THESIS

DECISION SUPPORT FOR ANAEROBIC DIGESTION INSTALLATIONS AT CATTLE OPERATIONS IN COLORADO

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ABSTRACT

DECISION SUPPORT FOR ANAEROBIC DIGESTION INSTALLATIONS AT CATTLE OPERATIONS IN COLORADO

Anaerobic digestion is a biological process used to convert organic wastes into a stable product while also producing methane for energy generation. The end product can be land applied without adverse environmental effects. The implementation possibilities of anaerobic digestion in Colorado have great potential with an estimated 14 million dollars in potential energy generation revenue. Anaerobic digestion systems in Colorado can provide great benefits for primarily in the cost savings associated with removal of manure and other biological waste products. The objective of this project was to develop web-based decision-making tools with a step-by-step guide for producers and their advisers to utilize as they consider installation of bioenergy conversion technology. The start of the project began with a field study, where manure samples were collected and analyzed for specific characteristics. Performance and applicability of anaerobic digesters varies greatly among individual farms, particularly in terms of gas production, moisture content, implementation, practicality and cost. The tool provides producers with a preliminary assessment of the feasibility of anaerobic digestion on their farm. The decision tool contains general information about anaerobic digestion systems, provides estimates of methane and electricity production, provides guidance on economic feasibility, selection of a most appropriate technology, and selection of a technology provider. Long term goals of the project include increasing adoption of animal waste to energy conversion technology and to improve the ability of producers to maintain operation of technologies post-installation.

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CHAPTER 1: INTRODUCTION

Cattle operations acts as an important contributor to the economy of Colorado, retaining these agricultural industries is critical for a healthy economy. One of the essential issues facing today's dairy farmers and feedlot producers is the manure management, created in large part by concentrated animal feeding operations (CAFO's). Implementing effective management strategies can protect air and water quality while avoiding environmental degradation and regulation infractions. In large part the manure management decision are left up to the individual farmer or producer with better management practices continuing to be limited and lacking in dissemination. The main objective of this thesis was to develop a decision support tool for anaerobic digestion (AD) installations at cattle operations in Colorado. The tool consists of a computerized decision support model posted online free for disruption. This tool is designed to aid in optimizing the dairy herd and feedlot management of manure through the use of AD.

AD technology offers many benefits over traditional methods including increasing the farm's business profitability, helping to create a more sustainable energy future and help produce a more valuable nutrient rich source of soil conditioner. Ever increasing advances in technology have allowed for the improved performance of AD systems to the point that they can become an acceptable form of a permanent manure management solution. Decreases in costs along with economics of scale have made AD systems more and more cost competitive as compared to other alternatives. Encouraging local farmers to work together as a group developing plants jointly, distributing capital costs and integrating co-digestion streams can even further improve economics.

The first step of this project was to conduct farm assessments, which consisted of both a survey and manure analysis when possible. Based on results from these farm assessments, commonalities were determined among facilities employing similar waste management practices. These commonalities were applied to provide general guidance on feasibility of installation of anaerobic digestion (Chapter 2) and development of the online decision support tool (Chapter 3). A multi-criteria decision analysis (MCDA) tool was developed to provide recommendations on most appropriate technologies based on user selected preferences (Chapter 4). Chapters two and three were also submitted as standalone documents to the Natural Resource Conservation Service (NRCS) as electronic field office technical guides. Chapters two and three were also co-written by Dr. Sybil Sharvelle and Dr. Catherine Keske with support from Luke Loetscher.

On-Farm Assessments

During the time period of May 2010 to January 2011 seven separate field studies were conducted in order to gather and obtain manure collection methods directly from producers. The main purpose of the on-site assessments was to establish trends among the various dairies and feedlots in Colorado. It was assumed that after a specific number of assessments, it would be possible to generalize the manure collection practices across the entire state as only minor difference would exist from farm to farm. The chapter outlines the practices followed at the seven farms visits, this by no means represents a large enough sample base to be able to extrapolate to all of the farms in Colorado careful consideration should be given when estimating general trends among dairy and feedlot farms. The following chapter discusses these trends and puts them in perspective of quantifiable metrics, such as the total solids content of the manure or the overall feasibility score as further discussed in section 0 "More Detailed Feasibility Analysis". Each of the sites assessed are located in Colorado. Five out of the seven sites are located north of Denver in the Fort Collins/Greely area. One of the assessments was located south of Denver and the last one was located west of Denver near the city of Montrose, CO. The location of the facilities had little bearing on the manure collection practices.

On-Site Farm Assessments Results

At each of the sites, the same general questions were asked of producers to determine an overview of the general manure collection process and the steps involved (See Appendix D: Section 0 for additional on-site questions). Out of a total of seven on-site farm surveys it was concluded that, three manure collection processes emerged. For the three distinct manure management practices five of the seven farms used dry lot practices, one farm used concrete scrape process and one farm used a flushing manure collection practice. Further details of the three processes include:

> Concrete Scrape Manure Collection: Concrete scrape is predominately found at dairy lots. This process is a result of housing cattle in large indoor hanger facilities often with concrete or sand as bedding. As the cattle are milked, a skip loader attached with a halved truck tire on the end pushed the manure to one end of the facilities. The manure is pushed into a trench which then in turn is flushed into the main lagoon. Often times the parlor is flushed with water to maintain cleanliness. This water can be used to assist in flushing the pen manure to the lagoon. Lastly, scraping can be done manually with hand held devices but this is a less common practice.
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> Dry Lot Manure Collection: The majority of facilities in Colorado are dry lot manure collection; all of the feedlots assessed were dry lot. Cows are housed outdoors in large pens and often with dirt or no bedding material. As the cows are taken to slaughter or routinely moved from pen to pen, the manure is collected

with back loaders or skip loaders. Once collected, the manure can either be directly land applied, stored in large piles, hauled offsite, or composted and sold. Lagoons at dry lot are more commonly used to store runoff and not as a treatment method for the manure.

Flushing Manure Collection: Flushing exists solely at dairy sites. Similar to the concrete scrape method, the cattle are housed in large covered hangers. As the cows are taken to be milked the housing area is flushed out with water or sometimes recycled wastewater. The flow rate out of the water valves can be as great as 70 gps (gallons per second). At this rate, a hanger the size of a football field can be flushed in less than a minute. The water used for flushing is often recycled to and from the lagoons along with added water from the parlor. Flushing also requires the installation of a solid liquid separator. As the flush manure flows to the lagoon it is allowed to settle increasing the total solids percentage.

Further explanations for the total solids associated with dry lot manure collection, concrete scraping and flushing can be found in section 0 "Preliminary Feasibility Questions".

General Trends of Dairy Farms and Feed Lots Assessed

The following sections contain a bulleted list of the common or general practices at the selected dairies and feedlots which affected the overall outcome of the feasibility of on-site AD system. For the site assessments conducted these general points applied:

- Manure collection for farms is a 24/7 operation. On-site personnel are needed for every day of the year.

- Size of facilities can range greatly, with the smallest at around 650 head to 50,000 head at the largest which is located at a feed lot operation.
- Of the farms selected they tended to use dry lot collection of manure or a mix of inside housing and outside. Manure flushing is not as common.
- When asked, the number one problem with the producers interviewed is manure management; either not enough land is available for land application or timing the application is difficult.
- Capital cost was considered the number one reason for not pursuing AD implementation. Second was fear that expected gas production could not be met.
- Of the farmers interviewed they maintain the position that AD is too costly and the capital would be too difficult to raise. This opinion is a result of several failed attempts made in previous years and a general lack of knowledge about available grant funding.
- Of the producers interviewed they have the general feeling that AD is only applicable to larger farms approximately over 5,000 head.
- For collection of manure on dry lot farms: The process occurs roughly 2-3 times a week, this practice mostly depends on size of staff on the farm. Manure that is flushed or concrete scraped can be collected up to three times per day.
- Dry lots collected the driest of the manure analyzed during this study, also resulting in the largest amount of inorganic matter in the sample set.
- Of the farms studied all of them had at least some manure hauled offsite. Farmers try to compost, but due to time constraints fully composted manure is difficult to produce. Farms also use manure for bedding, however these practices combined with land application are

still not enough to handle all of the wastes produced. Once a sufficient amount of manure has accumulated, famers will hire trucks to haul the waste to either another farm or land fill.

