGE and CEF	25,000 – 55,000
	CEE	Composition of Emissions from Engine	% or ppm	Monthly analysis	4-8% O2
12	TCI	Temperature of Coolant, Inlet to Engine, (Jacket and Exhaust Coolant)	°F	Not installed	NA
	FC	Flow of Coolant	GPM	Not Installed	NA
13	TCO	Temperature of Coolant, Outlet of Engine (Between Jacket and Exhaust)	°F	Type-K TC, 6 in probe	177-207
	TCE	Temperature of Coolant, Exit to Heat Exchanger (After Exhaust Heat Recovery)	°F	Not installed	NA
14	TWI	Temperature of Water Inlet (Process Water into Heat Exchanger)	°F	Type-K TC, 6 in probe	97-190
15	TWO	Temperature of Water Outlet (Process Water out of Heat Exchanger)	°F	Type-K TC, 6 in probe	158-206
	FWP	Flow of Water to Process	GPM	Onicon F1100	0-18
16	WGO	Watts of Generator Output (Power at Generator)	kW	Gen-Tec power meter	0-72
17	WGT	Watts of Generator Total (Power at Utility Meter)	kW	PG&E meter - pulse	0-68
18	WNT	Watts of Net Total (Power after Parasitic Loads)	kW	PG&E meter - pulse	0-68

The flow of manure into the digester (FMI) was measured with a clamp-on ultrasonic flow meter. It was assumed that influent and effluent flow were approximately balanced, therefore

FMO is estimated to be equal to FMI. The flow of manure solids was measured monthly by weighing the solids separated by the screw press over a 24-hour period.

The thermal output recovered from the engine jacket to the heat exchanger was be determined from the coolant water flow and temperature difference data (FC, TCI, TCO, TCE). The thermal energy actually utilized for process water heating was determined from the process water flow and temperature difference data (FWP, TWI, TWO).

The parasitic power consumption of various components in the system were determined by power readings with a hand-held meter capable of measuring true power. The sum of all parasitic loads not accounted for in the net metering was compared with the power generated by the system.

The composition of the manure influent and effluent was measured on a monthly basis by taking representative samples at the dairy and subsequently sent overnight for laboratory analysis for the components described in Appendix A. Samples were prepared using an aggregate of five grab samples collected during the manure flushing cycle. Because of the inherent problems with using a sample from a single day to represent the composition for an entire month, a smoothing function that included the prior and subsequent month results was used to represent the reported monthly composition. The amount of solids removed by the separator was also estimated on a monthly basis by estimating the pile volume and collection period. Solids were also laboratory analyzed on a quarterly basis for the components described in Appendix A.

The composition of the biogas was measured using a GEM™2000 Portable Gas Analyzer from Landtec on a monthly basis. This sampling included raw and conditioned biogas. The portable Landtec meter was used to determine the percentage of CH_4, CO_2, O_2, H_2S and balance gas on a monthly basis. The emissions from the engine were measured using a Testo 350XL portable analyzer. The metering equipment was calibrated on a routine basis and the estimated accuracy is shown in Appendix A.

Periodic samples of the influent to and effluent from the digester was subjected to a Biochemical Methane Potential (BMP) analysis in a specially-designed apparatus in the Summers Consulting laboratory. BMP analysis is an efficient and economical method for evaluating the rate and extent of biomass conversion to methane under anaerobic conditions. The effluent BMP shows the remaining methane production potential after digestion and provides an estimate of the potential methane produced in a liquid storage pond after digestion.

Annual greenhouse gas emissions reductions were also estimated using the Climate Action Registry Livestock Protocol. This protocol uses a particular methodology to estimate the baseline emissions or emissions from the manure management system without the digester and compares these with estimated emissions from the digester system.

4.3 Dairy 2 Results and Analysis

The following sections summarize the monitoring results of this year-long monitoring campaign and provide annual operational factors including digester feeding, digester performance, biogas production, biogas generator performance, and climate change impact. The digester monitoring system for Dairy 2 was designed in 2010 and installation was completed in early 2011. The monthly sampling was initiated in June of 2011 and completed by June of 2012. The actual cow and heifer numbers during the data collection period are shown in Table 3 along with the estimated daily manure production as predicted by typical estimation method from ASABE.

Table 4.3: Dairy Herd Size Characteristics and Estimated Manure Production at Dairy 2.

DAIRY HERD			ESTIMATED MANURE PRODUCTION	
	HEAD (#)	WEIGHT (LB/HEAD)	VOLATILE SOLIDS (LB/HEAD/DAY)	TOTAL VOLATILE SOLIDS (LB/DAY)
Milk Cows	338	1499	17.0	5746
Dry Cows	43	1507	9.2	396
Heifers	234	897	7.1	1661
			Total Manure Volatile Solids	7803

4.3.1 Digester Feeding

The rate of influent feeding of the digester averaged 60,000 gallons per day over the entire year, but varied monthly from 40,000 to over 100,000 gallons per day. This averages to a flush system flow of about 77 gallons per animal unit per day. Figure 8 shows the average digester influent flows for each month of the study year. Factors like inconsistent daily operations impacting the amounts of flushwater and wastewater from the cheeseplant and the impact of rainwater accumulating in the flush system are sources of this variability. This shows that the digester needs to have adequate residence time to adjust to the variations that can occur with the flush-type manure collection system.

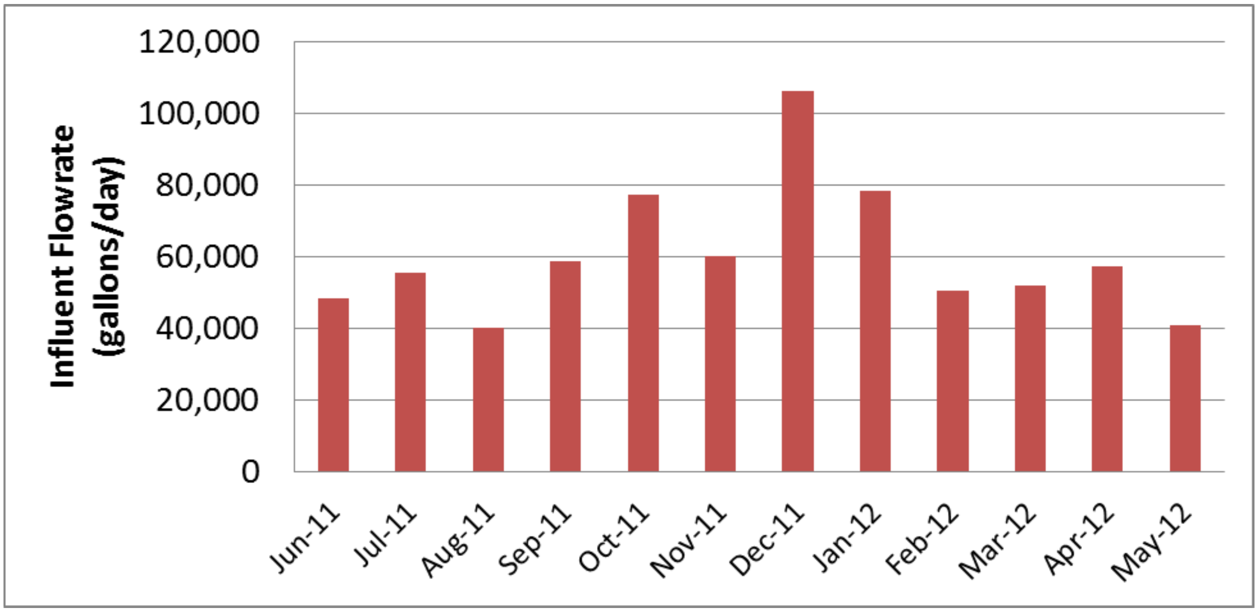

Figure 4.8: Average Monthly Influent Flowrate.

The results for the monthly solids composition of the influent mixture is shown in Figure 9. Total solids concentration ranged from 7,4000 to 20,400 milligrams per liter with an average of 16,500 milligrams per liter. Volatile solids ranged from 5,300 to 15,400 milligrams per liter with an average of 12,300 milligrams per liter. The volatile solids were consistently 71 to 77 percent of the total solids. The variability seen in these samples can also be attributed to variable system flows and the limitations of taking a single aggregated grab sample to represent an entire month of flow. The aggregation of all of the samples taken over the year is a better representation of the typical influent composition and for comparison with effluent samples. Table 4 shows the annual average and standard deviation for all of the samples taken over the year for constituents of the influent.

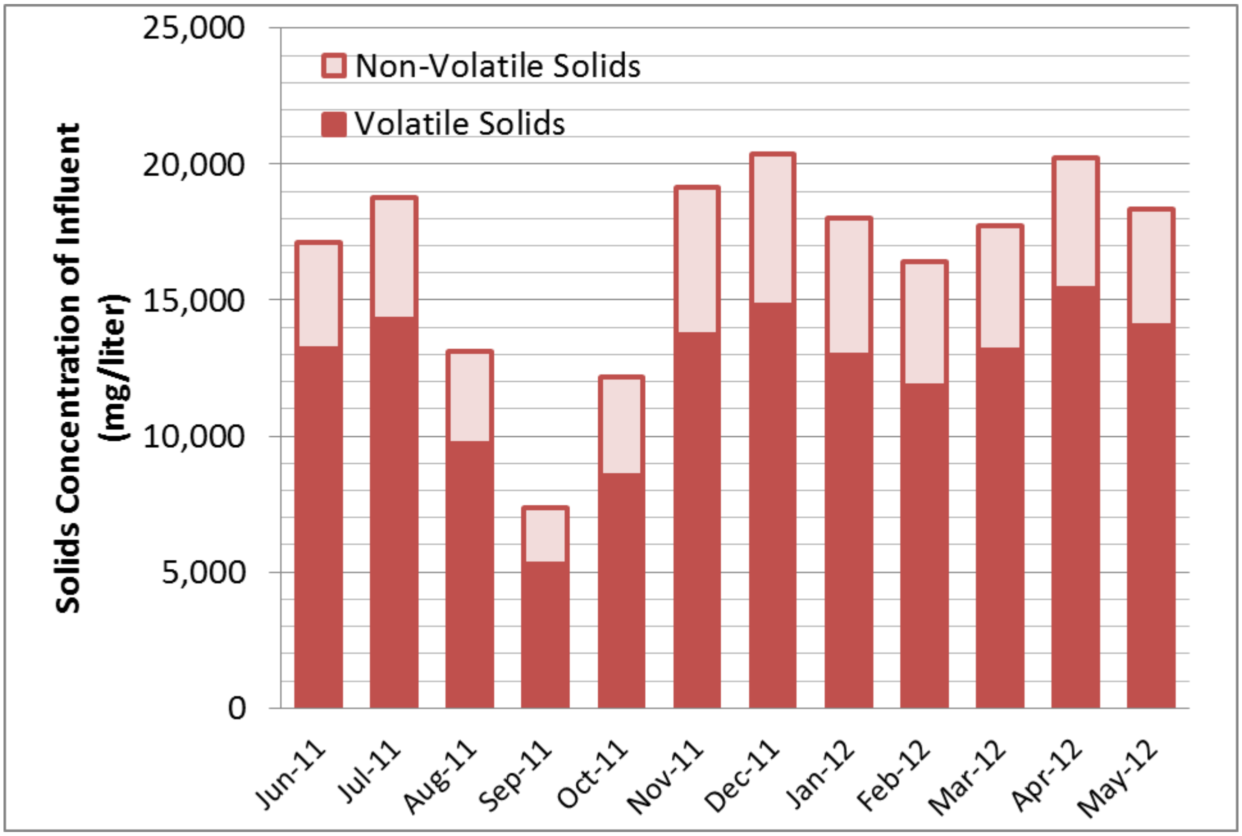

Figure 4.9: Total Solids Concentration of Digester Influent With Volatile and Non-Volatile Fractions.

Using pile size estimates and monthly moisture and density samples, it was determined that about 36 percent of the total solids in the flushed manure stream or about 2,600 pounds of total solids per day are removed by the solid separator before the digestion process. These separated solids can be valuable as a composted bed material or for use in farming or horticultural soil amendment. Table 5 shows the typical composition of these separated solids. Additional information on the flows of liquids and solids throughout the dairy facility are shown in the section below on Mass and Energy Balance.

Table 4.4: Composition of Various Constituents of the Digester Influent. Average and Standard Deviation of the Monthly Samples Taken Over the Study Year.

Analyte	Units	Method	Average	St Dev
Total Solids	mg/L	SM 2540B	15,640	5,928
Volatile Solids	mg/L	EPA 160.4	11,507	4,616
Total Dissolved Solids	mg/L	SM 2540 C	6,359	2,287
Chemical Oxygen Demand	mg/L	SM 5220D	20,264	10,423
Specific Conductance	µS/cm	SM 2540B	9.6	3.8
pH		Field Test	6.5	0.7
Ammonia-N	mg/L	SM 4500	393	179
Ammonium-N	mg/L	SM 4500G	1.7	2.4
Nitrate-Nitrogen	mg/L	EPA 300.0	6.1	6.3
Total Nitrogen	mg/L	EPA 351.2	934	372
Total Phosphorus	mg/L	SM 4500P B	133	59
Total Potassium	mg/L	SM 3120 B	1,105	623
Total Sulfur	mg/L	SM 3120 B	92	35
Total Clorine	mg/L	SM 3120 B	628	251
Total Calcium	mg/L	SM 3120 B	264	121
Total Magnesium	mg/L	SM 3120 B	118	55
Total Sodium	mg/L	SM 3120 B	309	64

Table 4.5: Composition of Various Constituents of the Separated Solids. Average and Standard Deviation of the Quarterly Samples Taken Over the Study Year.

Analyte	Units	TMECC Method	Average	St Dev
Dry Matter (eq TS)	Wt %	03.09-A	32.79	4.78
Organic Matter (eq VS)	Wt %	05.07-A	23.58	3.91
Total Nitrogen	Wt %	04.02-D	0.57	0.25
Total Phosphorus	Wt %	04.03-A	0.05	0.02
Total Potassium	Wt %	04.04-A	0.15	0.04
Sodium	Wt %	04.05-Na	0.04	0.02
Calcium	Wt %	04.05-Ca	0.22	0.05
Magnesium	Wt %	04.05-Mg	0.06	0.01
Iron	mg/kg	04.05-Fe	586	270
Copper	mg/kg	04.07-Cu	7.8	9.2
Manganese	mg/kg	04.05-Mn	24.8	4.3
Zinc	mg/kg	04.05-Zn	16.8	7.3
Sulfur	Wt %	04.05-S	0.05	0.01

4.3.2 Digester Performance

The digester was fed a daily dose of volatile solids from the manure and cheese-plant wastewater throughout the study, the fuel or food for the anaerobic digestion process. The average amount of volatile solids loaded into the digester was 6,200 pounds per day although there was some variability due to real variations in operations and due to the measurement limitations discussed above. The measured loading of the digester can be seen in Table 6 – Digester Feeding.

Table 4.6: Digester Influent Feeding and Performance Parameters.

	DIGESTER FEEDING				DIGESTER PERFORMANCE			
YEAR/ MONTH	**INFLUENT FLOWRATE**	**TOTAL SOLIDS CONC.**	**VOLATILE SOLIDS CONC.**	**INFLUENT VOLATILE SOLIDS**	**AVERAGE DIGESTER TEMP**	**ORGANIC LOADING RATE**	**HYDRAULIC RETENTION TIME**	**VOLATALE SOLIDS CONSUMP TION**
(YYMM)	**(GAL/DAY)**	**(%)**	**(% TS)**	**(LBS /DAY)**	**(DEG F)**	**(LB VS /1000 CF/DAY)**	**(DAY)**	**(%)**
1106	48,266	1.71	77.1	5,312	83.5	15.9	51.8	73.3
1107	55,580	1.87	76.3	6,633	87.6	19.8	45.0	78.5
1108	40,269	1.31	74.2	3,270	88.8	9.8	62.1	72.3
1109	58,687	0.74	72.0	2,600	88.0	7.8	42.6	47.0
1110	77,105	1.22	70.3	5,499	85.9	16.5	32.4	22.9
1111	60,103	1.91	71.8	6,883	78.6	20.6	41.6	21.3
1112	106,073	2.04	72.7	13,092	73.3	39.2	23.6	39.2
1201	78,343	1.80	72.0	8,481	73.0	25.4	31.9	41.2
1202	50,612	1.64	72.2	5,002	76.3	15.0	49.4	32.2
1203	51,750	1.77	74.1	5,673	72.9	17.0	48.3	50.0
1204	57,261	2.02	76.3	7,366	76.5	22.0	43.7	61.4
1205	40,952	1.83	76.7	4,803	80.9	14.4	61.0	62.8
AVE	60,417	1.66	73.8	6,218	80.4	18.6	44.4	50.2

The pattern of influent solids rates were lower in the summer when the cows were in the pastures most of the day, and higher in the winter when the cows were confined to the freestalls. The overall average input volatile solids equates to 9.9 pounds of volatile solids per animal unit per day which compares with published data[3] estimating total volatile solids production for dairy manure production is 11.3 pounds of volatile solids per animal unit per day. However, in this system there are also a certain amount of solids that come with the recycle water and with the cheese plant wastewater that are not derived from the fresh cow manure flushed into the system. The cheese plant wastewater was approximately 3000 gallons per day which at an estimated 0.7 percent to 0.8 percent volatile solids concentration contributed 200 pounds of VS per day (2 percent of total VS) to the overall flushed manure. The recycled flush water contained about 1.0 percent VS accounting for another 2,700 pounds per

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[3] ASABE Standard No. D384.2, Manure Production and Characteristics, March 2005.

day (30 percent of total VS) likely to be mostly stable and non-digestible. The raw manure derived volatile solids was estimated to be an annual average of about 6,000 pounds per day (68 percent of total VS) which is about 78 percent of the estimated 7800 pounds per day of manure volatile solids estimated to be generated by a herd this size (Table 3). A 78 percent manure capture seems reasonable given that the dairy herd numbers in Table 3 were already corrected for the amount of time that the cows spent in pasture during the year.

The digester appeared to maintain stable anaerobic digestion throughout the study as evidenced by the consistent volatile solids consumption observed averaging 50 percent. The average daily organic loading rate of 19 pounds of volatile solids per thousand cubic feet is almost double the recommended loading rate of 10 pounds of volatile solids per thousand cubic feet (NRCS, 2007). The 44 day average hydraulic retention time is in line with the recommended HRT of 40 to 45 days for this type of lagoon digester. The digester temperature varied from 70 to 90 degrees Fahrenheit on a seasonal basis but these temperatures are sufficient to maintain mesohpillic anaerobic activity. All of these performance factors calculated for each month of the study period are shown in Table 6 – Digester Performance.

Consumption, conversion, and accumulation of the wastewater constituents within the digestion system are of interest and were analyzed by looking at the difference between the influent and effluent compositions (Table 7). Statistical analysis was applied to the data observations to determine if there was a statistically significant difference between the influent and the effluent compositions. A two-tailed pair-wise Student's T-test was applied to the data sets for the influent and effluent composition. The null hypothesis is rejected for alpha was less than 0.05, meaning that for p-values less than 0.05, we conclude that there is a statistically significant difference between the influent and the effluent composition and that some conversion occurred within the digester.

The observed averages for composition of influent and effluent are shown in Table 7 along with the percentage difference observed with a bold negative value meaning a reduced concentration after digestion and a bold positive value meaning an increased concentration. The differences that are statistically significant are shown in bold including Total Solids, Volatile Solids, Total Dissolved Solids, Carbon Oxygen Demand, pH, and Ammonia-Nitrogen. Solids and Oxygen Demand are reduced as expected and pH and Ammonia increase.

All other constituents do not show statistically significant differences (non-bold results) between influent and effluent. These results do not contradict the assumption that nutrients are conserved in the digestate during anaerobic process while volatile solids are consumed, although they may be converted in form. For example, although ammonia nitrogen increases during the digestion process, the total nitrogen difference between inlet and outlet of the digester was not statistically significant.

Table 4.7: Differences Between Influent and Effluent Compositions Observed During the Study.

Analyte	Units	Method	Influent	Effluent	Difference	P-Value[4]
Total Solids	mg/L	SM 2540B	15,640	10,291	**-34.2%**	**0.0030**
Volatile Solids	mg/L	EPA 160.4	11,507	6,409	**-44.3%**	**0.0008**
Total Dissolved Solids	mg/L	SM 2540 C	6,359	5,084	**-20.1%**	**0.0092**
Chemical Oxygen Demand	mg/L	SM 5220D	20,264	11,183	**-44.8%**	**0.0005**
Specific Conductance	µS/cm	SM 2540B	9.6	10.6	10.6%	0.0669
pH		Field Test	6.5	7.4	**13.5%**	**0.0334**
Ammonia-N	mg/L	SM 4500	393	527	**34.1%**	**0.0017**
Ammonium-N	mg/L	SM 4500G	1.7	4.1	148.2%	0.0638
Nitrate-Nitrogen	mg/L	EPA 300.0	6.1	5.8	-5.1%	0.9021
Total Nitrogen	mg/L	EPA 351.2	934	941	0.8%	0.8888
Total Phosphorus	mg/L	SM 4500P B	133	141	6.7%	0.5111
Total Potassium	mg/L	SM 3120 B	1,105	1,301	17.8%	0.2129
Total Sulfur	mg/L	SM 3120 B	92	79	-14.0%	0.3915
Total Clorine	mg/L	SM 3120 B	628	576	-8.3%	0.3095
Total Calcium	mg/L	SM 3120 B	264	250	-5.2%	0.5968
Total Magnesium	mg/L	SM 3120 B	118	125	6.6%	0.3115
Total Sodium	mg/L	SM 3120 B	309	298	-3.7%	0.7144

The mass and energy flow diagram in Appendix B illustrates how water and solids and energy are transported and converted in the system. One significant feature to note is that the system is utilizing recycled flushwater with significant solids and thus results in higher solids input to the lagoon than would be supplied by fresh manure alone. It is estimated that nearly half of the solids introduced to the digester are recycled and these are not likely to contribute as much to gas production as the fresh manure solids. Overall, the measurement effort carried out resulted in an accurate quantification of the system flows as evidenced by the good closure on mass and energy balances for the system.

4.3.3 Biogas Production

The daily biogas delivered to the engine was very consistent throughout the study with a daily production of 32,500 cubic feet per day with little monthly variation throughout the study time period as shown in Table 8 and Figure 10. The system collects data on the biogas that is delivered to the engine or the flare but may not account to any leakage of biogas from the cover or other systems. It should be noted that the inflation of the cover of the digester can store several days' worth of biogas so it tends to buffer any inconsistencies between biogas production and engine generator operation. By observation of the relative cover inflation, the

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[4] P-Values generated from a Paired Two-Tailed Student's T-Test for the difference between influent and effluent data sets with alpha = 0.05. Statistically significant differences are shown in bold.

system operator can adjust the generator setpoint to consume all of the gas being produced. It is unlikely that a significant amount of gas escapes the system.

The average specific biogas production for both added and consumed volatile solids are estimated in Table 8. The average value of 6.3 cubic feet per pound of volatile solids added is in agreement with yields of 6 to 8 cubic feet per pound from successful and stable dairy manure digesters. The average value of 14.4 cubic feet per pound of volatile solids consumed is consistent from a mass balance perspective because about 15 cubic feet of biogas weighs one pound. The observed biogas production per unit of volatile solids excreted by the herd was 4.2 cubic feet per day (or about 0.3 pounds per pound VS excreted) which can be compared with other dairy digester systems as a performance metric.

Table 4.8: Biogas Production Parameters Observed From the Digester System.

	BIOGAS PRODUCTION					
YEAR / MONTH	TOTAL BIOGAS*	SPECIFIC BIOGAS	SPECIFIC BIOGAS	SPECIFIC BIOGAS	METHANE	PERCENT FLARED BIOGAS
(YYMM)	(SCFD)	(SCF/LB VS ADDED)	(SCF/LB VS CONSUMED)	(SCF/LB VS EXCRETED)	(VOL %)	(%)
1106	30,270	5.7	7.8	3.9	67.2	0%
1107	31,675	4.8	6.1	4.1	64.4	0%
1108	37,412	11.4	15.8	4.8	65.3	0%
1109	34,028	13.1	27.9	4.4	66.3	0%
1110	35,288	6.4	28.1	4.5	67.3	0%
1111	34,027	4.9	23.3	4.4	67.3	0%
1112	31,917	2.4	6.2	4.1	69.3	0%
1201	26,456	3.1	7.6	3.4	71.2	0%
1202	36,149	7.2	22.5	4.6	65.9	0%
1203	31,570	5.6	11.1	4.0	66.3	0%
1204	31,270	4.2	6.9	4.0	65.1	0%
1205	30,342	6.3	10.1	3.9	63.8	0%
AVE	32,534	6.3	14.4	4.2	66.6	0%

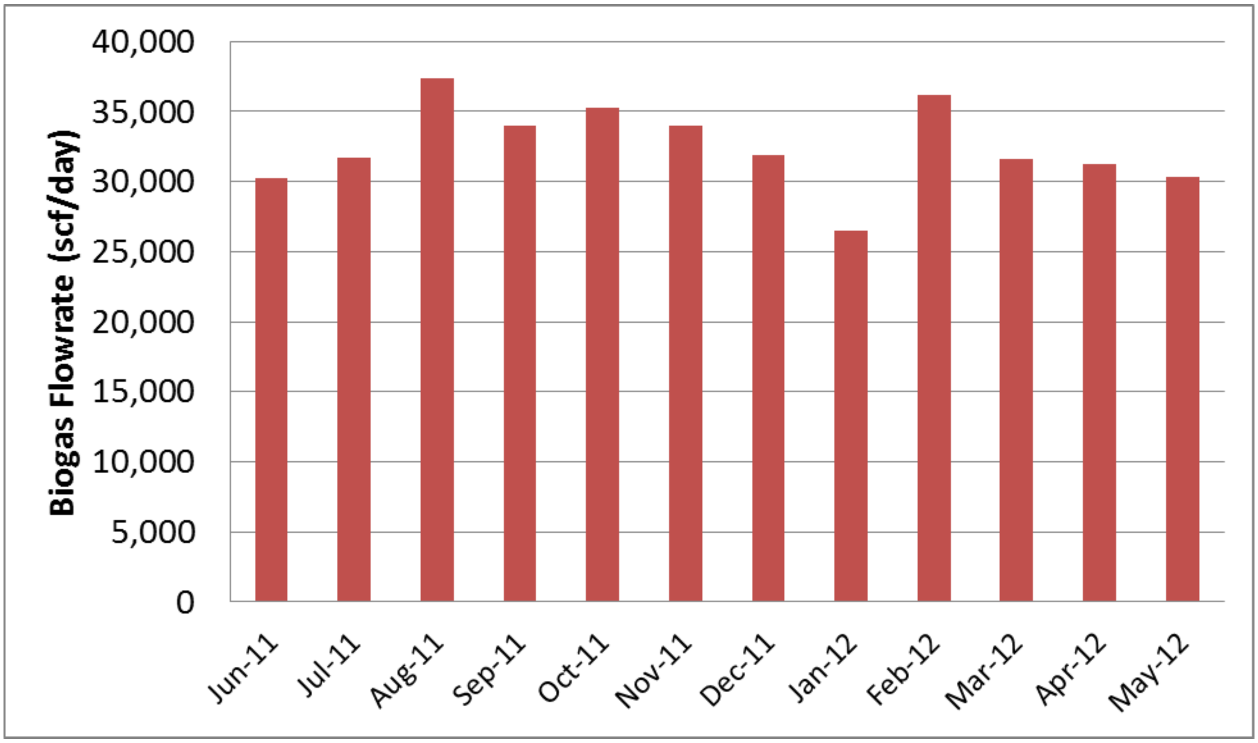

Figure 4.10: Average Daily Biogas Flowrate by Month From the Dairy 2 Digester System. All Captured Biogas Was Delivered to the Engine Generator System.

The composition of the biogas was monitored throughout the study during monthly sampling and analysis. These observations are shown in Figure 11. The methane content was consistently 65-71 percent of the biogas (66.6 percent average). Methane appeared to be slightly higher in the winter months although not substantially. The balance of the gas is primarily carbon dioxide (31.6 percent average), the other major gas product of anaerobic digestion. A small amount of nitrogen (1.7 percent average) and oxygen (0.1 percent average) were present in the gas due to an air injection system that puts a small amount of air below the cover to help control sulfur generation from the digester. The hydrogen sulfide content of the biogas was observed to be between 0 and 195 parts per million by volume as shown in Figure 12. More that 50 percent of the observations were showed hydrogen sulfide less than 50 ppmv. This compares favorably to the 2500+ parts per million hydrogen sulfide content observed in the raw biogas from this digester before the air injection system was installed.

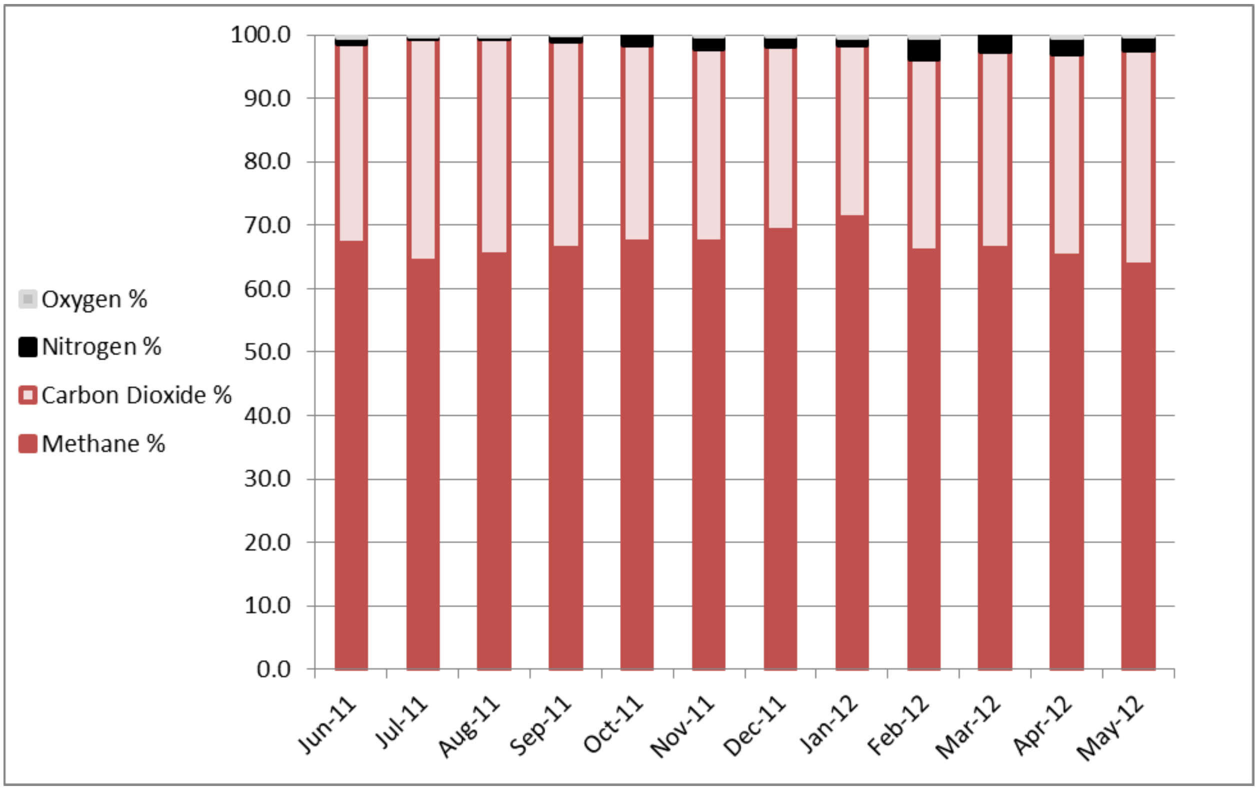

Figure 4.11: Biogas Composition Observed During the Study.

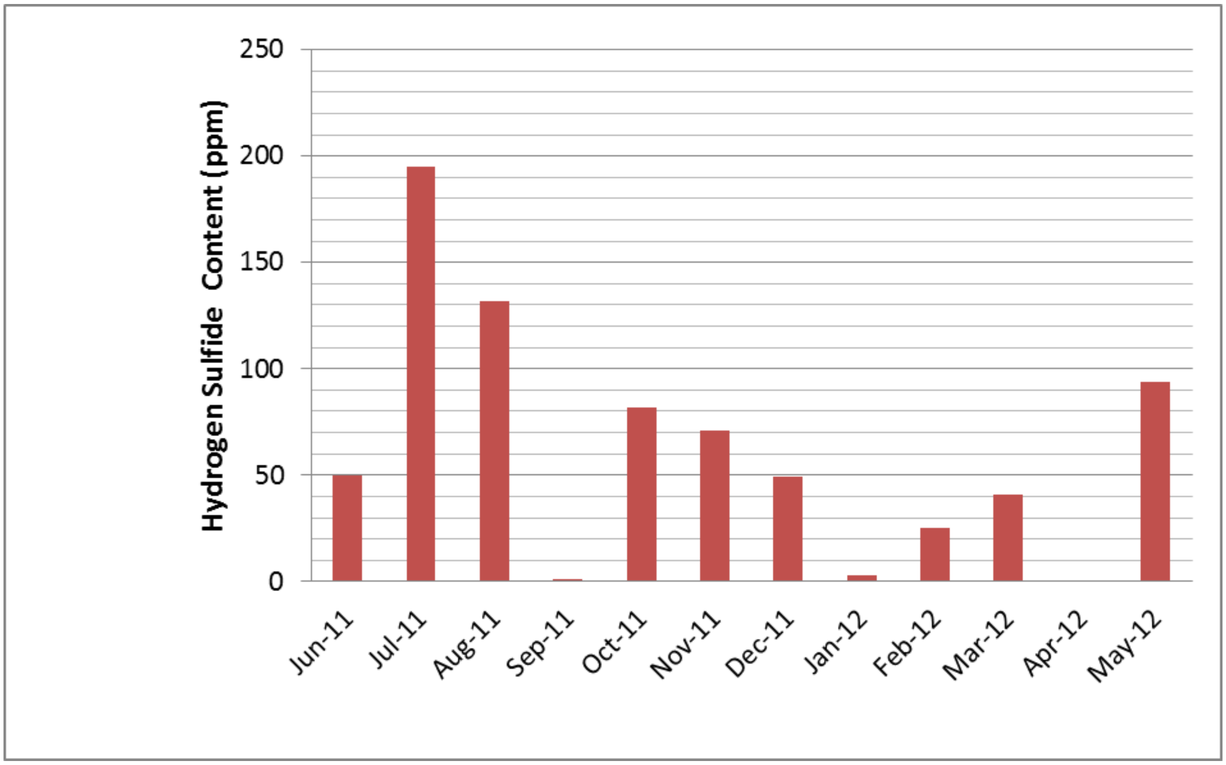

Figure 4.12: Hydrogen Sulfide Concentration in the Biogas Observed During the Study.

Biological methane potential (BMP) was also examined for the digester influent feed to compare the methane production at ideal mesophillic conditions with actual performance of the digester system. In addition, the biomethane potential of the digester effluent was quantified to determine what additional biogas production potential remains after the digestion process. Using the standard BMP test, average biogas production was 6.8 standard cubic feet (SCF) per pound of volatile solids added for the digester feed which compared favorably with the average digester performance of 6.3 SCF per pound of volatile solids added. The biological methane potential was determined to be 4.3 SCF per pound of volatile solids added and 11.2 SCF per pound of volatile solids consumed. The methane potential of the digester effluent was 1.2 SCF per pound of volatile solids showing methane potential for the digestate to be only 28 percent that of the digester feed.

4.3.4 Biogas Generator Performance

The biomass combined heat and power generator performance was observed including the power and heat utilization from the 75-KW engine generator set. Table 9 shows the results. After a small amount of parasitic load from the pump, gas chiller, and engine skid, the amount of output electrical power was an average of 51 kilowatts. The amount of actual heat recovery for use at the dairy and cheese plant was another 49 kilowatts which is equivalent to 1.7 Therms per hour. This is only about half of what was available from the heat recovery system which included both the engine jacket and exhaust heat exchanger. An additional approximately 50 kilowatts of heat was rejected using the radiator system.

The system was run at approximately 68 percent of the system's biogas capacity. The actual online time for the engine generator was 96 percent so the system was consistently set to run at only 75 percent of the nameplate capacity. It is unclear why the system was not run at closer to capacity. The electrical efficiency of the system was observed to be 21 percent with a heat efficiency of 21 percent for an overall combined-heat and power efficiency of 42 percent, on a lower heating value basis. This is below the values reported by the engine manufacturer. This may be due to the parasitic loads or due to a lower electrical efficiency from the lowered engine setpoint. Efficiency is generally optimized at full capacity and drops off at lower heat rates. The heat recovery efficiency was only about half of the available heat because the heat demand did not meet the total production of the system and this heat was rejected by the radiator.

Table 4.9: Engine Generator Performance Observed During the Study.

	BIOGAS CHP PERFORMANCE							
YEAR / MONTH	ELECTRICAL POWER OUTPUT	SPECIFIC POWER OUTPUT	AVERAGE HEAT RECOVERY	SPECIFIC HEAT RECOVERY	CAPACITY FACTOR*	ELECTRICAL EFFICIENCY	HEAT EFFICIENCY	OVERALL CHP EFFICIENCY
(YYMM)	(kW)	(kWh/LB VS ADDED)	(kW)	(kWh/LB VS ADDED)	(%)	(% LHV)	(% LHV)	(% LHV)
1106	47.0	0.21	47.1	0.21	63%	21%	21%	42%
1107	47.4	0.17	45.0	0.16	63%	21%	20%	41%
1108	61.9	0.45	45.7	0.34	83%	23%	17%	40%
1109	52.3	0.48	45.2	0.42	70%	21%	18%	39%
1110	57.3	0.25	46.3	0.20	76%	22%	18%	39%
1111	52.9	0.18	51.4	0.18	71%	21%	20%	41%
1112	49.2	0.09	50.9	0.09	66%	20%	21%	41%
1201	39.1	0.11	43.5	0.12	52%	19%	21%	39%
1202	58.3	0.28	54.7	0.26	78%	22%	21%	43%
1203	47.3	0.20	54.2	0.23	63%	20%	23%	44%
1204	48.8	0.16	53.3	0.17	65%	22%	24%	45%
1205	52.9	0.26	54.9	0.27	71%	25%	26%	50%
AVE	51.2	0.24	49.3	0.22	68%	21%	21%	42%

4.3.5 Mass and Energy Flows

The mass flows throughout the flush dairy system are shown in Table 10 below. It can be seen where volumes of liquids and masses of water, solids, and volatile solids (VS) are removed from the recycled water manure collection and handling system at the dairy. The average daily amounts of fresh water, recycled water, fresh collected manure, and cheese plant wastewater make up the total flush composition. The screw press removes larger fibers and particles from the flush water with a solids removal efficiency of 30 percent before the influent liquid goes into the digester. The digester then converts 50 percent of the volatile solids to produce biogas, further reducing the solids loading on the process water. The effluent from the digester goes into a storage pond where it is recycled as flush water and used to irrigate pasture land around the dairy. Figure 13 is a graphical representation of the average mass, solids, and energy balances for the Dairy 2 Digester system, based on the data collection and analysis from the 12 month study.

Table 4.10: Daily Process Water Volume and Mass Flows.

Process Water/Solids Stream	Liquid Volume (gal/day)	Total Mass (lbs/day)	Solids Conc. (%)	VS Conc. (%TS)	Water Mass (lbs/day)	Solids Mass (lbs/day)	VS Mass (lbs/day)	Solids Removal (%)	VS Removal (%)
Fresh Water	2,000	16,700	-	-	16,700	-	-		
Recycled Flush Water	49,600	413,400	1.0	62.3	409,200	4,300	2,700		
Collected Manure	7,200	59,800	12.5	80.0	52,300	7,500	6,000		
Cheeseplant Wastewater	3,000	25,000	0.8	90.0	24,800	200	200		
Total Flush	61,700	514,900	2.3	73.9	502,900	11,900	8,800		
Screw Press Separator	-	11,000	32.8	71.9	7,400	3,600	2,600	30.2%	29.4%
Digester Influent	60,400	503,900	1.7	73.8	495,500	8,300	6,200		
Digester Effluent	60,000	500,700	1.0	62.3	495,500	5,200	3,200	38.3%	50.2%

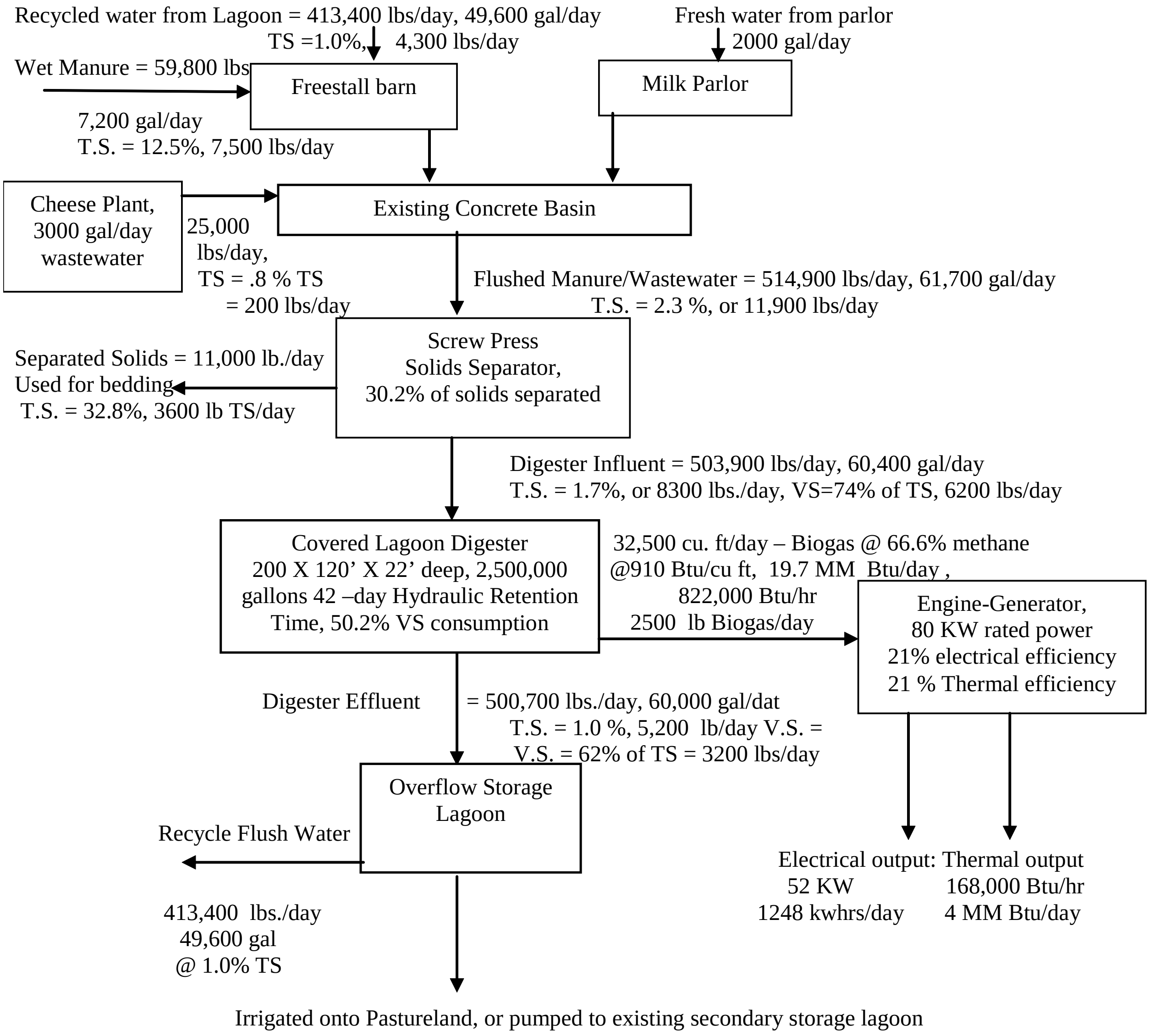

Figure 4.13: Average Mass and Energy Flow Diagram With Daily Flows for Dairy and Digester System.

4.3.6 Climate Change Impact

Using the data collected from the study, the Climate Action Registry Livestock Protocol was used to compute the amount greenhouse gas emissions reductions that have resulted from the digester project. The protocol provides a methodology for quantifying the baseline greenhouse gas emissions and comparing those with the emissions estimated to still be generated from the digester system or biogas control system (BCS) as the digester system is called by the Registry. The baseline emissions are the methane emissions that would have occurred from decomposition of manure in an open lagoon system if the digester was not constructed. The project emissions are from un-burned methane from the engine and digester leakage/venting and methane generated in the effluent storage pond. The difference between the baseline and project emissions are a conservative estimate of the climate impact of the digester system and these could be available to the facility as carbon credits. The results are shown in Table 11.

The results show that the baseline methane emissions of the facility are about 86 tonnes per year. The project methane emissions of the facility are estimated to be 16 tonnes from the BCS and 12 tonnes from the effluent storage pond or 28 tonnes total. The difference is 58 tonnes of methane for a total reduction of 1216 tonnes of carbon dioxide equivalents to the atmosphere. This represents a 68 percent reduction in greenhouse gas emissions associated with manure management at the facility. The is equal to 3.6 tonnes of carbon dioxide equivalents per year for each lactating cow at the facility. Note that the methane reduction is substantially less than the 130 tonnes of methane that is actually destroyed by the engine each year but better represents the climate impact of the digester project than the actual methane destruction.

Table 4.11: Climate Modeling Results for Digester Project Including Estimated Methane Reductions.

	Tonnes CH4 Per Year	*Tonnes CO2e Per Year*
Total Modeled Baseline Methane Emissions	***85.7***	***1801***
Project Methane Emissions from the BCS	16.2	340
Project Methane Emissions from Effluent Pond	11.7	245
Total Project Methane Emissions	***27.9***	***585***
Total Methane Reductions	***57.9***	***1216***
Methane Destroyed in the BCS	130.1	2731

Carbon credits represent a potential source of revenue depending on the value of the credits in the marketplace. Note that there is also a cost in establishing these credits (including monitoring system installation costs, data collection costs, and third-party reporting and verification) and this has been seen to potentially be prohibitive for smaller projects like this one.

4.4 Dairy 2 Conclusions

The project generated results for the annual performance of an un-heated covered lagoon dairy digester system coupled with a cogeneration system for conversion of biogas into power and heat. The following conclusions provide normalized results so that the study of this system can be compared with other digester systems in terms of overall characteristic performance.

DIGESTER FEEDING: The digester influent feed came from a flushed freestall dairy system utilizing recycled water for the flush media with separation of fibrous solids using a screw press separator. The volatile solids collected in the flush system were estimated to consist of 68 percent raw manure solids and bedding, 30 percent recycle water solids, and 2 percent cheese plant wastewater solids. The estimated manure collection rate corrected for the number of animals in confinement was 78 percent. After separation of 30 percent of the solids, the influent had an average total solids concentration of 1.66 percent which consisted of 73.5 percent volatile solids. A more detailed constituent analysis of the digester influent is shown in Table 4.

DIGESTER PERFORMANCE: The project results demonstrate that the un-heated covered lagoon digester having a long hydraulic retention time and low organic loading rate has the capability to accept varying flows and still maintain stable anaerobic digestion. The digester showed consistent volatile solids reduction and gas production over the year. The average hydraulic retention time was 44 days with an organic loading rate of 18.6 pounds of volatile solids per thousand cubic feet per day. Average digester temperature was 80°F. The study showed that the digester reduced total solids by 34 percent, volatile solids by 44 percent, dissolved solids by 20 percent, and chemical oxygen demand by 45 percent during the digestion process. Ammonia nitrogen increased by 34 percent and pH increased from 6.5 to 7.4. There were no other statistically significant changes to the digestate composition within the digester system as shown in Table 7.

BIOGAS PRODUCTION: The digester produced an average of 6.3 cubic feet of biogas per pound of volatile solids added which also equated to 14.4 cubic feet per pound of volatile solids consumed. The composition of the biogas was consistently high in methane at an average of 66.6 percent, but also consisted of 31.6 percent carbon dioxide, 1.7 percent nitrogen, and 0.2 percent oxygen. Hydrogen sulfide content in the biogas was an average of 62 ppmv lowered by an air injection system from original levels of over 2,500 ppmv.

BIOGAS GENERATOR PERFORMANCE: The engine-generator for this project operated at a capacity factor of 68 percent although the actual engine online time was 95 percent meaning the engine generator was typically operated below capacity. The electrical efficiency averaged 21 percent and the recovered heat efficiency was 21 percent for a total combined energy efficiency of 42 percent expressed on a lower heating value basis. The actual efficiency might have been increased by running the generator closer to capacity and increasing the heat utilization. Nearly 50 percent of the available heat from the engine jacket and exhaust was rejected by the radiator.

CLIMATE CHANGE IMPACT: Utilizing the methodology developed for predicting livestock emissions reductions using digesters, it is estimated that the baseline and digester project emissions of methane are 86 and 28 tonnes per year respectively, for a total reduction due to the installation and operation of the digester of 68 percent. This is equates to 915 tonnes of carbon dioxide equivalents per year that could potentially be traded as carbon credits which is about 3.6 tonnes per lactating cow at the dairy.

CHAPTER 5: Dairy 3 Results

5.1 Dairy 3 Background

Dairy 3 is a part of a larger farming, dairy and cheese production business in the Central Valley of California. The dairy is the largest dairy with a digester system in California housing up to 5000 cows and 500 dry cows. This dairy is adjacent to a cheese plant that produces several varieties of cheese and other protein byproducts from the milk produced at Dairy 3 and several other dairy facilities. A covered lagoon anaerobic digester system was installed in 2003 to manage the manure and wastewater that is generated from the dairy and cheese plant and produce renewable power and heat for the facility.

The covered lagoon digester system is a 7-1/2 acre covered lagoon digester located adjacent to the dairy facility which has a capacity for up to 5000 lactating Holstein cows housed in freestall barns, Figure 1. Dry Holstein cows are housed in a dry lot with a flushed feed lane having a capacity for up to 500 dry cows. The flushed manure from the freestall barns flows by gravity to concrete collection troughs along each side of the freestall barn area, Figure 2. The flushed manure then flows to three inclined screen solids separators as shown in Figure 3. , where the fibrous solids are collected and composted for use as bedding and fertilizer. The manure liquids then flow by gravity into the 45-million-gallon lagoon resulting in an approximate 30 to 40-day hydraulic retention time. This covered lagoon, Figure 4, is maintained under anaerobic conditions, and provides favorable conditions for natural microbial action to convert the organic matter in the manure and cheese plant wastewater into over 400,000 cubic feet per day of methane-rich biogas. The effluent from this covered lagoon overflows to an adjacent storage lagoon, Figure 5, and provide valuable fertilizer for the dairy’s field crops. A custom-engineered HDPE system encloses the covered lagoon, captures the biogas, and channels it into a pipeline where it is transported to the co-generation system located adjacent to the cheese plant. The system has a retrofitted- air injection system to reduce hydrogen sulfide in the raw biogas to below 25 ppm.

The gas first passes through the gas conditioning unit, Figure 6, where it is filtered to remove any residual hydrogen sulfide, dried with a chiller-type gas drier, is lightly compressed to be delivered to the prime mover located near the cheese plant. The fuel is delivered to the two engine-generators, Figure 7 that together produce up to 750-kilowatts of synchronous electrical power for 24 hours per day. The electricity generated provides a substantial portion of the electrical requirements of the cheese plant through a net metering interconnection agreement with PG&E. The heat from the generator engines is captured via an exhaust gas boiler Figure 8 and used to produce process steam for the cheese plant, and pre-heat air for the whey drier.

Figure 5.1: Freestall Flush Lane.

Figure 5.2: Concrete Manure Flush Troughs.

Figure 5.3: Inclined Screen Solids Separator.

Figure 5.4: Covered Lagoon Digester.

Figure 5.5: Overflow Storage Lagoon.

Figure 5.6: Gas Handling System.

Figure 5.7: 325 KW Engine-Generator.

Figure 5.8: 425 KW Engine-Generator with Exhaust Steam Boiler.

Table 5.1: Dairy 3 Digester System Description.

Digester	Covered lagoon digester, 45 Million gallon capacity Unheated and unmixed HDPE cover Fibrous solids separation before digestion
Engine-Generators	Two Synchronous Engine-Generators: 1. Caterpillar G3412 TA, 325 kW capacity on biogas, 440 VAC, 3 phase, rich-burn 2. Caterpillar G399, 425 kW capacity on biogas, 440 V, 3-Phase, rich-burn Manufacturer estimated 28% LHV shaft efficiency
Biogas Treatment	Air injection system under digester cover Iron sponge-type H2S Scrubber Biogas chiller for "dewatering"
Heat Recovery	Preheat hot water steam boiler, exhaust steam boilers provide steam for cheese plant. Back-up radiator systems, one radiator provides preheated air for whey drier Jacket and exhaust heat exchangers

The flare combusts excess biogas not consumed by the engine-generators, based on a manual setting of the blower feeding the flare. If the engine-generator(s) are shut off the blower output can be manually increased to the flare so that it destroys all the unused biogas.

Figure 9 schematically shows the overall biogas and power generation systems. Biogas from the digester is used in the engine or flared. The hot water leaving the engine jacket and the steam leaving the exhaust boiler are used to provide useful heating for the cheese making process. The hot air exiting one of the remote radiators provides preheated air for the whey drier.

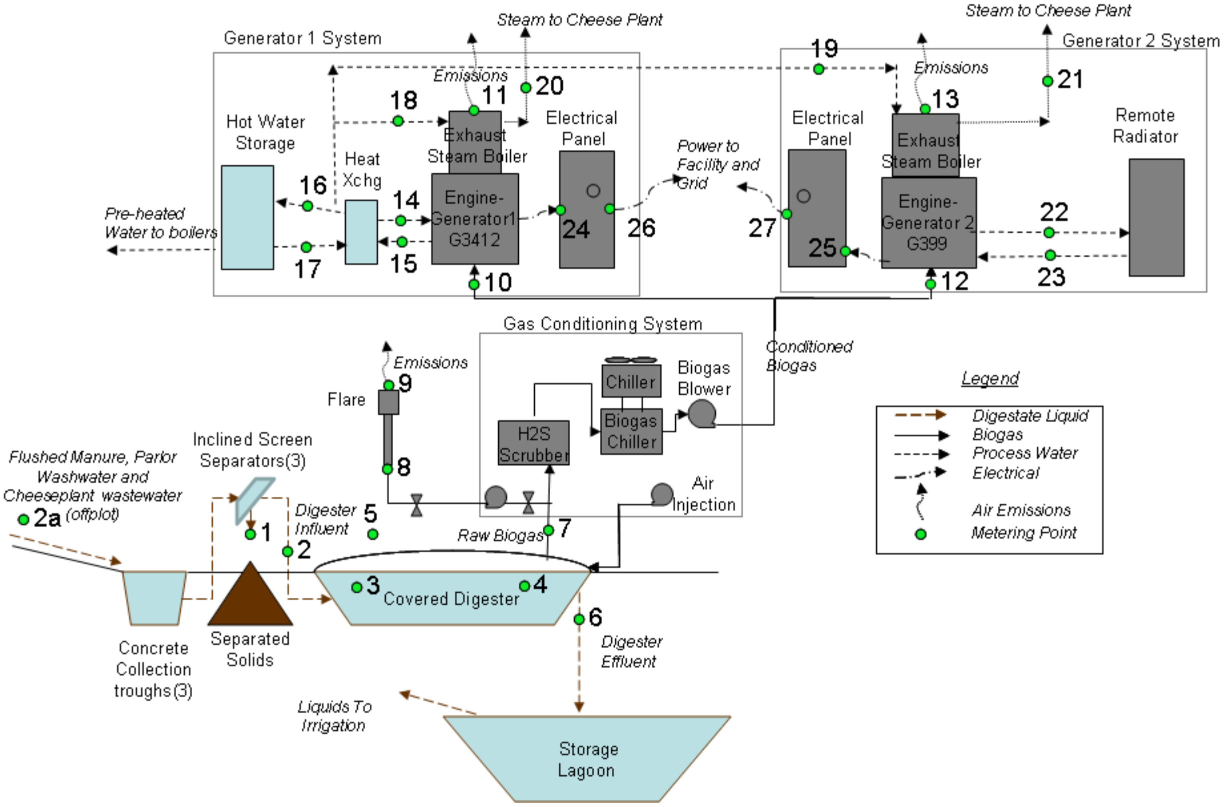

Figure 5.9: Schematic of Biogas System with Metering Points.

5.2 Dairy 3 Materials and Methods

The monitoring methodology and system followed protocols developed by ASERTTI, Climate Action Registry, and US EPA. Continuous sensors monitored pertinent system flows and conditions including those shown in Table 2. This data was recorded in data logger equipment and 15-minute averages were continuously logged and transmitted via the internet to a central system maintained by the investigators. Sampling locations are shown on the schematic in Figure 7. These sampling points cover all pertinent manure, biogas, power and process water flows and temperatures. Composition samples (24-hour aggregated) were taken on a monthly basis to establish the mass distribution for each flow of manure, biogas and emissions.

The monitoring system supplied by Summers Consulting was configured to capture the data points listed in Table 2. The sensors were sampled at 1-minute intervals and averaged or summed into 15-minute data as appropriate. The PLC-based system provided the investigators and CEC access to the time-stamped 15-minute data via the internet. The on-site controller had the ability to store and retain several hundred days of 15-minute data in the event that communications were lost.

The electrical output of the engine-generators (WGO1, 2) were measured with a Gen-Tec power transducer already installed in the engine control panel. The net power exported to the grid was supplied by the existing PG&E metering (WNT1, 2).

The biogas delivered to the engines (FGE1, 2) was measured by a Sage gas flow meter (hot-wire probe) that determined the mass flow in standard cubic feet per minute. In addition a Sage meter measured biogas flow to the flare (FGF). The total biogas flow (FGT) was the sum of FGE and FGF. From the biogas and power measurements the engine efficiency was calculated using the measured gas composition data. The gas flows also allowed for an estimate of emissions from the engines (FEE1, 2) and the flare (FEF) using standard combustion assumptions and monthly measurement of exhaust composition.

The digester temperatures (TMI, TME, TD1 and TD2) were measured by thermocouples at the influent and effluent pipes and placed in the two vent pipes on the cover of the digester. The ambient temperature (TAO) was recorded to understand how digester performance varied with weather conditions.

Table 5.2: Monitoring Points on the Dairy 3 Digester System. Metering Locations Shown Figure 5.9.

Loc #	Data Point	Description	Eng. Units	Sensor or Instrument	Typical Range
1	FMS	Flow of Manure Solids	lb/day	Monthly weight est.	NA
	CMS	Composition of Manure Solids	% by wt.	Quarterly samples	18-25% TS
2	FMI	Flow of Manure, Influent to Digester	Gal/day	Ultrasonic Flowmeter	600,000-1,300,000
	TMI	Temperature of Manure, Influent to Digester	°F	Type-K TC, 6 in probe	50-90
	CMI	Composition of Manure, Influent to Digester	mg/l	Monthly samples, 24h	3,500 – 5,300 TS
2a	FCW	Flow of Cheese plant Wastewater	Gal/day	Estimated By Volume	0 - 500,000
	CCW	Composition of Cheese plant Wastewater	mg/l	Monthly samples, 24h	NA
3	TD1	Temperature of Digester at Vent Valve 1	°F	Type-K TC, 72 in depth	60-90
4	TD2	Temperature of Digester at Vent Valve 2	°F	Type-K TC, 72 in depth	60-90
5	TAO	Temperature of Ambient Out	°F	Type-K TC, near digester	30-110
6	FME	Flow of Manure, Effluent from Digester	Gal/day	Estimated from FMI	=FMI
	TME	Temperature of Manure, Effluent from Digester	°F	Not Installed	= TD2
	CME	Composition of Manure, Effluent to Digester	mg/l	Monthly samples, 24h	3,000 – 15,000
7	FGT	Flow of Gas Total (Raw Biogas)	SCF/day	Estimated from FGE & FGF	450,000-550,000
	CGT	Composition of Gas Total (Raw Biogas)	% by vol.	Monthly analysis	[1]
8	FGF	Flow of Gas to Flare (Raw Biogas)	SCF/day	Sage Prime SIP	100,000-250,000
	CGF	Composition of Gas to Flare (Raw Biogas)	% by vol.	Monthly analysis	63-71% CH4
9	FEF	Flow of Emissions from Flare	SCF/day	Estimated from FGF	=FGF*CF
	CEF	Composition of Emissions from Flare	% or ppm	Estimated from EF's	5% O2
10	FGE1	Flow of Gas to Engine 1	SCF/day	Sage Prime SIP	120,000
	CGF1	Composition of Gas to Engine 1 (Conditioned Biogas)	% by vol.	Monthly analysis	63-71% CH4
11	FEE1	Flow of Emissions from Engine 1	SCF/day	Estimated from FGE and CEF	=FGE1*CF
	CEE1	Composition of Emissions from Engine 1	% or ppm	Monthly analysis	>1% O2

Loc #	Data Point	Description	Eng. Units	Sensor or Instrument	Typical Range
12	FGE2	Flow of Gas to Engine 2	SCF/day	Sage Prime SIP	230,000
	CGF2	Composition of Gas to Engine 2	% by vol.	Same as CGF1	63-71% CH4
13	FEE2	Flow of Emissions from Engine 2	SCF/day	Estimated from FGE and CEF	=FGE2*CF
	CEE2	Composition of Emissions from Engine 2	% or ppm	Monthly analysis	>1% O2
14	TCI 1	Temperature of Coolant, Inlet to Engine 1, (Jacket and Exhaust Coolant)	°F	Not Required	NA
15	TCO 1	Temperature of Coolant, Outlet of Engine 1 (Between Jacket and Exhaust)	°F	Not Required	NA
16	TPO1	Process Water Temperature out of Engine 1 Jacket Heat Exchanger	F	Type-K TC, 6 in probe	147-180
17	TPI1	Temperature of Process Water Inlet (Process Water into Heat Exchanger)	°F	Type-K TC, 6 in probe	116-166
	FPI1	Flow of Process Water Inlet (Process Water into Heat Exchanger)	gpm	Onicon F1100	22-25
18	FSE1	Flow of Steam Process Water into Engine 1 Exhaust Steam Boiler	gpm	Onicon F1100	0-2
19	FSE2	Flow of Steam Process Water into Engine 2 Exhaust Steam Boiler	gpm	Onicon F1100	0-2
20	PSE1	Steam Pressure, from Engine 1 Exhaust Steam Boiler to Cheese plant	psi	Pressure transducer	0-150
21	PSE2	Steam Pressure, from Engine 2 Exhaust Steam Boiler to Cheese plant	psi	Pressure transducer	=PSE1
23	TCO2	Temperature of Coolant, Outlet of Engine 1 (Between Jacket and Exhaust)	°F	Not Required	NA
24	TCI2	Temperature of Coolant, Inlet to Engine 1, (Jacket and Exhaust Coolant)	°F	Not Required	NA
	FCI2	Jacket Coolant Flow, from Remote Radiator back to Engine 2	gpm	Not Required	NA
25	WGO1	Watts of Generator 1 Output (Power at Generator)	kW	Gen-Tec power meter	295-320
26	WNT1	Watts of Net Total 1(Power after Parasitic Loads for Generator)	kW	PG&E meter - pulse	285-300
27	WGO2	Watts of Generator 2 Output (Power at Generator)	kW	Gen-Tec power meter	371-420
28	WNT2	Watts of Net Total 2 (Power after Parasitic Loads for Generator)	kWh	PG&E meter - pulse	360-410

The flow of manure into the digester (FMI) was measured with existing ultrasonic flow meters. It was assumed that influent and effluent flow are approximately balanced, therefore FMO was estimated to be equal to FMI. The flow of manure solids was measured monthly by estimating the volume of solids separated by the three inclined screen separators over a 24-hour period.

The thermal output recovered from Engine 1 jacket to the heat exchanger and then to the steam boilers was determined from the coolant flow and temperature difference data (FC1, 2, TCI1, 2, TCO1, 2). The thermal energy actually utilized for process water heating was determined from the process water flow and temperature difference data (FPI1, TPI1, TPO1). Steam energy utilization was determined by the feed water flows into the exhaust steam boilers and the pressures of the output steam (FSE1, FSE2, PSE1, PSE2)

The parasitic power consumption of various components in the system was determined by power readings with a hand-held meter capable of measuring true power. The sum of all parasitic loads not accounted for in the net metering was compared with the power generated by the system.

The composition of the manure influent and effluent was measured on a monthly basis using a 24-hour aggregated sample that was laboratory-analyzed for the analytes described in Appendix A. The composition of the biogas was measured using a GEM™2000 Portable Gas Analyzer from Landtec on a monthly basis. This sampling included raw and conditioned biogas. The portable meter was used to determine the percentage of CH_4, CO_2, O_2, H_2S and balance gas on a monthly basis. The emissions from the engine were measured using a Testo 350XL portable analyzer. The metering equipment was calibrated on a routine basis and the estimated accuracy is shown in Appendix A.

Periodic samples of the influent to the digester were subjected to a Biochemical Methane Potential (BMP) analysis in a specially-designed apparatus in the Summers Consulting laboratory. BMP analysis is an efficient and economical method for evaluating the rate and extent of biomass conversion to methane under anaerobic conditions.

Also on a quarterly basis, samples were taken of the fresh well water and flush water (cheese plant wash water) and analyzed using the applicable methods in Appendix A – Table A1. This allowed for a more complete mass flow accounting throughout the manure collection system. In addition, on a quarterly basis, the solids separated from before the digester were analyzed according to the analyses in Appendix A - Table A2.

5.3 Dairy 3 Results and Analysis

The following sections summarize the monitoring results of this year-long monitoring campaign and provide annual operational factors including digester feeding, digester performance, biogas production, biogas generator performance, and climate change impact. The digester monitoring system for Dairy 3 was designed in 2010 and installation was completed in early 2011. The monthly sampling was initiated in July of 2011 and completed by July of 2012. The actual cow and heifer numbers during the data collection period are shown in Table 3 along with the estimated daily manure production as predicted by typical estimation method from ASABE.

Table 5.3: Dairy Herd Size Characteristics and Estimated Manure Production at Dairy 3.

DAIRY HERD			ESTIMATED MANURE PRODUCTION[5.]	
	HEAD (#)	WEIGHT (LB/HEAD)	VOLATILE SOLIDS (LB/HEAD/DAY)	TOTAL VOLATILE SOLIDS (LB/DAY)
Milk Cows	3,174	1,499	17.0	53,958
Dry Cows	359	1,508	9.2	3,303
Heifers	0	897	7.1	0
			TotalManure Volatile Solids	57,261

5.3.1 Digester Feeding

The rate of influent feeding of the digester averaged just under 1.3 million gallons per day over the entire year, with variations monthly from approximately one million to over 1.4 million

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[5] ASABE Standard No. D384.2, Manure Production and Characteristics, March 2005.

gallons per day. Figure 10 shows the average digester influent flows for each month of the study year. The cheese plant wastewater was a substantial contributor to this influent, amounting to approximately 500,000 gallons per day.

The results for the monthly solids composition of the influent mixture is shown in Figure 11. Total solids concentration ranged from 3400 to 5300 milligrams per liter with an average of 4400 milligrams per liter. Volatile solids ranged from 2,200 to 4,300 milligrams per liter with an average of 3,300 milligrams per liter. The volatile solids were from 64 to 81 percent of the total solids. The variability seen in these samples can also be attributed to variable system flows and the limitations of taking a single aggregated grab sample to represent an entire month of flow. The aggregation of all of the samples taken over the year is a better representation of the typical influent composition and for comparison with effluent samples. Table 4 shows the annual average and standard deviation for all of the samples taken over the year for constituents of the influent.

Using pile size estimates and monthly moisture and density samples, it was determined that about 19 percent of the total solids in the manure stream or about 11,900 pounds of total solids per day are removed by the solid separator before the digestion process. These separated solids can be valuable as a composted bed material or for use in farming or horticultural soil amendment. Table 5 shows the typical composition of these separated solids.

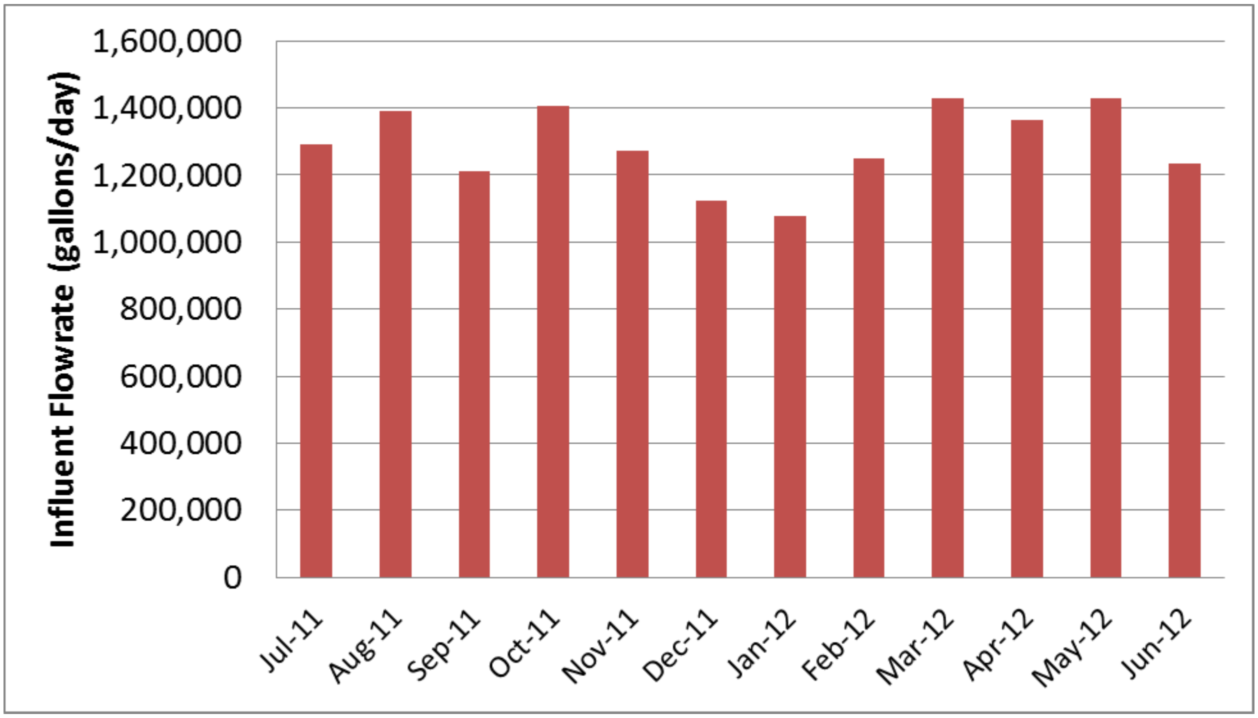

Figure 5.10: Average Monthly Influent Flow Rate to the Digester System.

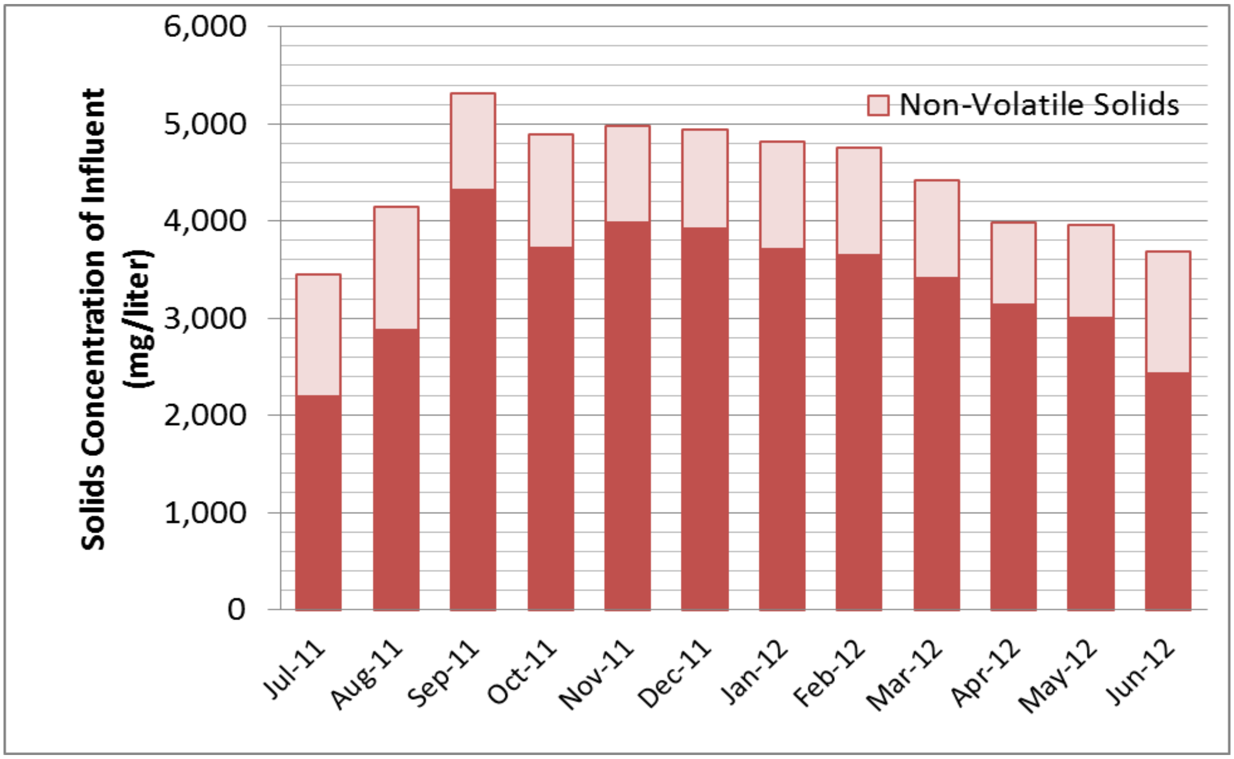

Figure 5.11: Total Solids Concentration of Digester Influent With Volatile and Non-Volatile Fractions.

Table 5.4: Composition of Various Constituents of the Digester Influent. Average and Standard Deviation of the Monthly Samples Taken Over the Study Year.

Analyte	Units	Method	Average	St Dev
Total Solids	mg/L	SM 2540B	4,316	873
Volatile Solids	mg/L	EPA 160.4	3,306	1,023
Total Dissolved Solids	mg/L	SM 2540 C	2,790	473
Chemical Oxygen Demand	mg/L	SM 5220D	5,171	783
Specific Conductance	µS/cm	SM 2540B	3.1	0.7
Ammonia-N	mg/L	SM 4500	82	20
Ammonium-N	mg/L	SM 4500G	0.3	0.3
Nitrate-Nitrogen	mg/L	EPA 300.0	2.7	3.3
Total Nitrogen	mg/L	EPA 351.2	218	52
Total Phosphorus	mg/L	SM 4500P B	71	12
Total Potassium	mg/L	SM 3120 B	265	48
Total Sulfur	mg/L	SM 3120 B	36	19
Total Clorine	mg/L	SM 3120 B	159	221
Total Calcium	mg/L	SM 3120 B	83	83
Total Magnesium	mg/L	SM 3120 B	31	5
Total Sodium	mg/L	SM 3120 B	268	3

Table 5.5: Composition of Various Constituents of the Separated Solids. Average and Standard Deviation of the Quarterly Samples Taken Over the Study Year.

Analyte	Units	TMECCMethod	Average	St Dev
Dry Matter (eq TS)	Wt %	03.09-A	18.50	2.69
Organic Matter (eq VS)	Wt %	05.07-A	17.25	2.27
Total Nitrogen	Wt %	04.02-D	0.233	0.055
Total Phosphorus	Wt %	04.03-A	0.033	0.015
Total Potassium	Wt %	04.04-A	0.067	0.031
Sodium	Wt %	04.05-Na	0.027	0.006
Calcium	Wt %	04.05-Ca	0.110	0.044
Magnesium	Wt %	04.05-Mg	0.040	0.026
Iron	mg/kg	04.05-Fe	142	64
Copper	mg/kg	04.07-Cu	5.1	3.6
Manganese	mg/kg	04.05-Mn	10.4	8.0
Zinc	mg/kg	04.05-Zn	8.5	3.4
Sulfur	Wt %	04.05-S	0.027	0.012

5.3.2 Digester Performance

The digester was fed a daily dose of volatile solids from the manure and cheese-plant wastewater throughout the study, the fuel or food for the anaerobic digestion process. The average amount of volatile solids loaded into the digester was 36,000 pounds per day although there was some variability due to real variations in operations and due to the measurement limitations discussed above. The measured loading of the digester can be seen in Table 6 – Digester Feeding.

The pattern of influent solids rates were lower in the summer when the cows were not confined to the freestalls and allowed to be in the drylot area part of the day, and higher in the winter when the cows were confined to the freestalls. The project results showed that covered lagoon digesters having reasonably long HRT's and low organic loading rates have the capability to maintain stable anaerobic digestion as evidenced by the volatile solids consumption averaging over 60 percent shown in the Digester Performance Table 6. The overall average of 36,000 lb VS/day consisted of not only manure volatile solids but also cheese wastewater VS. The cheese waste VS comprise half the total VS (18,000 lb VS cheese wastewater VS versus 36,000 lb total VS, Table 7). The net amount of VS from the cows at Dairy 3 averaged approximately 18,000 lb VS/day, which compares with the estimated total volatile solids production from the herd size shown in Table 6 is over 57,000 lb VS/day; therefore this indicates a collection rate of approximately 32 percent. This low collection rate is due mainly to the amount of time the cows spend on the large drylot areas adjacent to the flush lanes. The average daily organic loading rate of 6 pounds of volatile solids per thousand cubic feet is less than the recommended loading rate of 10 pounds of volatile solids per thousand cubic feet. The 35 day average hydraulic retention time was somewhat less than the recommended HRT of 40 to 45 days for this type of lagoon digester. The digester temperature varied from 70 to 90 degrees Fahrenheit on a seasonal basis but these temperatures are sufficient to maintain mesophillic anaerobic activity.

Table 5.6: Digester Influent Feeding and Performance Parameters.

	DIGESTER FEEDING				DIGESTER PERFORMANCE			
YEAR / MONTH	INFLUENT FLOWRATE	TOTAL SOLIDS CONC.	VOLATILE SOLIDS CONC.	INFLUENT VOLATILE SOLIDS	AVERAGE DIGESTER TEMP	ORGANIC LOADING RATE	HYDRAULIC RETENTION TIME	VOLATALE SOLIDS CONSUMPTION
(YYMM)	(GAL/DAY)	(%)	(% TS)	(LBS /DAY)	(DEG F)	(LB VS /1000 CF/DAY)	(DAY)	(%)
1107	1,289,992	0.34	63.6	23,592	NA	3.9	34.9	62.5
1108	1,390,596	0.41	69.6	33,444	91.1	5.6	32.4	71.4
1109	1,209,605	0.53	81.3	43,597	89.5	7.2	37.2	78.1
1110	1,407,275	0.49	76.1	43,711	84.2	7.3	32.0	71.9
1111	1,272,152	0.50	80.1	42,262	75.7	7.0	35.4	66.3
1112	1,124,165	0.49	79.3	36,752	71.1	6.1	40.0	63.6
1201	1,077,598	0.48	77.0	33,342	70.5	5.5	41.8	61.3
1202	1,249,624	0.48	76.8	38,017	73.6	6.3	36.0	58.1
1203	1,430,007	0.44	77.1	40,671	75.9	6.8	31.5	54.1
1204	1,364,136	0.40	78.7	35,669	80.2	5.9	33.0	46.9
1205	1,430,334	0.40	75.8	35,796	86.3	6.0	31.5	50.6
1206	1,234,416	0.37	65.9	25,017	89.4	4.2	36.5	55.8
AVE	1,289,992	0.44	75.1	35,989	80.7	6.0	35.2	61.7

Table 5.7: Cheese Plant Wastewater Solids Characteristics and Flow.

YEAR / MONTH (YYMM)	TOTAL SOLIDS CONC. (%)	VOLATILE SOLIDS CONC. (% TS)	VOLATILE SOLIDS FLOW (lbs/day)
1107	0.47	76.72	15,081
1108	0.46	76.52	14,634
1109	0.51	75.31	16,095
1110	0.54	75.39	16,885
1111	0.62	79.87	20,559
1112	0.64	85.38	22,749
1201	0.63	84.59	22,343
1202	0.67	81.58	22,654
1203	0.53	80.07	17,827
1204	0.43	83.28	15,072
1205	0.56	86.01	20,198
1206	0.60	80.49	20,038
AVERAGE	0.56	80.43	18,678

Consumption, conversion, and accumulation of the wastewater constituents within the digestion system are of interest and were analyzed by looking at the difference between the influent and effluent compositions (Table 8). Statistical analysis was applied to the data observations to determine if there was a statistically significant difference between the influent and the effluent compositions. A two-tailed pair-wise Student's T-test was applied to the data sets for the influent and effluent composition. The null hypothesis is rejected for alpha was less than 0.05, meaning that for p-values less than 0.05, we conclude that there is a statistically significant difference between the influent and the effluent composition and that some conversion occurred within the digester.

The observed averages for composition of influent and effluent are shown in Table 8 along with the percentage difference observed with a bold negative value meaning a reduced concentration after digestion and a bold positive value meaning an increased concentration. The differences that are statistically significant are shown in bold including Total Solids, Volatile Solids, Total Dissolved Solids, Carbon Oxygen Demand, Specific Conductance, and Ammonia-Nitrogen. Solids and Oxygen Demand are reduced as expected and Conductance and Ammonia increase.

Table 5.8: Differences Between Influent and Effluent Compositions Observed During the Study Period.

Analyte	Units	Method	Influent	Effluent	Difference	P-Value
Total Solids	mg/L	SM 2540B	4,316	2,431	**-43.7%**	**0.00019**
Volatile Solids	mg/L	EPA 160.4	3,306	1,210	**-63.4%**	**0.00013**
Total Dissolved Solids	mg/L	SM 2540 C	2,790	2,064	**-26.0%**	**0.00229**
Chemical Oxygen Demand	mg/L	SM 5220D	5,171	716	**-86.2%**	**0.00000**
Specific Conductance	µS/cm	SM 2540B	3.0	4.3	**36.4%**	**0.00001**
Ammonia-N	mg/L	SM 4500	82	185	**125.1%**	**0.00000**
Ammonium-N	mg/L	SM 4500G	0.25	0.25	0.0%	NA
Nitrate-Nitrogen	mg/L	EPA 300.0	2.7	0.7	-75.6%	0.0682
Total Nitrogen	mg/L	EPA 351.2	218	221	1.6%	0.2165
Total Phosphorus	mg/L	SM 4500P B	71	81	15.1%	0.1007
Total Potassium	mg/L	SM 3120 B	265	276	4.0%	0.3228
Total Sulfur	mg/L	SM 3120 B	36	20	-44.7%	0.0778
Total Clorine	mg/L	SM 3120 B	293	317	99.2%	0.3180
Total Calcium	mg/L	SM 3120 B	83	109	31.2%	0.2822
Total Magnesium	mg/L	SM 3120 B	31	39	26.1%	0.2836
Total Sodium	mg/L	SM 3120 B	268	253	-5.8%	0.9683

All other constituents do not show statistically significant differences (non-bold results) between influent and effluent. These results do not contradict the assumption that nutrients are conserved in the digestate during anaerobic process while volatile solids are consumed, although they may be converted in form. For example, although ammonia nitrogen increases during the digestion process, the total nitrogen difference between inlet and outlet of the digester was not statistically significant.

The mass and energy flow diagram in Figure 15 illustrates how water and solids and energy are transported and converted in the system. One significant feature to note is that a significant portion of the influent is cheese wastewater that contributes one-half of the volatile solids loading to the digester. Overall, the measurement effort carried out resulted in an accurate quantification of the system flows as evidenced by the good closure on mass and energy balances for the system.

5.3.3 Biogas Production

The average specific biogas production for both added and consumed volatile solids are estimated in Table 8. The average value of 12.3 cubic feet per pound of volatile solids added is much higher than reported yields of 6 to 8 cubic feet per pound from successful and stable dairy manure digesters (USEPA AgSTAR)[6]. This high biogas yield is believed to be due to the rather large fraction of volatile solids that are contained in the cheese plant wastewater, shown in Table 7 to be over 18,000 lb VS/day compared with the total VS of 36,000 lb VS/day in the influent. The cheese wastewater VS consist mainly of lactose sugars and are more soluble than the manure VS; therefore the cheese wastewater yields more biogas/lb VS than the manure VS.

The daily biogas delivered to the engine was very consistent throughout the study with a daily average production of almost 450,000 cubic feet per day with little monthly variation throughout the study time period as shown in Table 9 and Figure 12. The system collects data on the biogas that is delivered to the engine or the flare but may not account to any leakage of biogas from the cover or other systems. It should be noted that the inflation of the cover of the digester can store several days' worth of biogas so it tends to buffer any inconsistencies between biogas production and engine generator operation. By observation of the relative cover inflation, the system operator can adjust the generator set point to consume all of the gas being produced. It is unlikely that a significant amount of gas escapes the system, except during the summer when more gas production and higher temperatures causing low gas densities resulted in occasional escape of the gas through the vent valves on the digester cover.

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[6] EPA. 2012. *Operating Anaerobic Digester Projects*: U.S. Environmental Protection Agency. http://www.epa.gov/agstar/projects/index.html

Table 5.9: Biogas Production Parameters Observed From the Digester System.