- Only two out of the seven farms had local access to gas pipe line with in close proximity.
- Of the farmers surveyed no lawsuits filed have won against any of the farms. Producers are careful to consider complaints by citizens and in general are quick to respond.
- Community involvement of famers appears to be a big driver of whether or not they want to consider installation of an AD system.

(See Appendix D: Results of On-Site Farm Assessments for more detailed information on each farm as well as the general outline followed for on-site farm assessments.)

On site Farm Assessments Manure Characteristics

During the on-site farm assessments, samples of manure were collected from various points in the manure collection process and then tested for basic parameters. Table 1 represents the averaged total solids and volatile solids values of the manure collection process across all of the farms surveyed.

Table 1: Total solids and Volatile Solids associated with Collection Method

Collection Practice	Avg. TS %	VS %	VS % of total	Range of TS %
Dry Lot	84%	29%	25%	62%-91%
Concrete Scrape	19%	61%	9%	11%-28%
Flush	6%	56%	7%	4%- 10%

In addition to total solids and volatile solids the chemical oxygen demand for each of the different manure samples was also taken. Table 2 shows the values for each manure sample collected along with a brief description of the manure. The standard Hach method for determining COD was used in order to determine the values in Table 2 (See section 0 for more information on Hach procedure)

Table 2: Chemical Oxygen Demand Associated with Collection Method

Description	Avg. COD (g/L)	COD (g/g)	Ranges of COD		Std COD
Dry manure	373.57	0.75	513	533	14.14
Dry Manure with hay	650.00	1.30	640	660	14.14
Wet Manure with hay	163.13	0.33	651	654	2.12
Concrete Scrape Manure	124.55	0.25	1,264	1,252	8.49
Concrete Scrape Manure	112.68	0.23	1,275	1,294	13.44
Wet flush Manure	58.78	0.12	850	937	61.52
Concrete Scrape Manure	88.45	0.18	1,157	1,125	22.63
Flush	26.05	0.05	896	844	36.77
Flush	42.55	0.09	698	655	30.41
Flush	31.17	0.06	678	606	50.91
Solid Liquid Separation	71.94	0.14	1,100	1,015	60.10
Solid Liquid Separation	88.35	0.18	1,136	1,055	57.28
Solid Liquid Separation	73.35	0.15	1,207	1,155	36.77

Although there is a large range represented between various collection methods, the ranges between sample events is relatively small when considering both the accuracy of the methodology and the variability of the sample events. The COD of the manure is also highly dependent on the total solids percentage as well. One relationship extracted from Table 2 is that the COD values for dry lots is much greater than those found in methods for flushing or concrete scraping. On Average this is because the manure has lost a lot of the initial moisture and thus became more dilute per gram of material. Even when comparing the grams COD per gram of manure, we observe that dry lot manure contains more COD per gram of material.

General Opinions of Producers surveyed on AD Implementation

Part of each assessment was inquiring the general opinion of the producers and farmers as to their concerns of implementing an anaerobic digester and it's feasibility for individual famers. In general their opinions were positive with the overall outcome of 5 out of the 7 interviewed in favor of AD installation on-site. Several major trends came out of the discussion with AD implementation, the first was that farmers were generally concerned with capital costs of AD systems. Most of the farmer have a difficult time meeting their daily cost requirements and have very thing margin, a single day of down time in operational could put some of the famers in the red (negative cash revenue). The idea of spending millions on an AD system or even fronting the bill for half of the cost is not feasible. One of the farmers suggested that before any real consideration could be taken to install a large AD project the price of milk must first rise to an acceptable margin. Another farmer suggested that AD is still not technologically advanced enough for consideration, stating that until expected gas production can be 100% guaranteed and capital costs go down AD is still not a viable source of renewable energy. He also indicated that installing solar panels on top of milking parlor or housing units would be a much better use of resources. A second misconception held by some producers was that AD systems had to be operated by a full time technician. This opinion stems from the fact that at large scale facilities, there is a need for two dedicated operators to maintain proper gas production, however in smaller scale settings this is not the case often time AD system can be maintained and operated with existing staff on hand. Another misconception held with producers was that AD could solve waste disposal issues. One farmer held the opinion that a 40% reduction in solids could be obtained by processing manure with AD technology. Trends are starting to emerge which indicate that AD is become a well-known source of electricity production in Colorado however it still has a ways to go before it is accepted as standard practice among farms.

How does Colorado compare with US for manure collection practices.

When comparing the manure collection practices for Colorado with the rest of the United States there appear several major trends. The first is that Colorado is considered a semi-arid area this places it with in the category geography the same as Arizona and New Mexico. In fact, when comparing the manure collection practices among these three states, we notice very similar aspects; predominately dry lot facilities, high inorganic content in collected manure, low moisture content and tendencies to store manure in larger piles. These processes can be contrasted to areas such as California and Wisconsin. Larger concentrations of dairy farms in these areas have allowed producers to claim massive water rights. Consequences of these high densities of dairies have led to a more centralized approach with AD implementation. An example of this kind of project includes the Cayuga Canyon Biogas pipeline initiative. This proposed project would lay over 500 miles of biogas pipe line and connect to over 13 separate dairies each with an onsite digester. A leading opinion in the industry is that massive collaboration among producers and utility companies is the future of the AD implementation projects

CHAPTER 2: ANAEROBIC DIGESTION GUIDANCE MANUAL

The following chapter outlines the general use and proper maintenance of Anaerobic Digestion (AD) in an agricultural setting. The chapter was provided to the NRCS has part of the online electronic technical field guides program, the chapter was written in large collaboration with Professor Catherine Keske.

AD is a proven, time tested process for managing residues. Hundreds of case studies have shown that properly managed AD projects which are integrated into animal waste management system have proven to be viable solutions (EPA AgStar, 2011). Benefits of AD include providing a source of renewable energy, reducing greenhouse gas emissions, decreasing odor, improvement of non-point source pollution concerns, and production of end products (liquid and solid) that can be land applied and used as fertilizer. In addition, energy generation from AD has the potential to decrease operational costs, or even provide revenue to producers with the ability to respond to ever increasing regulations and public pressure. Today there are more than 150 electrical generating AD projects operating in the United States with an expected exponential growth curve (EPA AgStar (1), 2011). With the recent rise of renewable energy initiatives culminating in a push to replace fossil fuels, AD offers a great potential for consistent 24/7 electricity and heat production. The total number of digesters has grown steadily for over a decade with an average of 16 new digesters every year in 2011 over 541 million kWh of electricity was produced using AD (EPA AgStar, 2011).

Understanding Anaerobic Digestion in Colorado

AD is the process by which organic materials in an enclosed vessel are broken down by microorganisms, in the absence of oxygen. The biogas produced via AD consists primarily of methane, carbon dioxide and hydrogen sulfide. AD systems are also often referred to as "biogas systems or biomass systems”. Depending on the system design, biogas can be combusted in a generator producing electricity and heat (Figure 1). This is called a co-generation system or combined heat and power (CHP). Other options for use of biogas include burning in a boiler or furnace, or purification to supply to natural gas lines (Figure 1). The AD process produces a liquid effluent called digestate that contains water, all the nutrients and approximately half of the carbon from the incoming materials.

AD requires that feed material be less than 17% solids by weight. Typically, manure collected on a dry lot in Colorado has much higher solids content than 17%. Microorganisms that convert organic materials into methane are very sensitive, requiring a pH near 7 and temperatures, around $95^{o}F$ or $35^{o}C$ for optimal performance.

Configurations of AD systems vary greatly from farm to farm, but generally include manure collection, pre-treatment process, biogas generation, biogas purification (H_2S removal), biogas utilization (electricity generation or gas use) and byproduct disposal AD System Configuration.