	BIOGAS PRODUCTION					
YEAR / MONTH	TOTAL BIOGAS	SPECIFIC BIOGAS	SPECIFIC BIOGAS	SPECIFIC BIOGAS	METHANE	PERCENT FLARED BIOGAS
(YYMM)	(SCFD)	(SCF/LB VS ADDED)	(SCF/LB VS CONSUMP)	(SCF/LB VS EXCRETED)	(VOL %)	(%)
1107	456,660	19.4	31.0	8.0	66.1	22%
1108	499,321	14.9	20.9	8.7	70.9	23%
1109	472,952	10.8	13.9	8.3	70.5	21%
1110	481,810	11.0	15.3	8.4	67.2	21%
1111	428,912	10.1	15.3	7.5	68.6	24%
1112	495,113	13.5	21.2	8.6	70.1	12%
1201	384,927	11.5	18.8	6.7	71.3	21%
1202	523,056	13.8	23.7	9.1	67.9	13%
1203	341,663	8.4	15.5	6.0	65.0	21%
1204	439,386	12.3	26.3	7.7	64.1	9%
1205	442,179	12.4	24.4	7.7	63.2	16%
1206	424,599	17.0	30.4	7.4	66.5	4%
AVERAGE	449,215	12.9	21.4	7.8	67.6	17%

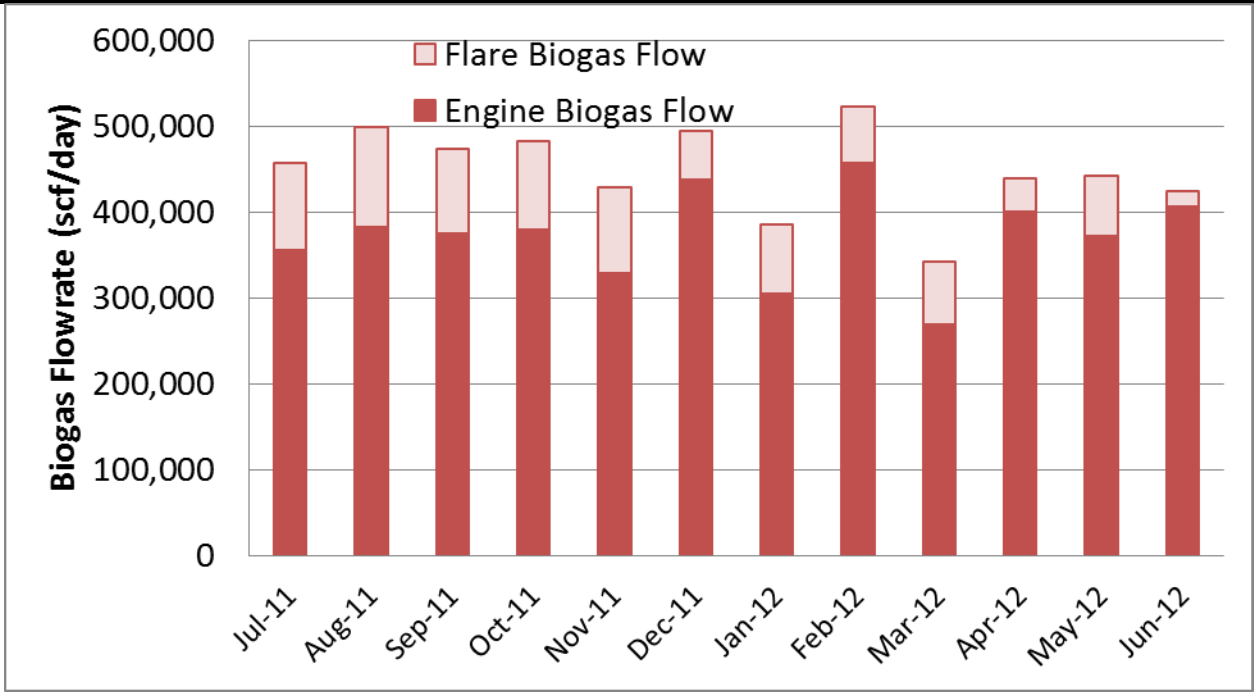

Figure 5.12: Average Daily Biogas Flow Rate by Month From the Digester System, Showing Proportion of Gas Utilized in the Engine and That Flared.

The composition of the biogas was monitored throughout the study during monthly sampling and analysis. These observations are shown in Figure 13. The methane content was consistently 63-71 percent of the biogas (67.6 percent average). The balance of the gas is primarily carbon dioxide (30.9 percent average), the other major gas product of anaerobic digestion. A small amount of nitrogen (0.1 percent average) and oxygen (1.4 percent average) were present in the gas due to an air injection system that puts a small amount of air below the cover to help control sulfur generation from the digester. The hydrogen sulfide content of the biogas was observed to be between 0 and 68 parts per million by volume as shown in Figure 14, and averaged under 20 ppmv. More that 90 percent of the observations were showed hydrogen sulfide less than 50 ppmv. This compares favorably to the 2000 to 3000 parts per million hydrogen sulfide content observed in the raw biogas from this digester before the air injection system was installed. In addition to the air injection, a polishing iron sponge filter is installed before the engine to ensure the H_2S levels are kept low as mandated by the Regional Air Quality Authority.

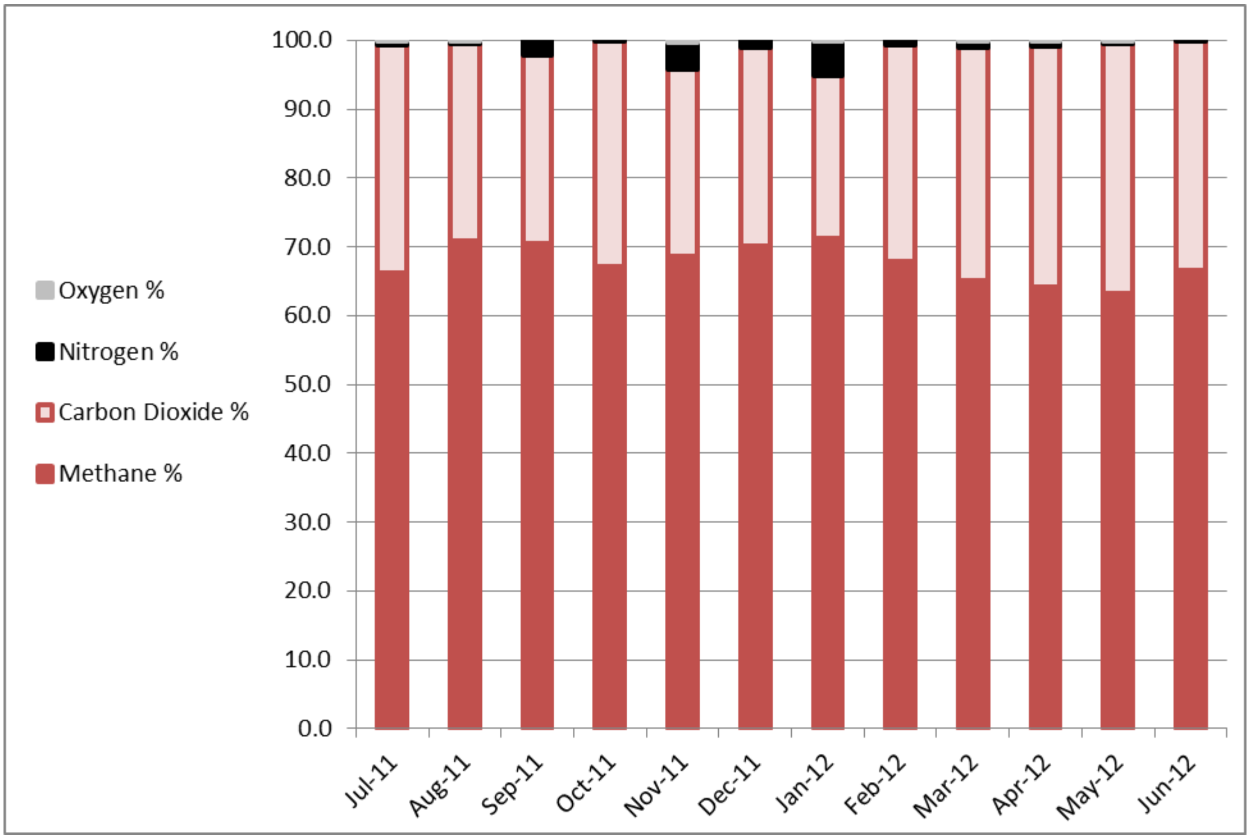

Figure 5.13: Biogas Composition Observed During the Study.

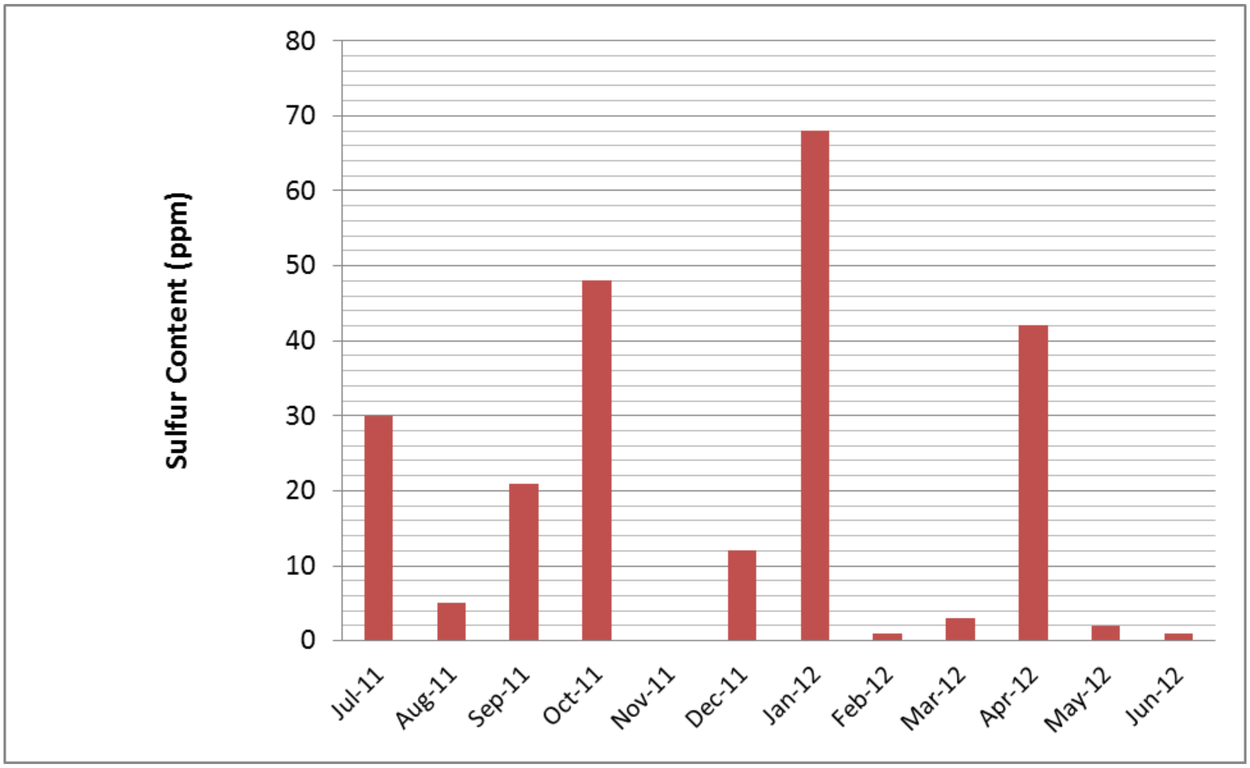

Figure 5.14: Hydrogen Sulfide Concentration in the Biogas Observed During the Study.

Biological methane potential (BMP) was also examined for the digester influent feed to compare the methane production at ideal mesophillic conditions with actual performance of the digester system. In addition, the biomethane potential of the digester effluent was quantified to determine what additional biogas production potential remains after the digestion process. Using the standard 30-Day BMP test, average biogas production was 10.8 standard cubic feet (SCF) per pound of volatile solids added for the digester feed water which was close but somewhat less than the average observed digester performance of 12.9 SCF per pound of volatile solids added. The BMP tests also showed an average of 19.3 SCF per pound of volatile solids consumed in the test which was comparable to the 21.4 SCF per pound consumed estimated in the field observations. The biological methane potential was determined to be 7.2 SCF per pound of volatile solids added and 12.7 SCF per pound of volatile solids consumed. The methane potential of the residual digester effluent was only 0.9 SCF per pound of volatile solids added showing the methane potential of the digested volatile solids to only be 13 percent that of the digester feed.

5.3.4 Biogas Generator Performance

The biogas combined heat and power generator performance was observed including the power and heat utilization from the 750-KW total capacity engine generator system. Table 10 shows the results. After a small amount of parasitic load from the pump, gas chiller, and engine skid, the amount of output electrical power was an average of 677 kilowatts. The amount of actual heat recovery for use at the dairy and cheese plant was another 608 kilowatts which is equivalent to 20.8 Therms per hour. This is over half of what was available from the heat recovery system which included both the engine jacket and exhaust heat exchanger boilers.

The system was run at approximately 82 percent of the manufacturer nameplate capacity. The actual online time for the engine generator was close to 98 percent so the system was consistently set to run at 80 percent of the nameplate capacity. This project had the advantage that the cheese plant power demand could always absorb the power produced by the engine-generator. The electrical efficiency of the system was observed to be 24 percent with a heat efficiency of 24 percent for an overall combined-heat and power efficiency of 48 percent, on a lower heating value basis. This is below the values reported by the engine manufacturer. This may be due to the parasitic loads or due to a lower electrical efficiency from the lowered engine set point. Efficiency is generally optimized at full capacity and drops off at lower heat rates. The heat recovery efficiency was only about half of the available heat because the heat demand did not meet the total production of the system and this heat was rejected by the radiator.

Table 5.10: Engine Generator(s) Performance Observed During the Study.

	BIOGAS CHP PERFORMANCE							
YEAR / MONTH	ELECTRICAL POWER OUTPUT	SPECIFIC POWER OUTPUT	AVERAGE HEAT RECOVERY	SPECIFIC HEAT RECOVERY	CAPACITY FACTOR*	ELECTRICAL EFFICIENCY	HEAT EFFICIENCY	OVERALL CHP EFFICIENCY
(YYMM)	(kW)	(kWh/LB VS ADDED)	(kW)	(kWh/LB VS ADDED)	(%)	(% LHV)	(% LHV)	(% LHV)
1107	630	0.64	713	0.73	84%	24%	27%	51%
1108	680	0.49	673	0.48	91%	23%	22%	45%
1109	672	0.37	656	0.36	90%	23%	22%	45%
1110	679	0.37	685	0.38	91%	24%	24%	48%
1111	567	0.32	532	0.30	76%	23%	21%	44%
1112	724	0.47	557	0.36	97%	21%	16%	38%
1201	529	0.38	602	0.43	70%	22%	25%	47%
1202	879	0.56	457	0.29	73%	23%	19%	42%
1203	607	0.36	669	0.39	81%	31%	34%	66%
1204	723	0.49	574	0.39	79%	24%	24%	48%
1205	651	0.44	693	0.46	87%	25%	27%	52%
1206	785	0.75	486	0.47	63%	24%	24%	48%
AVE	677	0.47	608	0.42	82%	24%	24%	48%

* Notes: Capacity factor was reduced in Feb, April, and June 2012 due to gas being diverted to a new engine generator set at the facility. Power output numbers include power produced in the new generator.

5.3.5 Mass and Energy Flows

The mass flows throughout the dairy and digester system are shown in Table 10 below. It can be seen where daily volumes of liquids and masses of water, solids, and volatile solids (VS) are added and removed in the process water system at the dairy. Fresh water, fresh collected manure, and cheese plant wastewater make up the total flush composition. Inclined screen separators remove larger fibers and particles from the flush water with a solids removal efficiency of 32 percent before the influent liquid goes into the digester. The digester then converts 62 percent of the volatile solids to produce biogas, further reducing the solids loading on the process water. The effluent from the digester goes into a storage pond where it is stored for use during the irrigation season for providing water and nutrients to crop land near the dairy. Figure 15 is a graphical representation of the average mass, solids, and energy balances for the Dairy 3 Digester system, based on the data collection and analysis from the 12 month study.

Table 5.11: Daily Process Water Volume and Mass Flows.

Process Water/Solids Stream	Liquid Volume (gal/day)	Total Mass (lbs/day)	Solids Conc. (%)	VS Conc. (%TS)	Water Mass (lbs/day)	Solids Mass (lbs/day)	VS Mass (lbs/day)	Solids Rem (%)	VS Rem (%)
Fresh Water	762,000	6,358,000	-	-	6,358,000	-	-		
Collected Manure	35,000	295,000	12.5	70.0	258,000	36,900	25,800		
Cheeseplant Wastewater	500,000	4,170,000	0.56	80.4	4,147,000	23,200	18,600		
Total Flush	1,298,000	10,823,000	0.55	74.0	10,763,000	60,000	44,400		
Inclined Screen Separator	-	64,000	18.5	72.0	52,000	11,900	8,600	32%	33%
Digester Influent	1,290,000	10,759,000	0.44	75.1	10,711,000	47,800	35,900		
Digester Effluent	1,287,000	10,737,000	0.24	49.2	10,711,000	26,100	12,800	45%	62%

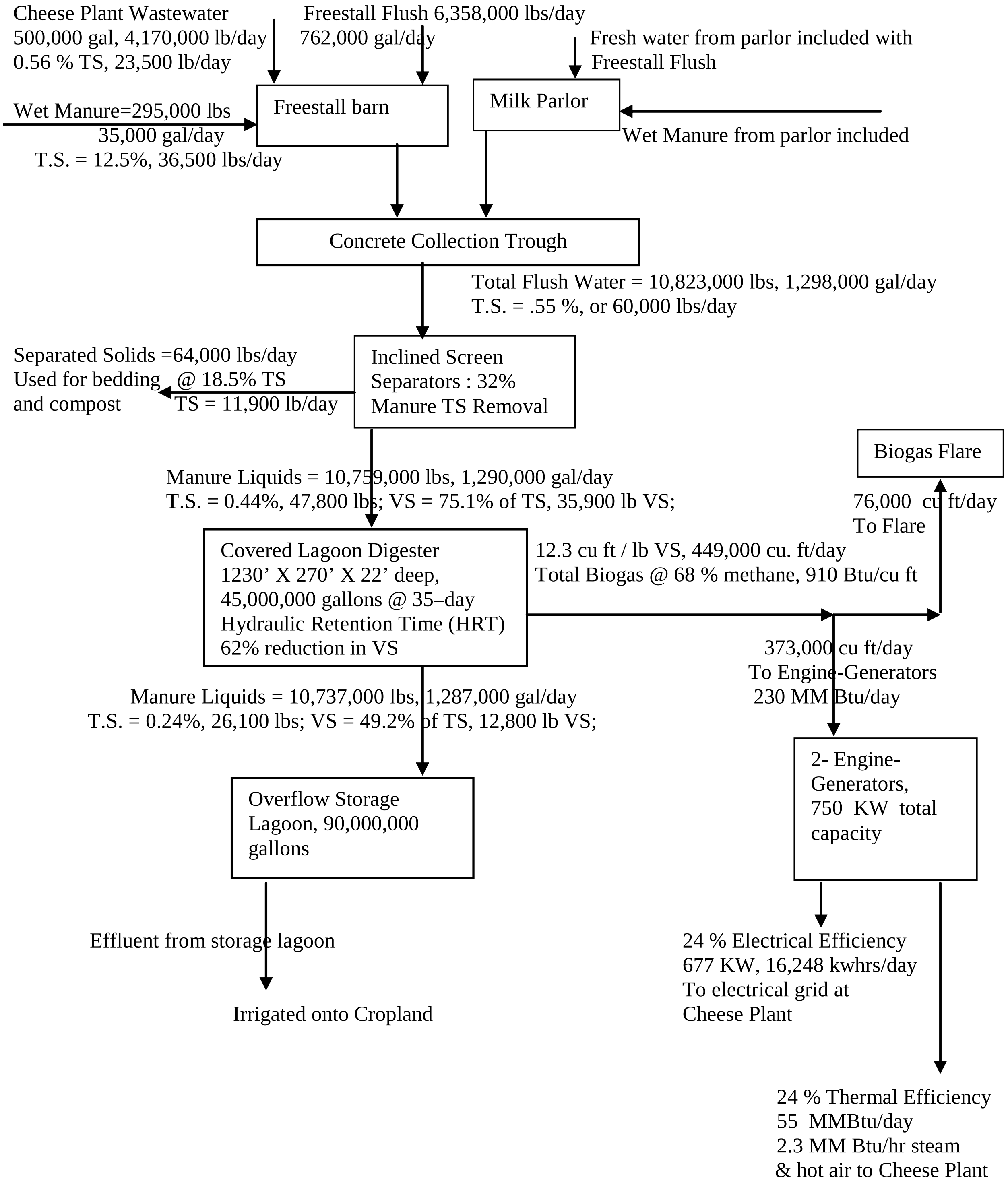

Figure 5.15: Average Mass and Energy Flow Diagram With Daily Flows for Dairy and Digester System.

5.3.6 Climate Change Impact

Using the data collected from the study, the Climate Action Registry Livestock Protocol was used to compute the amount greenhouse gas emissions reductions that have resulted from the digester project. The protocol provides a methodology for quantifying the baseline greenhouse gas emissions and comparing those with the emissions estimated to still be generated from the digester system or biogas control system (BCS) as called by the Registry. The baseline emissions are the methane emissions that would have occurred from decomposition of manure in an open lagoon system if the digester was not constructed. The project emissions are from un-burned methane from the engine and digester leakage/venting and methane generated in the effluent storage pond. The difference between the baseline and project emissions are a conservative estimate of the climate impact of the digester system and these could be available to the facility as carbon credits. The results are shown in Table 10.

The results show that the baseline methane emissions of the facility are about 715 tonnes per year. The project methane emissions of the facility are estimated to be 132 tonnes from the BCS and 90 tonnes from the effluent storage pond or 222 tonnes total. The difference is 493 tonnes of methane for a total reduction of 10,350 tonnes of carbon dioxide equivalents to the atmosphere. This is equivalent to 3.2 tonnes per lactating cow per year. Note that this is substantially less than the nearly 1,942 tonnes of methane that is actually destroyed by the engine each year. The calculation is meant to represents the real emissions impact of implementing the digester project not the actual methane production and destruction. These reductions could be verified as carbon credits representing a potential source of revenue depending on the value of the credits in the marketplace. Note that there are costs associated with monitoring, reporting, and validating these credits that must be considered.

Table 5.12: Climate Modeling Results for Digester Project Including Estimated Methane Reductions.

	Tonnes CH4 Per Year	***Tonnes CO2e Per Year***
Total Modeled Baseline Methane Emissions	***714.9***	***15012***
Project Methane Emissions from the BCS	131.8	2767
Project Methane Emissions from Effluent Pond	90.3	1896
Total Project Methane Emissions	***222.0***	***4663***
Total Methane Reductions	***492.8***	***10349***
Methane Destroyed in the BCS	1942	40785

5.4 Dairy 3 Conclusions

The project generated results for the annual performance of an un-heated covered lagoon dairy digester system coupled with a cogeneration system for conversion of biogas into power and heat. The following conclusions provide normalized results so that the study of this system can be compared with other digester systems in terms of overall characteristic performance.

DIGESTER FEEDING: The digester influent feed came from a flushed freestall dairy system utilizing fresh water and cheese plant wastewater for the flush media. The influent flow rate averaged about 1.3 million gallons per day. The influent had an average total solids concentration of 0.44 percent which consisted of 75 percent volatile solids. The volatile solids loading of 36,000 lbs per day is estimated to consist of 50 percent raw manure solids and 50 percent cheese plant wastewater solids. A more detailed constituent analysis of the digester influent is shown in Table 4.

DIGESTER PERFORMANCE: The project results demonstrate that the un-heated covered lagoon digester having a long hydraulic retention time and low organic loading rate has the capability to accept varying flows and still maintain stable anaerobic digestion. The digester showed consistent volatile solids reduction and gas production over the year. The average hydraulic retention time was 35 days with an organic loading rate of 6 pounds of volatile solids per thousand cubic feet per day. Average digester temperature was 81°F. The study showed that the digester reduced total solids by 44 percent, volatile solids by 63 percent, total dissolved solids by 26 percent, and carbon oxygen demand by 86 percent during the digestion process. Ammonia nitrogen increased by 125 percent. There were no other statistically significant changes to the digestate composition within the digester system as shown in Table 8.

BIOGAS PRODUCTION: The digester produced an average of 12.9 cubic feet of biogas per pound of volatile solids added which also equated to 21.4 cubic feet per pound of volatile solids consumed. The composition of the biogas was consistently high in methane at an average of 67.6 percent, but also consisted of 30.9 percent carbon dioxide, 0.1 percent nitrogen, and 1.4 percent oxygen. Hydrogen sulfide content was low for biogas at due to an air injection system which kept it at an average of about 20 ppmv. Biomethane potential tests came close to predicting the average gas production of the digester and showed that the digested solids had on 13 percent of the biomethane potential of the digester feed.

BIOGAS GENERATOR PERFORMANCE: The engine-generator for this project operated at a capacity factor of 82 percent although the actual engine online time was almost 100 percent. The electrical efficiency averaged 24 percent and the recovered heat efficiency was 24 percent for a total efficiency of 48 percent expressed on a lower heating value basis. The efficiency might have been increased by running the generator closer to capacity and increasing the heat utilization. Only about ___ percent of the available recoverable heat was utilized.

CLIMATE CHANGE IMPACT: Utilizing the methodology developed for predicting livestock emissions reductions using digesters, it is estimated that the baseline and digester project emissions of methane are 715 and 222 tonnes per year respectively , for a total reduction in atmospheric emissions due to manure emissions of 69 percent or 493 tonnes per year. This is equates to 10,350 tonnes of carbon dioxide equivalents per year (3.2 tonnes per lactating cow) that could potentially be traded as carbon credits.

CHAPTER 6:
Dairy 4 Results

6.1 Dairy 4 Background

This report describes the performance of the Dairy 4 anaerobic digester and power production system in the Northern Central Valley region of California. Anaerobic digester gas (biogas) is being captured from a heated, mixed digester at this large dairy milk production operation. The biogas is used to fuel a 212 kW engine-generator unit. The electrical power is being exported back to the local utility district grid. Waste heat from the engine and exhaust is captured and recovered to the digester system.

A monitoring system was developed to collect the measured data necessary to quantify the economic and technical performance of the biogas system including the digester conversion of manure to biogas, the energy conversion of biogas to electricity and heat as well as the pertinent air and water emissions to the environment. A mass and energy balance of the system over a 12-month period was developed along with other system performance according to industry protocols.

The mixed lagoon digester system was designed by a digester engineering firm and the gas cleanup and generation systems by an engine-generator system provider. The digester is a concrete lined lagoon digester, shown in Figures 1 and 2, located adjacent to the freestall dairy barns at the facility. The digester is heated and has six internal mixers that intermittently mix the lagoon to keep solids suspended during the digestion process. Flushed manure from Dairy 4 is collected daily in a pit prior to being pumped across the farm and directly into the digester. A receiving pit at the head of the digester also allows for waste from the milk parlor and nursery to be pumped into the digester. This receiving pit would also allow for future import of other mixed feedstock but is not being used for this purpose at this time. The digester was fed with a large volume of flush water per day containing both recycled solids and fresh manure solids. Due to the high flow of this flush water, the digester had a very low hydraulic retention time. The effluent from the digester lagoon overflows to an effluent pit, Figure 3, where it is passed over a rotary screen separator to remove solids. Liquid effluent from the separator is delivered to a set of storage lagoons and is utilized for recycle manure flushing and for crop irrigation. Both the separated solids and the stored liquids provide valuable fertilizer for the dairy feed crops. A custom-engineered HDPE system encloses the covered lagoon, Figure 2, captures produced biogas, and channels to a gas cleanup system and co-generation system located adjacent to the digester.

The gas first passes through a hydrogen sulfide gas scrubber unit, Figure 4, where it is filtered to remove hydrogen sulfide, dried with a chiller-type gas drier, and is pumped to be delivered to the prime mover located adjacent to the conditioning skid. The fuel is delivered to the 212-kilowatt synchronous generator system, Figure 5.

Figure 6.1: Digester Lagoon in Construction.

Figure 6.2: Digester with HDPE Cover Installed.

Figure 6.3: Effluent Pit and Solids Separator.

Figure 6.4: H2S Scrubber Behind Receiving Pit.

Figure 6.5: 212-KW Engine-Generator System.

Figure 6.6: Custom Digester Heat Exchanger.

Table 6.1: Dairy 6 Digester System Description.

Digester	Concrete Lined Lagoon, 3.4 Million gal capacity Partially heating and Intermittent mixing HDPE cover Fibrous Solids Separation After Digester
Engine-Generator	Lean Burn Gas Engine 212 kW Capacity on Biogas 38.5% LHV, Shaft Efficiency 480 VAC, 3 phase Synchronous Generator
Biogas Treatment	H2S Scrubber/sparger system Biogas Chiller for Vapor Removal
Heat Recovery	Heat Recovery From Exhaust and Engine Jacket Custom External Shell-in-Tube Heat Exchanger for Direct Heating of Digester Liquids

All of the electricity generated from the facility is being compensated by the local electrical utility based on a power purchase agreement. The heat from the generator engine and exhaust system is captured and exchanged with digestate liquids via a customized heat exchanger, Figure 6, which adds heat directly to the digester with the intention of increasing the digestion temperature.

A flare is provided for emergency or when generator system is down. The flare is normally off so that biogas can be used by the engine to produce electricity. If the engine-generator is shut off and the gas pressure under the cover increases above safe levels, the flare is manually activated to destroy the unused biogas.

The Figure 7 schematic shows the overall biogas and power generation systems. Details on typical mass and energy flows are given in the process flow diagram in Appendix B. Biogas from the digester is used in the engine or flared. The hot water leaving the engine jacket and exhaust is used to provide heat to the digester. A more detailed schematic of the waste heat recovery system is given in Appendix A.

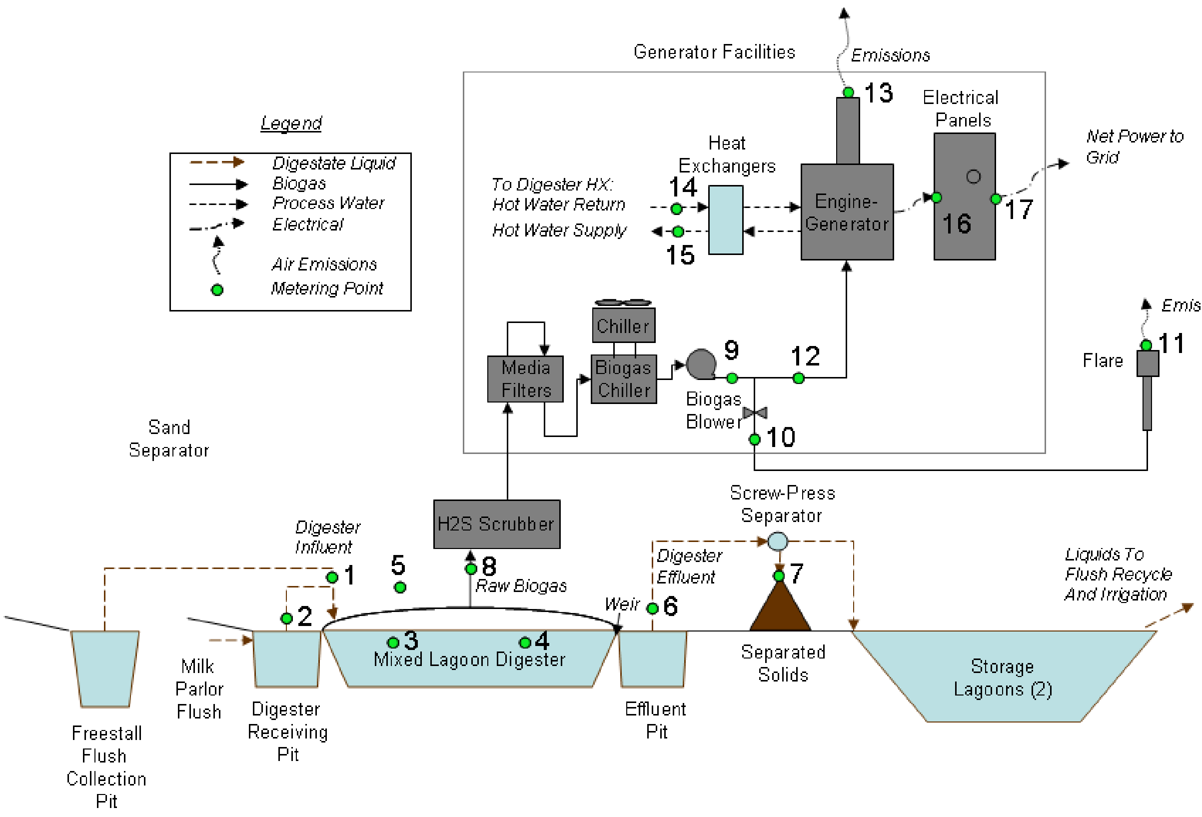

Figure 6.7: Schematic of Biogas System With Metering Points.

6.2 Dairy 4 Materials and Methods

The monitoring methodology and system followed protocols developed by ASERTTI, Climate Action Registry, and US EPA. Continuous sensors monitored pertinent system flows and conditions including those shown in Table 2. This data was recorded in data logger equipment and 15-minute averages will be continuously logged and transmitted via the internet to a central system maintained by the investigators. Sampling locations are shown on the schematic in Figure 8. These sampling points cover all pertinent manure, biogas, power and process water flows and temperatures. Composition samples were taken on a monthly basis to establish the mass distribution for each flow of manure, biogas and emissions.

The monitoring system supplied by Summers Consulting was configured to capture the data points listed in Table 2. The sensors were sampled at 1-minute intervals and averaged or summed into 15-minute data as appropriate. The PLC-based system provided the investigators access to the time-stamped 15-minute data via the internet. The on-site controller has the ability to store and retain several hundred days of 15-minute data in the event that communications are lost.

The electrical output of the engine-generator (WGO) is measured with a power transducer already installed in the engine control panel. A utility-supplied power meter also indicates the amount of power that is exported (WGT) by the engine-generator. The net power (WNT) was supplied by difference utilizing a utility-supplied meter measuring the amount of parasitic power (WPS) imported by the system.

The biogas delivered to the engine (FGE) is measured by a gas flow meter (thermal probe) that determines the mass flow in standard cubic feet per minute. Another gas meter measures biogas flow to the flare (FGF). The flare temperature (TEF) establishes that the flare is lit and biogas is being burned in the flare. The total biogas flow (FGT) is the sum of FGE and FGF but it independently measured with a third gas meter. From the biogas and power measurements the engine efficiency is estimated using the measured monthly gas composition data as it becomes available. The gas flows also allow for an estimate of emissions from the engine (FEE) and the flare (FEF) using standard combustion assumptions and measurement of exhaust composition.

The digester temperatures (TMI, TME, TD1 and TD2) are measured by thermocouples at the influent and effluent pipes and placed in the two vent pipes on the cover of the digester. The ambient temperature (TAO) is also recorded to understand how digester performance varies with weather conditions.

The flow of manure into the digester (FMI) is measured by two clamp-on ultrasonic flow meters. One flow meter monitors the flow of freestall flush water that is delivered to the digester. The second monitors the influent flow from the receiving pit that includes milk parlor and nursery flush water and any materials added to the receiving pit. It was assumed that influent and effluent water flow are balanced, therefore the water portion of FMO is estimated to be equal to the total of the two FMI measurements. The flow of manure solids (FMS) will be measured monthly by weighing the solids separated by the rotary screen separator over a known period (typically 24-hours).

The thermal energy utilized for digester heating is determined from the process water flow and temperature difference data (FWP, TWI, TWO). This hot process water is delivered to the shell-in-tube heat exchanger and heat is exchanged directly to circulated digestate.

The parasitic power consumption of various components in the system is determined by power readings with a hand-held meter capable of measuring true power. The sum of all parasitic loads not accounted for in the net metering is compared with the power generated by the system.

Table 6.2: Monitoring Points on the Dairy 4 Digester System.

Loc #	Data Point	Description	Eng. Units	Sensor or Instrument	Typical Range
1	FMI	Flow of Manure, Influent to Digester	gpm	Ultrasonic Flowmeter	0-500
	TMI	Temperature of Manure, Influent to Digester	°F	Type-K TC, 6 in probe	45-90
	CMI	Composition of Manure, Influent to Digester	mg/l - TS	Monthly samples, 24h	15,000 – 26,000
2	FRI	Flow from Receiving Pit, Influent to Digester	gpm	Ultrasonic Flowmeter	0-70
	TRI	Temperature of Manure, Influent to Digester	°F	Type-K TC, 6 in probe	= TMI
	CRI	Composition from Receiving Pit, Influent to Digester	mg/l	Monthly samples, 24h	=CMI
3	TD1	Temperature of Digester at Location 1	°F	Type-K TC, 72 in depth	50-85
4	TD2	Temperature of Digester at Location 2	°F	Type-K TC, 72 in depth	50-85
5	TAO	Temperature of Ambient Out	°F	Type-K TC, near digester	25-105
6	FME	Flow of Manure, Effluent from Digester	gpm	Estimated from FMI	= FMI
	TME	Temperature of Manure, Effluent from Digester	°F	Type-K TC, 6 in probe	50-85
	CME	Composition of Manure, Effluent from Digester	mg/l - TS	Monthly samples, 24h	14,000 – 25,000
7	FMS	Flow of Manure Solids (Screw Press)	lb/day - TS	Monthly weight est.	6,000-10,000
	CMS	Composition of Manure Solids (Screw Press)	%TS by wt	Quarterly samples	19-23%
8	CGR	Composition of Gas, Raw Biogas before Conditioning	% by vol.	Monthly analysis	65
9	FGT	Flow of Gas Total (Conditioned Biogas)	cf/h	Sage Prime SIP	0-4000
	CGT	Composition of Gas Total (Raw Biogas)	% by vol.	Monthly analysis	65
10	FGF	Flow of Gas to Flare (Raw Biogas)	cf/h	Sage Prime SIP	0-3500
	CGF	Composition of Gas to Flare (Raw Biogas)	% by vol.	Monthly analysis	65
11	FEF	Flow of Emissions from Flare	cf/h	Estimated from FGF	= FGF
	CEF	Composition of Emissions from Flare	% or ppm	Monthly analysis	5% O2
12	FGE	Flow of Gas to Engine (Conditioned Biogas)	cf/h	Sage Prime SIP	0-3500
	CGF	Composition of Gas to Engine (Conditioned)	% by vol.	Monthly analysis	65
13	FEE	Flow of Emissions from Engine	cf/h	Estimated from FGE and CEF	= FGE
	CEE	Composition of Emissions from Engine	% or ppm	Monthly analysis	0-4% O2
14	TWI	Temperature of Water Inlet (Process Water into Heat Exchanger)	°F	Type-K TC, 6 in probe	Amb.-170
15	TWO	Temperature of Water Outlet (Process Water out of Heat Exchanger)	°F	Type-K TC, 6 in probe	Amb. -125
	FWP	Flow of Water to Process	gpm	Onicon F1100	0-30
16	WGO	Watts of Generator Output (Power at Generator)	kWh/int	Gen-Tec power meter	0-200
	WGT	Generator Output	kWh/int	SMUD meter - pulse	0-200
17	WPS	Parasitic Loads	kWh/int	SMUD meter - pulse	25-300

The composition of the manure influent and effluent is measured on a monthly basis using an aggregated sample made up of at least 5 individual samples taken over a cycle. The aggregate samples were shipped to a local laboratory analyzed for the analytes described in Appendix A using the standard QA/QC procedures established by the laboratory and as described in the standard methods. The composition of the biogas was measured using a field-calibrated GEM™2000 Portable Gas Analyzer from Landtec on a monthly basis. This sampling included raw and conditioned biogas. The portable meter is used to determine the percentage of CH4, CO2, O2, H2S and balance gas (presumed to be N2) on a monthly basis. The metering equipment is calibrated on a routine basis and the estimated accuracy is shown in Appendix A.

Also on a monthly basis, samples of the separated solids were taken using an aggregate of at least five samples and the solids density, moisture content, and total pile volume were estimated to come up with an estimated daily amount of production from the solids separator. On a quarterly basis, separated solids samples were laboratory analyzed according to the analyses in Appendix A - Table A2.

Periodic samples of the influent to and effluent from the digester were subjected to a Biochemical Methane Potential (BMP) analysis in a specially-designed apparatus in the Summers Consulting laboratory. BMP analysis is an efficient and economical method for evaluating the rate and extent of biomass conversion to methane under anaerobic conditions. The effluent BMP shows the remaining methane production potential after digestion and provides an estimate of the potential methane produced in a liquid storage pond after digestion.

Annual greenhouse gas emissions reductions were also estimated using the Climate Action Registry Livestock Protocol. This protocol uses a particular methodology to estimate the baseline emissions or emissions from the manure management system without the digester and compares these with estimated emissions from the digester system.

6.3 Dairy 4 Results and Analysis

The following sections summarize the monitoring results of this year-long monitoring campaign and provide annual operational factors including digester feeding, digester performance, biogas production, biogas generator performance, and climate change impact. The digester monitoring system for Dairy 6 was designed in 2011 and installation was completed in mid-2011. Additional gas production and engine performance data was available back to the start of the digester in 2009 and some of this was used in the analysis. The monthly liquid and solids sampling was initiated in January of 2012 and completed by January of 2013. The actual milk cow and heifer numbers during the data collection period are shown in Table 3 along with the estimated daily manure production as predicted by typical estimation method from ASABE. The total manure volatile solids represent the total available feedstock for conversion in the digester system although the collection system only collects the manure that is recovered via recycled water flushing of the concrete feed lanes.

Table 6.3: Average Dairy Herd Size and Estimated Manure Production.

DAIRY HERD			ESTIMATED MANURE PRODUCTION	
	HEAD (#)	WEIGHT (LB/HEAD)	VOLATILE SOLIDS (LB/HEAD/DAY)	TOTAL VOLATILE SOLIDS (LB/DAY)
Milk Cows	837	1499	17.0	14,229
Dry Cows	187	1507	9.2	1,720
Heifers	990	897	7.1	7,029
			Total Manure Volatile Solids	22,978

6.3.1 Digester Feeding

The rate of influent feeding of the digester averaged about 700,000 gallons per day over the entire year, but varied monthly from 620,000 to 780,000 gallons per day. Figure 8 shows the average digester influent flows for each month of the study year. Factors like seasonal animal activity, operation variability, rainfall, and use of wash water are potential sources of this variability. This is an unexpectedly large flush flow for the amount of solids being flushed by the manure handling system. It also represents almost one-fifth of the volume of the digester which can create problems for digestion.

The results for the monthly solids composition of the influent mixture is shown in Figure 9. Total solids concentration ranged from 15,000 to 26,000 milligrams per liter with an average of 21,000 milligrams per liter. Volatile solids ranged from 10,000 to 18,000 milligrams per liter with an average of 14,200 milligrams per liter. The volatile solids were consistently 65 to 70 percent of the total solids. The variability seen in these samples can also be attributed to variable system flows and the limitations of taking a single aggregated grab sample to represent an entire month of manure flow. Table 4 shows the annual average and standard deviation for all of the samples taken over the year for constituents of the influent digester stream.