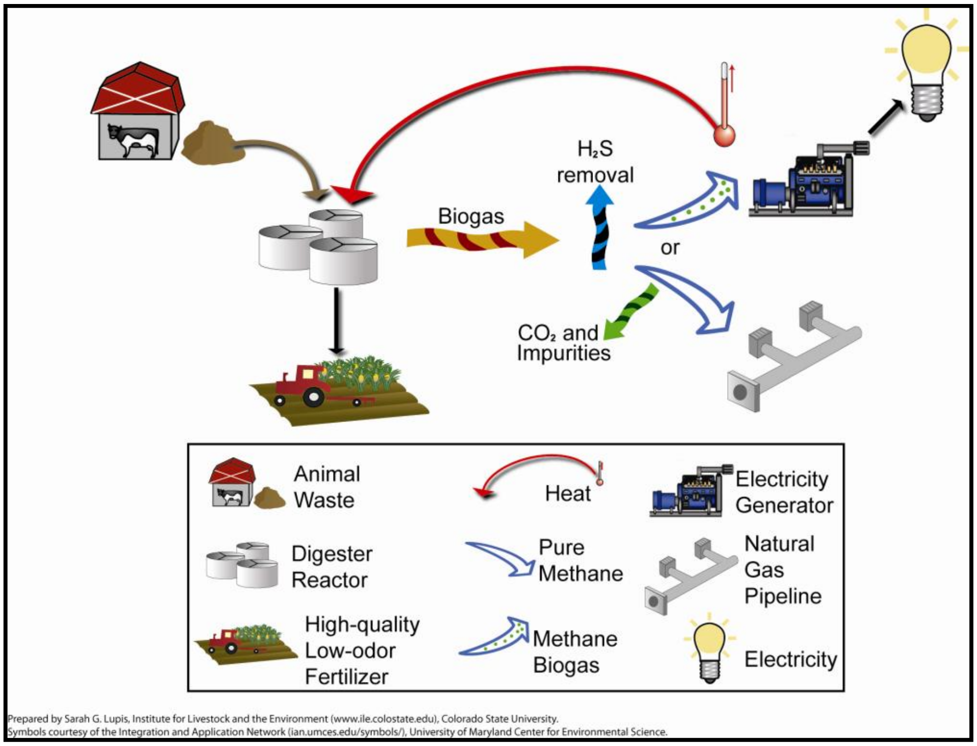


Figure 1: AD System Configuration

Biogas generated by AD typically contains between 60-70% methane (CH_4). The other primary constituent is carbon dioxide (CO_2) and small amounts of hydrogen sulfide, ammonia, water and trace organics (hydrocarbons) are also present. In order to extend the life of the equipment and purify the gas the hydrogen sulfide is removed often using iron filings.

Scale of AD Systems

There are two distinct scales in which AD operates including farm and centralized. The main difference between two scales is that farm scale involves one farm, while the centralized scale involves collection of waste from multiple locations.

Farm Scale

Onsite AD systems for the “farm scale” are designed to fit the needs of a single entity or producer. The farm scale is defined by having personal ownership of the AD system. Farm scale AD systems typically only accept the waste produced for that site and offset the owner's electricity use or can add electricity to the grid when supplemental energy is produced by the system. Farm scale systems are smaller, more commonly implemented and also tend to be more economically viable than centralized systems (Keske, 2010). Farm scale AD systems use lower cost components and often involve a lower level of control or complexity, thus decreasing overall costs. Some farm-scale systems can accept off-farm input materials such as commercial food processing byproducts or slaughter house effluent, however this can lead to regulation difficulties and should be thoroughly considered before pursuing. Farm scale AD systems are economically viable when there are on-site uses for the biogas such as heat or power for the farm or use to compress refrigerant lines (Keske, 2010).

Centralized System Scale

Centralized AD systems are predominantly found throughout Europe. Material from multiple farms, food processing plants and industrial waste streams is hauled to a centralized facility through a high biosecurity hauling process. Other materials, such as source-separated organics, are often added to boost gas production. Often the digestate is immediately transferred to remote field storage to allow for easier handling for land application. In many instances, heat from the centralized AD system is used nearby by either a commercial facility or for heating residences.

Uses for Biogas Generated from AD

The use of biogas and natural gas is rapidly growing. With ever decreasing sources of oil and the need for a more independent energy plan, the United States is adopting practices which increase the use of natural gas. Increasing infrastructure for the use of natural gas improves the capacity to make use of biogas generated through AD. Some of the potential uses for use of biogas include conversion to electricity, compression to natural gas and compression to liquid methane.

Conversion to Electricity

Biogas can be directly supplied to a generator and converted into electricity (Figure 2). Electricity can then be used on-site or excess electricity can be sold to a utility. Biogas generated from AD of animal waste contains hydrogen sulfide, which is corrosive to generator parts. Successful generator operation depends on removal of hydrogen sulfide from biogas which can be done by passing biogas through iron filings prior to introduction to the generator.

Figure 2: A generator for conversion of biogas to electricity at a hog farm (photo by Catherine Keske, Colorado State University

Purification to Compressed Natural Gas

Biogas can be purified and compressed to be injected into natural gas lines (Figure 3). This requires an extensive cleanup of the biogas resulting in gas containing 93-99% methane. Carbon dioxide, water, and hydrogen sulfide must be removed from the biogas. Methane can be directly injected into natural gas pipelines (with quality control) or transported to an injection facility. Vehicles can be retrofitted to use compressed natural gas.

Figure 3: Biogas Purification Station (*Source: Gas Technology Institute*)

Conversion of Compressed Natural Gas to Liquid Natural Gas

After biogas is purified to compressed natural gas, it can be converted to liquid natural gas rather than injected into natural gas pipelines. Compressed natural gas is cooled to -260^{o}F and stored as a cryogenic liquid in insulated storage vessels at 50-150 psi. Liquid natural gas has a lower storage volume than compressed natural gas, so natural gas is often liquefied when it will be transported long distances.

Operational Temperature for AD

Deciphering which temperature to operate an AD system can be difficult, since operation at varying temperatures has multiple benefits and considerations. The appropriate temperature setting depends on the type of AD system, the purpose, and overall goals of the project. Given the wide variety of parameters, it is best to first consult with a professional before making a final decision. The possible temperatures to run an AD system are psychrophilic, mesophilic and thermophilic.

Psychrophilic (15 ^{o}C or 60 ^{o}F)

In cases where it is desired to keep AD systems simple, they may be operated without heating. In cold climates, an unheated AD system may operate at temperatures as low as 15^{o}C (60^{o}F). These AD systems operate with very long retention times ranging from 50-150 days. Such systems are stable, easy to manage and require very little energy inputs, but produce very little biogas and in colder climates are susceptible to bacteria upsets. They require large volume and would require additional processes to achieve pathogen removal if the end product is to be land applied. These systems are most desirable when gas production is a secondary concern and the primary purpose of the system is to achieve odor reduction, greenhouse gas emission reduction, or organic and solids removal at low cost.

Mesophilic (35 ^{o}C or 100 ^{o}F)

Mesophilic systems need a longer treatment time compared to thermophilic systems with hydraulic retention times of at least 20–30 days generally required. These systems are reported to be more robust when considering bacterial upsets in comparison to thermophilic systems and are the most common application for on-farm AD. Mesophilic AD systems require larger tank volumes than thermophilic, produce less biogas and in cases where higher quality effluent is desired, may need a secondary treatment step. Mesophilic systems in general can handle a more varied or inconsistent co-digestion sources than thermophilic AD tanks.

Thermophilic (55 ^{o}C or 130 ^{o}F)

Thermophilic AD operates at the highest temperature of all AD technologies. Microorganisms rapidly break down organic matter and produce large volumes of biogas. The quick breakdown means that the AD system volume can be smaller reducing the hydraulic retention time to 12-20 days. The high temperature lends itself to improved pathogen removal, thus providing a more valuable residual effluent compared to operation under mesophilic or psychrophlic conditions. Heat exchangers can be utilized in thermophilic system for general space heating or as return energy back into the AD system. Greater insulation is necessary to maintain the optimum temperature range. Thermophilic AD systems require high energy input and extensive monitoring. These systems are very sensitive to nitrogen concentration and pH. Additional monitoring of incoming materials is required and chemical additions may be necessary. It is generally recommended that thermophilic systems not be installed above the 40^{o} longitudinal line unless proper considerations are taken.

Understand and Apply Technical Considerations for an Onsite AD System

AD is not a good fit for all animal feeding operations. Care should be taken to ensure that AD is feasible at an operation before installation. While typical management practices in the arid west do create challenges for installation of AD technology, there are technologies that can be a good fit. After you have determined that AD may be both technically and economically feasible at your facility, you will need to become informed on types of AD system technologies and which of those may be the best fit at your site. AD technologies include covered lagoons, plug flow, complete mix, upflow sludge blanket, and fixed film reactors. Guidance is required to select appropriate technologies. The web based decision tool can be utilized to determine feasibility at your site and determine most appropriate technologies for application <http://www.eramsinfo.com/erams_beta/AD_feasibility_ad_tool/>

Dry Wastes in the Arid West

In arid climates, collected animal wastes can have very high solids content. Dairies are typically thought to be a good fit for installation of AD technology. However, waste management methods applied at dairies located in the arid west differ from other parts of the

United States. As a result of water scarcity, water is not often utilized to flush dairy barns as is done in areas where water is plentiful. Instead, manure is often scraped from concrete floors or dry lots. While dairy waste has a solids content of 10-14% as excreted, solids content has been measured as high as 90% on dry lots in Colorado. For wastes containing more than 17% solids, substantial quantities of water may be required for AD. This can add to the cost of operating the AD system. In addition, when clean water is added to an AD system, it will adsorb nutrients and pathogens and become a nuisance. Dilution of waste with water is most practical when there is an available source of wastewater (domestic or food processing) to utilize.

High Inorganic Content

When manure is collected from dry lots, the collected waste is often dry with high inorganic content consisting of rocks and soil particles. Rocks and soil particles cause major operational problems for AD systems and must be removed before the waste is processed. This has been one of the most prominent causes for failure of on-farm AD and thus is very important to consider. Sand in bedding can also be a problem for AD if it ends up in the waste material supplied to the system. Removal of rocks, soil, and sand is possible, but typically involves addition of water to the waste and subsequent settling of the particles. Such processes add complexity, capital cost, and additional maintenance for an AD system.

Biogas Handling

Methane in a concentration of 6% to 15% with air is an explosive mixture. Since it is lighter than air, it will collect under rooftops and other enclosed areas. It is relatively odorless, and detection may be difficult. Extreme caution and special safety features are necessary in the AD system design and storage tank, especially if the gas is compressed.

Corrosive Biogas

The biogas generated from AD contains highly corrosive hydrogen sulfide. Sulfides must be removed prior to supplying the biogas to a generator. A simple, low cost method for removal of sulfides from biogas is passage through iron particles. Sulfides attach to the solid surfaces and are removed from the gas. The iron particles must be replaced every six to twelve months.

Co-Digestion

Combining animal feeding operation wastes with wastewater generated onsite or by nearby facilities such as food processing plants or municipal wastewater treatment plants can be beneficial by both increasing water content and increasing methane production capacity. This is typically referred to as co-digestion and is gaining popularity. The ability to combine manure with other wastes must be carefully evaluated prior to AD system installation/operation. (Stewart, 2008) In particular, it is recommended that waste streams are not varied seasonally or daily, but rather that a consistent waste is supplied to the AD system at all times. The microorganisms in an AD system are very sensitive and when the waste source is changed, it can take a long time (up to three months) for them to adjust and begin producing methane. Therefore, when the waste stream is changed on a daily or seasonal basis, the organisms do not have enough time to recover. If you are considering adding a waste in addition to manure into the AD system, you need to make sure that the waste will be available on a daily basis throughout the year to add into your system. Some typical waste streams applied for co-digestion include way which is a byproduct of milk, cheese and yogurt production, and paunch, a byproduct of slaughter houses. Care should be taken to address the high content of fats oil and grease in paunch. While these components can be converted to methane biogas, they also can result in buildup if not managed appropriately. Some of the most common sources for co-digestion are from the following sectors:

- Agricultural Food Crop Wastes- examples include sugar beet waste and corn silage. These high in sugar materials are excellent for adding to an AD system, but pre-processing requirements and solids content should be carefully considered.

- Food Processing Wastes – Many food processing facilities generate wastes which are highly digestible and contribute to biogas production. Examples include sugar manufacturing residues and dog food processing effluent. Such wastes also can yield high revenues from tipping fees (See section 0 "Economic Feasibility" for more information).

- Industrial by-products – Waste streams from industries, such as ethanol and biodiesel production are common candidates for AD.

- Municipal Wastewater - The wastewater from residential or commercial facilities is also a possible waste stream for AD system. Bio solids from nearby municipal wastewater treatment plants can also be added to an on-farm AD system.

Handling of End Products

AD effluent must be handled properly. One common misconception about AD is it will reduce the quantity of manure and the amount of nutrients that remain for utilization or disposal. Sometimes the volume of material handled from an AD system increases because of required dilution water for satisfactory pumping or AD system operation. It is important to understand that roughly 4% - 30% of the total solids are converted to biogas (Heinmann, 1998). This means that a farm loading 1000 lb. per day into an AD system can expect to have anywhere from 300 to 960 lb. of material to store and ultimately handle.

AD effluent is slurry, containing 1-15% solids, depending on the solids content of the waste which is input to the system. . The effluent leaves the AD system as a stable, nutrient rich, weed seed free, reduced or pathogen free and nearly odorless product. The processed material containing solids can be applied by a honey wagon, or solids can be separated for composting and subsequent land application by a manure spreader. The weight of the processed slurry material containing liquid and solids (5-15% solids) may be too expensive to transport large distances. Solids separation in combination with composting can result in a lower weight product which can be transported at lower costs compared to slurry for land application. Utilizing the nutrient rich liquid component for irrigation is referred to as fertigation or chemigation and is regulated in most states. When fertigation systems are connected to a freshwater source, appropriate measures must be taken to avoid contamination of the freshwater source such as inclusion of a backflow preventer and shutoff valve. Fertigation systems must adhere to state and local regulations. If land application is not an option, you will need to find another method for AD effluent storage or treatment on site.

General Summary of Criteria for AD Feasibility

A technical feasibility study will be needed in order to completely asses the complexity and cost for even a small on-farm AD project. You can use the online AD feasibility tool for a preliminary feasibility assessment for AD installation

<http://www.erams.colostate.edu/AD_feasability/ >

There are several criteria which can be applied to begin thinking critically about an AD project and weather the opportunity presents itself as reasonable. There are several factors which will typically determine feasibility:

- *Manure is collected from concrete by scraping or flushing:* Manure collection methods that are most feasible for AD application are collection from concrete by scraping or flushing. If manure is collected from dry lots, a reliable source of wastewater is present either from the lagoon or other outside source must be supplied. See the discussion on Dry Waste in the Arid West (Section 0)

- *Reliable source of wastewater for co-digestion:* See discussion on co-digestion (Section 0).

- *Sustainable outlet for effluent*: See discussion on Handling of End-products (Section 0).

- *Uses of biogas for either heat and/or electricity:* Before beginning any AD project, first determine what current uses your farm may have for electricity or heat production. Identify how steady the sources are, if they require the same energy during the day as night. Having consistent outlets for biogas production will minimize flaring and increase overall profitability. Information on estimating energy generation potential is provided in Section 5.

- *Size and location of plant:* AD systems can require substantial area and need to be located in an area that is not too far from manure production to minimize transport of manure. Take advantage of slopes, where gravity could be used to assist in the flow of manure. Additionally, if you are considering expanding current operations, look for areas where the AD system can be installed without impacting future growth. This is critical as installation of AD technology often allows for a greater cow density.

- *Staffing concerns including additional training and proper work loading:* Ensuring that the necessary staff and personnel are on hand is critical for when operational problems occur. Generator downtimes can substantially impact economic viability of a project. Timely repairs are critical when you are reliant for energy generated either on-farm or for selling off-site. Take into consideration that larger AD systems may require a full time staff member to monitor and perform maintenance for the AD systems.

Estimating Energy Generation Potential

Biogas generated by AD typically contains between 60-70% methane. The predicted energy production for different types of animal wastes is shown in (Table 3). To put the energy value of animal waste into perspective, a well-insulated, three-bedroom home takes about 32 kilowatt hours (kWh), or 110,000 BTU, per day for heating during cold weather. If 50% of the biogas goes back into maintaining the necessary temperature of the AD system, it would take the manure from approximately 21 cows to produce enough biogas to heat an average home during winter months. This assumes an efficiency of 65% for a furnace using biogas.