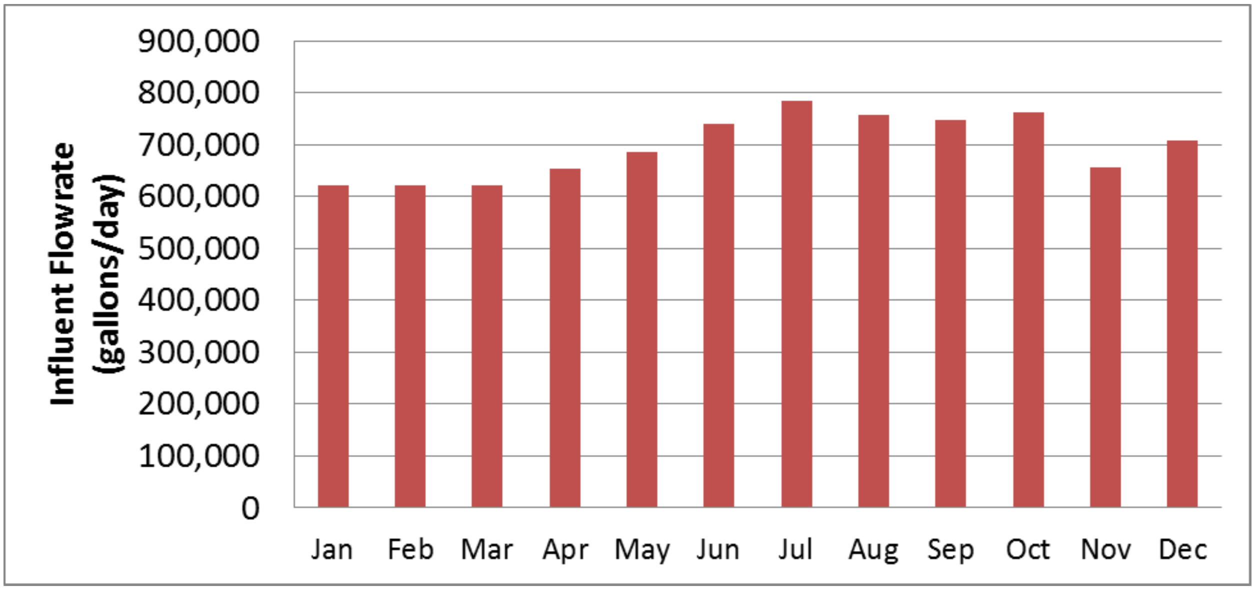

Figure 6.8: Average Monthly Influent Flowrate.

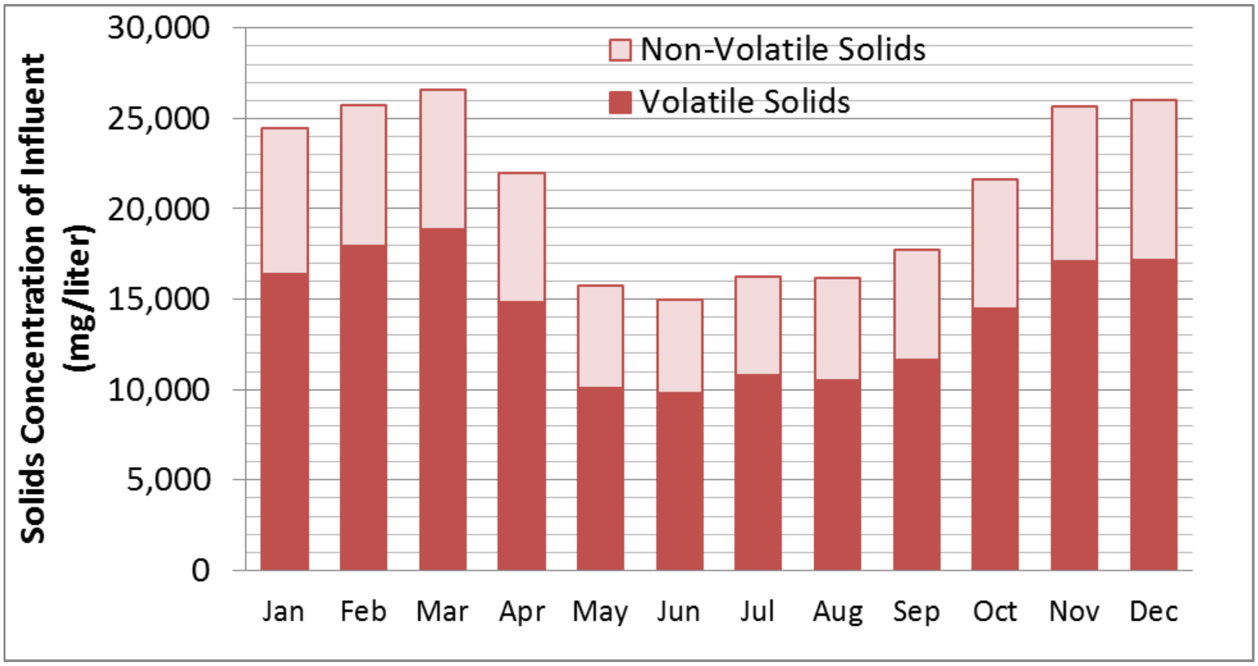

Figure 6.9: Total Solids Concentration of Digester Influent With Volatile and Non-Volatile Fractions.

Using pile size estimates and monthly moisture and density samples, it was determined that about 6 percent of the total solids in the effluent stream or about 7,100 pounds per day of total solids per day are removed by the rotary screen solids separator after the digestion process. While this solids yield appears to be low, the amount of solids is about 30 percent of the fresh manure solids originally collected by the manure flush which is reasonable. These separated solids are stabilized by the digestion process and can be valuable for use in the farming operations at the dairy or marketed as a horticultural soil amendment. Table 5 shows the composition of these separated solids and Table 10 shows the daily generation rates.

Table 6.4: Composition of Various Constituents of the Digester Influent. Average and Standard Deviation of the Monthly Samples Taken Over the Study Year.

Analyte	Units	Method	Average	St Dev
Total Solids	mg/L	SM 2540B	21,084	5,768
Volatile Solids	mg/L	EPA 160.4	14,194	4,262
Total Dissolved Solids	mg/L	SM 2540 C	5,648	862
Chemical Oxygen Demand	mg/L	SM 5220D	20,016	8,593
Specific Conductance	µS/cm	SM 2540B	11.1	1.4
pH		Field Test	7.6	0.1
Ammonia-N	mg/L	SM 4500	715	96
Ammonium-N	mg/L	SM 4500G	10.7	6.1
Nitrate-Nitrogen	mg/L	EPA 300.0	2.1	1.9
Total Nitrogen	mg/L	EPA 351.2	1,531	296
Total Phosphorus	mg/L	SM 4500P B	324	75
Total Potassium	mg/L	SM 3120 B	1,129	184
Total Sulfur	mg/L	SM 3120 B	140	32
Total Clorine	mg/L	SM 3120 B	488	34
Total Calcium	mg/L	SM 3120 B	605	152
Total Magnesium	mg/L	SM 3120 B	328	47
Total Sodium	mg/L	SM 3120 B	189	25

Table 6.5: Composition of the Separated Solids From the Rotary Screen Separator. Average and Standard Deviation of Quarterly Samples Taken Over the Study Year.

			Rotary Screen Solids	
Analyte	Units	TMECC Method	Average	St Dev
Dry Matter (eq TS)	Wt %	03.09-A	22.39	0.11
Organic Matter (eq VS)	Wt %	05.07-A	20.14	0.12
Total Nitrogen	Wt %	04.02-D	0.287	0.067
Total Phosphorus	Wt %	04.03-A	0.047	0.006
Total Potassium	Wt %	04.04-A	0.127	0.006
Sodium	Wt %	04.05-Na	0.017	0.006
Calcium	Wt %	04.05-Ca	0.123	0.032
Magnesium	Wt %	04.05-Mg	0.043	0.006
Iron	mg/kg	04.05-Fe	218	168
Copper	mg/kg	04.07-Cu	12.8	3.8
Manganese	mg/kg	04.05-Mn	10.5	4.8
Zinc	mg/kg	04.05-Zn	11.0	3.0
Sulfur	Wt %	04.05-S	0.037	0.012

6.3.2 Digester Performance

The digester was fed a daily dose of liquid consisting of mostly recycled solids and a small amount of fresh manure solids, throughout the study period. The average amount was 700,000 gallons per day with about 2 percent solids although there was some variability due to real variations in operations and due to the measurement limitations discussed above. The measured loading of the digester can be seen in Table 6 – Digester Feeding.

Table 6.6: Digester Influent Feeding and Performance Parameters.

	DIGESTER FEEDING				DIGESTER PERFORMANCE			
MONTH	INFLUENT FLOWRATE	TOTAL SOLIDS CONC.	VOLATILE SOLIDS CONC.	INFLUENT VOLATILE SOLIDS	AVERAGE DIGESTER TEMP	ORGANIC LOADING RATE	HYDRAULIC RETENTION TIME	VOLATALE SOLIDS CONSUMPTION
(MM)	(GAL/DAY)	(%)	(% TS)	(LBS /DAY)	(DEG F)	(LB VS /1000 CF/DAY)	(DAY)	(%)
01	621,391	2.4	67.0	84,992	54.0	187	5.5	7.6
02	621,182	2.6	69.8	92,891	53.0	204	5.5	5.3
03	621,600	2.7	70.8	97,659	55.5	215	5.5	10.9
04	653,871	2.2	67.4	80,876	60.0	178	5.2	12.8
05	686,141	1.6	64.0	57,805	62.7	127	5.0	9.2
06	739,779	1.5	65.7	60,664	69.9	133	4.6	4.2
07	783,676	1.6	66.5	70,667	72.7	155	4.3	-0.8
08	757,576	1.6	65.2	66,551	77.0	146	4.5	-15.1
09	748,571	1.8	65.6	72,603	66.7	160	4.5	-16.2
10	761,345	2.2	66.7	91,707	63.8	202	4.5	-0.2
11	655,968	2.6	66.6	93,521	57.8	206	5.2	11.6
12	708,657	2.6	66.1	101,471	56.0	223	4.8	16.1
AVE	696,646	2.1	66.8	80,951	62.4	178	4.9	3.8

The influent volatile solids averaged 81,000 pounds per day. Of this, only 19,000 pounds were estimated to be from the most digestible fresh manure or about 23 percent of the influent volatile solids. Compared with the estimated volatile solids excretion of 23,000 pounds per day for this dairy herd, this equates to an estimated manure capture of 83 percent by the flush system. This seems like a reasonable result given that the animals are confined in the free-stall area most of the year at this facility.

The digester maintained fairly poor anaerobic digestion through the study period as evidenced by the observed volatile solids consumption of less than 4 percent. In fact, the consumption was not statistically significant so it was difficult to even measure above the variability in the monthly samples. Several other indicators show that the digester was overloaded. For example, the average daily organic loading rate of 178 pounds of volatile solids per thousand cubic feet is almost ten times the recommended loading rate of 20 pounds of volatile solids per thousand cubic feet for this type of system. The 4.9 day average hydraulic retention time low compared with the recommended HRT of at least 30 days for this type of digester. The digester temperature was in the range of 55-80°F depending on time of year and largely influenced by ground temperature. There was little evidence that the heating system substantially heated the system. These lower temperatures are still suitable for maintenance of psychrophillic anaerobic activity but also require longer retention times. All of these performance factors calculated for each month of the study period are shown in Table 6 – Digester Performance.

Consumption, conversion, and accumulation of the wastewater constituents within the digestion system are of interest and were analyzed by looking at the difference between the influent and effluent compositions (Table 7). Statistical analysis was applied to the data observations to determine if there was a statistically significant difference between the influent and the effluent compositions. A two-tailed pair-wise Student's T-test was applied to the data sets for the influent and effluent composition. The null hypothesis is rejected for alpha was less than 0.05, meaning that for p-values less than 0.05, we conclude that there is a statistically significant difference between the influent and the effluent composition and that some conversion occurred within the digester.

Table 6.7: Differences Between Influent and Effluent Compositions Observed During Study Period.

Analyte	Units	Method	Influent	Effluent	Difference	P-Value[7]
Total Solids	mg/L	SM 2540B	21,084	20,167	-4.3%	0.2186
Volatile Solids	mg/L	EPA 160.4	14,194	13,688	-3.8%	0.2568
Total Dissolved Solids	mg/L	SM 2540 C	5,648	5,631	-0.3%	0.9052
Chemical Oxygen Demand	mg/L	SM 5220D	20,016	16,899	-15.6%	0.1129
Specific Conductance	μS/cm	SM 2540B	11.1	11.5	3.3%	0.0955
pH		Field Test	7.6	7.6	0.0%	1.0000
Ammonia-N	mg/L	SM 4500	715	682	-4.6%	0.4631
Ammonium-N	mg/L	SM 4500G	11	8.3	-22.8%	0.5684
Nitrate-Nitrogen	mg/L	EPA 300.0	2.1	2.5	19.0%	0.4165
Total Nitrogen	mg/L	EPA 351.2	1,531	1,472	-3.8%	0.2208
Total Phosphorus	mg/L	SM 4500PB	324	299	-7.8%	0.0519
Total Potassium	mg/L	SM 3120 B	1,129	1,111	-1.6%	0.5972
Total Sulfur	mg/L	SM 3120 B	140	134	-4.2%	0.6349
Total Clorine	mg/L	SM 3120 B	488	486	-0.5%	0.6206
Total Calcium	mg/L	SM 3120 B	605	542	-10.3%	0.0740
Total Magnesium	mg/L	SM 3120 B	328	296	-9.8%	0.0638
Total Sodium	mg/L	SM 3120 B	189	184	-2.5%	0.5538

The observed averages for composition of influent and effluent are shown in Table 7 along with the percentage difference observed. No constituents showed statistically significant differences between influent and effluent. This is probably largely due to the relatively small amount of

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[7] P-Values generated from a Paired Two-Tailed Student's T-Test for the difference between influent and effluent data sets with alpha = 0.05. Statistically significant differences are shown in bold.

digestion that took place in the digester. In other systems the total, volatile, and dissolved solids and chemical oxygen demand showed reductions in the digestion process and ammonia nitrogen showed an increase but these differences were not statistically significant for this system.

The mass and energy flow diagram in Figure 13 illustrates how water and solids and energy are transported and converted in the system. While the conversion within the digester was small, the results still show fairly good closure on mass and energy balances for the system.

6.3.3 Biogas Production

The measured daily biogas production varied from 18,000 to 58,000 cubic feet per day with an average of 45,000 as shown in Table 8 and Figure 10. There were issues with the gas metering and places where biogas could bypass the metering system to be vented to the flare so there is some overall uncertainty with this amount. The last three months were confirmed to have missing flared gas data so they were not included in the biogas production calculations.

The average specific biogas production for both added and consumed volatile solids are estimated in Table 8. The average value of 0.6 cubic feet per pound of volatile solids added is far below reported yields of 6 to 8 cubic feet per pound from successful and stable dairy manure digesters (US EPA, 2012). This is probably largely due to the overloading of this digester and the large amount of poorly digestible recycled solids. The average value of 16.3 cubic feet per pound of volatile solids consumed is consistent from a mass balance perspective because 15 cubic feet of biogas weighs about one pound. The observed biogas production per pound of volatile solids excreted by the herd was 2.0 cubic feet (or about 0.15 pounds per pound VS excreted) which can be compared with other dairy digester systems as a performance metric.

The composition of the biogas was monitored throughout the study during monthly sampling and analysis. These observations are shown in Figure 11. The methane content was consistently 62-74 percent of the biogas (67.8 percent average). The balance of the gas is primarily carbon dioxide (29.6 percent average), the other major gas product of anaerobic digestion. There was an amount of nitrogen (2.1 percent average) and oxygen (0.1 percent average) in the gas attributed to air added by an air injection system to control hydrogen sulfide emissions. We obtained monthly data from two years and to show the difference before and after adding the air injection system. The hydrogen sulfide content of the biogas was observed to average 2400 parts per million by volume without air injection and 56 parts per million with air injection as shown in Figure 12. This shows the air injection system had a substantial benefit to the quality of the gas with only a very small impact on gas composition of added nitrogen.

Table 6.8: Biogas production parameters observed from the digester system.

	BIOGAS PRODUCTION					
MONTH	TOTAL BIOGAS*	SPECIFIC BIOGAS	SPECIFIC BIOGAS	SPECIFIC BIOGAS	METHANE	PERCENT FLARED BIOGAS
(MM)	(SCFD)	(SCF/LB VS ADDED)	(SCF/LB VS CONSUMED)	(SCF/LB VS EXCRETED)	(VOL %)	(%)
01	18,092	0.2	5.6	0.8	70.7	0%
02	33,514	0.4	9.5	1.5	66.9	0%
03	57,575	0.6	15.5	2.5	65.0	0%
04	57,281	0.7	18.6	2.5	67.9	0%
05	61,095	1.1	27.8	2.7	66.5	0%
06	55,958	0.9	24.3	2.4	65.0	0%
07	42,625	0.6	15.9	1.9	66.1	0%
08	32,905	0.5	13.0	1.4	71.2	84%
09	45,796	0.6	16.6	2.0	70.5	43%
10	23,693				67.2	
11	11,801				62.6	
12	7,876				74.1	
AVE	44,982	0.6	16.3	2.0	67.8	14%

* Note: Flare gas flow meter was bypassed in October-December therefore the Total Biogas values for these months includes engine biogas only and could not be used in biogas production calculations.

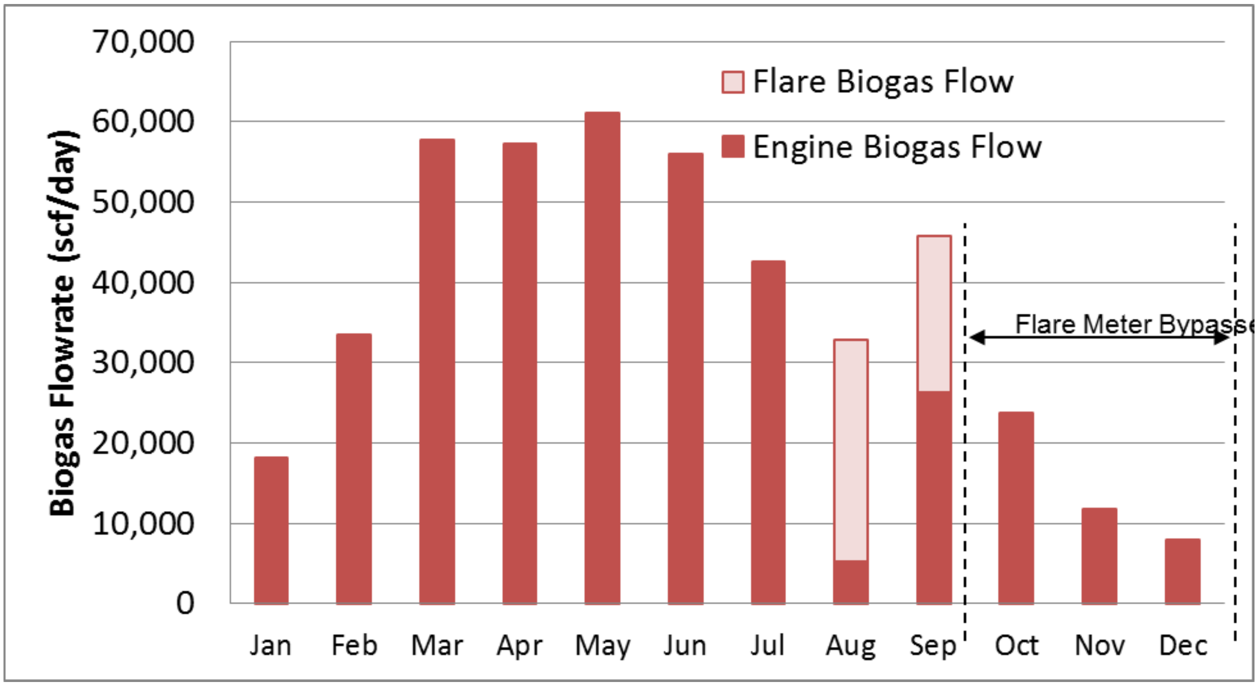

Figure 6.10: Average Daily Biogas Flowrate by Month From the Digester System.

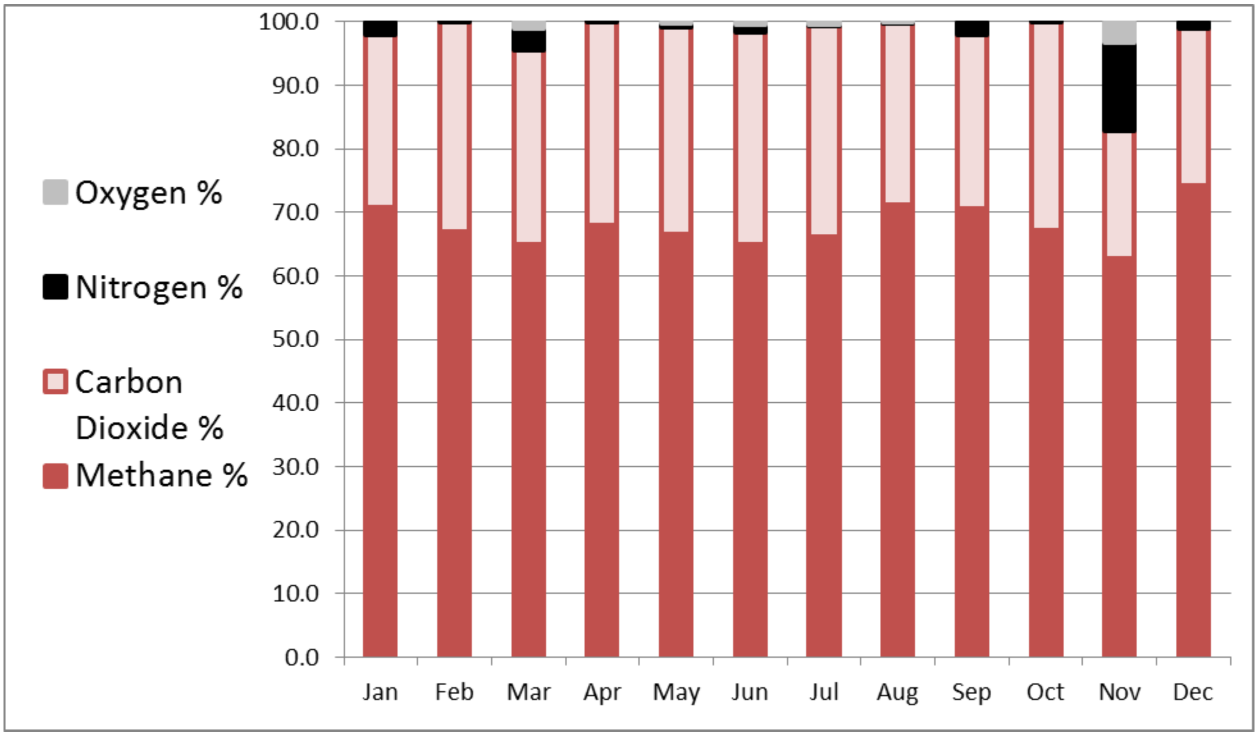

Figure 6.11: Biogas Composition Observed During the Study.

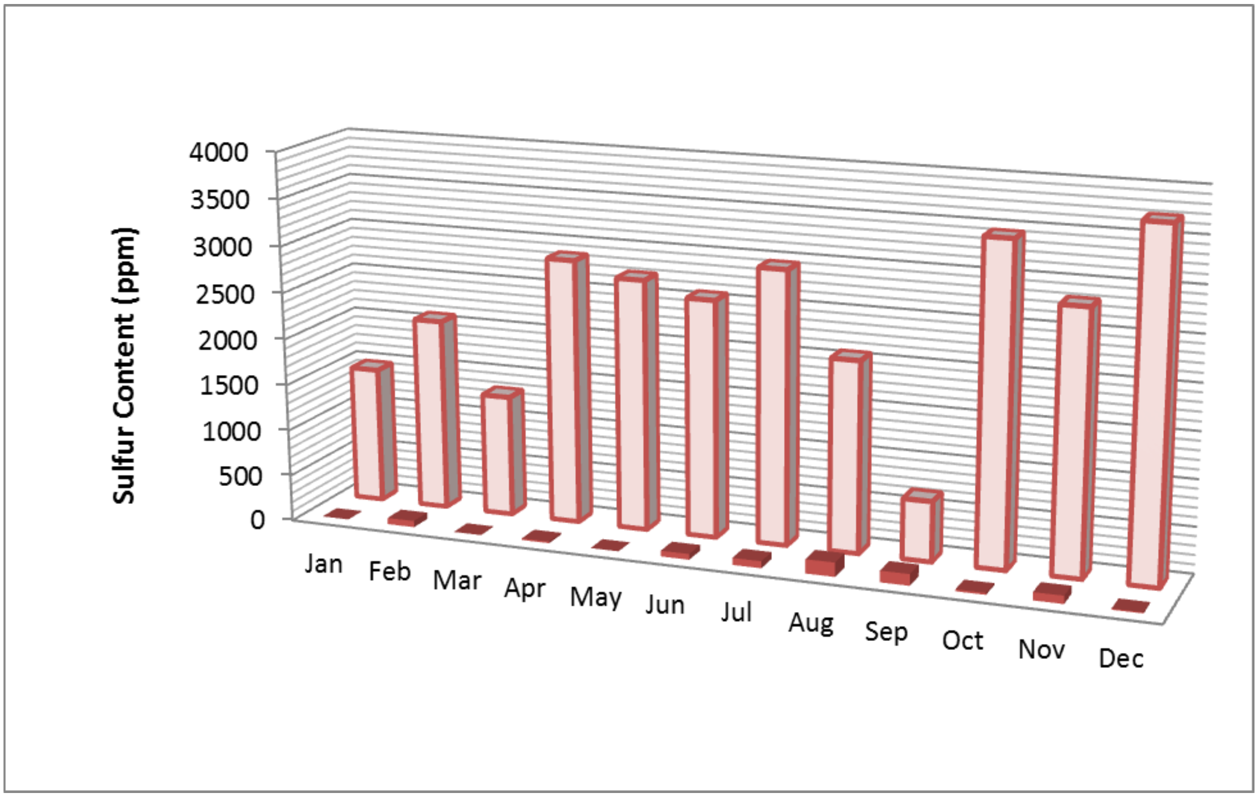

Figure 6.12: Hydrogen Sulfide Concentration in the Biogas Observed With No Control (Light, Back) and With Air Injection (Dark, Front) From Subsequent Measurement Years.

Biological methane potential (BMP) was also examined for the digester influent feed to compare the methane production at ideal mesophillic conditions with actual performance of the digester system. In addition, the biomethane potential of the digester effluent was quantified to determine what additional biogas production potential remains after the digestion process. Using the standard BMP test, average biogas production was 2.0 standard cubic feet (SCF) per pound of volatile solids added for the digester feed which was more than the estimated digester performance of 0.6 SCF per pound of volatile solids added. The biological methane potential was determined to be 1.3 SCF per pound of volatile solids added. The methane potential of the digester effluent was 0.5 SCF per pound of volatile solids showing methane potential for the effluent to be 35 percent that of the digester feed.

6.3.4 Biogas Generator Performance

The biomass combined heat and power generator performance was observed including the power and heat utilization from the 212-KW engine generator set. Table 9 shows the results. After a small amount of parasitic load from the pump, gas chiller, and engine skid, the electrical power output was an average of only 71 kilowatts over the 12 month period. The digester mixers also presented additional parasitic load but this was not counted against the generator system efficiencies system. The heat recovery for use in the digester was monitored for the first five months at 100 kilowatts which is equivalent to about 4 Therms per hour. It should be noted that this heat was used internally to attempt to heat the digester system and not for other energy use. This heat might be better utilized for some other purpose.

Table 6.9: Engine Generator Performance Observed During the Study.

	BIOGAS CHP PERFORMANCE							
MONTH	ELECTRICAL POWER OUTPUT	SPECIFIC POWER OUTPUT	AVERAGE HEAT RECOVERY	SPECIFIC HEAT RECOVERY	CAPACITY FACTOR*	ELECTRICAL EFFICIENCY	HEAT EFFICIENCY	OVERALL CHP EFFICIENCY
(MM)	(kW)	(kWh/LB VS ADDED)	(kW)	(kWh/LB VS ADDED)	(%)	(% LHV)	(% LHV)	(% LHV)
01	41	0.012	58	0.016	19%	29%	41%	70%
02	75	0.019	107	0.028	35%	30%	43%	73%
03	128	0.032	183	0.045	61%	31%	44%	75%
04	130	0.039	183	0.054	61%	30%	42%	72%
05	137	0.057	194	0.080	65%	30%	43%	73%
06	120	0.047	178	0.070	56%	30%	44%	74%
07	77	0.026	134	0.045	36%	25%	43%	67%
08	8	0.003	15	0.005	4%	19%	37%	56%
09	48	0.016	37	0.012	23%	23%	18%	42%
10	45	0.012	48	0.013	21%	25%	27%	52%
11	23	0.006	33	0.008	11%	29%	40%	69%
12	17	0.004	25	0.006	8%	27%	38%	64%
AVE	71	0.023	100	0.032	33%	27%	38%	66%

* Note: Heat recovered from engine was used internally for digester heating. Heat not recovered for other use.

The system was run at approximately 33 percent capacity factor. The actual online time for the engine generator was only about 40 percent so the system was consistently operated at about 80-90 percent of the nameplate biogas capacity when operated. The electrical efficiency of the system was observed to be 28 percent with a recovered heat efficiency of 38 percent from the jacket water and exhaust for an overall combined-heat and power efficiency of 66 percent, on a lower heating value basis.

6.3.5 Mass and Energy Flows

The process flows throughout the manure handling system are shown in Table 10 below. It can be seen where volumes of liquids and masses of water, solids, and volatile solids (VS) are added and removed from the manure collection and handling system at the dairy. The estimated average daily amounts of recycled flush water and fresh collected manure make up the total digester influent composition. The digester then converts 4 percent of the volatile solids to produce biogas, only slightly reducing the solids loading on the process water largely dominated by recycled solids. After the digester, the rotary screen separator removes another 6 percent of solids. The final liquid remaining after the process goes to an intermediate storage to be recycled for flushing or to a secondary storage pond to irrigate feed crop land around the dairy. Figure 13 is a graphical representation of the average mass, solids, and energy balances for the Dairy 2 Digester system, based on the data collection and analysis from the study.

Table 6.10: Daily Process Volume and Mass Flows.

Process Water/ Solids Stream	Liquid Volume (gal/day)	Total Mass (lbs/day)	Solids Conc. (%)	VS Conc. (%TS)	Water Mass (lbs/day)	Solids Mass (lbs/day)	VS Mass (lbs/day)	Solids Removal (%)	VS Removal (%)
Fresh Water	9,000	75,100	-	-	75,100	-	-		
Recycle Water	664,900	5,545,000	1.8	62.8	5,446,200	98,700	62,000		
Collected Manure	22,800	190,000	12.5	80.0	166,300	23,800	19,000		
Influent	696,600	5,810,000	2.1	66.8	5,687,500	122,500	81,000		
Effluent	696,000	5,804,800	2.0	66.5	5,687,500	117,300	77,900	4.3%	3.8%
Rotary Screen Separator	-	31,500	22.4	75.0	24,500	7,100	5,300	6.0%	6.8%
To Lagoon	692,200	5,773,300	1.9	65.9	5,663,100	110,200	72,600		

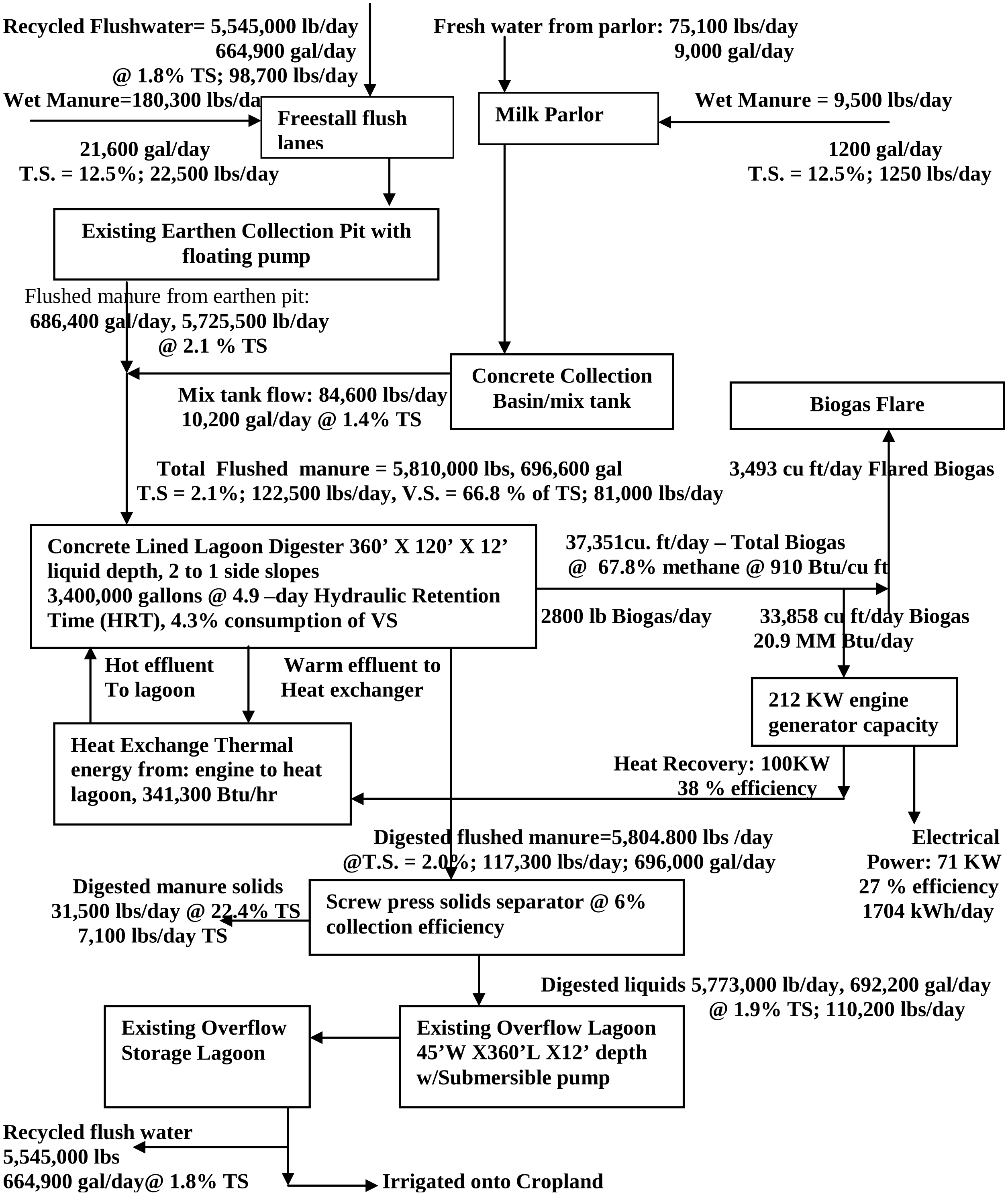

Figure 6.13: Average Mass and Energy Flow Diagram Wth Daily Flows For Dairy and Digester System.

6.3.6 Climate Change Impact

Using the data collected from the study, the Climate Action Registry Livestock Protocol was used to compute the amount greenhouse gas emissions reductions that have resulted from the digester project. The protocol provides a methodology for quantifying the baseline greenhouse gas emissions and comparing those with the emissions estimated to still be generated from the digester system or biogas control system (BCS) as the digester system is called by the Registry. The baseline emissions are the methane emissions that would have occurred from decomposition of manure in a lagoon storage system if the digester was not constructed. The project emissions are from un-burned methane from the engine and digester leakage and/or venting and methane generated in the effluent storage pond. The difference between the baseline and project emissions are a conservative estimate of the climate impact of the digester system. The results are shown in Table 11.

The total methane reductions are available to the facility as carbon credits through a verification process with the registry. Carbon credits represent a potential source of revenue depending on the value of the credits in the marketplace. Note that there is also a cost in establishing these credits (including monitoring system installation costs, data collection costs, and third-party reporting and verification) and this has been seen to potentially be prohibitive for some small projects.

The results show that the baseline methane emissions of the facility are about 176 tonnes (metric tons or 1000 kg) per year. The project methane emissions of the facility are estimated to be 37 tonnes from the BCS and 29 tonnes from the effluent storage pond or 66 tonnes total. The difference is 109 tonnes of methane for a total reduction of almost 1400 tonnes of carbon dioxide equivalents to the atmosphere. This represents a 62 percent reduction in greenhouse gas emissions associated with manure management at the facility. Note that this is not the 127 tonnes of methane that is actually destroyed by the engine and flare each year but better represents the climate impact of the digester project than the actual methane destruction.

Table 6.11: Climate Modeling Results for Digester Project Including Estimated Methane Reductions.

	Tonnes CH4 Per Year	***Tonnes CO2e Per Year***
Total Modeled Baseline Methane Emissions	***175.5***	***3685***
Project Methane Emissions from the BCS	37.0	777
Project Methane Emissions from Effluent Pond	29.3	614
Total Project Methane Emissions	***66.3***	***1391***
Total Methane Reductions	***109.2***	***2293***
Methane Destroyed in the BCS	127.1	2669

6.4 Dairy 4 Conclusions

The project generated results for the annual performance of a hybrid mixed lagoon dairy digester system coupled with a cogeneration system for conversion of biogas into power and heat. The following conclusions provide normalized results so that the study of this system can be compared with other digester systems in terms of overall characteristic performance.

DIGESTER FEEDING: The digester influent feed came from recycled flush water containing solids and an amount of fresh manure solids. The influent volatile solids contained about 80 percent of the volatile solids estimated to be generated by the dairy herd, but these only made up about 24 percent of the solids in the influent feed. The influent had an average total solids concentration of 2.1 percent which consisted of 68 percent volatile solids. The digester was only fed with fresh and recycled manure solids with a more detailed constituent analysis shown in Table 4.

DIGESTER PERFORMANCE: The project results showed relatively low performance for this digester. The digester had low volatile solids reduction and gas production over the year. The average hydraulic retention time was 4.9 days with an organic loading rate of 178 pounds of volatile solids per thousand cubic feet per day which are well outside the recommended range for digestion. Average digester temperature was 62°F and varied seasonally throughout the year. The study estimated that the digester reduced volatile solids by 4 percent, but these results were not statistically significant due to the variability in the monthly influent and effluent samples. There were no other statistically significant changes to the digestate composition within the digester system as shown in Table 7.

BIOGAS PRODUCTION: The digester produced an average of only 0.6 cubic feet of biogas per pound of volatile solids added or 16 cubic feet per pound of volatile solids consumed. The composition of the biogas was consistently about 68 percent methane and 29 percent carbon dioxide with a small amount of nitrogen and oxygen from an air injection system. Hydrogen sulfide content was very high at an average of 2400 parts per million without control to an average of 56 parts per million after the addition of an air injection system.

BIOGAS GENERATOR PERFORMANCE: The engine-generator for this project operated at a capacity factor of 33 percent. The electrical efficiency averaged 27 percent and the recovered heat efficiency 38 percent for a total efficiency of 66 percent expressed on a lower heating value basis. The engine jacket water was used to heat the digester system and additional available heat from the exhaust was not utilized.

CLIMATE CHANGE IMPACT: Utilizing the methodology developed for predicting livestock emissions reductions from manure digester projects, it is estimated that the baseline and digester project emissions of methane are 175 and 66 tonnes per year respectively , for a total reduction due to the installation and operation of the digester of 62 percent. This is equates to 2300 tonnes of carbon dioxide equivalents per year that could potentially be traded as carbon credits which is about 2.7 tonnes per lactating cow at the dairy.

CHAPTER 7:
Dairy 5 Results

7.1 Diary 5 Background

Dairy 5 is a dairy farm located in the Northern San Joaquin Valley of California. Anaerobic digester gas (biogas) is being captured from two heated complete mix digesters at this combined dairy and farmstead cheese making operation. The biogas is used to drive a 710 kW engine-generator unit. The electrical power is being utilized by the dairy and sold to the grid through a metering arrangement with the local utility district. Waste heat from the generator is utilized for hot water in the dairy farm and the on-site cheese-making operation.

The complete mix digester system was designed by and equipment supplier from Germany. The digesters are two above ground concrete tanks with an 82 ft diameter and 26 foot depth. The digesters are located adjacent to the freestall dairy barns. Flushed manure from Dairy 5's 1700-cow dairy along with whey from the cheese plant is collected in a multi-staged settling basin, Figure 1. Through settling and screening, the solids content of the manure is increased prior to being pumped into the digester where the desired total solids content is 10 percent. Liquids are recycled for flushing the freestall barns. The concentrated manure liquids are then pumped into the 850,000-gallon tanks resulting in an approximate 28-day hydraulic retention time. Approximately 30 tons of green chopped Sudan grass hay and the screened solids from the manure are also added directly to each digester via a solids loading bin and auger system, Figure 2. The digesters, Figure 3, are maintained at a mesophilic temperature of approximately 100°F under anaerobic conditions, providing favorable conditions for natural microbial action to convert the organic matter in the manure and cheese plant wastewater into approximately 300,000 cubic feet per day of methane-rich biogas. The effluent from the digesters is pumped through two screw press solids separators, Figure 4, where the fibrous solids are collected and composted for use as bedding and fertilizer.

A dome-shaped cover that encloses each digester tank, Figure 3, captures the biogas, and channels it into a pipeline where it is chilled to remove liquids and pumped across the dairy farm to the co-generation system located adjacent to the site of the future cheese plant. The biogas fuel is delivered to the 710-KW synchronous generator system, Figure 5, which operates 24 hours per day except during maintenance. The generator system uses a lean burn engine. The generator exhaust is filtered by a selective catalytic reduction (SCR) system that reduces NOx in the exhaust.

Figure 7.1: Manure Collection Settling Basins.

Figure 7.2: Bin for Loading Solids to Digesters.

Figure 7.3: Complete Mix Digester Tanks.

Figure 7.4: Manure Solids Separation.

Figure 7.5: 710-KW Engine-Generator System.

Figure 7.6: Heat Radiators Near Engine Room.

Table 7.1: Dairy 1 Digester System Description.

Digester	Two Concrete Tanks, 850,000 Gallon capacity each Heated and Mixed Dome Shaped HDPE cover Fibrous solids separation after digestion Digester feed of thickened manure, whey, manure solids, and green chopped Sudan grass hay
Engine-Generator	Lean Burn Engine/ Synchronous Generator 710 kW output on biogas, 480 VAC, 3 phase Estimated 36% LHV shaft efficiency
Biogas Treatment	Air injection system under digester cover Biogas chiller for "dewatering"
Heat Recovery	Hot water for dairy and cheese plant Currently using back-up radiator system for heat rejection Jacket and exhaust heat exchangers utilized

The electricity generated provides for the electrical requirements of the dairy farm and the future cheese plant expansion and provides excess power to the grid through a metering interconnection agreement with the utility district. The heat from the generator engine and exhaust system is captured via heat exchanger which is used to produce hot water for the cheese plant expansion or is exhausted via radiators adjacent to the engine room, Figure 6.

The flare is normally off so that biogas can be used by the engine to produce electricity. If the engine-generator is shut off and the gas pressure under the covers increases above safe levels, the flare is automatically activated to destroy the unused biogas.

The Figure 7 schematic shows the overall biogas and power generation systems. Details on typical mass and energy flows are given in the process flow diagram in Figure 13. A manure and water flow diagram for the Dairy 5 facility is shown in Figure 14.

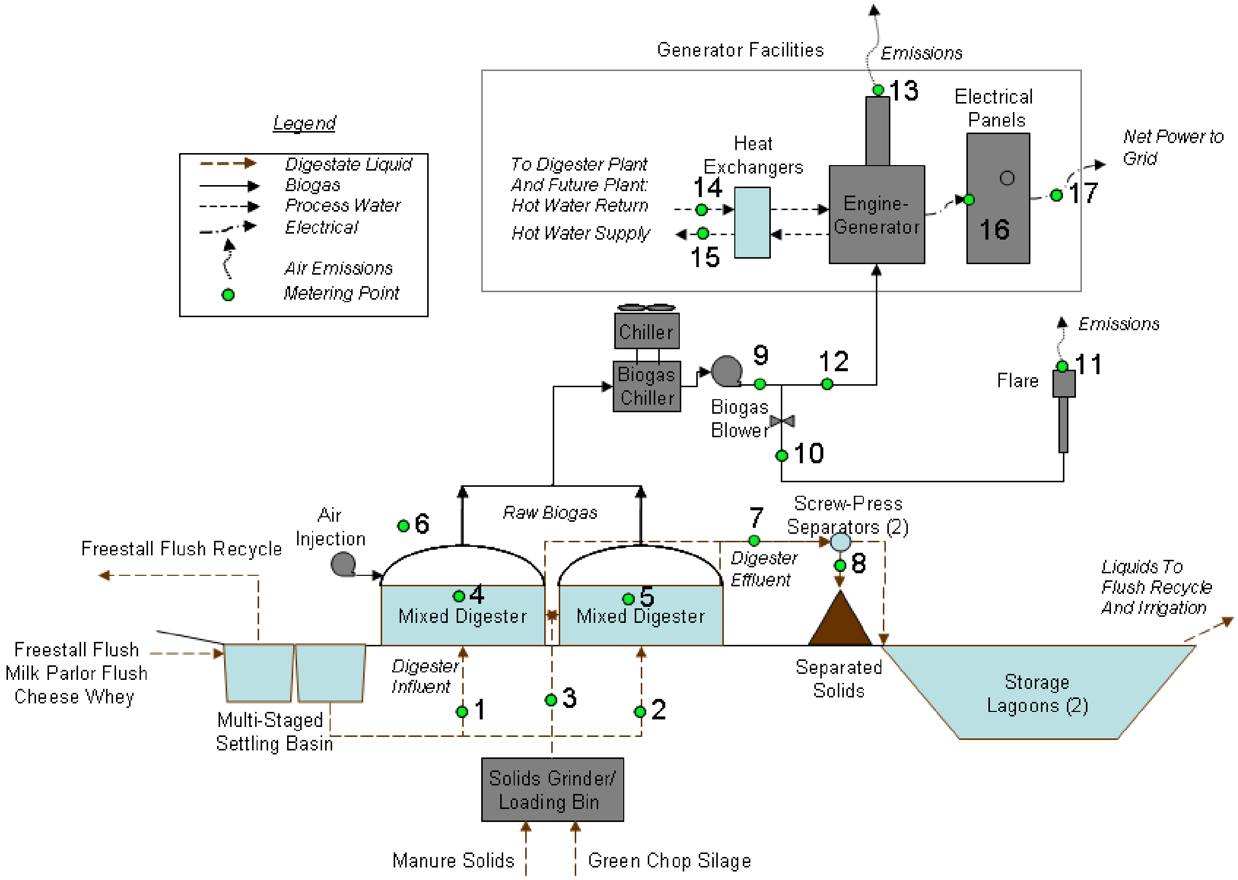

Figure 7.7: Schematic of Biogas System With Metering Points.

7.2 Dairy 5 Materials and Methods

The monitoring methodology and system followed protocols developed by ASERTTI, California Climate Action Registry, and US EPA. Continuous sensors will monitored pertinent system flows and conditions including those shown in Table 2. This data was recorded in data logger equipment and 15-minute averages were continuously logged and stored on site before periodic downloads by the investigators. Sampling locations are shown on the schematic in Figure 7. These sampling points cover all pertinent manure, biogas, power and process water flows and temperatures. Composition samples were taken on approximately a monthly basis to establish the mass distribution for each flow of manure, biogas and emissions. These samples were collected on behalf of the dairy owner who provided them to this study for analysis using the same protocols used for the other digester systems.[8]

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[8] The same raw data was also analyzed in the following study using a somewhat different methodology than used in this study: Stringfellow, William, Mary Kay Camarillo, Jeremy Hanlon, Michael Jue, and Chelsea Spier, Final Report, Assistance Agreement DE-EE0001895 “Measurement and Evaluation of a Dairy Anaerobic Digestion/Power Generation System” from the United States Department of Energy National Energy Technology Laboratory, October 2011.

The monitoring system takes advantage of the existing data collection by the control systems at the site configured to capture the specific data points listed in Table 2. Some new sensors will be added to these systems to cover all of the needs. Each sensor will be sampled and averaged or summed into 15-minute data as appropriate. The PLC-based systems will provide the investigators and CEC access to the time-stamped 15-minute data via the internet. The on-site control system also has the ability to store and retain several hundred days of 15-minute data in the event that communications are lost.

The electrical output of the engine-generator (WGO) will be measured with a generator power transducer already installed in the engine control panel. A utility supplied power meter also indicated the amount of power that is exported (WGT) by the engine. The net power exported to the grid will also be supplied by the utility supplied metering (WNT).

The biogas delivered to the engine (FGE) is measured by a calibrated gas flow meter (hot-wire probe) that determines the mass flow in standard cubic feet per minute. In addition another meter measures biogas flow to the flare (FGF). The flare temperature (TEF) establishes when the flare is lit and biogas is being burned in the flare. The total biogas flow (FGT) is the sum of FGE and FGF. From the biogas and power measurements we can calculate the engine efficiency using the measured gas composition data. The gas flows also allow for an estimate of emissions from the engine (FEE) and the flare (FEF) using standard combustion assumptions.

The digester temperatures (TMI, TME, TD1 and TD2) are measured by thermocouples at the influent and effluent pipes and placed within each digester. The ambient temperature (TAO) will be recorded to understand how digester performance varies with weather conditions.

The flow of manure into the digester (FMI) was measured with an in-line flow meter supplied with the digester system. Since the digesters are maintained at constant volume, it was assumed that influent and effluent water flow were balanced, therefore the water portion of FMO is estimated to be equal to the water portion of FMI. Note that solids are consumed in the process but water is assumed to be balanced. In addition, the solids input (FSI) to the digesters is monitored using load cells in the loading bin. The flow of manure solids (FMS) separated from the effluent stream was estimated by balancing the solids going into and out of the screw press separator. Also pile size volume and density estimates were used for comparison.

The thermal output recovered from the engine jacket to the heat exchanger was be determined from the coolant water flow and temperature difference data (FC, TCI, TCO, TCE). The thermal energy actually utilized for process water heating was determined from the process water flow and temperature difference data (FWP, TWI, TWO).

Table 7.2: Monitoring Points on the Dairy 5 Digester System. Monitoring Locations Shown on Figure 7.

Loc #	Data Point	Description	Eng. Units	Sensor or Instrument	Typical Range
1&2	FMI	Flow of Manure, Influent to Digesters	gallon/day	System inline flowmeters	0-25,000
	TMI	Temperature of Manure, Influent to Digesters	°F	Thermocouple	40-85
	CMI	Composition of Manure, Influent to Digesters	mg/l	Monthly samples	35,000-90,000 TS
3	FSI	Flow of Solids, Influent to Digesters	Lbs/day	Load cells on solids bin	0-50,000
	CSI	Composition of Solids, Influent to Digesters	mg/kg	Monthly samples	130,000-315,000 TS
4	TD1	Temperature of Digester 1	°F	Thermocouple	95-105
5	TD2	Temperature of Digester 2	°F	Thermocouple	95-105
6	TAO	Temperature of Ambient Out	°F	Thermocouple	35-105
7	FME	Flow of Manure, Effluent to Digester	gallon/day	Estimated from FMI	=FMI (water balance)
	TME	Temperature of Manure, Effluent to Digester	°F	Type-K TC, 6 in probe	95-105
	CME	Composition of Manure, Effluent to Digester	mg/l	Monthly samples, 24h	65,000 – 90,000 TS
8	FMS	Flow of Manure Solids	lb/day	Monthly weight est.	35,000 – 50,000
	CMS	Composition of Manure Solids	mg/kg	Monthly samples	200,000 – 250,000
9	FGT	Flow of Gas Total (Raw Biogas)	SCF/day	Estimated from FGE & FGF	180,000-250,000
	CGT	Composition of Gas Total (Raw Biogas)	% by vol.	Online analyzer	60-70% CH4
10	FGF	Flow of Gas to Flare (Raw Biogas)	SCF/day	Sage Prime SIP	0-200,000
	CGF	Composition of Gas to Flare (Raw Biogas)	% by vol.	Monthly analysis	=CGT
11	FEF	Flow of Emissions from Flare	SCF/day	Estimated from FGF	0-300,000
	CEF	Composition of Emissions from Flare	% or ppm	Monthly analysis	8% O2
12	FGE	Flow of Gas to Engine (Conditioned Biogas)	SCF/day	Sage Prime SIP	0-240,000
	CGF	Composition of Gas to Engine (Conditioned)	% by vol.	Monthly analysis	=CGT
13	FEE	Flow of Emissions from Engine	SCF/day	Estimated from FGE and CEF	0-400,000
	CEF	Composition of Emissions from Engine	% or ppm	Monthly analysis	2-4% O2
14	TWI	Temperature of Water Inlet (Process Water into Heat Exchanger)	°F	Type-K TC, 6 in probe	177-207
15	TWO	Temperature of Water Outlet (Process Water out of Heat Exchanger)	°F	Type-K TC, 6 in probe	150-200
	FWP	Flow of Water to Process	gpm	Onicon F1100	0-40
16	WGO	Watts of Generator Output (Power at Generator)	kWh/int	Genset power meter	0-650
17	WNT	Watts of Net Total (Power after Parasitic Loads)	kWh/int	Utility meter - pulse	0-640

The parasitic power consumption of various components in the system were determined by power readings with a hand-held meter capable of measuring true power. The sum of all parasitic loads not accounted for in the net metering was compared with the power generated by the system.

The composition of the manure influent and effluent was measured on a monthly basis by taking representative samples at the dairy and subsequently sent overnight for laboratory analysis for the components described in Appendix A. Samples were prepared using an aggregate of five grab samples collected during the manure input cycle. Because of the inherent problems with using a sample from a single day to represent the composition for an entire month, a smoothing function that included the prior and subsequent month results was used to represent the reported monthly composition. The amount of solids removed by the separator was also estimated on a monthly basis by estimating the pile volume and collection period. Solids were also laboratory analyzed on a quarterly basis for the components described in Appendix A.

The composition of the biogas was measured using online sensors on the system and compared with results from a GEM™2000 Portable Gas Analyzer from Landtec on a monthly basis. This sampling included raw and conditioned biogas. The portable Landtec meter was used to determine the percentage of CH_4, CO_2, O_2, H_2S and balance gas on a monthly basis. The emissions from the engine were measured using a Testo 350XL portable analyzer. The metering equipment was calibrated on a routine basis and the estimated accuracy is shown in Appendix A.

Periodic samples of the influent to and effluent from the digester was subjected to a Biochemical Methane Potential (BMP) analysis in a specially-designed apparatus in the Summers Consulting laboratory. BMP analysis is an efficient and economical method for evaluating the rate and extent of biomass conversion to methane under anaerobic conditions. The effluent BMP shows the remaining methane production potential after digestion and provides an estimate of the potential methane produced in a liquid storage pond after digestion.

Annual greenhouse gas emissions reductions were also estimated using the Climate Action Registry Livestock Protocol. This protocol uses a particular methodology to estimate the baseline emissions or emissions from the manure management system without the digester and compares these with estimated emissions from the digester system.

7.3 Dairy 5 Results and Analysis

The following sections summarize the monitoring results of this year-long monitoring campaign and provide annual operational factors including digester feeding, digester performance, biogas production, biogas generator performance, and climate change impact. The monthly sampling was initiated in 2009 and continued through early 2012. The time period of January through December of 2010 was selected for this analysis because there was the most control over the inputs and outputs to the digester. Additional data on the heat recovery from 2012 was added for this assessment. The actual cow and heifer numbers during the 2010 data collection period are shown in Table 3 along with the estimated daily manure production as predicted by typical estimation method from ASABE.

Table 7.3: Dairy Herd Size Characteristics and Estimated Manure Production at Dairy 5.

DAIRY HERD			**ESTIMATED MANURE PRODUCTION**	
	HEAD (#)	WEIGHT (LB/HEAD)	VOLATILE SOLIDS (LB/HEAD/DAY)	TOTAL VOLATILE SOLIDS (LB/DAY)
Milk Cows	1700	1499	17.0	28,900
Dry Cows	120	1508	9.2	1,104
Heifers	220	897	7.1	1,562
			Total Manure Volatile Solids	31,566

7.3.1 Digester Feeding

During the analysis period, the digesters were fed with a combination of thickened manure solids, screened manure solids, and silage solids. The estimated volumetric flow-rate of influent feeding of the digester including these streams and averaged 35,600 gallons per day over the entire year, but varied monthly from 28,000 to over 53,000 gallons per day. There were some digester adjustments going on during the early months of this period so this lead to a higher variability than would be expected for a timer controlled system. Figure 8 shows the average digester influent flows for each month of the study year and it can be seen that the flowrate stabilized around 30,000 gallons per day by the end of 2010.

The solids loading was also fairly variable in the first few months and then settled in at about 26,000 to 30,000 pounds per day. The average solids feedrate results for the influent mixture is shown in Figure 9. Total solids input to the digester tanks ranged from 26,0000 to 42,000 pounds per day with an average of 28,000 pounds per day over the year. The solids were consistently 75 to 85 percent volatile solids. Volatile solids ranged from 21,000 to 31,000 pounds per day with an average of 24,300 pounds per day over the year.

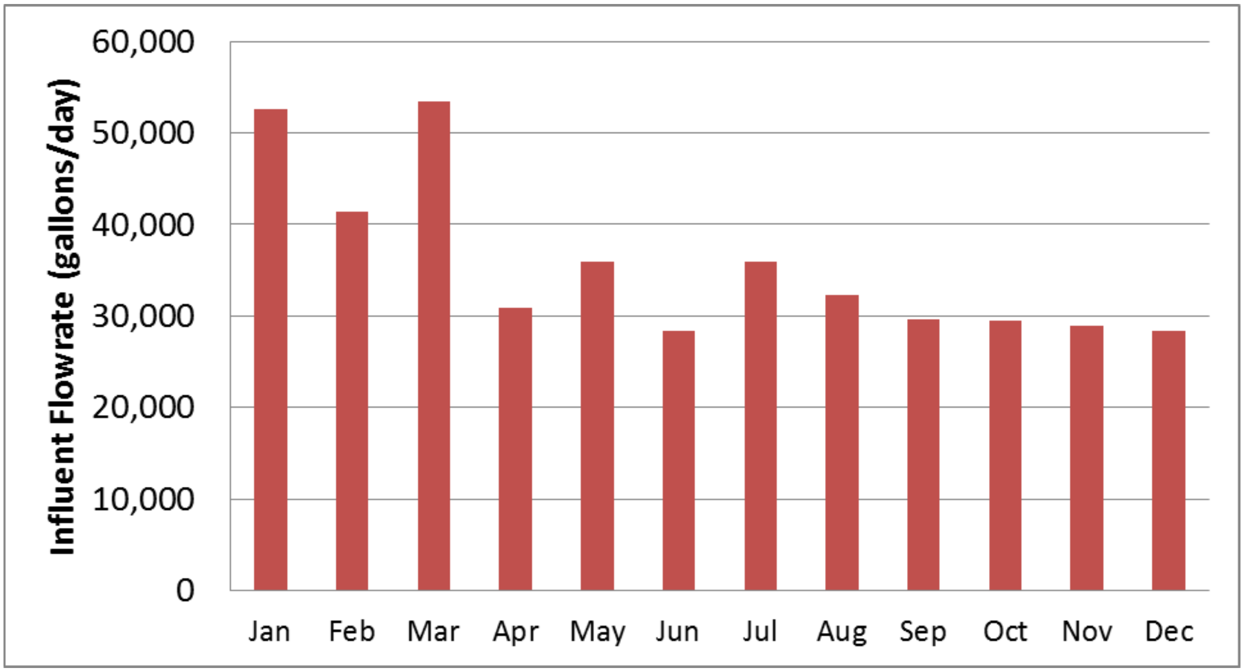

Figure 7.8: Average Monthly Influent Flowrate.

From this system where separation and thickening were used to concentrate the manure fed to the digester, it is interesting to examine the amount of manure solids delivered to the digester. Of the daily volatile solids fed to the digester, it is estimated that 9,300 pounds (38 percent) came from the manure slurry, 6,200 pounds (26 percent) coming from the screened manure with the remaining volatile solids (8,800 pounds or 36 percent) coming from the silage. This means that about 15,500 pounds or 49 percent of the estimated 31,500 pounds of volatile solids excreted from the dairy herd, were added to the digester on a daily basis. A manure capture close to 50 percent with the flush and thickening system used in this project seems like a reasonable result. However, it is lower than direct fed flush and scraped dairy systems analyzed in this study. Table 10 and Figure 13 show the average estimated daily volume and mass flows for the system.

More details on the composition of each of the streams are given in Tables 4 and 5 showing the annual average and standard deviation for all of the samples taken over the year. The input slurry is shown in Table 4 and the silage and screened solids are shown in Table 5.

Also shown in Table 5 are the screwpress separated solids generated from the digester effluent. Using solids balances, it was determined that about 53 percent of the total solids in the digester effluent or about 11,000 pounds of total solids per day are removed by the screwpress separator after the digestion process. These separated solids can be valuable as a composted bed material or for use in farming or horticultural soil amendment. Additional information on the flows of liquids and solids throughout the dairy facility are shown in Table 10 and Figure 13 in the section on mass and energy balances.

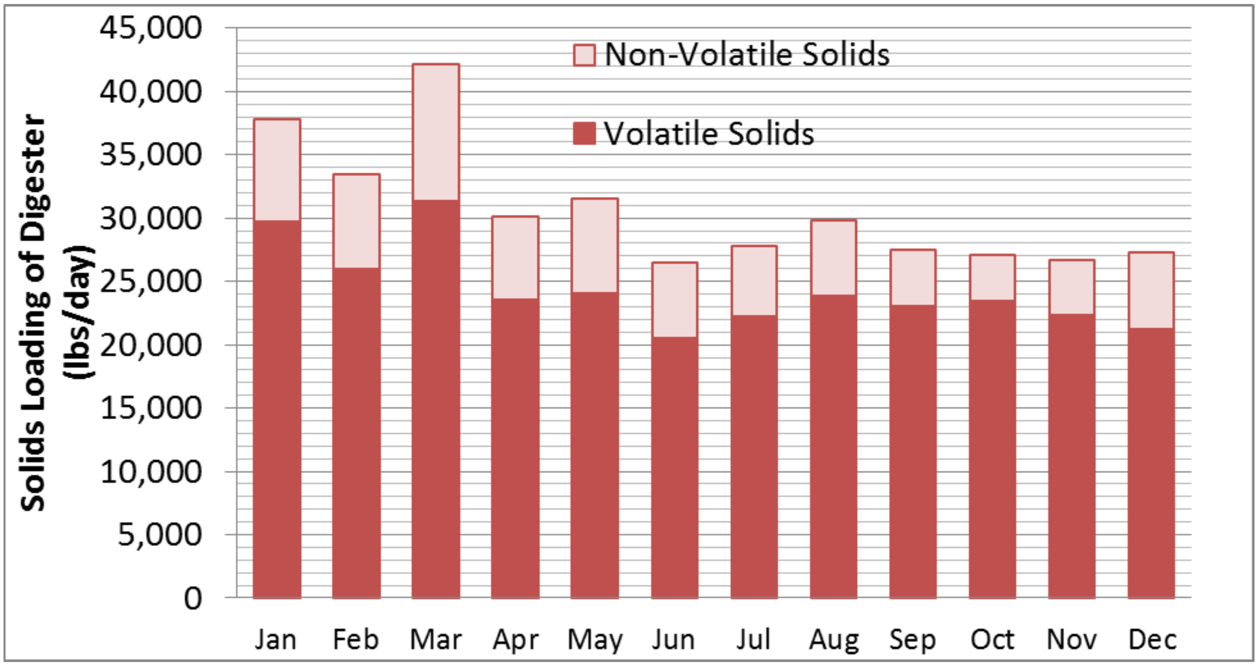

Figure 7.9: Total Solids loading of Digester Influent With Volatile and Non-Volatile Fractions.

Table 7.4: Composition of Various Constituents of the Thickened Manure Slurry Input to the Digester. Average and Standard Deviation of the Samples Taken Over the Study.

Analyte	Units	Average	St Dev
Total Solids	mg/L	64,788	20,936
Volatile Solids	mg/L	41,994	11,963
Total Dissolved Solids	mg/L	7,811	1,449
Ammonia-N	mg/L	295	81
Total Nitrogen	mg/L	1,000	172
Total Phosphorus	mg/L	266	66
Total Potassium	mg/L	717	173
Total Cl	mg/L	368	80

Table 7.5: Composition of Various Constituents of the Silage and Screened Manure Solids (Input to Digester) and Screwpress Solids (Removed From Digester Effluent). Average and Standard Deviation of the Samples Taken Over the Study.

		Silage Solids		Screened Manure		Screwpress Solids	
Analyte	Units	Average	St Dev	Average	St Dev	Average	St Dev
Total Solids	mg/kg	259,182	51,180	177,931	25,105	224,758	29,362
Volatile Solids	mg/kg	219,930	47,384	155,353	22,318	180,102	18,771
Total Nitrogen	mg/kg	16,900	3,639	15,056	1,532	20,785	1,852
Total Potassium	mg/kg	27,186	12,263	3,612	1,270	5,568	1,238
Total Sulfur	mg/kg	1,441	351	2,315	412	3,661	500

7.3.2 Digester Performance

The digester was fed a daily dose of volatile solids from the manure and silage throughout the study, the fuel or food for the anaerobic digestion process. The average amount of volatile solids loaded into the digester was 24,300 pounds per day with 64 percent coming from concentrated manure and 36 percent coming from silage as discussed above. The actual measured loading of the digester for each month of operation that was monitored can be seen in Table 6 – Digester Feeding.

Table 7.6: Digester Influent Feeding and Performance Parameters.

	DIGESTER FEEDING				DIGESTER PERFORMANCE			
MONTH	INFLUENT FLOWRATE	TOTAL SOLIDS CONC.	VOLATILE SOLIDS CONC.	INFLUENT VOLATILE SOLIDS	AVERAGE DIGESTER TEMP	ORGANIC LOADING RATE	HYDRAULIC RETENTION TIME	VOLATALE SOLIDS CONSUMPTION
(MM)	(GAL/DAY)	(%)	(% TS)	(LBS /DAY)	(DEG F)	(LB VS /1000 CF/DAY)	(DAY)	(%)
01	52,636	8.6	78.5	29,675	99.6	131	37.0	30.0
02	41,421	9.7	77.5	25,952	99.6	114	55.3	33.8
03	53,411	9.5	74.3	31,336	101.9	138	36.7	29.4

04	30,835	11.7	78.2	23,550	102.3	104	80.9	47.6
05	35,902	10.5	76.3	24,088	102.2	106	66.1	39.5
06	28,404	11.2	77.4	20,493	102.0	90	65.4	43.7
07	35,941	9.3	80.1	22,281	102.1	98	55.9	37.4
08	32,239	11.1	80.2	23,902	103.1	105	62.0	47.0
09	29,665	11.1	83.7	23,022	102.0	101	66.3	51.0
10	29,478	11.0	86.7	23,494	101.5	103	66.2	53.3
11	28,934	11.1	83.6	22,326	100.8	98	68.0	50.6
12	28,415	11.5	77.9	21,214	100.6	93	73.3	45.9
AVE	35,607	10.5	79.5	24,278	101.5	107	61.1	42.4

The digester appeared to maintain stable anaerobic digestion throughout the study as evidenced by the consistent volatile solids consumption observed averaging 42.4 percent. The average daily organic loading rate of 107 pounds of volatile solids per thousand cubic feet is on the low end of the recommended loading rate of 100-200 pounds of volatile solids per thousand cubic feet for a heated mixed digester system. The 61 day average hydraulic retention time is also longer the recommended HRT of 30 days for this type of digester system. This indicates that the system is under-loaded and has the potential to absorb additional solids loading to generate additional biogas. It is the intention of this dairy to expand the feedstock to the digester over time. The digester temperature was controlled very close to 100 degrees Fahrenheit maintaining mesophillic anaerobic activity. All of these performance factors calculated for each month of the study period are shown in Table 6 – Digester Performance.

Consumption, conversion, and accumulation of the wastewater constituents within the digestion system are of interest and were analyzed by looking at the difference between the influent and effluent compositions (Table 7). Statistical analysis was applied to the data observations to determine if there was a statistically significant difference between the influent and the effluent compositions. A two-tailed pair-wise Student's T-test was applied to the data sets for the influent and effluent composition. The null hypothesis is rejected for alpha was less than 0.05, meaning that for p-values less than 0.05, we conclude that there is a statistically significant difference between the influent and the effluent composition and that some conversion occurred within the digester.

The observed averages for composition of influent and effluent are shown in Table 7 along with the percentage difference observed with a bold negative value meaning a reduced concentration after digestion and a bold positive value meaning an increased concentration. The differences that are statistically significant are shown in bold including Total Solids, Volatile Solids, Total Dissolved Solids, and Ammonia-Nitrogen. Solids are reduced as expected and Ammonia increases during the anaerobic process.

All other constituents do not show statistically significant differences (non-bold results) between influent and effluent. These results do not contradict the assumption that nutrients are conserved in the digestate during anaerobic process while volatile solids are consumed, although they may be converted in form. For example, although ammonia nitrogen increases during the digestion process, the total nitrogen difference between inlet and outlet of the digester was not statistically significant.

Table 7.7: Differences Between Influent and Effluent Compositions Observed During the Study.

Analyte	Units	Influent	Effluent	Difference
Total Solids	lb/day	38,309	24,352	**-36.4%**
Volatile Solids	lb/day	28,578	16,637	**-41.8%**
Total Dissolved Solids	lb/day	2,441	2,005	**-17.9%**
Ammonia-N	lb/day	76	185	**144.5%**
Total Nitrogen	lb/day	544	387	-29.0%
Total Potassium	lb/day	498	563	13.1%
Total Cl	lb/day	186	208	11.6%

7.3.3 Biogas Production

The daily biogas generation was primarily delivered to the engine and was fairly consistent throughout the study with a daily production of 220,000 cubic feet per day with little monthly variation throughout the study time period as shown in Table 8 and Figure 10. The system controls and the system operators were able to keep the engine consuming most of the biogas by making adjustments in set-point as can be seen by the fact that only about 1 percent of the gas was flared.

The average specific biogas production for both added and consumed volatile solids are estimated in Table 8. The average value of 9.1 cubic feet per pound of volatile solids added is somewhat higher than yields of 6 to 8 cubic feet per pound from successful and stable dairy manure digesters (US EPA, 2012) but not surprising given that this digester also had 36 percent silage added to the mixture. The average value of 21.9 cubic feet per pound of volatile solids consumed is somewhat higher than would be expected from a mass balance perspective because about 15 cubic feet of biogas weighs one pound. The observed biogas production per unit of volatile solids excreted by the herd was 7.0 cubic feet per day (or about 0.5 pounds per pound VS excreted) which can be compared with other dairy digester systems as a performance metric.

Table 7.8: Biogas Production Parameters Observed From the Digester System.

	BIOGAS PRODUCTION					
MONTH	TOTAL BIOGAS*	SPECIFIC BIOGAS	SPECIFIC BIOGAS	SPECIFIC BIOGAS	METHANE	PERCENT FLARED BIOGAS
(MM)	(SCFD)	(SCF/LB VS ADDED)	(SCF/LB VS CONSUMED)	(SCF/LB VS EXCRETED)	(VOL %)	(%)
01	197,639	6.7	22.2	6.3	66.0	0.0%
02	194,470	7.5	22.2	6.2	63.0	5.8%
03	227,966	7.3	24.8	7.2	64.7	0.0%
04	229,586	9.7	20.5	7.3	64.7	0.3%
05	227,875	9.5	23.9	7.2	65.4	0.6%
06	198,130	9.7	22.1	6.3	62.1	1.4%
07	201,803	9.1	24.2	6.4	63.8	6.8%
08	233,022	9.7	20.7	7.4	64.3	0.2%
09	248,507	10.8	21.2	7.9	65.0	0.2%
10	253,552	10.8	20.3	8.0	65.7	0.2%
11	231,785	10.4	20.5	7.3	66.6	0.4%
12	198,590	9.4	20.4	6.3	68.4	0.0%
AVE	220,244	9.2	21.9	7.0	65.0	1.3%

The composition of the biogas was monitored throughout the study. These observations are shown in Figure 11. The methane content was consistently 62-68 percent of the biogas (65.0 percent average). The balance of the gas is primarily carbon dioxide (31.5 percent average), the other major gas product of anaerobic digestion. A small amount of nitrogen (2.7 percent average) and oxygen (0.8 percent average) were present in the gas due to an air injection system that puts a small amount of air below the cover to help control sulfur generation from the digester. The hydrogen sulfide content of the biogas was observed to be between 170 and 350 parts per million by volume (256 ppmv average) as shown in Figure 12. This compares favorably to the 2500+ parts per million hydrogen sulfide content observed in the raw biogas from digester systems without air injection installed but may not be sufficient to get to levels below 250 ppmv if desired.

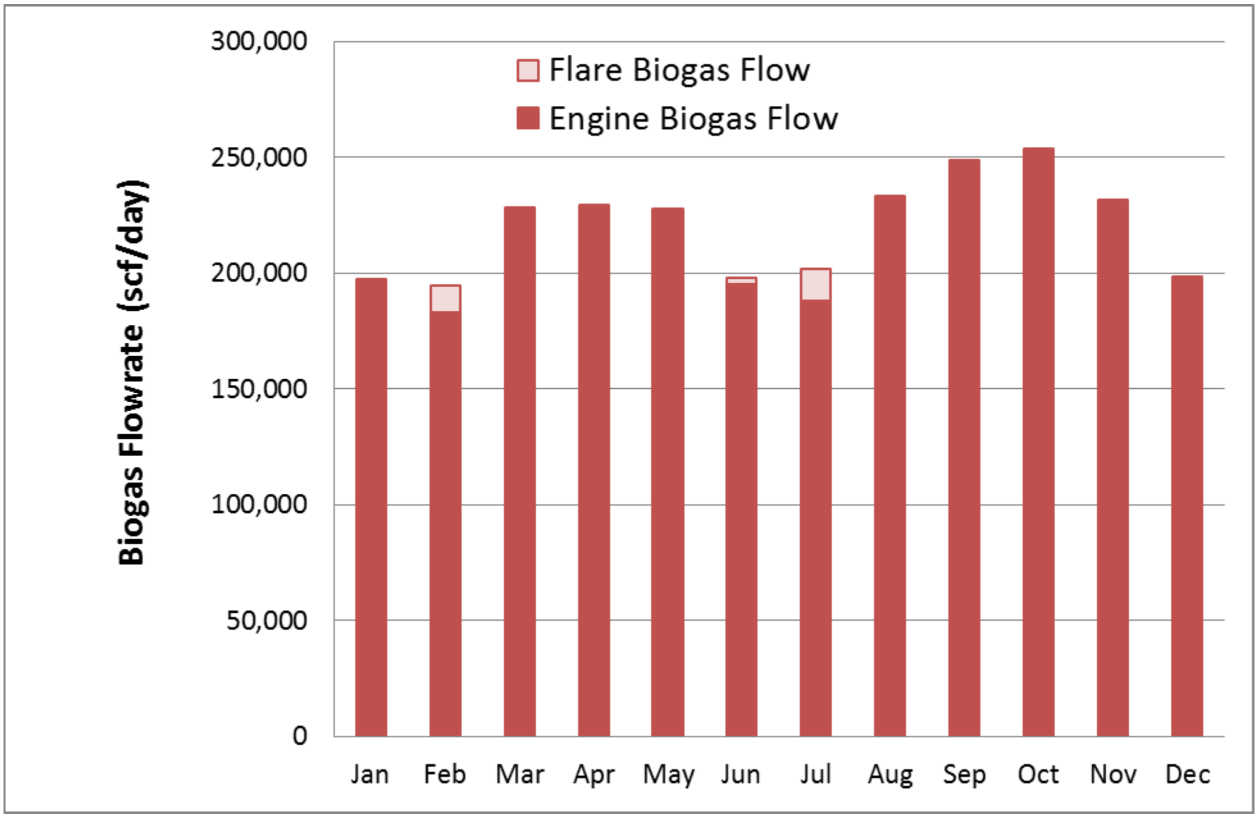

Figure 7.10: Average Daily Biogas Flowrate by Month From the Dairy 5 Digester System.

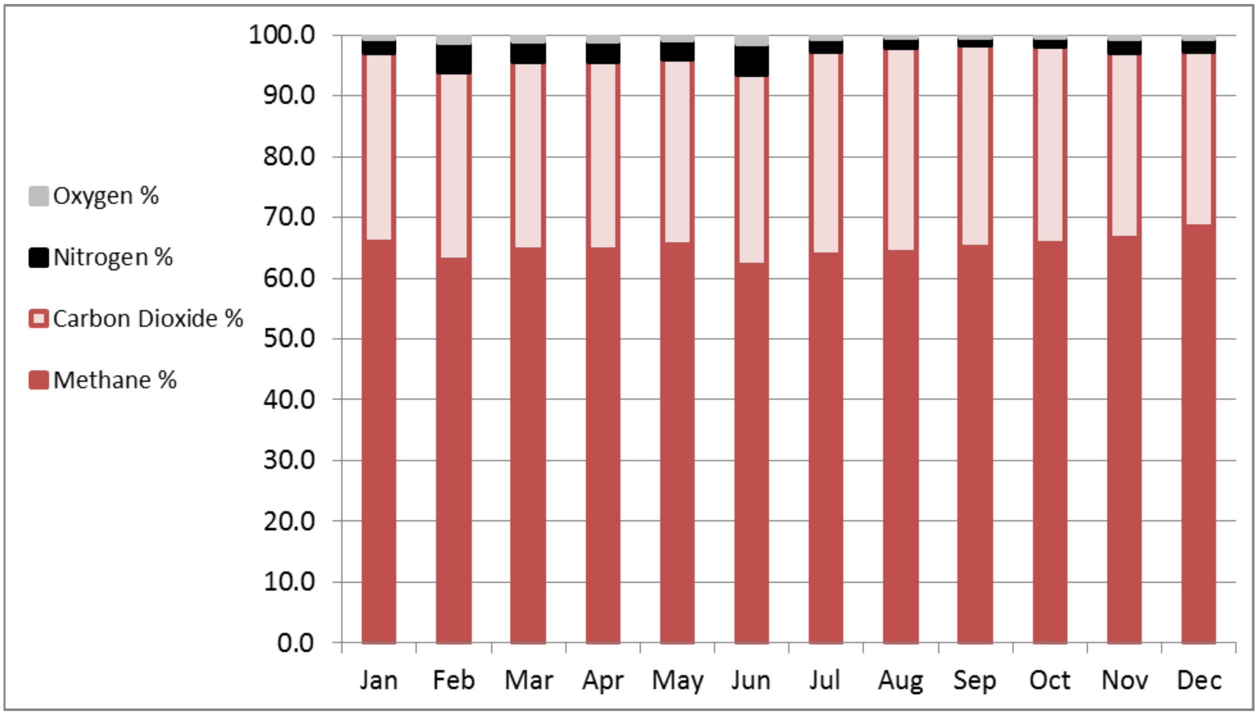

Figure 7.11: Biogas Composition Observed During the Study.

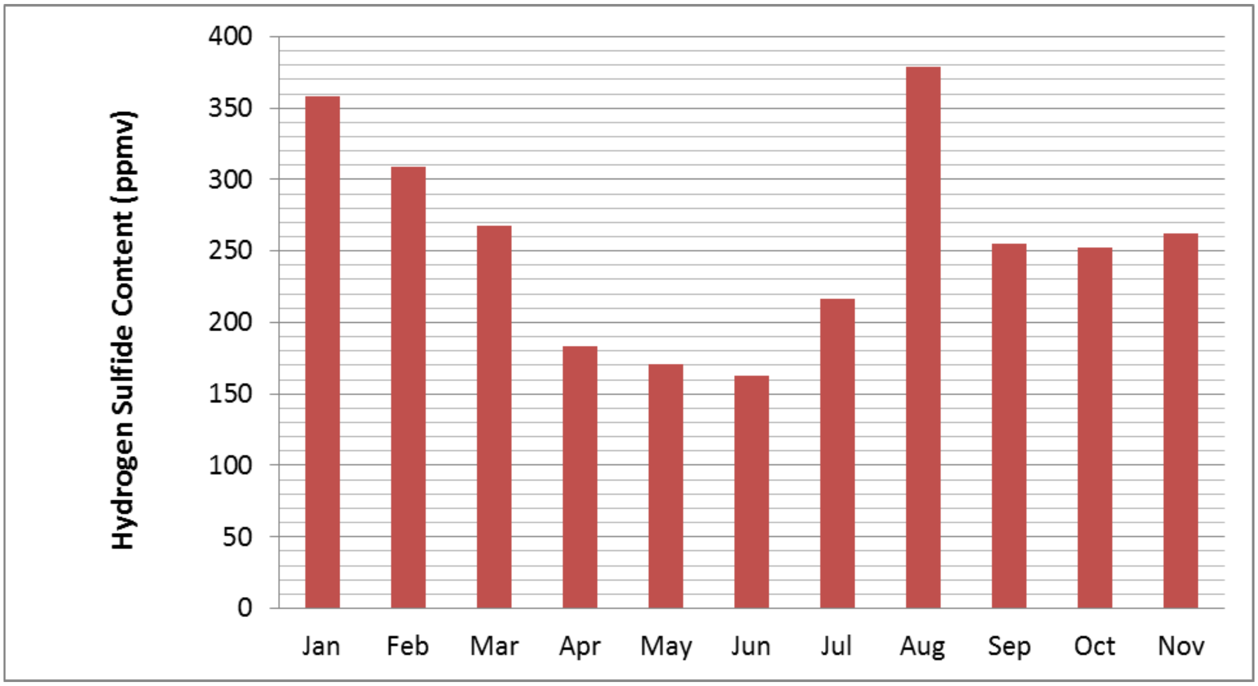

Figure 7.12: Average Monthly Hydrogen Sulfide Concentration in the Biogas Observed.

Biological methane potential (BMP) was also examined for the manure slurry fed to the digester to compare the methane production with actual performance of the digester system with mixed feed. In addition, the biomethane potential of the digester effluent was quantified to determine what additional biogas production potential remains after the digestion process. Using the standard BMP test, average biogas production was 4.8 standard cubic feet (SCF) per pound of volatile solids added for the manure slurry which was only half of the average digester performance of 9.2 SCF per pound of volatile solids added. The biological methane potential was determined to be 3.3 SCF per pound of volatile solids added and 11.4 SCF per pound of volatile solids consumed. The methane potential of the digester effluent was 0.4 SCF per pound of volatile solids showing methane potential for the digestate to be only 10 percent that of the slurry and maybe 5 percent of the actual mixed digester feed.

7.3.4 Biogas Generator Performance

The biomass combined heat and power generator performance was observed including the power and heat utilization from the 710-KW engine generator set. Table 9 shows the results. After a small amount of parasitic load from the pump, gas chiller, and engine skid, the amount of output electrical power was an average of 402 kilowatts over the year. Once installed, the amount of actual heat recovery for use at the dairy and cheese plant was another 420 kilowatts which is equivalent to 16 Therms per hour. This does not include the heat that was used internally to heat the digesters.

The system was run at approximately 57 percent of the generator system's biogas capacity. The actual online time for the engine generator was 95 percent so the system was consistently set to run at only 60 percent of the nameplate capacity. It is suspected that the digester system, because it was not used to capacity, did not produce enough gas to run at closer to capacity. The electrical efficiency of the system was observed to be 26 percent with a heat efficiency of 27 percent for an overall combined-heat and power efficiency of 53 percent, on a lower heating value basis. This is below the values reported by the engine manufacturer. This may be due to the parasitic loads and due to an expected lower electrical efficiency with a setpoint significantly lower than the generator capacity. Efficiency is generally optimized at full capacity and drops off at lower heat rates. The heat recovery efficiency was only about half of the available heat because the a portion of the heat went to the digester and the heat demand did not meet the total production of the system and some heat was rejected by the radiator.

Table 7.9: Engine Generator Performance Observed During the Study.

	BIOGAS CHP PERFORMANCE							
MONTH	ELECTRICAL POWER OUTPUT	SPECIFIC POWER OUTPUT	AVERAGE HEAT RECOVERY	SPECIFIC HEAT RECOVERY	CAPACITY FACTOR	ELECTRICAL EFFICIENCY	HEAT EFFICIENCY	OVERALL CHP EFFICIENCY
(MM)	(kW)	(kWh/LB VS ADDED)	(kW)	(kWh/LB VS ADDED)	(%)	(% LHV)	(% LHV)	(% LHV)
01	390	0.32	429	0.35	55%	27%	30%	57%
02	283	0.26	301	0.28	40%	22%	23%	46%
03	430	0.33	288	0.22	61%	26%	18%	44%
04	431	0.44	260	0.27	61%	26%	16%	42%
05	434	0.43	431	0.43	61%	26%	26%	53%
06	317	0.37	575	0.67	45%	24%	43%	66%
07	348	0.37	454	0.49	49%	26%	34%	60%
08	435	0.44	510	0.51	61%	26%	31%	57%
09	473	0.49	459	0.48	67%	26%	26%	52%
10	452	0.46	379	0.39	64%	24%	21%	45%
11	438	0.47	526	0.57	62%	26%	31%	56%
12	390	0.44	424	0.48	55%	26%	28%	54%
AVE	402	0.40	420	0.43	57%	26%	27%	53%

7.3.5 Mass and Energy Flows

The mass flows throughout the dairy and digester system are shown in Table 10 below. It can be seen where volumes of liquids and masses of water, solids, and volatile solids (VS) are removed from the r system at the dairy. The average daily amounts of thickened manure slurry, screened manure solids, and silage solids make up the total digester influent feed. The digester then converts 42 percent of the volatile solids to produce biogas, reducing the solids loading of the process water as it leaves the digester. The screw press removes larger fibers and particles from the effluent with a solids removal efficiency of 53 percent before the final liquid goes into the storage pond where can be recycled as flush water or used to irrigate crop land around the dairy. The overall solids reduction efficiency of the combined digester and screw press system is about 68 percent. Figure 13 is a graphical representation of the average mass, solids, and energy balances for the Dairy 5 Digester system, based on the data collection and analysis from the 12 month study.

Table 7.10: Daily Process Water and Solids Volumes and Mass Flows.