Table 3: Energy value for various animal wastes based on a 1000lb animal

	Volatile Solids (lb/day/1,000 lb)	Methane Production (ft^3/animal/day)	Energy Value (kWh/animal/day)
Dairy cattle	8	17	4.7
Beef cattle	6	13	3.5
Swine	5	18	5.0

The steps to estimate energy generation from animal waste at your facility and associated cost savings are outlined below.

1. Calculate the energy production per day (EPD) in kWh/day

$$EPD(kWh/day) = Number\ of\ animals \times \frac{kWh}{1000\ lb\ animal \cdot day} \times Typical\ weight\ per\ animal\ EPD(kWh/day) =$$
$$Numberof\ animals \times \frac{kWh}{1000lbanimal\ day} \times Typicalweight\ per\ animal\ (lb)$$

Equation 1: EPD equations

Note: kWh/1,000 lb animal/day is the energy value available in the third column of Table 3.

2. Estimate savings associated with use of biogas for on-site heating.

   a. You will first need to determine the available energy after biogas is utilized for heating the AD system (AEB). A conservative estimate is that 50% of the produced biogas will be used to meet the heating requirement:

$$AEB\ (kWh/day) = EPD \times 0.50$$

Equation 2: AEB Calculation

   b. Determine your on-site natural gas demand (ONGD). ONGD can be estimated by looking at your utility bill over the last year. Most utilities can provide one year of records upon request.

   c. If AEB is not in excess of ONGD, the following equation can be used to estimate cost savings (assuming 65% efficiency for use of biogas as a fuel):

$$Cost\ Savings\ (\$/day) = AEB \times 0.65\ Efficiency \times \frac{Cost\ of\ Energy}{day}$$

Equation 3: Cost Savings AEB

Note: The cost of energy per day should be in units of dollars per kWh. Gas bills often report energy in BTU. There are 3412 BTU in 1 kWh.

If the AEB is in excess of the on-site natural gas demand, then ONGD should be used in place of AEB:

$$\text{Cost Savings (\$/day)} = ONGD \times 0.65\ Efficiency \times \frac{\text{Cost of Energy}}{day}$$

Equation 4: Cost Savings ONGD

Note: The cost of energy per day should be in units of dollars per kWh

3. If you will be installing a generator for on-site use of electricity and/or selling the electricity to a utility, you will need to determine your on-site electricity demand (OED). OED can be estimated by looking at your utility bill over the last year. Most utilities can provide one year of records upon request. Energy in excess of the OED can be sold to the utility if the local utility is amenable to purchasing the electricity. You will need to research this possibility if you are interested in selling generated energy to the utility.
   a. Determine electricity available (EA) from the generator kWh/day (assuming and efficiency of 35% for use of biogas in a generator):

$$EA\ (kWh/day) = EPD \times 0.35\ Efficiency$$

Equation 5: Electricity Available

   b. Estimate savings from on-site use of energy. If the EA is lower than OED, than only EA, rather than the total OED, should be used for calculation of cost savings.

$$Cost\ Savings\ (\$/day) = OED \times \frac{Cost\ of\ Energy}{day}$$

Equation 6: Cost Savings OED

Note: The cost of energy per day should be in units of dollars per kWh

If the EA exceeds OED, then some energy may be sold to the utility and you must determine the price they are willing to pay (P) in dollars per kWh. P is the wholesale rate of electricity, not the retail you are charged from the utility to purchase electricity. In Colorado, P is often 0.01-0.03 dollars per kWh (1-3 cents per kWh), but can be as high as 0.10 dollars per kWh (10 cents per kWh) in other states. You can then estimate revenue from electricity sales (RE):

$$RE\ (\$/day) = (EA - OED) \times P$$

Equation 7: Revenue Generation

See Appendix E: Section 10.2 for more information on electricity production equations.

Determining Economic Feasibility for an AD System

If AD appears to be technically feasible and you have estimated the energy generation potential, it is important to consider whether the project would be economically feasible. You can use the online to find more information on and evaluate the economic feasibility of AD at your facility

On-farm AD units typically cost at least $1.5 million when there are more than 1500 animals. Some of these costs can be offset by federal or state grants, or loans. Costs could also increase, depending upon the size of the unit, design, and features. Annual operation and maintenance costs (like maintenance, repairs, parts, labor, and insurance), must also be recovered.

You will need to determine whether AD costs can be offset by generating revenues or reducing expenditures on energy over the life of the AD system. The typical life of a system is estimated to be 10-15 years. Most AD systems are semi-customized by the technology producer, so the capital outlay and operating/maintenance costs will vary. The U.S. Department of Agriculture AgSTAR website provides a good overview of expected costs and revenues (EPA Agstar, 2011). The website is frequently updated with information about federal and state funding opportunities for AD projects.

Producers should be wary of relying on AD to generate revenues from utility energy buy-back. Some states have “net metering” policies, where small energy generators (like those with an anaerobic AD system), can provide surplus energy to the utility, in order to offset their energy consumption. For example, Colorado recently implemented a net metering policy in 2009. However, the price per kWh received for net metering is relatively low. While this varies according to utility company, operators should expect a buy-back price of approximately $0.02 per kWh. To increase profitability, producers should focus on reducing operation and maintenance costs, as well as offsetting on-farm energy usage with the anaerobic AD system.

During the process of selecting a technology provider to build the AD system, you should outline some of the expected costs and revenues over the life of the system. Once a technology provider is contacted, more detailed information can be obtained and if necessary a consultant should compute costs.

Indicators of Economic Feasibility

Although it is important to actually crunch the numbers, there are five indicators that AD might be economically feasible on-farm. These indicators can help determine whether you should pursue a comprehensive feasibility study for your operation. These criteria have been selected based upon studies conducted in the intermountain west (Keske, 2010) .If operations meet at least two of the criteria, you should conduct a more detailed spreadsheet analysis for you facility. The indicators are as follows:

- *Operation meets the definition of a Confined Animal Feeding Operation (CAFO):* Before considering economic feasibility, determine if your operation meets the definition of a CAFO. CAFOs must comply with state and federal laws governing waste management practices. An anaerobic AD system might complement a CAFO's plan for air emissions, nutrient, or waste management.
- *There is potential for co-digestion:* In other words a waste stream exists that could be combined with the waste stream of another operation or business. When agricultural producers and other industries producing high organic waste products are located nearby, there are typically efficiencies that can improve the economic viability of a project. Feasibility studies have shown that co-digestion projects might be economically viable in the intermountain west
- *Operation receives frequent and/or credible complaints about odor:* AD units can provide a measurable reduction in odor, which can help to improve neighbor relations and mitigate nuisance lawsuits. The financial risk associated with an odor-related nuisance lawsuit can be difficult to estimate because information about damage awards is not readily available. The majority of cases are settled outside of court and insurance companies typically pay a

portion of the settlements. Most verdicts and settlements are not publicly reported. A summary of some recent settlements is provided in Table 2 which was originally presented in (Keske, 2009).

Table 4: Summary of Financial Awards from Agricultural Nuisance Suits

Claims Awarded in Nuisance Suits				
Year	**State**	**Award**	**Plaintiff/Case**	**Operation**
1991	NE	$375,600	Kopecky v. National Farms, Inc.	Swine
1996	KS	$12,100	Settlement—plaintiff/respondent both undisclosed in news article.	Swine
1998	KS	> $15,000	Twietmeyer v. Blocker	Beef feedlot
1999	MO	$5,200,000	Vernon Hanes et al. v. Continental Grain Company	Swine
2001	OH	$19,182,483	Seelke et al. v. Buckeye Egg Farm, LLC and Pohlman	Egg/Poultry
2002	IA	$33,065,000	Blass, McKnight, Henrickson, and Langbein v. Iowa Select Farms	Swine
2004	OH	$50,000,000	Bear et al. v. Buckeye Egg Farm, Anton Pohlman and Croton Farms, LLC	Egg/Poultry
2006	AL	$100,000	Sierra Club, Jones, and Ivey v. Whitaker and Sons LLC	Swine
2006	MO	$4,500,000	Turner v. Premium Standard Farms Inc.; Contigroup Co., Inc.	Swine
2007	IL	$27,000	State of Illinois (Plaintiff). Respondent undisclosed.	Swine

- *Operation produces swine or chickens:* Many odor nuisance claims involve swine or poultry operations. These operations have also involved high punitive damage awards. This history may encourage swine and poultry producers to consider adoption of AD units as a management practice to reduce the risk of nuisance claims.
- *Operation incurs more than $5,000 in average energy expenditures per month:* In the intermountain west, electricity costs are generally lower than the eastern United States.

This is primarily due to relatively inexpensive coal and hydroelectric resources that are available for electricity generation. While the environmental damages resulting from burning coal could be factored into future energy policy, the current price per KWh of electricity is low compared to other regions of the country (Symbios, 2009). Low energy costs make it more difficult to justify a AD system investment. This is because operations current energy expenses are relatively lower than in other parts of the country and the value of selling excess energy produced is also lower. In the intermountain west, a good rule of thumb is an average of $5,000 in energy costs to offset costs of installing and maintaining an AD system.

Direct on-farm use of biogas to supplement natural gas demands is the most cost-effective means for using the energy from the AD system. Avoiding energy costs will yield a higher net economic impact compared to any potential revenues that might be generated from supplying electricity to the grid (Keske, 2009). A generator is required to convert methane gas into electricity, making it more expensive to operate. In addition to the extra capital outlay for a generator, operations will need to plan on maintenance, labor costs, and back-up electricity resources. An operation that strictly uses biogas would likely incur fewer expenses. If your operation incurs at least $5,000 in energy costs per month, it has the potential to offset many of these costs with an anaerobic AD system and it will be worthwhile to conduct an individualized economic feasibility analysis.

Other Considerations for Economic Feasibility

A general rule of thumb for transportation costs is to try and stay under $1/per ton of manure / per mile (Mass Natural, 2010). This is typically the range at which AD system projects can begin to dip into the red for operational costs. Avoid transporting water as much as possible. Pumping for high solids materials is typically done with rotating screw augurs. Although these augurs have higher capital costs when compared to positive displacement pumps on the whole they will last longer and require less maintenance when compare to positive displacement pumps. Whenever possible, take advantages of slopes and gravity fed system as they will greatly reduce operation and maintenance costs.

The intermountain west presents unique environmental issues that might affect economic feasibility for a AD system. For example, low humidity and scarce water resources result in low water and high solids content in manure. This means that rocks and other inorganic solids could cause AD system maintenance expenses if not managed properly. Likewise, it may be expensive to add water necessary for microbial function, compared to eastern dairies. Most AD feasibility studies that are currently available are relevant to the eastern United States, where electricity prices are relatively higher and water resources are more readily available. As follows are considerations for spreadsheet analysis of economics:

1. Include the cost of water into the spreadsheet when water must be supplied to the system.
2. Do not count on revenues from greenhouse gas offsets to fund the system. These markets are voluntary in the United States and have shown considerable price volatility and low prices in recent years.
3. Review state guidelines to determine waste transport policies for on- or off-site locations, before calculating potential tipping fees.
4. Account for maintenance and labor costs, in addition to the capital outlay of an electricity generator.

5. Include the costs of energy back-ups, in the event that the system is down for maintenance.
6. Understand state and utility company's policies about net metering and energy buy-back programs.
7. Be sure to consider all of the costs associated with building, storing and transporting manure. The cost to tie into the grid, for example, can be high depending on the operation's proximity to the utility infrastructure.
8. Estimate methane generation potential and maintain a realistic perspective of energy costs that might be able to offset.
9. Factor in risk. Prices can vary considerably. Be sure to look at the most likely, and the worst case scenarios.

Selecting an Appropriate AD Technology

Several technologies are available for AD including; covered lagoons, plug flow, complete mix, upflow sludge blanket, and fixed film reactors. Technology selection is highly dependent on waste solids content. Swine waste is generally in the form of a slurry (<15% solids) and thus amenable to conventional anaerobic AD system technology while cattle waste collected from dry lots can be very high in total solids (TS) content (>50%). Dairy manure collected on concrete (by scraping) generally has a total solids content between 10-17%, while flushed manure can have a TS content less than 3%, but can vary substantially depending on the amount of water used for flushing manure. Use the online decision support tool for additional guidance on technology selection based on current waste management methods <http://www.eramsinfo.com/erams_beta/AD_feasibility_ad_tool>

Table 5: Recommended Waste Solids Content for AD Technologies

Technology	Recommended Waste Solids Content
Plug Flow	11-17%
Complete Mix	5-10%
Upflow Sludge Blanket	1-5%
Covered Lagoon	<3%
Fixed Film	<1%

<u>Covered Lagoons</u>

Covered lagoons are one of the cheapest and simplest AD technologies available. AD and subsequent production of methane takes place naturally in lagoons which contain manure wastewater. A synthetic cover, typically plastic or rubber is used to trap and store the biogas. Covered lagoons are difficult to heat and they are only recommended in warm climates where freezing temperatures are rarely observed. Too little methane is generated by covered lagoons during cold winter months in Colorado to justify installation of biogas capture and use equipment.

Figure 4: Image of Covered Lagoon (Photo taken by Catherine Keske at Colorado State University)

Covered Lagoon Advantages:

- Low cost
- Covering of lagoon can quickly mitigate odor concerns
- Advancements in HDPE (high density polyethylene) have increased durability and lowered cost of covers

Covered Lagoon Considerations:

- Retention times are long resulting in a large required area
- Lagoons need to be excavated or cleaned routinely and covers add an additional layer of complexity to this process
- Biogas production is inconsistent since it varies greatly with temperature
- Covered lagoons become increasingly impractical in cold climates

Plug Flow

Plug flow AD systems are a low tech AD technology for treatment of high solids content waste. The thick, high solids content waste travels down the AD system in a "plug," as a continuous mass. Plug flow AD systems can be a good fit with the high solids content waste generated by animal feeding operations in the arid west.

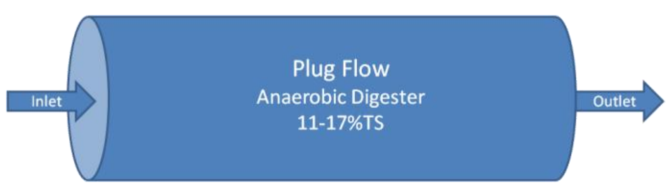


Figure 5: Plug Flow Technology (figure developed by Luke Loetscher at Colorado State University)

Plug Flow Advantages:

- Able to handle high solids content waste (11-17% TS)
- Substantially lower operations and maintenance compared to complete mix AD
- Reliable and tested technology
- Minimal upsets or downtimes
- Low capital costs

Plug Flow Considerations:

- Issues with stratification can lead to decrease in efficiency
- Inconsistent bacterial concentrations cause variability in gas production
- Low volatile solids destruction rates

Complete Mix

Complete mix reactors are large, often cylindrical, tanks which have a mechanism to keep the reactor completely stirred. The stirring mechanism can be injected biogas, or a motorized paddle. Mixing produces an ideal environment for anaerobic microorganisms by spreading the nutrients evenly throughout the reactor, while simultaneously helping to dampen shock loads of toxins which may enter the system since influent is instantaneously diluted through mixing. Complete mix reactors operate best when solids content is between 5-10%. Because solids content of waste produced at most intermountain west cattle feeding operations is higher than 5-10%, complete mix reactors are often not a good fit unless an external source of water or wastewater is readily available.

Figure 6: Complete Mix Technology (figure developed by Luke Loetscher at Colorado State University).

Complete Mix Advantages:

- Allows for variability in substrate
- Works over a wide range of solids content
- More consistent and reliable methane production compared to plug flow or covered lagoon

Complete Mix Considerations:

- Requires a large hydraulic retention time (volume), or settling and recycling of solids
- Large energy required for mechanical mixing
- High capital cost compared to other technologies

Upflow Sludge Blanket

In an upflow sludge blanket AD system, settling of solids is encouraged so that a sludge blanket is formed, maintaining biomass within the system, thus reducing the required holding time. These reactors are highly efficient and have been successfully up-scaled for commercial application. In general, waste generated at intermountain west animal feeding operations is too high in solids for application of an upflow sludge blanket reactor.