Process Water/Solids Stream	Liquid Volume (gal/day)	Total Mass (lbs/day)	Solids Conc. (%)	VS Conc. (%TS)	Water Mass (lbs/day)	Solids Mass (lbs/day)	VS Mass (lbs/day)	Solids Removal (%)	VS Removal (%)
Thickened Manure Slurry	25,500	213,000	6.5	67.2	199,200	13,800	9,300		
Screened Manure Solids		38,600	17.8	90.5	31,700	6,900	6,200		
Silage Solids		38,600	25.9	88.0	28,600	10,000	8,800		
Digester Influent	35,600	291,300	10.5	79.5	260,600	30,700	24,300		
Digester Effluent	33,700	281,300	7.4	68.3	260,600	20,700	14,200	32.4%	42.4%
Screw Press Sep.		49,000	22.5	80.1	37,900	11,000	8,800	53.1%	62.3%
Final Liquid	27,900	232,400	4.2	63.5	222,700	9,700	6,200	68.3%	74.5%

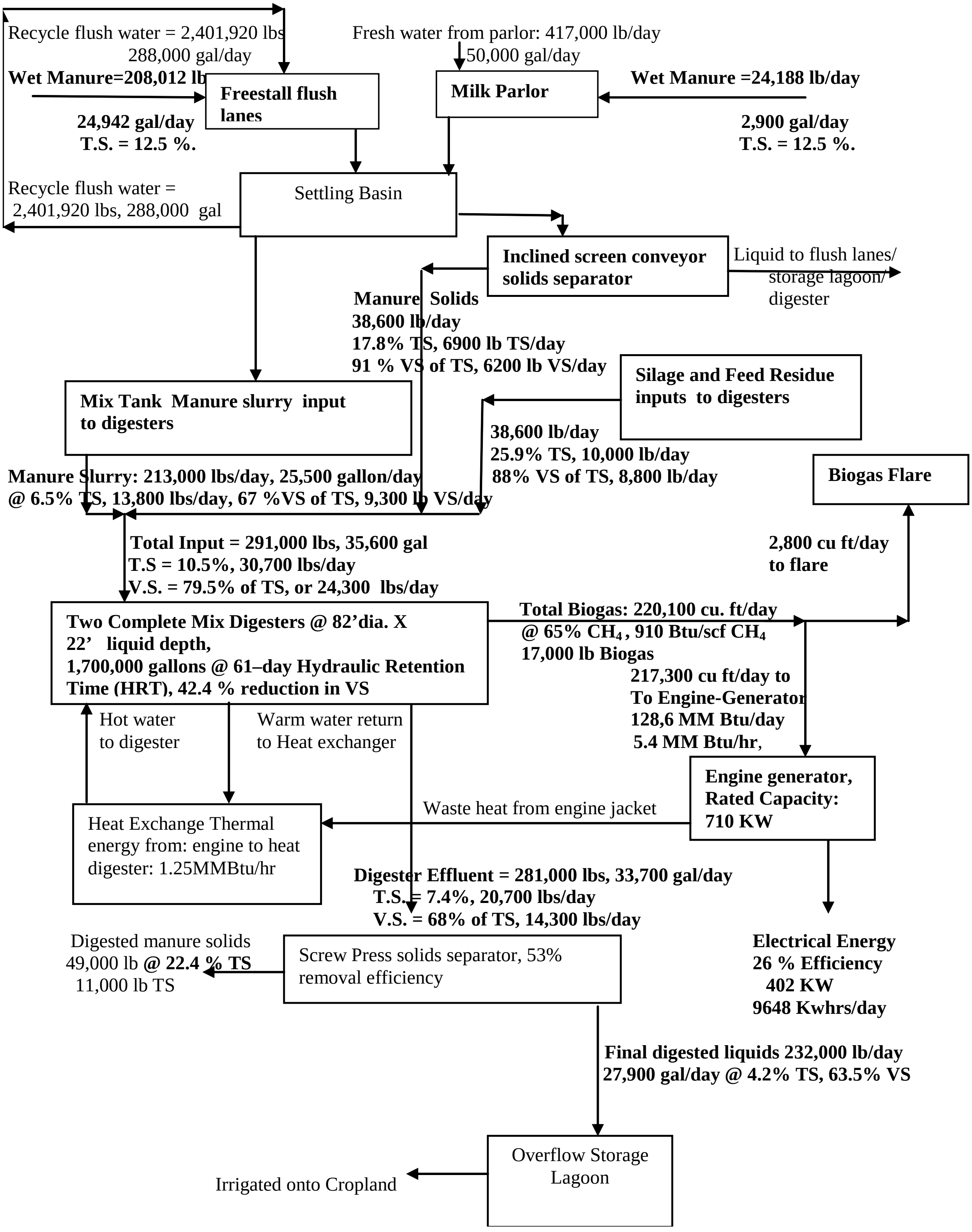

Figure 7.13: Average Mass and Energy Flow Diagram With Daily Flows For Dairy and Digester.

7.3.6 Climate Change Impact

Using the data collected from the study, the Climate Action Registry Livestock Protocol was used to compute the amount greenhouse gas emissions reductions that have resulted from the digester project. The protocol provides a methodology for quantifying the baseline greenhouse gas emissions and comparing those with the emissions estimated to still be generated from the digester system or biogas control system (BCS) as the digester system is called by the Registry. The baseline emissions are the methane emissions that would have occurred from decomposition of manure in an open lagoon system if the digester was not constructed. The project emissions are from un-burned methane from the engine and digester leakage/venting and methane generated in the effluent storage pond. The difference between the baseline and project emissions are a conservative estimate of the climate impact of the digester system and these could be available to the facility as carbon credits. The results are shown in Table 11.

The results show that the baseline methane emissions of the facility are about 328 tonnes (1 metric ton or 1000 kg) per year. The project methane emissions of the facility are estimated to be 85 tonnes from the BCS and 42 tonnes from the effluent storage pond or 127 tonnes total. The difference is 201 tonnes of methane for a total reduction of 4218 tonnes of carbon dioxide equivalents to the atmosphere. This represents a 61 percent reduction in greenhouse gas emissions associated with manure management at the facility. Note that this is substantially less than the 940 tonnes of methane that is actually destroyed by the engine and flare systems each year but better represents the climate impact of the digester project than the actual methane destruction.

Table 7.11: Climate Modeling Results for Digester Project Including Estimated Methane Reductions.

	Tonnes CH4 Per Year	***Tonnes CO2e Per Year***
Total Modeled Baseline Methane Emissions	***327.9***	***6886***
Project Methane Emissions from the BCS	84.8	1780
Project Methane Emissions from Effluent Pond	42.3	888
Total Project Methane Emissions	***127.0***	***2668***
Total Methane Reductions	***200.8***	***4218***
Methane Destroyed in the BCS	940.1	19743

Carbon credits represent a potential source of revenue depending on the value of the credits in the marketplace. Note that there is also a cost in establishing these credits (including monitoring system installation costs, data collection costs, and third-party reporting and verification) and this has been seen to potentially be prohibitive.

7.4 Dairy 5 Conclusions

The project generated results for the annual performance of a complete mix and heated dairy digester system coupled with a cogeneration system for conversion of biogas into power and heat. The following conclusions provide normalized results so that the study of this system can be compared with other digester systems in terms of overall characteristic performance.

DIGESTER FEEDING: The digester influent feed came from a flushed freestall dairy system utilizing a novel thickening and concentrating process to generate manure solids for the digester, mixed with Sudan grass silage solids. The volatile solids introduced to the digester were estimated to consist of 38 percent thickened manure slurry, 26 percent screened solids, and 36 percent silage solids. The estimated total manure collection efficiency from this flush and thickening system was 49 percent. Combining the feed streams, the digester influent had an average total solids concentration of 10.5 percent which consisted of 79.5 percent volatile solids. A more detailed constituent analysis of the digester influent components are shown in Tables 4 and 5.

DIGESTER PERFORMANCE: The digester showed consistent volatile solids reduction and gas production over the year. The average hydraulic retention time was 61 days with an organic loading rate of 102 pounds of volatile solids per thousand cubic feet per day which indicate an under-loaded digester system by industry standards. Average digester temperature was 101.5°F. The study showed that the digester reduced total solids by 36 percent, volatile solids by 42 percent, and dissolved solids by 18 percent during the digestion process. Ammonia nitrogen increased by 145 percent. There were no other statistically significant changes to the digestate composition within the digester system as shown in Table 7.

BIOGAS PRODUCTION: The digester produced an average of 9.2 cubic feet of biogas per pound of volatile solids added or about 22 cubic feet per pound of volatile solids consumed. The composition of the biogas was consistently high in methane at an average of 65.0 percent, but also consisted of 31.5 percent carbon dioxide, 2.7 percent nitrogen, and 0.8 percent oxygen. Hydrogen sulfide content in the biogas was an average of about 250 ppmv lowered by an air injection system from expected levels of over 2,500 ppmv.

BIOGAS GENERATOR PERFORMANCE: The engine-generator for this project operated at a capacity factor of 57 percent although the actual engine online time was 95 percent meaning the engine generator was typically operated below capacity. The electrical efficiency averaged 26 percent and the recovered heat efficiency was 27 percent for a total combined energy efficiency of 53 percent expressed on a lower heating value basis. The actual efficiency might have been increased by running the generator closer to capacity and increasing the heat utilization. Nearly 50 percent of the available heat from the engine jacket and exhaust was used for digester heating or rejected by the radiator.

CLIMATE CHANGE IMPACT: Utilizing the methodology developed for predicting livestock emissions reductions using digesters, it is estimated that the baseline and digester project emissions of methane are 328 and 127 tonnes per year respectively , for a total reduction due to the installation and operation of the digester of 61 percent. This is equates to 4218 tonnes of carbon dioxide equivalents per year that could potentially be traded as carbon credits which is about 2.5 tonnes per lactating cow at the dairy.

CHAPTER 8:
Dairy 6 Results

8.1 Dairy 6 Background

This describes the performance of the Dairy 6 anaerobic digester and power production system in the arid Mojave Desert region of Southern California. Anaerobic digester gas (biogas) is being captured from a heated plug-flow digester at this dairy milking operation. The biogas is used to drive a 190 kW engine-generator unit. The produced electrical power is being utilized by the dairy through a net metering arrangement with Southern California Edison. Waste heat is recovered from the generator to heat the digester.

A monitoring system collected the measured data necessary to quantify the economic and technical performance of the biogas system including the digester conversion of manure to biogas, the energy conversion of biogas to electricity and heat as well as the pertinent air and water emissions to the environment. A mass and energy balance of the system over a 12-month period was developed.

The digester system at Dairy 6 was designed by a digester engineering firm and constructed by dairy staff. The digester is a 500,000 gallon concrete lined rectangular tank digester, Figure 1, operated in a plug-flow mode located adjacent to the dry lot dairy operation. Manure is vacuumed from the concrete feed lanes, Figure 2, of the 2500-cow dairy and delivered to a concrete collection pit, Figure 3. A vacuum truck is used to scrape the manure from the feed lanes and unloaded. During hot weather most of the year, water is added to the drying manure before it is scraped to improve its ability to flow. The digester operator also believes that reducing the thickness of the manure allows more sand to be removed. The manure is mixed and intermittently pumped to a cyclonic sand separator (seen in background of Figure 3) to reduce the amount of sand material entering the digester. On this dry lot dairy, some sand is blown and is pushed by the dairy cows into the feed lanes. Prior to the addition of this sand separator, sand settling and accumulation in the digester was an issue.

Manure is pumped from the collection pit into the digester on a once-daily basis. Approximately 25,000 to 50,000 gallons of manure at about 8 percent solids is pumped into the digester giving the manure a 10-20 day hydraulic retention time. The digester is maintained under mesophilic anaerobic conditions, and provides favorable conditions for natural microbial action to convert the organic matter in the manure into approximately 100,000 cubic feet per day of methane-rich biogas. A custom-engineered cover system encloses the digester tank, captures the biogas, and channels it into a pipeline that exits the digester, Figure 5, and it is transported to a 220-KW co-generation system located adjacent to the digester. The effluent from the digester overflows into a weir into and effluent collection pit at the end of the digester.

Liquid digestate from the effluent pit is pumped to a screening system to remove stabilized solids that provide valuable fertilizer for the farming operation that grows the primary feed for the dairy’s cows. The screening system consists of an inclined screen for coarse solids and a vibrating screen for the fine solids. The remaining liquid effluent is collected in a storage lagoon that provides nutrient rich irrigation water for the farm.

After exiting the digester system, the biogas passes is pulled by a blower through a gas conditioning system intended to remove water vapor and particulate contaminants, Figure 6 background. The fuel is delivered to the engine generator system, Figure 6 foreground, which typically operates 24 hours per day. The system uses an engine and synchronous generator that has a capacity to produce 190 kW on biogas. The electricity generated provides a substantial portion of the electrical requirements of the dairy milking center and on-site facilities through a net metering interconnection agreement with SCE. The heat from the engine system is captured via heat exchanger and used to produce hot water that heats the digester through an internal piping system within the digester. There is no heat recovery on the engine exhaust. The control system for the digester and the generator system, Figure 7, is located on the generator building between the digester and the generator.

Figure 8.1: Plug Flow Digester System at Meadowbrook Dairy with Generator Building in Background.

Figure 8.2: Concrete Feed Lanes of Dry Lot Dairy.

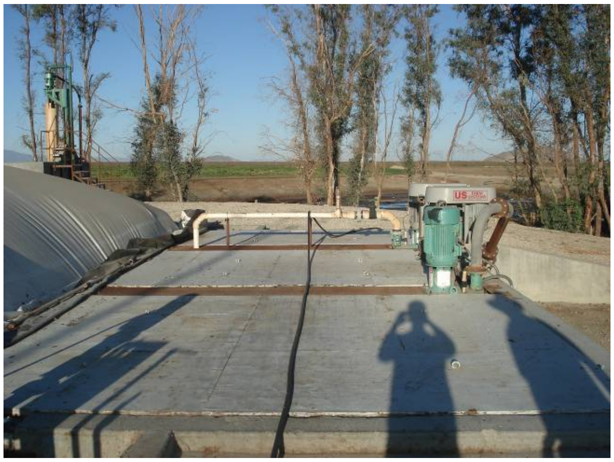

Figure 8.3: Manure Collection Pit at Head of Digester.

Figure 8.4: Vacuum Truck Unloading Scraped Manure.

Figure 8.5: Biogas Outlet from Digester.

Figure 8.6: Gas Conditioning and Generator.

Figure 8.7: Electrical Controls for Digester.

Table 8.1: Dairy 6 Digester System Description.

Digester	Plug – Flow Digester, 0.5 Million gallon capacity Heated, Unmixed HDPE cover Sand separation before digestion
Engine-Generator	190KW Synchronous Generator Rich Burn Caterpillar Gas Engine 190 kW output on biogas, 240 VAC, 3 phase Estimated 26% LHV shaft efficiency
Biogas Treatment	Biogas knockout for vapor "dewatering" and filters for particulate removal
Heat Recovery	Preheat hot water for digester heating Back-up radiator system Jacket water heat exchanger only

A flare system is also provided in the case that the engine system is not consuming all of the biogas. The genset throttle setting adjusts to maintain a constant pressure under the digester cover. A mechanical pressure valve will open when the gas pressure under the cover increases above the setpoint levels, and sends gas to the flare to destroy the unused biogas.

The Figure 8 schematic shows the overall biogas and power generation systems and it includes the monitoring systems described in the next section. Details on typical mass and energy flows were developed as part of this study and are given in the process flow diagram given in the results section.

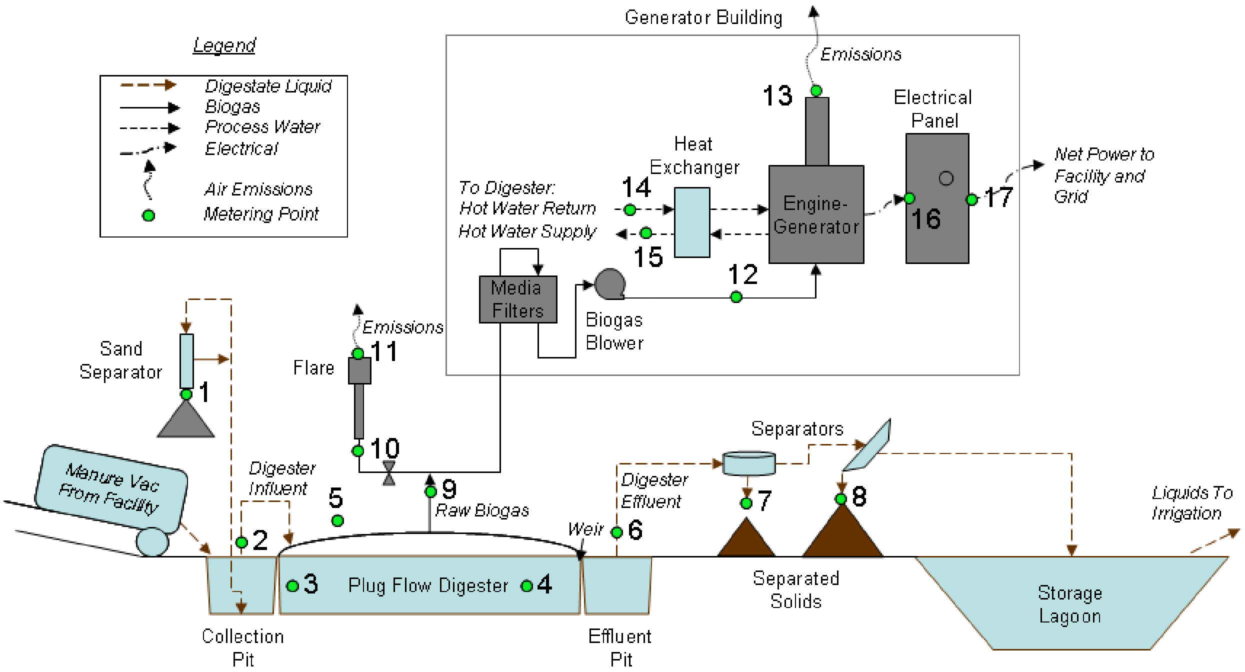

Figure 8.8: Schematic of Biogas System at Meadowbrook Dairy With Proposed Monitoring Points.

8.2 Dairy 6 Materials and Methods

The monitoring methodology and system followed protocols developed by ASERTTI, Climate Action Registry, and US EPA. Continuous sensors monitored pertinent system flows and conditions including those shown in Table 2. This data was recorded in data logger equipment and 15-minute averages will be continuously logged and transmitted via the internet to a central system maintained by the investigators. Sampling locations are shown on the schematic in Figure 8. These sampling points cover all pertinent manure, biogas, power and process water flows and temperatures. Composition samples were taken on a monthly basis to establish the mass distribution for each flow of manure, biogas and emissions.

The monitoring system supplied by Summers Consulting was configured to capture the data points listed in Table 2. The sensors were sampled at 1-minute intervals and averaged or summed into 15-minute data as appropriate. The PLC-based system provided the investigators access to the time-stamped 15-minute data via the internet. The on-site controller has the ability to store and retain several hundred days of 15-minute data in the event that communications are lost.

The electrical output of the engine-generator (WGO) was measured with the Gen-Tec power transducer already installed in the engine control panel. The net power exported to the grid will also be supplied by the SCE metering at the site (WNT).

The biogas delivered to the engine (FGE) was measured by a Sage gas flow meter (hot-wire probe) that determines the mass flow in standard cubic feet per minute. In addition a Sage meter measured biogas flow to the flare (FGF). The flare temperature (TEF) establishes that the flare is lit and biogas is being burned in the flare. The total biogas flow (FGT) is the sum of FGE and FGF. From the biogas and power measurements we can calculate the engine efficiency using the measured gas composition data available from monthly gas samples. The gas flows also allow for an estimate of emissions from the engine (FEE) and the flare (FEF) using standard combustion assumptions and measurement of exhaust composition.

Table 8.2: Monitoring Points on the Dairy 6 Digester System.

Loc #	Data Point	Description	Eng. Units	Sensor or Instrument	Typical Range
1	FSS	Flow of Separated Solids (Sand Filter)	lb/day	Monthly weight est.	300
	CSS	Composition of Separated Solids (Sand)	% by wt.	Quarterly samples	10-20% TS
2	FMI	Flow of Manure, Influent to Digester	Gal/day	Ultrasonic Flowmeter	25,000-50,000
	TMI	Temperature of Manure, Influent to Digester	°F	Type-K TC, 6 in probe	65-95
	CMI	Composition of Manure, Influent to Digester	mg/l	Monthly samples, 24h	73,00 to 86,000
3	TD1	Temperature of Digester at Location 1	°F	Thermistors – 4 north	88-102
4	TD2	Temperature of Digester at Location 2	°F	Thermisors – 4 south	88-102
5	TAO	Temperature of Ambient Out	°F	Type-K TC, near digester	40-105
6	FME	Flow of Manure, Effluent from Digester	gpm	Estimated from FMI	=FMI
	TME	Temperature of Manure, Effluent from Digester	°F	Type-K TC, 6 in probe	99-102
	CME	Composition of Manure, Effluent from Digester	mg/l	Monthly samples, 24h	51,000 to 70,000
7	FMS	Flow of Manure Solids (Screen 1)	lb/day	Monthly weight est.	6000
	CMS	Composition of Manure Solids (Screen 1)	% by wt.	Quarterly samples	20-25% TS
8	FMS	Flow of Separated Solids (Screen 2)	lb/day	Monthly weight est.	1000
	CMS	Composition of Separated Solids (Screen 2)	% by wt.	Quarterly samples	15-20%TS
9	FGT	Flow of Gas Total (Raw Biogas)	SCF/day	Estimated from FGE & FGF	80,000-150,000
	CGT	Composition of Gas Total (Raw Biogas)	% by vol.	Monthly analysis	58-62% CH4
10	FGF	Flow of Gas to Flare (Raw Biogas)	SCF/day	Sage Prime SIP	0-70,000
	CGF	Composition of Gas to Flare (Raw Biogas)	% by vol.	Monthly analysis	58-62% CH4
11	FEF	Flow of Emissions from Flare	cf/h	Estimated from FGF	=FGF*CF
	CEF	Composition of Emissions from Flare	% or ppm	Monthly analysis	4 - 8% O2
12	FGE	Flow of Gas to Engine (Conditioned Biogas)	cf/h	Sage Prime SIP	70,000-100,000
	CGF	Composition of Gas to Engine (Conditioned)	% by vol.	Monthly analysis	58-62% CH4
13	FEE	Flow of Emissions from Engine	cf/h	Estimated from FGE and CEF	=FGE*CF
	CEE	Composition of Emissions from Engine	% or ppm	Monthly analysis	0.0 - 0.2% O2
14	TWI	Temperature of Water Inlet (Process Water into Heat Exchanger)	°F	Type-K TC, 6 in probe	145-155
15	TWO	Temperature of Water Outlet (Process Water out of Heat Exchanger)	°F	Type-K TC, 6 in probe	165-211
	FWP	Flow of Water to Process	gpm	Onicon F1100	130-140
16	WGO	Watts of Generator Output (Power at Generator)	kWh/int	Gen-Tec power meter	155-200
17	WNT	Watts of Net Total (Power after Parasitic Loads)	kWh/int	PG&E meter - pulse	145-190

The temperatures (TMI, TME) are measured by thermocouples at the influent and effluent pipes and the digester temperatures (TD1, TD2) are averaged from an array of thermistors placed inside the digester system at multiple locations along the front and back end. The ambient temperature (TAO) is recorded to understand how digester performance may vary with ambient weather conditions.

The flow of manure into the digester (FMI) was measured with a clamp-on ultrasonic flow meter. It will be assumed that influent and effluent flow are balanced, therefore FMO is estimated to be equal to FMI. The flow of manure solids (FMS) from the digestate screening was measured monthly by estimating the volume and density of the solids separated by the screening system over a 24-hour period. The solids from the sand separator were measured using this same method.

The thermal output recovered from engine jacket to the heat exchanger is determined from the coolant water flow and temperature difference data available from the Gen-Tec control system (FC, TCI, TCO). The thermal energy actually utilized for process water heating is determined from the process water flow and temperature difference data (FWP, TWI, TWO).

The parasitic power consumption of various components in the system is determined by power readings with a hand-held meter capable of measuring true power. The sum of all parasitic loads not accounted for in the net metering is compared with the power generated by the system.

The composition of the manure influent and effluent is measured on a monthly basis using a 24-hour aggregated sample that will be laboratory analyzed for the analytes described in Appendix A. The composition of the biogas was measured using a GEM^{TM}2000 Portable Gas Analyzer from Landtec on a monthly basis. This sampling included raw and conditioned biogas. The portable meter is used to determine the percentage of CH4, CO2, O2, H2S and balance gas (presumed to be N2) on a monthly basis. The metering equipment is calibrated on a routine basis and the estimated accuracy is shown in Appendix A.

Also on a quarterly basis, samples will be taken of the fresh well water and flush water to be analyzed using the applicable methods in Appendix A – Table A1. This will allow for a more complete mass flow accounting throughout the manure collection system. In addition, on a quarterly basis, the solids separated from before the digester will be analyzed according to the analyses in Appendix A - Table A2. Sampling of the settled solids will also be attempted on a quarterly basis using a sludge sampler through the vent ports in the digester cover. The amount of solids settling in these systems is critical for understanding mass balance and maintenance of the long-term performance.

Periodic samples of the influent to and effluent from the digester was subjected to a Biochemical Methane Potential (BMP) analysis in a specially-designed apparatus in the Summers Consulting laboratory. BMP analysis is an efficient and economical method for evaluating the rate and extent of biomass conversion to methane under anaerobic conditions. The effluent BMP shows the remaining methane production potential after digestion and provides an estimate of the potential methane produced in a liquid storage pond after digestion.

Annual greenhouse gas emissions reductions were also estimated using the Climate Action Registry Livestock Protocol. This protocol uses a particular methodology to estimate the baseline emissions or emissions from the manure management system without the digester and compares these with estimated emissions from the digester system.

8.3 Dairy 6 Results and Analysis

The following sections summarize the monitoring results of this year-long monitoring campaign and provide annual operational factors including digester feeding, digester performance, biogas production, biogas generator performance, and climate change impact. The digester monitoring system for Dairy 6 was designed in 2010 and installation was completed in early 2011. The monthly sampling was initiated in June of 2011 and completed by June of 2012. The actual milk cow and heifer numbers during the data collection period are shown in Table 3 along with the estimated daily manure production as predicted by typical estimation method from ASABE. The total manure volatile solids represent the total available feedstock for conversion in the digester system although the collection system only collects the manure that is available on the concrete feed lane.

Table 8.3: Dairy Herd Size Characteristics and Estimated Manure Production at Dairy 6.

DAIRY HERD			ESTIMATED MANURE PRODUCTION	
	HEAD (#)	WEIGHT (LB/HEAD)	VOLATILE SOLIDS (LB/HEAD/DAY)	TOTAL VOLATILE SOLIDS (LB/DAY)
Milk Cows	2100	1499	17.0	35700
Dry Cows	150	1507	9.2	1380
Heifers	300	897	7.1	2130
			Total Manure Volatile Solids	39210

8.3.1 Digester Feeding

The rate of influent feeding of the digester averaged 40,000 gallons per day over the entire year, but varied monthly from under 30,000 to over 50,000 gallons per day. Figure 8 shows the average digester influent flows for each month of the study year. Factors like seasonal animal activity, operator variability, and use of dilution water are potential sources of this variability.

The results for the monthly solids composition of the influent mixture is shown in Figure 9. Total solids concentration ranged from 67,000 to 92,000 milligrams per liter with an average of 80,400 milligrams per liter. Volatile solids ranged from 50,000 to 75,000 milligrams per liter with an average of 64,000 milligrams per liter. The volatile solids were consistently 76 to 82 percent of the total solids. The variability seen in these samples can also be attributed to variable system flows and the limitations of taking a single aggregated grab sample to represent an entire month of manure flow. Table 4 shows the annual average and standard deviation for all of the samples taken over the year for constituents of the influent.

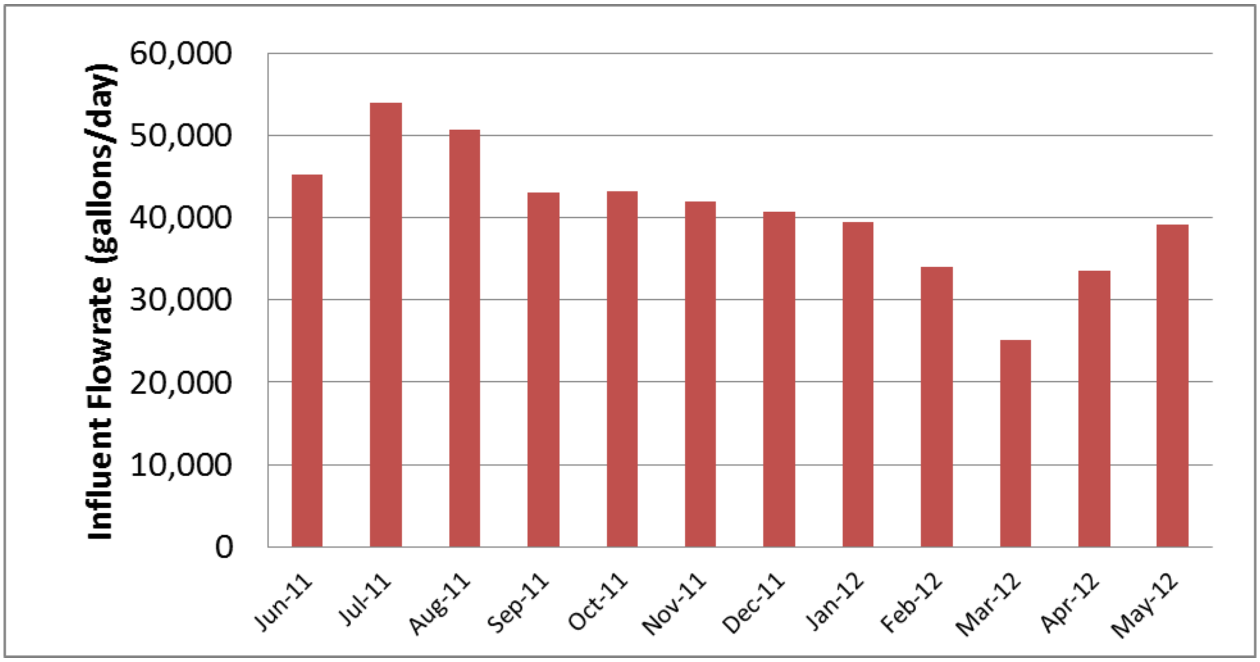

Figure 8.9: Average Monthly Influent Flowrate.

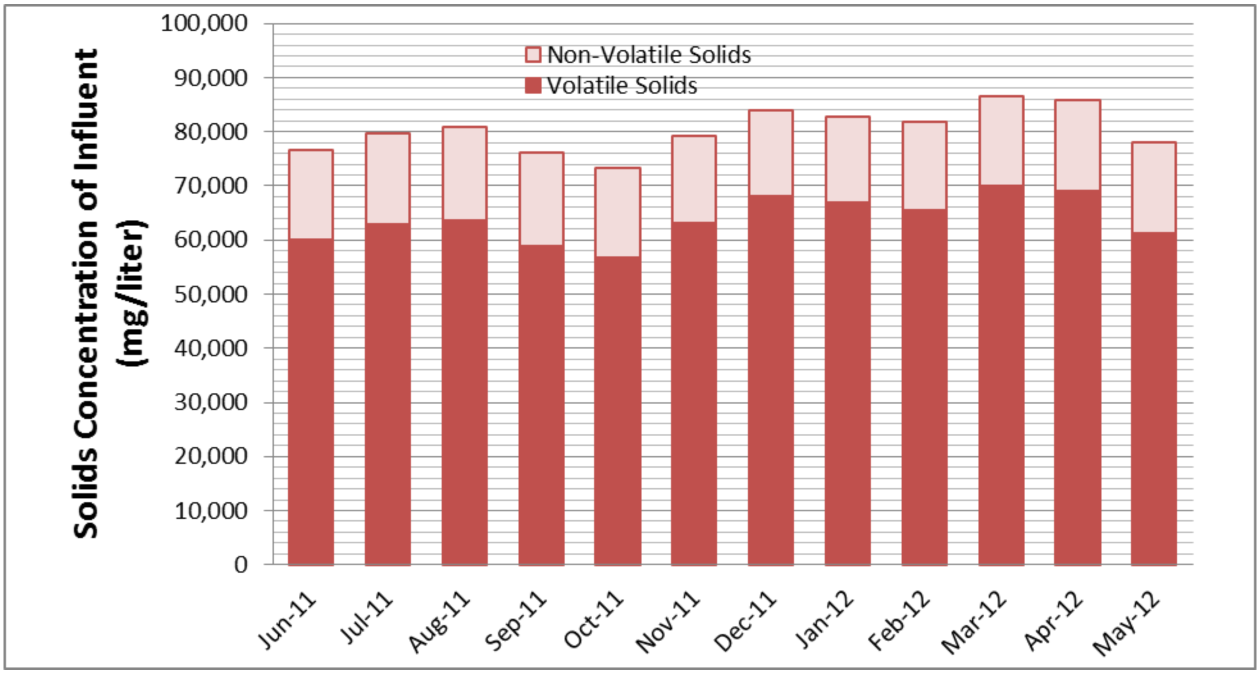

Figure 8.10: Total Solids Concentration of Digester Influent With Volatile and Non-Volatile Fractions.

Using pile size estimates and monthly moisture and density samples, it was determined that about 42 percent of the total solids in the effluent stream or about 8600 pounds per day of total solids per day are removed by the sloped screen solids separator after the digestion process. An additional 600 pounds per day of solids are separated using a vibrating screen following the sloped screen. These separated solids are stabilized by the digestion process and can be valuable for use in the farming operations at the dairy or marketed as a horticultural soil amendment. Table 5 shows the typical composition of these separated solids and Table 10 shows the daily generation rates.

Table 8.4: Composition of Various Constituents of the Digester Influent. Average and Standard Deviation of the Monthly Samples Taken Over the Study Year.

Analyte	Units	Method	Average	St Dev
Total Solids	mg/L	SM 2540B	80,352	7,401
Volatile Solids	mg/L	EPA 160.4	63,907	7,238
Total Dissolved Solids	mg/L	SM 2540 C	21,714	2,807
Chemical Oxygen Demand	mg/L	SM 5220D	76,771	24,557
Specific Conductance	µS/cm	SM 2540B	24.0	3.7
pH		Field Test	793	233
Ammonia-N	mg/L	SM 4500	7.5	2.4
Ammonium-N	mg/L	SM 4500G	12.4	16.4
Nitrate-Nitrogen	mg/L	EPA 300.0	3,179	466
Total Nitrogen	mg/L	EPA 351.2	366	72
Total Phosphorus	mg/L	SM 4500P B	3,263	580
Total Potassium	mg/L	SM 3120 B	446	60
Total Sulfur	mg/L	SM 3120 B	1,122	182
Total Clorine	mg/L	SM 3120 B	1,710	141
Total Calcium	mg/L	SM 3120 B	722	29
Total Magnesium	mg/L	SM 3120 B	1,015	7
Total Sodium	mg/L	SM 3120 B	80,352	7,401

Table 8.5: Composition of the Separated Solids From the Sloped Screen Separator and Vibrating Screen. Average and Standard Deviation of Quarterly Samples Taken Over the Study Year.

			Sloped Screen		Vibrating Screen	
Analyte	Units	TMECC Method	Average	St Dev	Average	St Dev
Dry Matter (eq TS)	Wt %	03.09-A	23.4	1.7	11.5	0.4
Organic Matter (eq VS)	Wt %	05.07-A	21.1	1.8	10.0	0.1
Total Nitrogen	Wt %	04.02-D	0.37	0.08	0.28	0.02
Total Phosphorus	Wt %	04.03-A	0.12	0.01	0.07	0.01
Total Potassium	Wt %	04.04-A	0.21	0.01	0.17	0.04
Sodium	Wt %	04.05-Na	0.07	0.01	0.05	0.01
Calcium	Wt %	04.05-Ca	0.43	0.10	0.17	0.01
Magnesium	Wt %	04.05-Mg	0.14	0.03	0.09	0.01
Iron	mg/kg	04.05-Fe	126	23	124	27
Copper	mg/kg	04.07-Cu	12.9	1.3	10.8	0.0
Manganese	mg/kg	04.05-Mn	17.5	6.3	10.1	0.5
Zinc	mg/kg	04.05-Zn	16.8	0.4	12.6	0.1
Sulfur	Wt %	04.05-S	0.07	0.00	0.05	0.01

8.3.2 Digester Performance

The digester was fed a daily dose of liquid manure solids, the feedstock required for the anaerobic digestion process, throughout the study period. The average amount was 40,800 gallons per day with about 8 percent solids although there was some variability due to real variations in operations and due to the measurement limitations discussed above. The measured loading of the digester can be seen in Table 6 – Digester Feeding.

Table 8.6: Digester Influent Feeding and Performance Parameters.

	DIGESTER FEEDING				DIGESTER PERFORMANCE			
YEAR / MONTH	INFLUENT FLOWRATE	TOTAL SOLIDS CONC.	VOLATILE SOLIDS CONC.	INFLUENT VOLATILE SOLIDS	AVERAGE DIGESTER TEMP	ORGANIC LOADING RATE	HYDRAULIC RETENTION TIME	VOLATALE SOLIDS CONSUMP TION
(YYMM)	(GAL/DAY)	(%)	(% TS)	(LBS /DAY)	(DEG F)	(LB VS /1000 CF/DAY)	(DAY)	(%)
1107	45,218	7.7	78.5	22,647	100.1	339	11.1	33.6
1108	53,947	8.0	79.0	28,289	99.9	423	9.3	41.1
1109	50,748	8.1	78.6	26,899	100.6	402	9.9	29.5
1110	43,029	7.6	77.5	21,167	100.3	317	11.6	19.8
1111	43,233	7.3	77.6	20,489	100.0	307	11.6	18.9
1112	42,011	7.9	79.7	22,083	99.5	330	11.9	24.9
1201	40,800	8.4	81.1	23,183	99.0	347	12.3	32.0
1202	39,435	8.3	80.7	21,979	98.5	329	12.7	32.4
1203	34,059	8.2	80.2	18,623	99.9	279	14.7	29.4
1204	25,067	8.7	80.8	14,619	103.4	219	19.9	32.5
1205	33,518	8.6	80.4	19,279	106.8	288	14.9	27.5
1206	39,126	7.8	78.6	20,005	105.3	299	12.8	19.4
AVE	40,849	8.0	79.4	21,605	101.1	323	12.7	28.4

The influent solids averaged 21,600 pounds per day. Compared with the estimated volatile solids excretion of 39,200 pounds per day for this dairy herd, this equates to an estimated manure capture of 55 percent by the collection system. This seems like a reasonable result given that the animals have access to a significant area of loafing pens and some of the scraped manure is pushed out of the concrete lanes during collection process.

The digester appeared to maintain stable anaerobic digestion throughout the study as evidenced by the consistent volatile solids consumption observed of 28.4 percent. Several other indicators show that the digester may have been somewhat overloaded and may have achieved higher conversion with a somewhat larger volume. For example, the average daily organic loading rate of 323 pounds of volatile solids per thousand cubic feet is almost double the recommended loading rate of 150 pounds of volatile solids per thousand cubic feet for this type of system. The 12.7 day average hydraulic retention time low compared with the recommended HRT of 20 to 30 days (NRCS, 2003) for this type of digester. The digester temperature was maintained in the range of 99 – 106°F and these temperatures are ideal for maintenance of mesohpillic anaerobic activity. All of these performance factors calculated for each month of the study period are shown in Table 6 – Digester Performance.

Consumption, conversion, and accumulation of the wastewater constituents within the digestion system are of interest and were analyzed by looking at the difference between the influent and effluent compositions (Table 7). Statistical analysis was applied to the data observations to determine if there was a statistically significant difference between the influent and the effluent compositions. A two-tailed pair-wise Student's T-test was applied to the data sets for the influent and effluent composition. The null hypothesis is rejected for alpha was less than 0.05, meaning that for p-values less than 0.05, we conclude that there is a statistically significant difference between the influent and the effluent composition and that some conversion occurred within the digester.

The observed averages for composition of influent and effluent are shown in Table 7 along with the percentage difference observed with a bold negative value meaning a reduced concentration after digestion and a bold positive value meaning an increased concentration. The differences that are statistically significant are shown in bold including Total Solids, Volatile Solids, Total Dissolved Solids, Carbon Oxygen Demand, and Ammonia-Nitrogen. Solids and Oxygen Demand are reduced as expected and Ammonia increases.

All other constituents do not show statistically significant differences (non-bold results) between influent and effluent. These results do not contradict the assumption that nutrients are conserved in the digestate during anaerobic process while volatile solids are consumed, although they may be converted in form. For example, although ammonia nitrogen increases during the digestion process, the total nitrogen difference between inlet and outlet of the digester was not statistically significant.

The mass and energy flow diagram in Figure 13 illustrates how water and solids and energy are transported and converted in the system. Overall, the measurement effort carried out resulted in an accurate quantification of the system flows as evidenced by the good closure on mass and energy balances for the system.

Table 8.7: Differences Between Influent and Effluent Compositions Observed During the Study.

Analyte	Units	Method	Influent	Effluent	Difference	P-Value[9]
Total Solids	mg/L	SM 2540B	80,352	61,058	**-24.0%**	**0.00008**
Volatile Solids	mg/L	EPA 160.4	63,907	45,621	**-28.6%**	**0.00004**
Total Dissolved Solids	mg/L	SM 2540 C	21,714	15,829	**-27.1%**	**0.02593**
Chemical Oxygen Demand	mg/L	SM 5220D	76,771	44,416	**-42.1%**	**0.00009**
Specific Conductance	μS/cm	SM 2540B	24	27	11.4%	0.14184
Ammonia-N	mg/L	SM 4500	793	1,101	**38.8%**	**0.00034**
Ammonium-N	mg/L	SM 4500G	8	128.85	1618.0%	0.2142
Nitrate-Nitrogen	mg/L	EPA 300.0	12	4.2	-66.5%	0.1765
Total Nitrogen	mg/L	EPA 351.2	3,179	3,151	-0.9%	0.8997
Total Phosphorus	mg/L	SM 4500P B	366	332	-9.4%	0.1101
Total Potassium	mg/L	SM 3120 B	3,263	3,430	5.1%	0.4265
Total Sulfur	mg/L	SM 3120 B	446	372	-16.5%	0.0535
Total Clorine	mg/L	SM 3120 B	1,122	1,155	3.0%	0.0663
Total Calcium	mg/L	SM 3120 B	1,710	3,180	86.0%	0.5127
Total Magnesium	mg/L	SM 3120 B	722	1,134	57.2%	0.4347
Total Sodium	mg/L	SM 3120 B	1,015	1,130	11.3%	0.1363

8.3.3 Biogas Production

The daily biogas delivered to the engine was very consistent throughout the study but the daily biogas production varied from 82,000 to 148,000 cubic feet per day as shown in Table 8 and Figure 10. The excess gas produced during certain months correlated with higher digester loading. This extra gas was flared via an automated system regulated by cover pressure. It is unlikely that a significant amount of gas escapes this system.

The average specific biogas production for both added and consumed volatile solids are estimated in Table 8. The average value of 4.9 cubic feet per pound of volatile solids added is slightly below reported yields of 6 to 8 cubic feet per pound from successful and stable dairy manure digesters (US EPA, 2012). The average value of 18.2 cubic feet per pound of volatile solids consumed is consistent from a mass balance perspective because 15-20 cubic feet of biogas weighs about one pound. The observed biogas production per pound of volatile solids excreted by the herd was 2.7 cubic feet (or about 0.2 pounds per pound VS excreted) which can be compared with other dairy digester systems as a performance metric.

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[9] P-Values generated from a Paired Two-Tailed Student's T-Test for the difference between influent and effluent data sets with alpha = 0.05. Statistically significant differences are shown in bold.

Table 8.8: Biogas Production Parameters Observed From the Digester System.