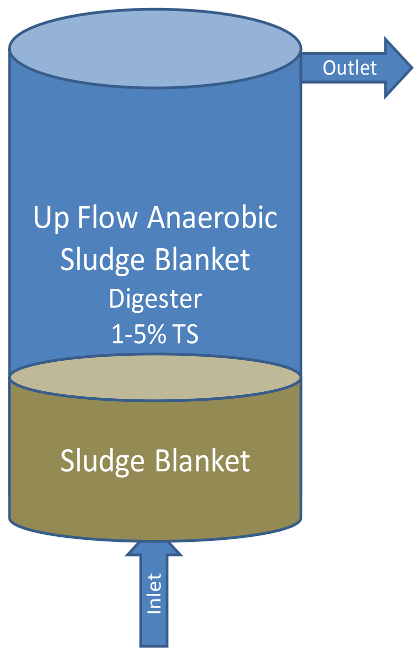


Figure 7: Upflow Anaerobic Sludge Blanket (figure developed by Luke Loetscher at Colorado State University).

Upflow Sludge Blanket Advantages:

- High destruction of volatile solids
- Lower solids output
- Low volume requirement
- Greater methane and biogas yields

Upflow Sludge Blanket Considerations

- High probability of upsets and downtimes
- Longer start up periods and difficult bacterial recovery

Fixed Film AD systems

In a fixed film AD system, bacteria colonize a support structure within the reactor. This support structure is a high surface area material suitable for colonization, such as PVC pipe or shredded plastic. Fixed film reactors have successfully been implemented with low solids content dairy manure wastewaters in Florida, but are not likely to be a good fit with animal wastes produced in the arid west.

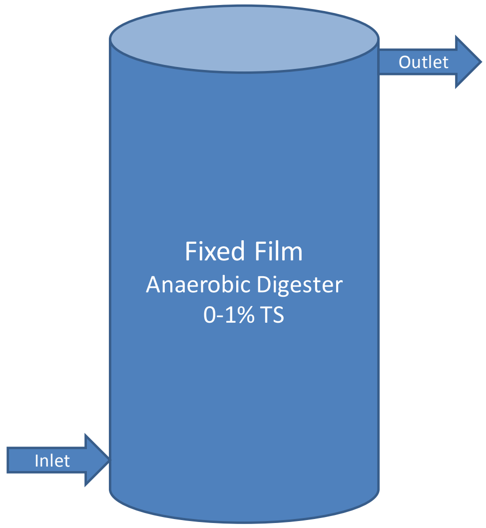


Figure 8: Fixed Film Anaerobic AD system Technology (figure developed by Luke Loetscher at Colorado State University).

Fixed Film Advantages:

- Very short Hydraulic retention times (low volume)
- High methane production

Fixed Film Considerations:

- Works only with high water content waste and solid particles must be small and therefore requires solid separation before processing manure
- Potential plugging or clogging issues

AD system Technology Provider Guidance

Once an appropriate technology has been selected for AD for your specific operations, you can begin contacting technology providers. You may choose to hire a consultant who will guide you through the process of technology provider selection. However, make sure that the consultant is not tied to a specific technology provider. Some technology providers may assist you with project financing, although it is also important to consider all financing options. Below follows a list of questions that should be asked of a technology provider (See Appendix: List of technology providers).

1. *How many on-farm anaerobic AD systems does your company currently have in operation and where are they located?*

The advantage of going with a company that has a large number of successfully operating projects is lower risk. Some of the newer companies offer novel systems that can be advantageous compared to conventional systems, however there is more risk in investing in a newer technology provider. Newer technology providers should be considered, but make sure that technologies have been successfully demonstrated on-farm at a large scale. Ask to speak with producers who have been involved in demonstrations. Many companies will also have published case studies which they can provide.

2. *Of the operating AD systems, how many are applied for animal feeding operation manure management?*

A company that specializes in AD of manure may be a good choice. Several companies have emerged who specialize in AD of food and yard wastes collected in urban areas. Manure is very different from these urban wastes, and technologies developed for food and yard waste may not work well for AD of manure.

3. *Where are successfully operating AD systems located? Are you willing to take on projects in the Mountain West region?*

Many technology providers have regions where they have had a lot of success, and may not be willing to move outside of their current service area. Companies that have experience working in the Mountain West region and are familiar with the challenges associated with working in arid climates may be a more suitable choice.

4. *What types of AD technologies does your company provide?*

Some companies may only offer one technology type (i.e. complete mix, plug flow, upflow sludge blanket, or fixed film). Work with a company that offers technologies suitable to the waste generated at your farm (see above Appendix: A "List for Technology Providers" for more information also see and the online decision support tool

<http://www.eramsinfo.com/erams_beta/AD_feasibility_ad_tool>

5. *What are the services your company provides?*

You need to be sure of what services the company provides, and determine if you will need to find additional support for other services.

6. *Are there case studies of your technology that you can share?*

Many technology providers have published case studies of their technology. If such publications are available, review them. This will help when comparing the performance of various technologies.

7. *Is pretreatment required?*

Some technologies will require pretreatment of waste. This can add substantial capital and maintenance costs to operation of an AD system. One example is pretreatment of waste to remove inorganics (rocks, soil, and/or sand). Make sure to understand the entire process before investing.

8. *How long are your project design, construction, and system lifetime on average?*

Often it can take up to 2-4 years for a AD system to move from initial feasibility study to gas production. Make sure you understand how long it will take to install the system and what the expected lifetime for the system is.

9. *Does your company provide a performance guarantee and/or warrant and if so what are the details?*

Different technology providers will provide different guarantees and/or warrantees and you should understand the details of those so that you can make comparisons between different companies.

10. *Does your company provide support and guidance for handling of end products?*

The end-product of AD is slurry, which can either be land applied or must be disposed of (see section 0 for more information regarding handling on end products) Some technology providers do not provide support for handling of end-products and make sure to consider how to handle the end product. The costs and maintenance of handling end products must be considered in the project feasibility study. You will need to determine how much support the technology provider or consultants you are working with can provide in this area.

11. *Will your company hire any subcontractors to complete portions of the project design/construction?*

Make sure you understand who will be the project team and that you are comfortable with the design-build process.

12. *What kind of training is provided to the client by the technology provider?*

Installation of an anaerobic AD system will increase maintenance required for animal waste management compared to composting or lagoon management. You need to make sure that the technology provider you work with is clear about maintenance activities which will be required after initiation of operation. AD system operation will be more successful if the technology provider provides a clear plan for maintenance activities and training on these activities.

13. *Will the technology provider help coordinate project financing?*

As with any large capital investment, it pays to research financing options. Numerous federal and state funding programs that provide grants, reduced interest loans, and/or tax credits for AD systems. A good place to start the research is the U.S. Environmental Protection Agency Ag Star website. This link will takes you directly to the funding programs:

<http://www.epa.gov/agstar/tools/funding/index.html>

Several technology providers offer loans directly for AD projects. The technology provider may also help to navigate through the numerous federal and state grants or loan programs that are available. The technology provider might be able to connect with privately funded niche programs, including greenhouse gas mitigation programs. Your local ag bank may be your best financial resource. While the technology provider might be able to help coordinate project financing, be sure that you fully understand the project financing package offered.

Maintenance of Anaerobic AD systems

Operation of an AD system will require more maintenance than other manure management practices, such as composting or waste lagoon management. Installation of an anaerobic AD system may require hiring 1 to 2 additional employees for routine maintenance, depending on the size of the operation. Be prepared to meet additional maintenance requirements if you are considering anaerobic AD system installation

Depending on AD system design and operation, solids can also settle out in the bottom of the AD system and/or form a floating scum mat. Both the scum mat and the solids will eventually need to be mechanically removed from the AD system to assure desired performance. When evaluating the actual performance and operation of a AD system it is important to determine and account for the amount and type of material retained in the AD system and the cost of lost AD system volume and ultimate cleaning. Some of the common maintenance activities are listed below with the frequency requirement in parenthesis.