	BIOGAS PRODUCTION					
YEAR / MONTH	TOTAL BIOGAS	SPECIFIC BIOGAS	SPECIFIC BIOGAS	SPECIFIC BIOGAS	METHANE	PERCENT FLARED BIOGAS
(YYMM)	(SCFD)	(SCF/LB VS ADDED)	(SCF/LB VS CONSUMED)	(SCF/LB VS EXCRETED)	(VOL %)	(%)
1106	136,194	6.0	17.9	3.5	58.4	32%
1107	141,386	5.0	12.2	3.6	58.6	36%
1108	147,837	5.5	18.6	3.8	61.0	47%
1109	102,044	4.8	24.3	2.6	61.5	20%
1110	84,973	4.1	21.9	2.2	62.0	5%
1111	88,690	4.0	16.1	2.3	61.3	6%
1112	84,964	3.7	11.5	2.2	61.3	6%
1201	86,040	3.9	12.1	2.2	60.5	3%
1202	99,204	5.3	18.1	2.5	60.4	21%
1203	87,114	6.0	18.3	2.2	60.5	12%
1204	82,045	4.3	15.5	2.1	60.6	9%
1205	121,400	6.1	31.3	3.1	59.3	33%
AVERAGE	105,158	4.9	18.2	2.7	60.4	19%

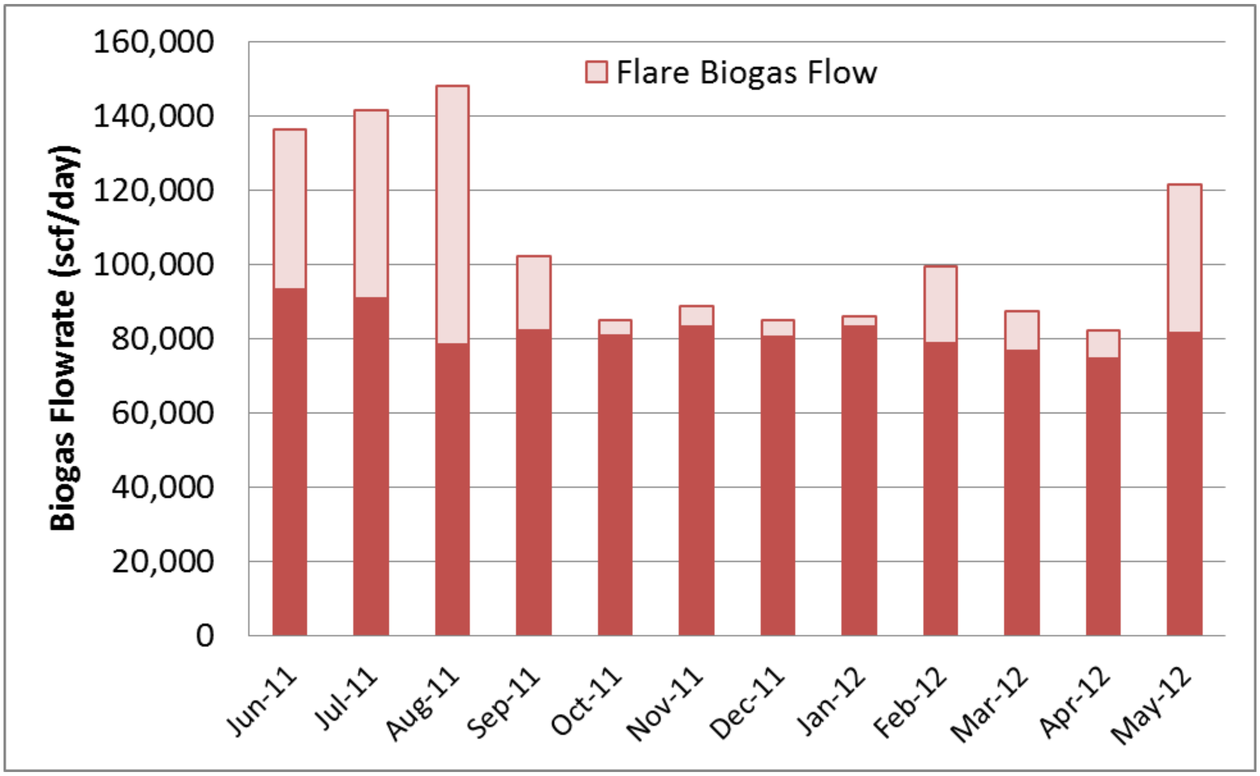

Figure 8.11: Average Daily Biogas Flowrate by Month From the Digester System.

The composition of the biogas was monitored throughout the study during monthly sampling and analysis. These observations are shown in Figure 11. The methane content was consistently 58-61 percent of the biogas (60.4 percent average). The balance of the gas is primarily carbon dioxide (39.3 percent average), the other major gas product of anaerobic digestion. Occasionally a trace amount of nitrogen (0.2 percent average) and oxygen (0.03 percent average) but these were just at the detection limits of the sensor. The hydrogen sulfide content of the biogas was observed to be between 3500 and 5000 parts per million by volume as shown in Figure 12. This was by far the highest hydrogen sulfide content observed in the digester study and presented a need for frequent engine maintenance to prevent acidity in the engine oil and exhaust.

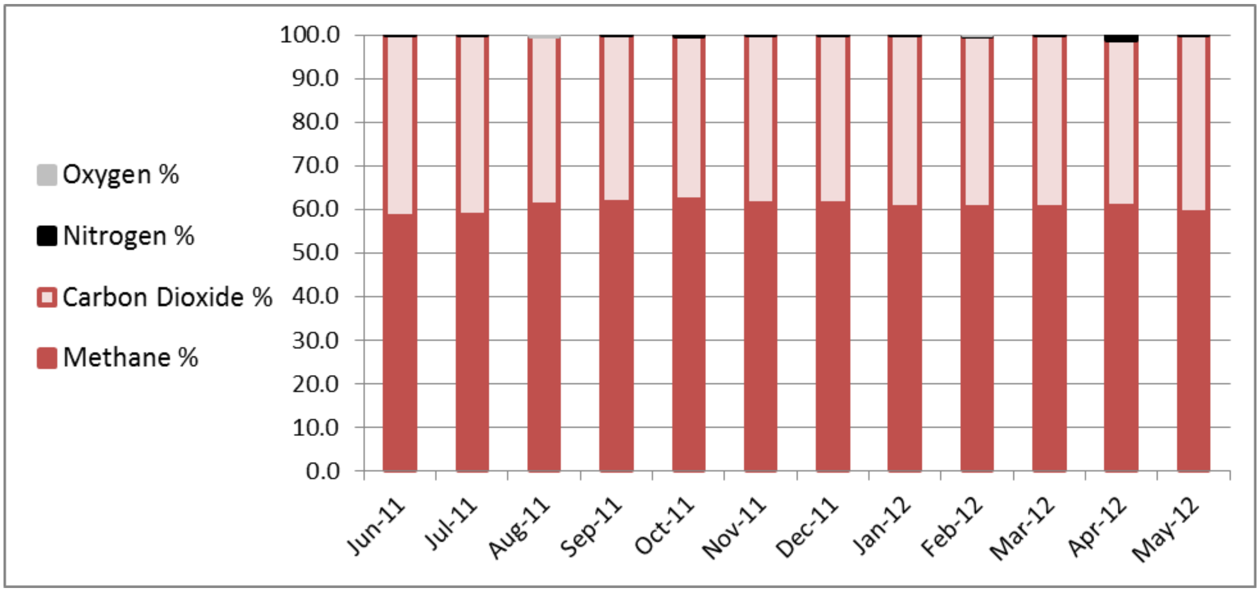

Figure 8.12: Biogas Composition Observed During the Study.

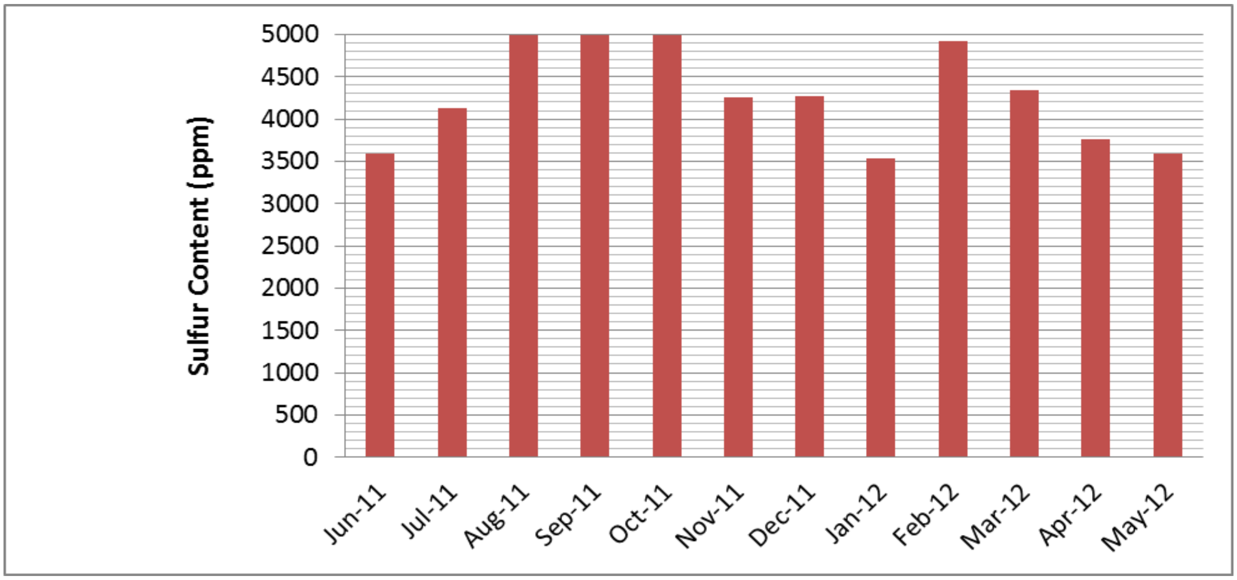

Figure 8.13: Hydrogen Sulfide Concentration in the Biogas Observed During the Study.

Biological methane potential (BMP) was also examined for the digester influent feed to compare the methane production at ideal mesophillic conditions with actual performance of the digester system. In addition, the biomethane potential of the digester effluent was quantified to determine what additional biogas production potential remains after the digestion process. Using the standard BMP test, average biogas production was 5.3 standard cubic feet (SCF) per pound of volatile solids added for the digester feed which was slightly more than the average digester performance of 4.9 SCF per pound of volatile solids added. The biological methane potential was determined to be 3.8 SCF per pound of volatile solids added and 15.2 SCF per pound of volatile solids consumed. The methane potential of the digester effluent was only 0.6 SCF per pound of volatile solids showing methane potential for the digestate to be only 16 percent that of the digester feed.

8.3.4 Biogas Generator Performance

The biomass combined heat and power generator performance was observed including the power and heat utilization from the 190-KW engine generator set. Table 9 shows the results. After a small amount of parasitic load from the pump, gas chiller, and engine skid, the electrical power output was an average of 153 kilowatts over the 12 month period. The heat recovery for use in the digester was monitored for the first five months at 140 kilowatts which is equivalent to about 5 Therms per hour. It should be noted that this heat is only used internally by the system and does not represent heat available for other energy use. It is estimated that an additional 150 kilowatts of heat could have been recovered from the engine exhaust with the appropriate exhaust boiler or heat exchanger.

Table 8.9: Engine Generator Performance Observed During the Study.

	BIOGAS CHP PERFORMANCE							
YEAR / MONTH	ELECTRICAL POWER OUTPUT	SPECIFIC POWER OUTPUT	AVERAGE HEAT RECOVERY	SPECIFIC HEAT RECOVERY	CAPACITY FACTOR*	ELECTRICAL EFFICIENCY	HEAT EFFICIENCY	OVERALL CHP EFFICIENCY
(YYMM)	(kW)	(kWh/LB VS ADDED)	(kW)	(kWh/LB VS ADDED)	(%)	(% LHV)	(% LHV)	(% LHV)
1106	178	0.19	131	0.14	94%	29%	22%	51%
1107	171	0.14	151	0.13	90%	29%	26%	54%
1108	147	0.13	141	0.13	77%	28%	27%	54%
1109	158	0.18	145	0.16	83%	28%	26%	54%
1110	159	0.19	129	0.15	84%	29%	23%	52%
1111	169	0.18			89%	30%		
1112	160	0.17			84%	29%		
1201	168	0.18			88%	30%		
1202	159	0.20			84%	30%		
1203	139	0.23			73%	27%		
1204	131	0.16			69%	26%		
1205	98	0.12			51%	18%		
AVE	153	0.17	140	0.14	80%	28%	25%	53%

* Note: Due to a faulty temperature signals, heat data was not available after October 2011.

The system was run at approximately 80 percent capacity factor. The actual online time for the engine generator was over 90 percent so the system was consistently operated at about 85-105 percent of the nameplate biogas capacity. The electrical efficiency of the system was observed to be 28 percent with a recovered heat efficiency of 25 percent from the jacket water for an overall combined-heat and power efficiency of 53 percent, on a lower heating value basis.

8.3.5 Mass and Energy Flows

The process flows throughout the manure handling system are shown in Table 10 below. It can be seen where volumes of liquids and masses of water, solids, and volatile solids (VS) are added and removed from the manure collection and handling system at the dairy. The estimated average daily amounts of dilution water and fresh collected manure make up the total digester influent composition. The digester then converts 30 percent of the volatile solids to produce biogas, further reducing the solids loading on the process water. After the digester, the sloped screen separator removes another 42 percent of solids followed by an additional 6 percent by a vibrating screen separator. The final liquid remaining after the process goes to a storage pond to irrigate feed crop land around the dairy and has an overall reduction of 60 percent solids and 69 percent volatile solids from the original manure liquids scraped from the dairy through a combination of anaerobic digestion and solids separation. Figure 13 is a graphical representation of the average mass, solids, and energy balances for the Dairy 2 Digester system, based on the data collection and analysis from the 12 month study.

Table 8.10: Daily Process Volume and Mass Flows.

Process Water/Solids Stream	Liquid Volume (gal/day)	Total Mass (lbs/day)	Solids Conc. (%)	VS Conc. (%TS)	Water Mass (lbs/day)	Solids Mass (lbs/day)	VS Mass (lbs/day)	Solids Removal (%)	VS Removal (%)
Collected Manure	26,300	219,000	12.5	79.4	191,600	27,400	21,700		
Dilution Water	14,600	121,700	-	-	121,700	-	-		
Digester Influent	40,800	340,700	8.0	79.4	313,300	27,400	21,700		
Digester Effluent	40,000	333,700	6.1	74.6	313,300	20,400	15,200	25.7%	30.1%
Sloped Screen Sep.	-	36,900	23.4	90.4	28,300	8,600	7,800	42.4%	51.4%
Vibrating Screen Sep.	-	5,600	11.5	87.2	4,900	600	600	5.5%	7.6%
Final Liquid	34,900	291,200	3.8	61.5	280,100	11,100	6,800	59.6%	68.7%

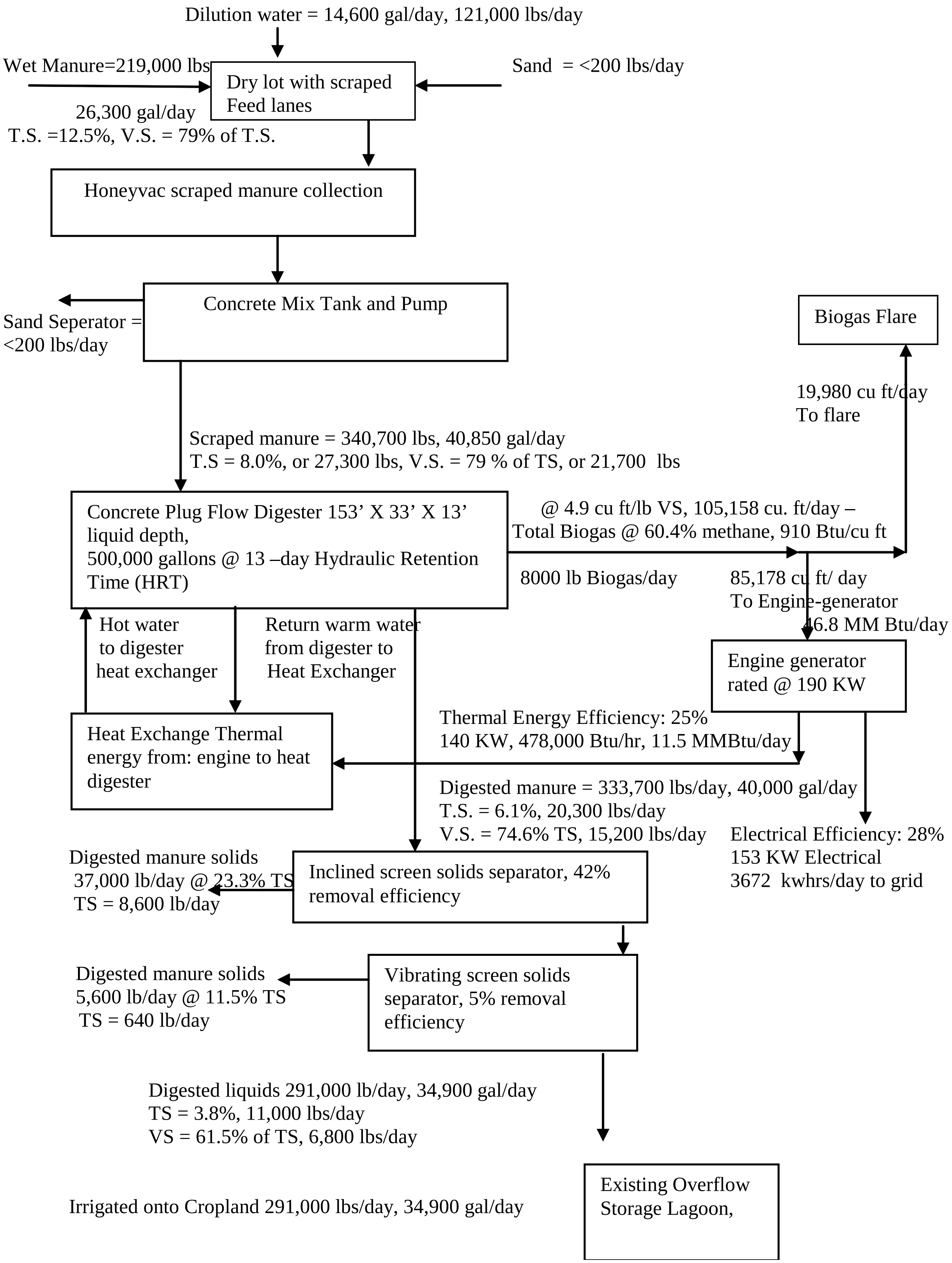

Figure 8.14: Average Mass and Energy Flow Diagram With Daily Flows for Dairy and Digester System.

8.3.6 Climate Change Impact

Using the data collected from the study, the Climate Action Registry Livestock Protocol was used to compute the amount greenhouse gas emissions reductions that have resulted from the digester project. The protocol provides a methodology for quantifying the baseline greenhouse gas emissions and comparing those with the emissions estimated to still be generated from the digester system or biogas control system (BCS) as the digester system is called by the Registry. The baseline emissions are the methane emissions that would have occurred from decomposition of manure in a dry lot system if the digester was not constructed. The project emissions are from un-burned methane from the engine and digester leakage and/or venting and methane generated in the effluent storage pond. The difference between the baseline and project emissions are a conservative estimate of the climate impact of the digester system. The results are shown in Table 11. The total methane reductions could be available to the facility as carbon credits. However this facility did not go through the process to quantify and verify these emissions reductions.

The results show that the baseline methane emissions of the facility are about 112 tonnes (metric tons or 1000 kg) per year. The project methane emissions of the facility are estimated to be 38 tonnes from the BCS and 45 tonnes from the effluent storage pond or 82 tonnes total. The difference is 29 tonnes of methane for a total reduction of 613 tonnes of carbon dioxide equivalents to the atmosphere. This represents a 26 percent reduction in greenhouse gas emissions associated with manure management at the facility. Note that this is substantially less than the 416 tonnes of methane that is actually destroyed by the engine and flare each year but better represents the climate impact of the digester project than the actual methane destruction.

Table 8.11: Climate Modeling Results for Digester Project Including Estimated Methane Reductions.

	Tonnes CH4 Per Year	***Tonnes CO2e Per Year***
Total Modeled Baseline Methane Emissions	***111.7***	***2345***
Project Methane Emissions from the BCS	37.5	788
Project Methane Emissions from Effluent Pond	45.0	944
Total Project Methane Emissions	***82.5***	***1732***
Total Methane Reductions	***29.2***	***613***
Methane Destroyed in the BCS	416.3	8741

Carbon credits represent a potential source of revenue depending on the value of the credits in the marketplace. Note that there is also a cost in establishing these credits (including monitoring system installation costs, data collection costs, and third-party reporting and verification) and this has been seen to potentially be prohibitive for projects like this one. In addition, because this dairy was a dry lot system handling manure in mostly a dried, solid form the baseline emissions are lower than facilities that manage manure in anaerobic ponds. This reduces the potential emissions credits it qualifies for.

8.4 Dairy 6 Conclusions

The project generated results for the annual performance of a heated plug-flow dairy digester system coupled with a cogeneration system for conversion of biogas into power and heat. The following conclusions provide normalized results so that the study of this system can be compared with other digester systems in terms of overall characteristic performance.

DIGESTER FEEDING: The digester influent feed came from scraped concrete feed lanes at a dry-lot dairy utilizing dilution water to improve the flow characteristics of the manure and ability to remove sand. The influent volatile solids averaged about 55 percent of the volatile solids estimated to be generated by the dairy herd. The influent had an average total solids concentration of 8.0 percent which consisted of 79 percent volatile solids. The digester was fed with 100 percent raw manure solids with a more detailed constituent analysis shown in Table 4.

DIGESTER PERFORMANCE: The project results demonstrate that a heated plug-flow manure digester having a fairly low hydraulic retention time and high organic loading rate has the capability to maintain stable anaerobic digestion. The digester showed consistent volatile solids reduction and gas production over the year. The average hydraulic retention time was 13 days with an organic loading rate of 320 pounds of volatile solids per thousand cubic feet per day. Average digester temperature was 101°F and was consistent throughout the year. The study showed that the digester reduced total solids by 24 percent, volatile solids by 28 percent, total dissolved solids by 27 percent, and carbon oxygen demand by 42 percent during the digestion process. Ammonia nitrogen increased by 39 percent. There were no other statistically significant changes to the digestate composition within the digester system as shown in Table 7.

BIOGAS PRODUCTION: The digester produced an average of 4.9 cubic feet of biogas per pound of volatile solids added or 18 cubic feet per pound of volatile solids consumed. The composition of the biogas was consistently about 60 percent methane and 40 percent carbon dioxide with little indication of air intrusion. Hydrogen sulfide content was very high at an average of 4280 ppmv which presented the need for frequent engine oil changes to manage acidity.

BIOGAS GENERATOR PERFORMANCE: The engine-generator for this project operated at a capacity factor of 80 percent although the actual engine online time was above 90 percent. The electrical efficiency averaged 28 percent and the recovered heat efficiency 25 percent for a total efficiency of 53 percent expressed on a lower heating value basis. The engine jacket water was used to heat the digester system and additional available heat from the exhaust was not utilized.

CLIMATE CHANGE IMPACT: Utilizing the methodology developed for predicting livestock emissions reductions from manure digester projects, it is estimated that the baseline and digester project emissions of methane are 112 and 83 tonnes per year respectively , for a total reduction due to the installation and operation of the digester of 26 percent. This is equates to

613 tonnes of carbon dioxide equivalents per year that could potentially be traded as carbon credits which is about 0.3 tonnes per lactating cow at the dairy.

CHAPTER 9:
Comparative Results and Analysis

The project generated detailed year-round data related to the performance of six working dairy manure digester systems coupled with cogeneration systems for conversion of biogas into power and heat. The study involved several different types of digester systems and each project proved to have unique characteristics and performance. In this chapter, we investigate the differences and the similarities between these systems towards finding generalized results that can be derived by the study. Presented are the normalized annual results so that each system can be compared with the other digester systems in terms of overall characteristic performance in the main study areas of digester feeding, digester performance, biogas production, biogas generator performance, mass and energy flows, and climate change impact.

The characteristics of the dairy digester systems investigated in this study are shown in Table 1 below. Note the order of magnitude range in some of these characteristics including dairy size range from 350 to 3200 lactating milk cows, digester size range from 0.5 to 45 million gallons, generator size from 65 kW to 750 kW, showing the range of different systems investigated. There were also differences in the digester solids feeding used to supply each digester with material to convert into biogas. In the simplest case, scraped fresh manure was the only solids feeding to the digester, while one system had both concentrated flush manure slurry, screened manure solids, and green chop silage added to the digester. Two systems included cheese plant wastewater as a feedstock to the digester. In addition, only three systems had external utilization of heat although some systems used heat internally for the digester.

Table 9.1: Characteristics of 12-Month Study Dairy Digester Systems.

DAIRY NO.	COWS MILKED	TYPES OF SOLIDS FEED TO DIGESTER SYSTEM	DIGESTER TYPE	DIGESTER VOLUME (GAL)	BIOGAS USE (KW CAP.)	EXTERNAL HEAT UTILIZATION
1	550	1) Recycled Flush Water 2) Fresh Manure	Covered Lagoon	6,400,000	Power (65 kW)	
2	350	1) Recycled Flush Water 2) Fresh Manure 3) Cheese Plant WW	Covered Lagoon	2,500,000	Power (75 kW)	X
3	3,200	1) Fresh Manure 2) Cheese Plant WW	Covered Lagoon	45,000,000	Power (750 kW)	X
4	850	1) Recycled Flush Water 2) Fresh Manure	Mixed Lagoon	3,400,000	Power (212 kW)	
5	1,700	1) Flush Manure Slurry 2) Screened Manure Solids 3) Green Chop Silage	Complete Mix	1,700,000	Power (710 kW)	X
6	2,100	1) Scraped Fresh Manure	Plug Flow	500,000	Power (195 kW)	

The dairy herd at each facility generates an estimated amount of manure volatile solids as shown in Table 2. These volatile solids will not all reach the digester as some will not be deposited on flushed or scraped surfaces and some will be purposefully screened or otherwise separated out by the manure collection system. However it is instructive to see the ratio of the volatile solids excreted by the herd relative to the amount of volatile solids that were measured entering the digester. In addition, because the recycled solids and non-manure solids flows were monitored during the study, the amount of raw manure solids entering the digester system can be estimated. It can be seen that this ranged widely from 34 percent to 83 percent with a weighted average for the study of 47 percent. This shows that the site and system specifics can make a very big difference in the amount of manure actually captured by a digester system.

Table 9.2: Comparison of Estimated Dairy Herd Manure Solids Excretion to Total and Raw Manure Solids Delivered to Digester (Expressed as Volatile Solids).

DAIRY NO.	MILK COWS	DRY COWS	HEIF-ERS	ANIMAL UNITS (1000 lb)	RAW MANURE SOLIDS EXCRETION	SOLIDS INFLUENT TO DIGESTER	RAW MANURE SOLIDS INFLUENT TO DIGESTER	RAW MANURE CAPTURE BY DIGESTER
	(#)	(#)	(#)	(#)	(LBS VS/DAY)	(LBS VS/DAY)	(LBS VS/DAY)	(%)
1	550	50	250	1,124	11,585	6,434	3,960	34%
2	338	43	234	782	7,803	6,218	3,387	43%
3	3,174	359	0	5,301	57,261	35,989	17,365	30%
4	837	187	990	2,425	22,978	80,951	18,967	83%
5	1,700	120	220	2,927	31,566	24,278	15,483	49%
6	2,100	150	300	3,644	39,210	21,605	21,605	55%
TOTAL	8,699	909	1,994	16,203	170,403	175,474	80,766	47%

9.1 Digester Feeding

The primary engineering function of each digester system is to reduce volatile solids from the influent liquid feedstream and convert those solids into methane rich biogas and a stabilized liquid effluent. Table 3 shows the amounts of volumetric and solids feeding to each digester system. Dairies 1-4 are the flush dairy systems. The least concentrated system is Dairy 3 with an average of 0.4 percent solids concentration because that facility uses large amounts of lightly concentrated cheese plant wash water and fresh water to flush the dairy facility. The other three flush systems use recycled water that is already laden with stable solids for flushing with solids concentrations ranging from 0.9 percent to 2.1 percent. The two high solids digester systems at Dairy 5 and 6 have a much higher solids concentrations of 10.5 and 8.0 respectively. It is instructive to also see the volume of water required to collect and feed each digester system which is near 2 gallons per pound of volatile solids for the high solids systems and from 9 to 36 gallons for the various flush systems. The flush systems thus require much higher volumes to accommodate the same amount of solids.

Table 9.3: Characteristics of Influent Volumetric and Solids Flow for Each Digester System.

DAIRY NO.	DIGESTER VOLUME	INFLUENT VOLUMETRIC FLOWRATE	SOLIDS COLLECTION WATER USAGE	TOTAL SOLIDS CONC.	VOLATILE SOLIDS CONC.	INFLUENT VOLATILE SOLIDS FLOW
	(GAL)	(GAL/DAY)	(GAL/LB VS)	(%)	(% of TS)	(LBS VS/DAY)
1	6,400,000	129,309	20.1	0.9	68.8	6,434
2	2,500,000	60,417	9.7	1.7	73.8	6,218
3	45,000,000	1,289,992	35.8	0.4	75.1	35,989
4	3,400,000	696,646	8.6	2.1	66.8	80,951
5	1,700,000	35,607	1.5	10.5	79.5	24,278
6	500,000	40,849	1.9	8.0	79.4	21,605

For each digester system in this study, the influent feed included raw manure solids that had been recovered daily by some method from the operating dairy facility. Several systems including Dairies 1, 2, and 4 used recycled water to flush the concrete lanes of the dairy and this recycle flush water contained an amount of stable solids. The Dairy 3 system used only cheese plant wastewater and fresh water to flush manure solids to the digester. The complete mix digester system at Dairy 5 used a unique settling basin system for generating concentrated manure slurry from flushed manure and mixing screened manure solids and green chopped silage directly to this slurry within the digester. Dairy 6 used only scraped manure solids with an amount of dilution water and delivered these to the high solids plug-flow digester. Based on the mass balance data collected in the study, Table 4 shows the composition of the volatile solids input to each digester based on the measured amount of recycle and non-manure solids that were added to the system. It can be seen that the amount of digester feed that was raw manure volatile solids was 48-65 percent except for Dairy 4 that had the very high recycle manure solids or Dairy 6 that was pure scraped dairy manure.

Table 9.4: Source of the Volatile Solids Influent to the Digester Systems in the Study.

DAIRY NO.	INFLUENT VOLATILE SOLIDS FLOW	RAW MANURE VOLATILE SOLIDS	RECYCLE WATER VOLATILE SOLIDS	NON-MANURE VOLATILE SOLIDS	VOLATILE SOLIDS SOURCES
	(LBS VS/DAY)	(%)	(%)	(%)	
1	6,434	62%	38%	-	Moderate recycled solids
2	6,218	54%	43%	3%	Moderate recycled solids 3% Cheese plant wastewater
3	35,989	48%	-	52%	52% Cheese plant wastewater
4	80,951	23%	77%	-	High recycled solids
5	24,278	64%	-	36%	38% Manure slurry VS 26% Screened manure VS 36% Sudan grass hay VS
6	21,605	100%	-	-	Vacuum scraped manure only

Using the laboratory data collected for the influent to each digester, the relative composition of the solids was calculated for each digester system for comparison across the study. Table 5 shows these results for each system except for Dairy 5 where the data was not available for the solids inputs to this digester. It can be seen that chemical oxygen demand ranges from 95 percent to 130 percent of solids and total dissolved solids ranges from 29 percent-66 percent of the total solids. The relative nutrient compositions are also shown for the major constituents of manure and wastewater and appear to be in a reasonable range for manure generated process water.

Table 9.5: Average Composition of the Digester Influent Solids From the Study (% of Total Solids).

NO.	CHEM. OXYGEN DEMAND	DISSOLVED SOLIDS	NH4-N	TOTAL N	TOTAL P	TOTAL K	TOTAL S	TOTAL Cl	TOTAL Ca	TOTAL Mg	TOTAL Na
	(% TS)	(% TS)	(% TS)	(% TS)	(% TS)	(% TS)	(% TS)	(% TS)	(% TS)	(% TS)	(% TS)
1	100%	53%	4.8%	10.6%	1.6%	7.0%	1.6%	3.8%	3.1%	2.1%	3.6%
2	130%	42%	2.5%	5.9%	0.9%	5.5%	0.6%	4.9%	2.0%	0.8%	2.9%
3	120%	66%	1.9%	5.2%	1.7%	5.9%	0.8%	3.8%	2.0%	0.7%	5.7%
4	95%	29%	3.6%	7.5%	1.6%	3.8%	0.7%	2.4%	2.8%	1.5%	0.9%
6	96%	48%	3.2%	7.3%	1.4%	5.6%	0.9%	3.7%	2.5%	1.3%	3.3%

Also of interest are the solids that are removed from the process water. These screened solids are an effective way to remove loading from process water at the dairy and can be a useful byproduct for animal bedding or other soil amendment use. In the first three digester systems, Dairy 1-3, the flush water was screened to remove fibrous solids before the digestion process. For Dairy 4-6, the fibrous solids are not removed from the feed to the digester system and are instead screened from the digester effluent after the digestion process. For these solids separation processes, the estimated separation efficiency is expressed here as the amount of solids removal relative to the estimated amount of raw manure solids and other fibrous solids originally added by the manure handling system as shown in Table 6. It should be noted that some of these separated solids could also be bedding washed down the flush system. In addition, for Dairy 5, there are additional fibrous solids added in the form of Sudan grass hay to the digester system that are included in the efficiency calculation. The pre-digestion separation showed separation efficiency of 32 percent to 56 percent while post-digestion was in the rage of 30 percent to 36 percent. Table 7 shows the comparative composition of these separated solids. The screening processes are higher moisture than the screw press processes, but the compositions do not seem to vary much across the different systems with the exception of the vibrating screen which generates a near-slurry with very fine solids in small daily quantities relative to the inclined screen at the same facility.

Table 9.6: Effectiveness of Solids Separation Systems Observed During in the Study.

DAIRY NO.	TYPE OF SEPARATOR	PRE OR POST DIGES-TION	AVERAGE DAILY SOLIDS REMOVAL	ESTIMATED MANURE SOLIDS ADDED	OTHER FIBROUS SOLIDS ADDED	SEPARATION EFFICIENCY OF ADDED SOLIDS
			(LBS/DAY)	(LBS/DAY)	(LBS/DAY)	(%)
1	Scraped Screen	PRE	6,196	11,065	-	56.0%
2	Screw Press	PRE	3,602	7,469	-	48.2%
3	Inclined Screen	PRE	11,900	36,875	-	32.3%
4	Rotary Screen	POST	7,063	23,750	-	29.7%
5	Screw Press	POST	11,002	20,659	9,996	35.9%
6	Inclined Screen + Vibrating Screen	POST	9,282	27,377	-	33.9%

Table 9.7: Average Composition of the Separated Solids Generated During the Study.

NO.	DRY MATTER (DM)	ORGANC MATTER	TOTAL N	TOTAL P	TOTAL K	TOTAL S	TOTAL Na	TOTAL Ca	TOTAL Mg	TOTAL Fe	TOTAL Cu
	(% Total)	(% DM)	(% DM)	(% DM)	(% DM)	(% DM)	(% DM)	(% DM)	(% DM)	(mg/kg)	(mg/kg)
1	20.8	90%	1.49%	0.29%	0.50%	0.22%	0.17%	0.98%	0.38%	1085	54
2	32.8	72%	1.74%	0.15%	0.46%	0.15%	0.12%	0.68%	0.19%	1786	24
3	18.5	93%	1.26%	0.18%	0.36%	0.14%	0.14%	0.59%	0.22%	767	28
4	22.4	90%	1.28%	0.21%	0.57%	0.16%	0.07%	0.55%	0.19%	975	57
5	22.5	80%	0.92%	0.15%	0.25%	0.16%					
6_{is}	23.4	90%	1.58%	0.49%	0.88%	0.30%	0.28%	1.84%	0.60%	537	55
6_{vs}	11.5	87%	2.40%	0.57%	1.44%	0.39%	0.44%	1.48%	0.74%	1081	94

Note: 6is and 6vs are the inclined screen and vibrating screen solids from Dairy 6 respectively.

9.2 Digester Performance

As discussed above, the purpose of the digester is to break down the digestable volatile solids in the manure and convert these to biogas and stabilized liquid effluent. Using the data collected at each site, the ability of each system to convert volatile solids was examined along with the performance point of each digester. Table 8 shows the performance of each digester in this regard.

The project results demonstrate that un-heated covered lagoon digesters having a long hydraulic retention time and low organic loading rate have the capability to maintain stable anaerobic digestion throughout the year in the moderate climate of the dairy regions of California. These digesters (Dairy 1-3) showed consistent volatile solids reduction and gas production over the year. The average hydraulic retention time was 35 to 49 days with an organic loading rates of 6 to 19 pounds of volatile solids per thousand cubic feet per day which is within the range expected for this type of digester. The average digester temperatures were 67 to 81°F with seasonal variation over the year depending on the site location. These facilities maintained high volatile solids consumption in the 44 to 62 percent range in an unheated, unmixed system which is quite remarkable. Note that specific biogas production somewhat follows volatile solids consumption as seen in the table.

Table 9.8: Performance Parameters and Solids Reductions for Study Digester Systems.

DAIRY NO.	AVERAGE DIGESTION TEMP.	ORGANIC LOADING RATE	HYDRAULIC RETENTION TIME	VOLATILE SOLIDS CONSUMPTION	SPECIFIC BIOGAS PRODUCED
	(DEG F)	(LB VS /1000 CF/DAY)	(DAYS)	(%)	(SCF/LB VS Added)
1	67.0	7.5	49.4	44.4	5.9
2	80.4	18.6	44.4	50.2	6.3
3	80.7	6.0	35.2	61.7	12.9
4	62.4	178	4.9	3.8	0.6
5	101.5	107	61.1	42.4	9.2
6	101.1	323	12.7	28.4	4.9

The digester at Dairy 5 also had a long hydraulic retention time and a low organic loading rate for a high solids digester. The volatile solids consumption of 42 percent for this system with a high gas production of 9.2 cubic feet per pound of volatile solids is very satisfactory for this type of system. Dairy 6 has a fairly low hydraulic retention time and high loading rate which may have resulted in lower volatile solids consumption of 28 percent and a higher resulting gas production could have been possible with this heated system. Dairy 4 had an extremely low hydraulic retention time and extremely high loading rate resulting in very poor volatile conversion within the system. This system is dominated by very high circulation of flush water and thus may not have sufficient time to generate good quality anaerobic activity within the digester.

The statistical analysis conducted on each set of site data showed the statistically significant conversions occurring within the digester systems. The results of this analysis are summarized in Table 9 where the statistically significant conversions are shown in bold for all of the facilities. Total solids were shown to be reduced by 24 percent to 44 percent, volatile solids by 28 percent to 62 percent, total dissolved solids by 18 percent to 27 percent, total dissolved solids from 18 percent to 27 percent, chemical oxygen demand by 42 percent to 68 percent, and sulfur by 43 percent (at only one facility) during the digestion process. Ammonia nitrogen was shown to increase by 34 percent to 38 percent in the good performing manure-only digester systems (Dairy 1, 2, and 6) and a much higher rate of conversion for the mixed feed systems at above 100 percent. The conversion of organic nitrogen to ammonia nitrogen is expected to occur in an anaerobic environment but total nitrogen is expected to be conserved. The study did no produce other statistically significant differences between the digester influent and effluent for the other nutrient constituents, providing no evidence to contradict the assumption that these nutrients are conserved within the digester systems. Note that the results for Dairy 4 where not statistically significant for any constituents. This is probably due to the very small amount of conversion occurring in this overloaded system that did not produce greater differences than the variability in the samples.

Table 9.9: Conversions Occurring Within the Digester System by Difference in Influent and Effluent.

DAIRY NO.	TOTAL SOLIDS	VOLATILE SOLIDS	TOTAL DISSOLVED SOLIDS	CHEMICAL OXYGEN DEMAND	AMMONIA-NITROGEN	SULFUR
	(%)	**(%)**	**(%)**	**(%)**	**(%)**	**(%)**
1	**-30.1%**	**-44.4%**	-2.2%	**-63.8%**	**36.2%**	**-42.9%**
2	**-34.2%**	**-50.2%**	**-20.1%**	**-44.8%**	**34.1%**	-14.0%
3	**-43.7%**	**-61.7%**	**-26.0%**	**-86.2%**	**125.1%**	-44.7%
4	-3.3%	-3.8%	-0.3%	-15.6%	-4.6%	-4.2%
5	**-36.4%**	**-42.4%**	**-17.9%**		**144.5%**	
6	**-24.0%**	**-28.4%**	**-27.1%**	**-42.1%**	**38.8%**	-16.5%

Note: Statistically significant differences between influent and effluent are shown in bold.
All non-bold differences are shown but were not statistically significant.

9.3 Biogas Production

An important relationship for digester system is the amount volatile solids consumed but also the amount of biogas or bio-methane produced in this process. This information is critical for the proper design of new digester systems and can vary by the type of feedstock. In general, as long as the process is active anaerobic digestion, the amount of gas production per unit of volatile solids consumption for dairy manure should be somewhat independent of the system or operation. In other words, whether there is a low or high rate of volatile solids consumption, the amount of gas should be proportional still to the measured amount of consumption.

To substantiate this concept, Figure 1 shows a plot of the volatile solids consumption rate (pound of volatile solids consumed per pound of volatile solids added) against the biogas production rate (standard cubic feet of biogas per pound of volatile solids added). For the dairies with manure as the only or dominant feedstock (Dairy 1, 2, 4, and 6) the slope of the best fit line is 13.49 SCF/lb VS consumed. For the facilities with a large amount of mixed feedstock volatile solids (Dairy 3 and 5) the slope appears to be somewhat higher than for the manure-only systems at 21.18 SCF/lb VS consumed. These simplified factors could prove useful for estimating expected gas production from dairy manure and mixed waste systems. Again this factor can only help describe the estimated biogas production if the volatile solids input and conversion amounts are known or can be accurately estimated.

Table 9 shows the biogas production for each of the digester systems and then the specific biogas production expressed in several different ways. The first is the amount of biogas produced per pound of volatile solids added. The second is the volume of biogas produced per pound of volatile solids consumed related to the estimation method above. The third is the volume of biogas produced per pound of manure volatile solids excreted by the herd. This factor can help with predicting how much potential biogas production can be generated from a given dairy herd. For the manure-only systems this factor ranges from a low of 2.0 to a high of 4.2 standard cubic feet per pound of volatile solids excreted. For the systems with mixed waste the factor is above 7 standard cubic feet per pound of volatile solids excreted (presumably due to the highly digestible solids supplementing the manure solids. Any of these factors could potentially be useful for engineering design and modeling purposes.

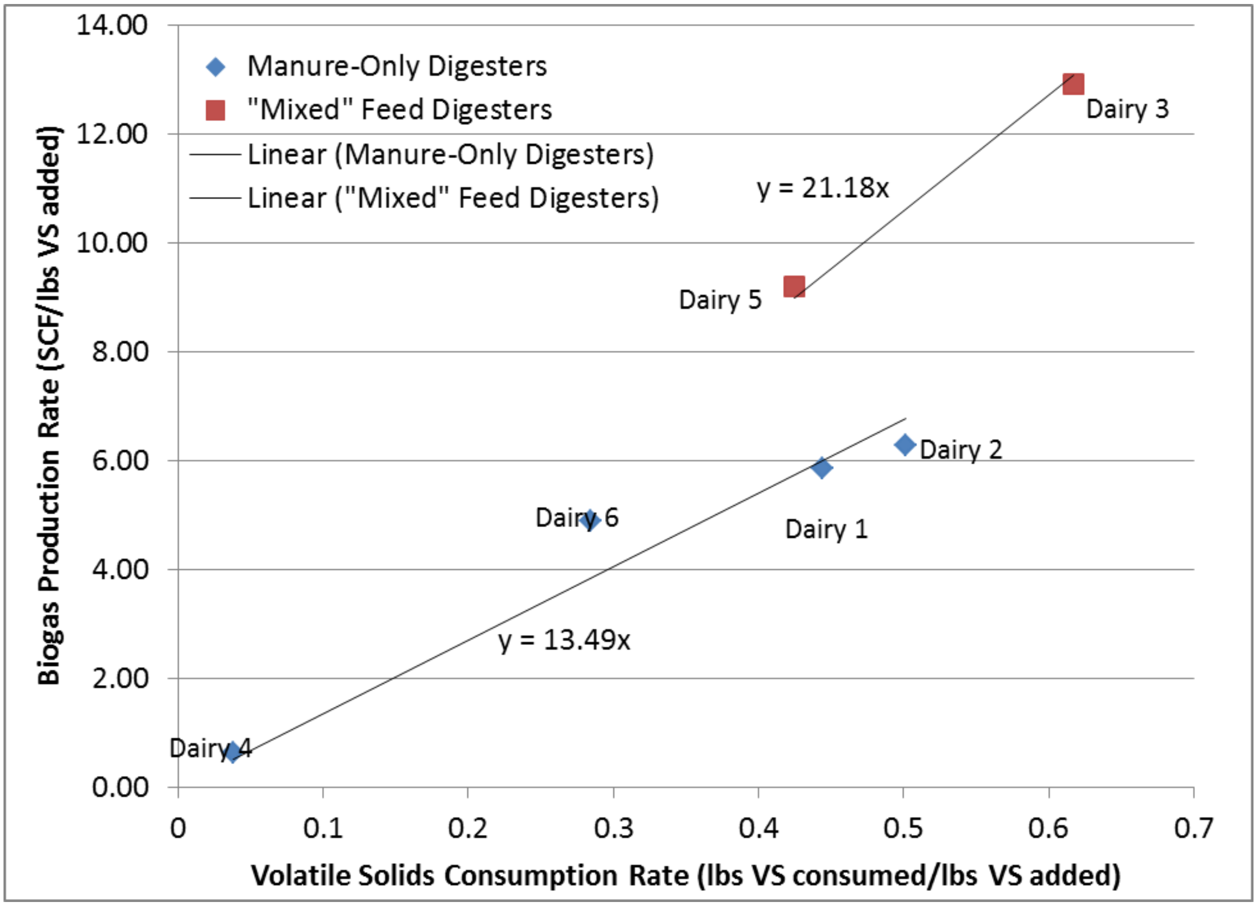

Figure 9.1: Biogas Production as a Function of Volatile Solids Consumption for the Digester Systems in the Study.

The methane content and the amount of biogas sent to the system flare instead of being utilized are also shown on Table 10. The composition of the biogas was consistently high in methane for all of the systems at average biogas methane contents between 60 percent and 68 percent. The biogas also consisted of 31 percent to 39 percent carbon dioxide, 0 percent to 3 percent nitrogen, and 0 percent to 1 percent oxygen as shown in Figure 2. Nitrogen and oxygen were intentionally added to the digester systems at Dairy 1, 2, 3 and 5 to reduce hydrogen sulfide composition. At Dairy 1 the hydrogen sulfide content in the biogas was lowered 43 percent by a biofilter system but was still fairly high with an average of 1,900 ppmv. At Dairy 2 and 3 an air injection system on the covered lagoon reduced the hydrogen sulfide content by over 96 percent to an average of 62 and 19 ppmv respectively. At Dairy 5 the air injection was a little less effective on the complete mix system but still very good reduction to an average concentration of 250 ppmv. At Dairy 4 and 6 the hydrogen sulfide composition was uncontrolled with average concentrations of 2400 and 4300 ppmv respectively. The average biogas hydrogen sulfide concentration measured at each facility is shown in Figure 3. A summary of the performance of the various sulfur dioxide control systems employed in the study is shown in Table 11.

Table 9.10: Biogas Production and Performance for the Digester Systems in the Study.

DAIRY NO.	TOTAL BIOGAS	SPECIFIC BIOGAS	SPECIFIC BIOGAS	SPECIFIC BIOGAS	METHANE	PERCENT FLARED BIOGAS
	(SCFD)	(SCF/LB VS ADDED)	(SCF/LB VS CONSUMED)	(SCF/LB VS EXCRETED)	(VOL %)	(%)
1	36,032	5.9	16.4	3.1	66.4	57%
2	32,534	6.3	14.4	4.2	66.6	0%
3	449,215	12.9	21.4	7.8	67.6	17%
4	44,982	0.6	16.3	2.0	67.8	14%
5	220,244	9.2	21.9	7.0	65.0	1%
6	105,158	4.9	18.2	2.7	60.4	19%

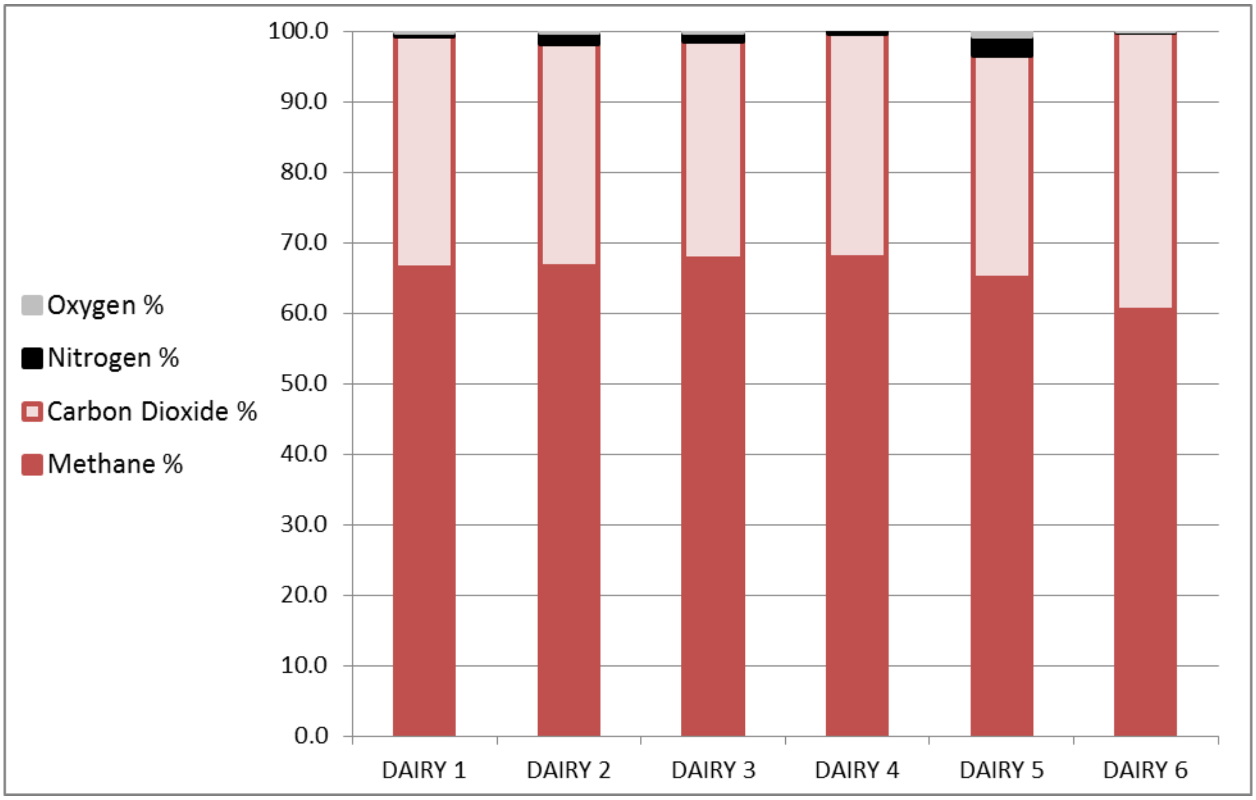

Figure 9.2: Average Biogas Composition at Each Dairy Digester Facility.

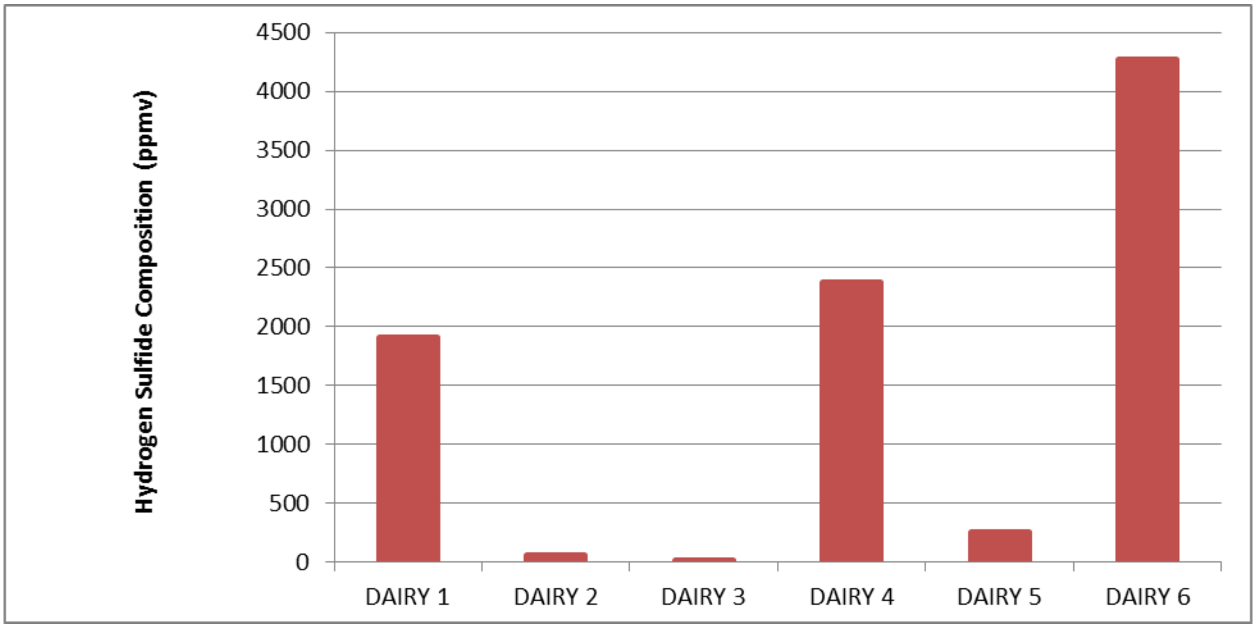

Figure 9.3: Average Biogas Hydrogen Sulfide Composition at Each Dairy Digester Facility.

Table 9.11: Average Hydrogen Sulfide Concentration in Biogas by Control Technology.

Control Strategy	Biogas H2S Concentration
Uncontrolled:	2400 – 4300 ppmv
Biofilter Controlled:	1900 ppmv
Air Injection - Covered Lagoon:	20 - 65 ppmv
Air Injection - Complete Mix:	260 ppmv
Iron Sponge:	0-5 ppmv*

*Note: Prior to saturation and breakthrough

9.4 Biogas Generator Performance

Each digester facility in this study utilized continuous duty engine-generator systems for electrical power production from the biogas generated by the digester and the performance of these systems is detailed in Table 12. The average power output, capacity factor, and electrical efficiency (after parasitic loads) are all shown in the table.

It is critical in these systems that the generator system be well matched with the production of the digester. For the most part, the facilities were successful at utilizing the majority of the biogas in the generator system. Two facilities, Dairy 3 and Dairy 6, ran at capacity factors of 82 percent and 80 percent respectively and only had to flare 17 percent and 19 percent of their biogas respectively over the study year. This means that these generator system capacities were designed to match very close to the actual biogas production of the digester system. Dairy 2 and Dairy 5 had good engine uptime well above 80 percent but they did not have sufficient biogas production to run the engine at capacity as evidenced by the low amounts of flared gas. In these cases the genset appeared to be oversized for the gas availability. This scenario can cause project cost penalties in terms of stranded capital and engine efficiency losses by having to operate at low heat rates. In both cases, the operators should look for more ways to get additional gas production out of their digester systems. Dairy 1 seemed to have a different problem, with plenty of gas to run the generator at a higher capacity factor, but continuous operational and maintenance issues on the engine that forced continuous use of the flare. At a capacity factor of 40 percent, nearly 60 percent of the gas was flared, a situation that the facility operator is trying to resolve. Finally Dairy 4 has too little gas production for the generator system at the site, due to the overloading of the digester system and overall poor digestion performance discussed above. Seeking ways to reduce the digester overfeeding should be a priority at this facility to improve overall system performance.

Table 9.12: Biogas Power Generation Performance for Each Dairy Digester Facility.

DAIRY NO.	GENSET CAPACITY	AVERAGE POWER OUTPUT	CAPACITY FACTOR	PERCENT FLARED BIOGAS	ELECTRICAL EFFICIENCY	SPECIFIC POWER OUTPUT
	(kW)	(kW)	(%)	(%)	(% LHV)	(kWh/ LB VS ADDED)
1	65	26	40%	57%	25%	0.10
2	80	51	68%	0%	21%	0.24
3	750	677	82%	17%	24%	0.47
4	212	71	33%	14%	27%	0.02
5	710	402	57%	1%	26%	0.40
6	190	153	80%	19%	28%	0.17

The electrical efficiencies were all in the expected range for engine generator systems. The electrical efficiencies ranged from 21 percent to 28 percent in terms of the biogas lower heating value. Operation of the generator set below the recommended heat rate due to biogas availability, may have reduced the performance of some of the systems.

The specific power output is instructive to look at for design and modeling purposes. In this case, electrical power output achieved by the system is expressed in terms of volatile solids added to the digester. In the case of the "manure-only" digesters, it appears that a specific output of 0.20 to 0.25 kWh per pound of volatile solids added is in the achievable range (Dairy 1 and 6 would have been in the same range with less flared biogas). For the "mixed feed" systems higher specific rates are achievable nearly double those achieved with the manure systems at 0.40 to 0.47 kWh per pound of volatile solids added.

The heat recovery for each of the engine generator systems was also tracked for each facility. Table 13 shows results for heat recovery from the generator system for each system. It should be noted that for Dairy 2, 3, and 5 that utilized heat was what was measured while Dairy 6 and 4 were delivering all recovered heat to the digester system and Dairy 1 was disposing of the heat with a radiator. The results show that heat recovery efficiencies can be expected in the range of 21 percent to 27 percent for facilities attempting to utilize the heat which is nearly the same range for the electrical efficiencies.

Table 9.13: Heat Recovery Performance for Each Dairy Digester Facility.

DAIRY NO.	GENSET CAPACITY	AVERAGE POWER OUTPUT	AVERAGE HEAT RECOVERY	HEAT RECOVERY EFFICIENCY	OVERALL CHP EFFICIENCY	SPECIFIC HEAT RECOVERY
	(kW)	(kW)	(kW)	(% LHV)	(% LHV)	(kWh/ LB VS ADDED)
1	65	26	31	33%	58%	0.12
2	80	51	49	21%	42%	0.22
3	750	677	608	24%	48%	0.42
4	212	71	100	38%	66%	0.03
5	710	402	420	27%	53%	0.43
6	190	153	140	25%	53%	0.14

Biogas engine emissions were also measured during the study. Table 14 shows the raw engine emission rates measured from five biogas engines that were sampled during the study period. The results are averages for all samples collected over the study period using the 15-minute exhaust stack sampling methodology discussed in Chapter 2. The engine heat rate, biogas methane content, and hydrogen sulfide content were also measured. The emissions were measured for both lean burn and rich (stoichiometric) burn spark ignition gas engines operating on biogas. The exhaust compositions are shown for oxygen (O2), carbon monoxide (CO), oxides of nitrogen (NOx), sulfur dioxide (SO2) and hydrocarbons (CxHy). Based on the air-fuel ratio, as determined by oxygen content, and the amount of exhaust generated by combusting the biogas, the emissions rates in terms of pounds per million BTU of fuel combusted in the engine are given along with a capacity weighted average for the engines observed. These results can be compared with rich and lean burn natural gas engine emissions factors supplied by the US EPA in AP-42. It can be seen that the engines in this study performed near or better than the standard emissions factors used for natural gas engine systems for all pollutants with the exception of sulfur dioxide.

Sulfur dioxide is generated from the combustion of the hydrogen sulfide contained in the biogas. The relationship between the hydrogen sulfide in the biogas and the emissions rate of sulfur dioxide were compared in Figure 9.4 showing a strong correlation as expected between the hydrogen sulfide in the biogas and the sulfur dioxide emissions. The relationship developed is that 0.031 lbs/MMBTU of sulfur dioxide is emitted for every hundred ppm of hydrogen sulfide in the biogas which makes sense from a mass conservation perspective.

The study also allowed us to analyze the performance of three catalytic engine emission control units placed on biogas engines to further reduce pollutant emissions. These included two years of quarterly source testing measurements on two three-way catalyst systems outfitted on stoichiometric burn gas engine systems with lambda sensors in a control scheme similar to gasoline automobile emissions control systems. Also included was one year of weekly source testing data on an engine system outfitted with a urea injected selective catalytic reduction (SCR) system outfitted on a lean burn gas engine system. The results from these three systems are shown in Table 15. While the primary target of these control systems is NOx, CO and hydrocarbons can also be reduced by the implementation of these controls. The three way catalyst systems were lower in NOx by 96 percent and 98 percent over the weighted average emissions for the rich burn engine systems. For hydrocarbons the results were 84 percent and 96 percent and for CO the results were mixed, one system performing better by 66 percent and one worse by 31 percent than the rich burn results. The SCR system showed lower NOx by 86 percent over the lean burn systems and lower hydrocarbons by 93 percent and lower CO by 61 percent. These stack emissions control systems have been operating for many years at these biogas facilities. These tests show that they continue to perform technically to reduce emissions by a significant margin, although with added cost.

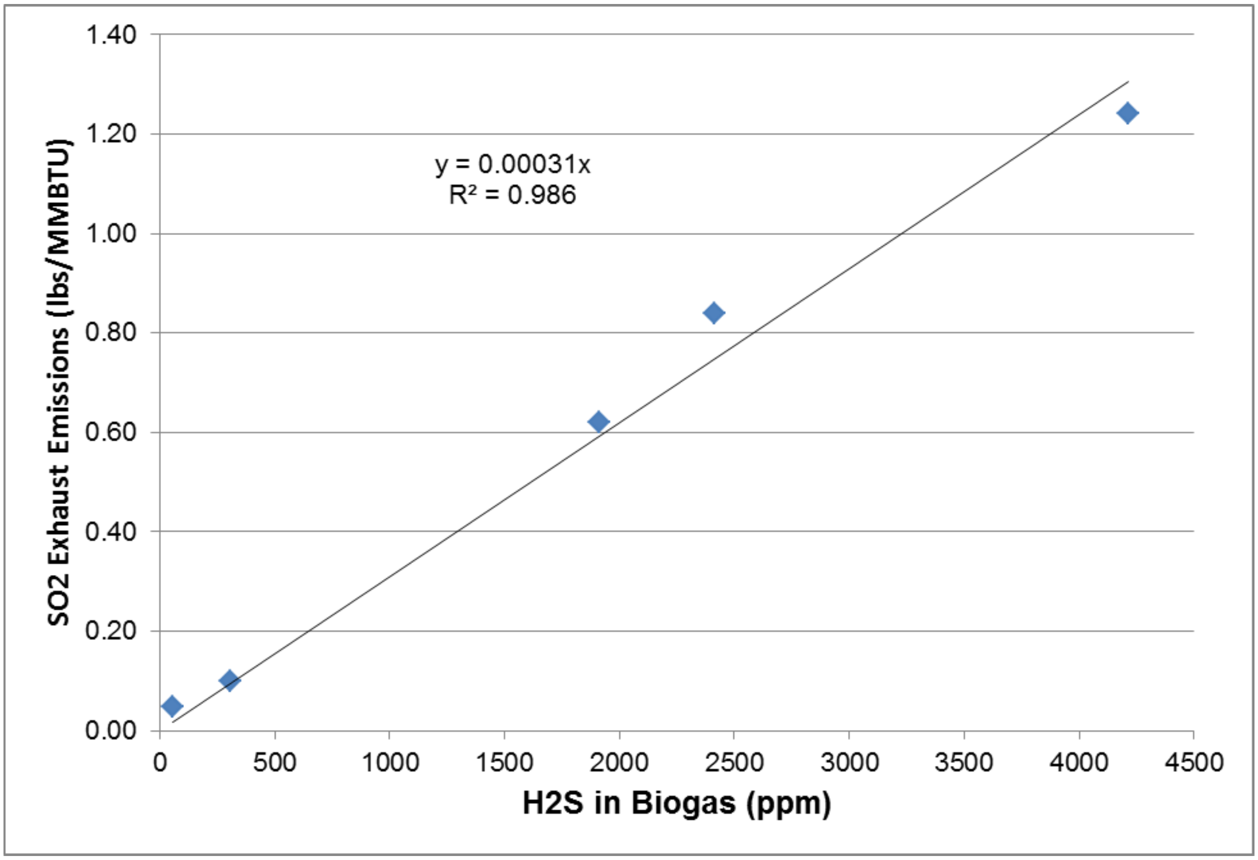

Figure 9.4: Relationship Between Hydrogen Sulfide in Biogas to SO2 Emissions.

Table 9.14: Raw Stack Emissions Performance for Biogas Engine Generator Systems.

		BIOGAS PROPERTIES			STACK EXHAUST COMPOSITION					EMISSIONS RATES			
#	ENG. TYPE	HEAT RATE	CH4	H2S	O2	CO	NO x	SO2	CxHy	CO	NO x	SO2	CxHy
		(BTU/ kWh)	(%)	(ppm)	(%)	(ppm)	(ppm)	(ppm)	(ppm)	(lb/MM BTU)	(lb/MM BTU)	(lb/MM BTU)	(lb/MM BTU)
A	Rich	13,828	66.4	1912	0.16	981	455	406	310	0.66	0.33	0.62	0.12
B	Lean	14,221	66.6	57	6.77	480	86	21	905	0.47	0.09	0.05	0.51
C	Lean	12,500	67.8	2415	3.87	566	220	451	801	0.46	0.19	0.84	0.37
D	Lean	13,375	65.0	310	4.50	577	177	52	481	0.49	0.16	0.10	0.23
E	Rich	12,294	60.4	4212	0.64	1401	1253	794	225	0.96	0.92	1.24	0.09
						Weighted Average Biogas – Rich Burn				***0.88***	***0.77***	***1.08***	***0.10***
						Weighted Average Biogas – Lean Burn				***0.48***	***0.16***	***0.25***	***0.28***
						AP-42 Natural Gas – Rich Burn				*3.51*	*2.27*	*<0.001*	*0.36*
						AP-42 Natural Gas – Lean Burn				*0.56*	*0.85*	*<0.001*	*1.47*

Table 9.15: Stack Emissions Performance From Biogas Engine Systems With Catalytic Emissions Control Systems.

			BIOGAS PROPERTIES			STACK EXHAUST COMPOSITION*				EMISSIONS RATES		
#	ENG. TYPE	CONTROL TYPE	HEAT RATE	CH4	H2S	O2	cCO	cNO x	cCxHy	CO	NO x	CxHy
			(BTU/ kWh)	(%)	(ppm)	(%)	(ppm)	(ppm)	(ppm)	(lb/MM BTU)	(lb/MM BTU)	(lb/MM BTU)
F	Rich	3-WAY	13,865	67.6	7	0.26	509 (25-1100)	6.6 (2-9)	11.2	1.20	0.016	0.015
G	Rich	3-WAY	14,523	67.6	7	0.16	129 (55-240)	12.2 (1-25)	3.0	0.30	0.031	0.004
H	Lean	SCR	12,294	65.0	310	4.50	81 (14-160)	8.8 (2-44)	14.8	0.19	0.022	0.020

Note: Pollutant compositions in ppm are corrected values at 15% O2. Range of results shown in brackets.

9.5 Climate Change

Utilizing the methodology developed for predicting methane emissions reductions by implementing digester projects at livestock facilities, the estimated baseline and digester project emissions of methane were generated by modeling these for each facility. Table 16 shows the results including the total estimated methane emissions reductions for each facility. Note that these predicted methane emissions reductions are all fairly similar (61 percent to 71 percent) for all of the dairies that flushed manure to a storage pond/lagoon in the baseline system (Dairy 1-5). The system that used a dry lot system with scraped manure in the baseline case had fewer emissions to reduce with the implementation of the digester project, thus showing a 26 percent reduction but achieving a smaller emissions reduction but still lowering the amount somewhat and not generating an increase by digesting the manure anaerobically.

Table 9.16: Modeled Baseline and Project Methane Emissions From Dairy Facilities (Tonnes/Year).

	DAIRY 1	DAIRY 2	DAIRY 3	DAIRY 4	DAIRY 5	DAIRY 6
Total Modeled Baseline Methane Emissions	***120.4***	***85.7***	***714.9***	***175.5***	***327.9***	***111.7***
Project Methane Emissions from the BCS	19.4	16.2	131.8	37.0	84.8	37.5
Project Methane Emissions from the BCS Effluent Pond	15.3	11.7	90.3	29.3	42.3	45.0
Total Project Methane Emissions	***34.7***	***27.9***	***222.0***	***66.3***	***127.0***	***82.5***
Total Methane Reductions	***85.7***	***57.9***	***492.8***	***109.2***	***200.8***	***29.2***
Percentage Methane Reduction	***71.2%***	***67.5%***	***68.9%***	***62.2%***	***61.3%***	***26.1%***

Another way to look at this data is in terms of volatile solid excretion from the herd at each facility since these manure volatile solids are the source of the methane from their decomposition. The amount of methane emissions per pound of volatile solids excreted is shown in Table 17 for the baseline and project. The dairies with flush systems are estimated to produce about 0.063 to 0.075 pounds of methane emissions for each pound of manure volatile solids excreted at the facility an amount reduced to 0.017 to 0.024 with the implementation of a digester project. The dry lot dairy is only estimated to produce 0.017 pounds of methane per pound of manure volatiles in the baseline case so the reduction is quite small with the implementation of a digester. It is also interesting to look at the methane generated in the digester in terms of volatile solids excreted which is 0.033 to 0.101 pounds for the manure-only digester systems and 0.180 to 0.205 pounds for the mixed feedstock systems. In all cases (with the exception of Dairy 4 with its performance issues) the methane generation is larger than the methane reductions and the original methane emissions of the facility in the baseline case.

Table 9.17: Normalized Modeled Baseline and Project Methane Emissions Per Unit of Volatile Solids Excretion (lbs Methane/lbs Manure Volatile Solids Excreted).

	DAIRY 1	DAIRY 2	DAIRY 3	DAIRY 4	DAIRY 5	DAIRY 6
Total Modeled Baseline Methane Emissions	**0.063**	**0.066**	**0.075**	**0.066**	**0.063**	**0.017**
Total Project Methane Emissions	**0.018**	**0.022**	**0.023**	**0.017**	**0.024**	**0.013**
Total Methane Reductions	***0.045***	***0.045***	***0.052***	***0.049***	***0.038***	***0.004***
Methane Generated in the Digester	***0.081***	***0.101***	***0.205****	***0.033***	***0.180****	***0.064***

* Dairy 3 and 5 included volatile solids from other feedstock besides manure in a co-digestion configuration.

CHAPTER 10:
Conclusions

This study showed that dairy manure digester systems can operate on a consistent basis and produce a substantial amount of energy in the form of biogas for natural gas replacement or in the form of power and heat to be utilized. It also showed that these digesters have impacts on manure solids management, nutrient management, air emissions, and climate change.

The potential impact of dairy digester systems being implemented on a wider scale in California can be more fully understood with the results of this study. With 1.8 million lactating cows in California and the supporting dairy herd to maintain this population, dairy manure solids are estimated to be generated at annual quantities of 7 million tons of volatile solids. This resource can be potentially utilized in anaerobic digestion systems and the technical potential and impacts of implementing this technology on a statewide scale should be considered.

10.1 Energy Impacts

In this study there was a range of biogas production per unit of manure volatile solids excretion at each facility due to factors like manure collection rate, solids separation, digester performance, and co-digestion. However, the manure-only digester systems operating in the recommended parameter range (excluding Dairy 4) had an average of 2.7 to 4.2 SCF of biogas generated per pound of volatile solids excreted at the dairy. The co-digestion systems increased this amount to 7.0 to 7.8 SCF but this was due to the addition of non-manure solids. In reality, the amount of biogas in these co-digestion systems that was due to manure was probably in the 2 to 4 SCF range because there were 35-50 percent non-manure volatile solids added. So an average technical potential value of 3.5 SCF of biogas per pound of estimated manure volatile solids excretion seems reasonable expectation for a well-designed dairy digester system in California.

The biogas quality was very consistent from facility to facility in this study in terms of methane content and, therefore, heating value. Average methane composition fell into a tight range of 60 percent to 68 percent with a weighted average of 65 percent. Inert gasses were also fairly consistent with CO2 from 30 percent to 39 percent, N2 from 0 percent to 3 percent, and O2 less than 1 percent. What was more variable in the gas was the hydrogen sulfide concentration. The measured raw hydrogen sulfide concentrations were quite high between 2000-5000 ppm. A variety of control technologies implemented to reduce these amounts as shown in Chapter 9 - Table 10. The successful implementation of digesters in California is going to require the implementation of hydrogen sulfide control strategies to protect engine equipment, protect emissions control catalysts, and control sulfur emissions to the atmosphere.

Applying the biogas production and composition data to the California dairy herd manure excretion estimates, gives an annual technical potential of 33 billion cubic feet of methane or about 33 million MMBTU. Co-digestion of manure with 35-50 percent other solids would likely double this result. This represents a substantial potential gas resource as a direct replacement for other types of fossil energy like natural gas, gasoline, and diesel.

This biogas can be converted to power and heat using a co-generation system similar to those employed in this study. In general, it was shown that most of the biogas generated from the digester could be delivered to a generator although some systems had a high amount of biogas that was flared due to lack of gas storage capacity to absorb variable biogas production or extended engine downtime. If a marketplace develops for more systems, it is expected that these issues will be worked out and at least 90 percent to 100 percent of the generated biogas can be delivered to the generator. These systems had measured net electrical efficiencies in the 21-28 percent range and it is believed that newer installations will use more efficient generation systems with 28 percent efficiency or greater. The efficiency for thermal heat recovery for utilization was quantified for these systems and was near the same rate as the electrical efficiency at 21 percent-28 percent. This gives a combined heat and power efficiencies in the 42 percent - 53 percent range.

Applying these power production results to the entire California industry gives a technical potential for power production of 2.4 million MWh from manure, assuming 90 percent biogas delivery to the generator and 28 percent efficiency. This would require the installation of about 300 MW of new capacity at a capacity factor of 90 percent.

Potential heat production is a different matter as there may be limited thermal host opportunities in the dairy industry for co-generation. Cheese plants and other food processing facilities are good candidates for a thermal host. All of the dairy facilities that were able to utilize the heat produced from the digester system were cheese plants. But it is uncertain how many of these opportunities exist with co-location of manure and heat load. The gross potential would be the same amount as the power production at 2.4 million MWh or 8 million MMBTU, but the real technical potential requires more study of the thermal host potential.

10.2 Manure Solids Management Impacts

The study showed significant conversions of solids occurring within the digester system converting these volatile solids to biogas. The total solids delivered to the digester in the process water were shown to be reduced by 24 percent to 44 percent, volatile solids by 28 percent to 62 percent, total dissolved solids by 18 percent to 27 percent, total dissolved solids from 18 percent to 27 percent, chemical oxygen demand by 42 percent to 68 percent, and biomethane potential from 70 percent to 90 percent. For the manure-only systems, the amount of volatile solids consumption was shown to be related to the biogas production by a factor of 13.5 SCF per pound of volatile solids consumed. For the facilities with co-digestion the factor was higher at 21.2 SCF per pound consumed. With an overall manure collection and digestion system performance of 3.5 SCF of biogas per pound of volatile solids excreted at the dairy, the amount of raw manure volatile solids consumed by the digester would be about 26 percent.

Applied to the manure produced in California, this would mean a technical potential to reduce the manure solids by 26 percent or about 1.9 million tons per year. For the digested manure streams, the COD would be reduced on the order of 50 percent, dissolved solids on the order of 25 percent, and biomethane potential on the order of 80 percent. The use of a solids separator would result in an additional 40 percent reduction in total solids from the process water stream if implemented before digestion and 30 percent if implemented after digestion.

10.3 Nutrient Management Impacts

Ammonia-nitrogen in the manure process water was shown to increase by 34 percent to 38 percent in the good performing manure-only digester systems and a much higher rate of conversion for the mixed feed systems at above 100 percent. The conversion of organic nitrogen to ammonia nitrogen is expected to occur in an anaerobic environment but total nitrogen was conserved. This is a positive impact because the ammonia-nitrogen form is preferred for immediate crop uptake. The organic bound form of nitrogen is less predictable and therefore higher risk for water quality impacts from nitrates. Manure process water treated with digester systems would have organic nitrogen reduced by about 30 percent to 40 percent making these better suited to fertilizing crops in an effective manner. The technical potential would be on the order of 100,000 tons of organic nitrogen converted to ammonia form if manure digesters were employed on an industry wide scale in California.

The study produced no other statistically significant differences between the digester influent and effluent nutrient composition with the exception of one facility that showed a reduction in sulfur. This result was not unexpected because some sulfur comes out in the biogas and this facility had very high sulfur in the raw biogas. The study produced no evidence to contradict the assumption that all other nutrients are conserved within digester systems. This can help give confidence to dairy producers and water quality regulators about understanding these systems.

10.4 Air Emissions Impacts

Using gas engines for production of power from biogas produces air pollutant emissions just like all other combustion processes that society utilizes for energy and transportation needs. This study measured the emissions rates from a number of biogas engines and they were on the same order of the standard emissions factors developed for natural gas engines. Since the industry is favoring lean-burn engines for their efficiency, the raw were 0.48, 0.16, and 0.28 pounds per MMBTU for carbon monoxide, oxides of nitrogen, and hydrocarbons respectively. The controlled emissions were much improved, at 0.19, 0.022, and 0.020 respectively for carbon monoxide, oxides of nitrogen and hydrocarbons respectively. Sulfur dioxide emissions were shown to be a function of sulfur content in the biogas. As feasible technologies were demonstrated in this study that can get biogas down to about 100 ppmv or less, this would produce an emissions factor of 0.031 pounds per MMBTU.

If digesters are adopted on a large scale, it is most likely that systems will be required to have the advanced emissions control systems. Industry wide adoption of biogas-to-power generation systems at the 300 MW capacity discussed above would result in emissions 1.0 tons per day of oxides of nitrogen and hydrocarbons, 1.5 tons per day of sulfur dioxide, and 8.6 tons per day of carbon monoxide. While this is an important impact to mitigate, it is comparable or better than other best available controls for fuel combustion systems. In addition, the development of this industry could hopefully replace older, higher emissions power generation systems resulting in a net decrease in pollutant emissions.

10.5 Climate Change Impacts

The study showed that implementation of a digester project at California dairy facilities utilizing flush systems to manage manure, resulted in a 61 percent to 71 percent reduction in methane emissions. The reduction was smaller for the dry lot dairy system in the study but this now represents only about 5 percent of the industry in the main California dairy regions according to recent studies (Meyer, 2009). The dairies with flush systems are estimated to produce about 0.063 to 0.075 pounds of methane emissions for each pound of manure volatile solids excreted at the facility an amount reduced to 0.017 to 0.024 with the implementation of a digester project.

The technical potential for digester technology applied at California dairies would be to reduce 500 thousand tons per year of methane emissions to 140 thousand tons per year or a total reduction of 360 thousand tons. This represents about 7 million metric tonnes of potential carbon credits that could be generated by this industry. These methane emissions reductions to the atmosphere represent one of the key ways that dairy digester systems help improve the environment and can represent a potential revenue source if these can be traded on the nascent carbon market. These additional ways to monetize the benefits of dairy digester systems is needed, as revenue from these systems seems to be less than the current operating cost for many of these projects as can be seen in the companion economic study.

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APPENDIX A:
Laboratory and Field Methods

Table A.1. Analysis and methods used for characterization of inflow and outflow digester samples

Analyte	Report Units	Method
Chemical Oxygen Demand	mg/L	SM 5220D
Ammonia-N	mg/L	SM 4500
Nitrate-Nitrogen	mg/L	EPA 300.0
Nitrogen, Kjeldahl	mg/L	EPA 351.2
Sodium	mg/L	EPA 6010B
Sulfate	mg/L	EPA 300.0
Specific Conductance*	µS/cm*	SM 2540B / Field Test
Total Dissolved Solids	mg/L	SM 2540 C
Total Phosphorus	mg/L	SM 4500P B E
Total Solids	mg/L	SM 2540B
Volatile Solids	mg/L	EPA 160.4
Volatile Fatty Acids	mg/L	SM 5560C
pH		Field Test

*Not a true measure of salts due to potential interference of high COD.

Table A.2. Analysis used for characterization of separated solids from digester systems

Analyte	Report Units	TMEC/RMMA Method*
Dry Matter (eq TS)	Wt %	03.09-A
Organic Matter (eq VS)	Wt %	05.07-A
Total Nitrogen	Wt %	04.02-D
Total Phosphorus	Wt %	04.03-A
Total Potassium	Wt %	04.04-A
Total Sulfur	Wt %	04.05-S
Sodium	Wt %	04.05-Na
Calcium	Wt %	04.05-Ca
Magnesium	Wt %	04.05-Mg
Iron	mg/kg	04.05-Fe
Copper	mg/kg	04.07-Cu
Manganese	mg/kg	04.05-Mn

Zinc	mg/kg	04.05-Zn

* TMECC: Test Methods for the Examination of Composting and Compost, USDA and U.S. Composting Council. 2002.

RMMA: Recommended Methods for Manure Analysis. University of Wisconsin Extension. 2003.

Table A3. Analysis and methods used for biogas characterization

Analyte	Units	MDL*	Method
O_2	%	0.2	Monthly Field Analyzer
CH_4	%	2	
CO_2	%	4	
N_2	%	By Diff.	
H_2S	ppm	High Range - 25 Low Range - 1	

*MDL = minimum detection limit

Table A.4. Instrument performance and calibration for portable equipment used for biogas engine and flare emissions testing using San Joaquin Valley Air Pollution Control District - Rule 4702

Analyte	Units	Resolution	Accuracy*	Calibration Standard
O_2	%	0.1	0.2%	20.9 ± 0.2
CO	Ppm	1	10%	722 ± 36
NOx	Ppm	1	10%	916 ± 46
SO_2	Ppm	1	10%	1018 ± 51
CxHy	Ppm	10	10%	10000 ± 500

*Accuracy is percentage of measured value and takes into account the instrument repeatability.

Table A.5. Monthly Collection Procedures

Wet Manure Samples	Monthly sampling locations include both Influent and Effluent sampling locations. Sampling locations should be consistent each month. All wastewater pipes should be inspected and any changes in digester flow or other parameters should be noted. With an automated sample collection device, a composite sample over 24 hours should be collected. With influent and effluent lift stations, a series of at least five grab samples should be collected at different depths when the lift station is at maximum capacity and then combined into a single composite sample. When possible, the contents of the lift station should be mixed before sample collection. When samples have to be collected from a continuously or periodically flowing influent or effluent stream, a series of at least six grab samples should be collected over a period of no less than one hour and combined into a single composite sample. Composite samples should be no less than 20 L (~5 gal) and sub samples withdrawn for analysis in appropriate containers with stabilizer compound as required (1L and 250ml containers). To insure that samples collected are representative, there should be an ongoing review of analytical results to determine if the degree of variability is reasonable or a modification of the sample collecting protocol is necessary. Samples should be sealed and placed on ice in an appropriate container or ice chest for shipping. Chain-of-custody forms for outside laboratory analysis should be filled out and included with

	the samples that are given to the shipping courier. Maximum sample hold time for laboratory analysis is 48 hours (NO3 analysis). For each sampling location (x2) the following samples are taken for analysis: 1 - 1-L to Dellavalle 1 –250ml with H2SO4 to Dellavalle 1 – 250ml with HNO3 to Dellavalle 2 – 1-L to Summers Consulting Follow QA/QC procedures for handling and delivery of samples as specified by laboratory
Gas Analysis	Monthly sampling locations include both Before Filter and After Filter locations to measure effectiveness of any filtering devices. Sampling locations should be consistent each month. All gas lines should be inspected and any changes in gas flow or other parameters should be noted. Use Landtec analyzer for gas analysis. Proper field calibration procedures for this analyzer should be followed. Care should be taken to insure that fittings are tight and that there is no infiltration on the sampling lines. Any sample that shows a significant amount of oxygen or balance gas should have the sample line re-installed and the gas re-sampled to insure that air infiltration is not an issue. Data from the analyzer is stored on the device but should be hand-written also to insure that the data is secure. Duplicate samples at each location should be taken over a 15 minute period.
Exhaust Analysis	Monthly sampling locations for exhaust include both Before Filter and After Filter to test the effectiveness of any exhaust cleanup devices after on the engine system. Sampling locations should be consistent each month. All exhaust pipes should be inspected and any changes in gas flow or other parameters should be noted. Use the Testo 350XL analyzer to sample the exhaust. Proper sample collection procedures should be followed as specified by the manufacturer and San Joaquin Valley Air District standard. Analyzer should sample over a 15 minute period to get an average exhaust emissions result.
Other Data	Average number, weight, and type of cows on the manure collection system for month Changes to the flush or scrape manure collection system in the prior month Estimate of any system maintenance costs incurred in prior month Frequency of oil changes on engine system for prior month Estimate of labor to maintain digester or engine system Changes to animal feed ration in prior month Any other operational changes in prior month

Table A.6. Quarterly Collection Procedures

Wet Manure Samples	Quarterly sampling locations include all of the following: Influent, Effluent, Flush Water, Water Before or After Solids Separator (one of these will be Influent or Effluent) All wastewater samples should be collected as described in the Monthly Collection Procedures. For each sampling location (x4) the following samples are taken for analysis: 1 - 1-L to Dellavalle 1 –250ml with H_2SO_4 to Dellavalle 1 – 250ml with HNO_3 to Dellavalle 1 – 1-L to ESB Labs 1 – 1-L to Summers Consulting Follow QA/QC procedures for handling and delivery of samples as specified by laboratory
Separated Solids	Separated solids are collected as an aggregate of the solids from the separated solids pile. Solids should be aggregated from five locations collected six inches into the pile to insure that surface drying has not had an effect on moisture content. A total of 20L (~5 gallons) of aggregated sample should be collected and mixed prior to sub-sampling. Samples should be double bagged in quart sized sealed bags prior to shipment to the laboratory. Samples should be stored in ice during transport. For each sampling location (x4) the following samples are taken for analysis: 1 - 1-quart sealed bag to Dellavalle 1 – 1-quart sealed bag to Summers Consulting Follow QA/QC procedures for handling and delivery of samples as specified by laboratory An estimate of solids generated during a 24-hour period should be conducted. This will involve coordination with the site operator to clear the solids pile at a recorded time, 24 hours prior to the on-site measurement time. The circumference and height of the solids pile generated in a 24-hour period should be recorded. Density samples should also be taken to estimate bulk density of the solids
Gas Analysis	Same as Monthly Collection Procedures
Exhaust Analysis	Same as Monthly Collection Procedures
Other Data	Same as Monthly Collection Procedures