Sludge Removal (every 1-2 years) - An AD system must be cleaned and removed of excess sludge. In well-designed systems, this is performed automatically with very little to no downtime. Other designs require manual removal of waste.

Pump Clearing (every 3-6 months) - When pumping high solids content waste, it is important to ensure that pumps are cleared of debris regularly. Items such as cow tails (when removed for ease of milking), sand, work tools and other inorganic substances can clog pumps hindering operation of the AD system.

Iron Packing Replacement (every 6-12 months) -It is important to remove the corrosive hydrogen sulfide compounds to avoid engine replacement if biogas collected from the AD systems is being refined and used for electricity generation. This can be done by passing the biogas through iron packing material. The iron packing should be replaced at least every 12 months.

General Engine Maintenance (every week) - Just as in your car, the generator producing electricity from the anaerobic AD system must be inspected for proper fluid levels.

Preventative Engine Maintenance (every month) - The electrical, fuel and air intake systems must also be inspected for each of the gen sets.

Valve Leak Checks (every 6-12 months) - To avoid safety hazards, it is recommended that the valves on the AD system be checked for leaks one to two times a year. Improperly working valves should be replaced as soon as possible.

Pipe Leak Checks (every 6-12 months) - Pipes must be checked for leaks at least once per year. It is also important that no open flames are anywhere near inflow or outflow pipe lines.

Fittings Leak Checks (every 6-12 months) - Any nonmetal fitting (i.e. ducted vents, plastic valves, rubber fittings) located on the gas or waste pipeline must be inspected.

Other maintenance activities may be required specific to the system in place. Make sure to discuss maintenance requirements with the technology provider to ensure that an adequate maintenance plan is put in place. Proper maintenance of an anaerobic AD system and related components will both extend the lifetime of the system as well as save money over the long term. Successful anaerobic AD system operation depends on routine maintenance activities.

CHAPTER 3: ONLINE DECISION TOOL FOR ANAEROBIC DIGESTION AT COLORADO CATTLE OPERATIONS: USER MANUAL

This document serves as a user manual for step-by-step instructions on how to use the On-Farm *Anaerobic Digestion Decision Tool (OFADT)* online tool herby referred to as the "OFADT". The work offered in this project is designed to inform the average dairymen or feedlot producer of AD technologies and to encourage the installation of on-site AD systems. Decisions made by the online tool act as a starting point for interested parties. The major intent of the tool is designed to act as a link to additional sources of information. Any specific data points given by the tool are to be taken as an estimate and are not intended to be used for AD system design specifications.

Background

The OFADT is an online decision support model developed by Colorado State University. The main purpose is to provide information for producers and their advisers on installation of an anaerobic digestion system at their facility. The secondary purpose of the website is to assist the user to assess feasibility for installation of anaerobic digestion (AD) technology for methane production, capture and utilization on cattle or dairy farms in Colorado. The tool addresses general information on AD systems, technical feasibility, economic indicators of feasibility, choosing a technology provider and maintenance of AD systems.

Constraints of Tool

The OFADT tool is only the first step in evaluating the feasibility of AD for your farm. The information provided should serve as a bird's eye view of the possibility for AD implementation and only be used as input for determining if a more detailed assessment is necessary. It is strongly recommended that a third party consulting firm perform an additional feasibility study before any action be taken. The OFADT tool does not estimate the total potential cost for implementing an AD system on your site. Instead, questions are asked regarding key economic indicators, and the tool then provides a yes or no answer as to whether AD may be economical. The tool was developed based on economic factors and waste quality in the state of Colorado, and therefore the OFADT is only intended for use in Colorado. Recommendations provided by OFADT may not apply for facilities located outside Colorado.

Java Enabled

In order for the tool to work properly you must have Java script enabled and it is advisable to have the latest version of Java installed on your computer. The latest version of Java can downloaded at the following link:

<http://java.com>

Website Layout

The website is structured into six different sections (Figure 9), each representing steps toward determination of feasibility for on-farm AD installation at Colorado cattle operations:

Figure 9: Image of Website Home Screen

1.) General Info: Explore a wide range of general information to gain a better understanding of AD.

2.) AD Feasibility Tool: Clicking here will begin a Colorado specific technical feasibility assessment for your farm. Please see Section 2.4, Input Values, before proceeding.

3.) Economic Feasibility: This link provides information on economic feasibility of AD in Colorado.

4.) Economic Feasibility Tool: A tool for economic feasibility assessment is contained within this link. Please see Section 2.4, Input Values, before proceeding.

5.) Technology Provider Selection: Clicking here will enable access to a list of questions that should be asked of technology providers and a list of current AD design and consulting firms with detailed information on each.

6.) Maintenance: This section summarizes maintenance activities required for long term operation of an AD system.

Input Values

The following is a list of required information for the feasibility assessment tool. Please be prepared with this information prior to starting:

- Number of lactating cattle (#)
- Number of non-lactating (dry) cattle (#)
- Number of feed lot cattle (#)
- Number of heifers (#)
- Average weight of cows (lbs)
- Cost of Electricity ($/Kwh)

Additional information that will improve information provided by the OFADT includes:

- Total milk production (gals)
- Manure production (tons)
- Lagoon volume (acft)
- Feed constituent (majority)
- Feed amount per day (lbs)

Statement of Confidentiality

The OFADT contains no components of data recording or data transmission abilities. All information entered into the tool will be stored only for a short time on your local computer through your internet browsers “cookies“. All data entered into the tool will remain confidential and it is up to the individual to determine how to save, print or screen shot the final results. All information contained on the website is considered open for public use and can be cited as such.

AD Feasibility Tool Guide

The AD feasibility tool provides an assessment of technical feasibility of anaerobic digestion at your facility. Output includes preliminary feasibility, technology recommendations, more detailed feasibility, estimation of methane production, and a summary of water addition required based on selected technology (Figure 110). The step by step guide that follows describes each question asked in the tool in the order in which it is asked, and provides additional information when needed.

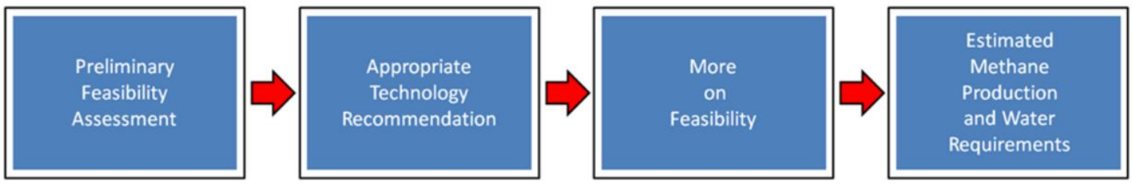


Figure 10: Outline of the four Steps for Assessing Feasibility.

Preliminary Feasibility Questions

What is your primary collection method for manure? (choose one):

Concrete Scrape Manure Collection: Select if your site collects the majority of its manure by the use of a mechanical scraping of manure collected on concrete.

Dry Lot Manure Collection: Select if the majority of your cows are housed outdoors in large pens where the manure is allowed to sit for at least several days before collection.

Flushing Manure Collection: Select if the majority of the manure onsite is collected by flushing concrete with water and storing the wastewater in a lagoon.

Do you have a nearby source of wastewater that you can access? (Yes/No)

Consider nearby industrial, food processing, and municipal wastewater facilities. These all may generate wastewater that you can access and add to your system. If you possess the ability to add wastewater to your manure to increase the moisture content, select “yes”. Additionally, if you are able to recycle water from an onsite lagoon to combine with manure, select “yes”.

Do you have parlor wash available? (Yes/No)

If you have a dairy and use water to flush waste from the parlor and possess the ability to transport that water to a holding tank, select “yes” to this question.

Do you have to remove water from your lagoon more than 2 times per year or do you use lagoon water for irrigation? (Yes/No)

Removing excess water from your lagoon implies that you need to haul water off site either by applying directly to the land or by trucking the lagoon water.

After you have answered the above questions, you will be provided with a preliminary assessment of feasibility as indicated with a green light for "Technical Feasibility is a Go", a yellow light for “Proceed with Caution”, and a red light for “Your Site is not a Good Fit.” The color of the light is based on the above questions and is represented on the decision tree schematic provided on the web site.

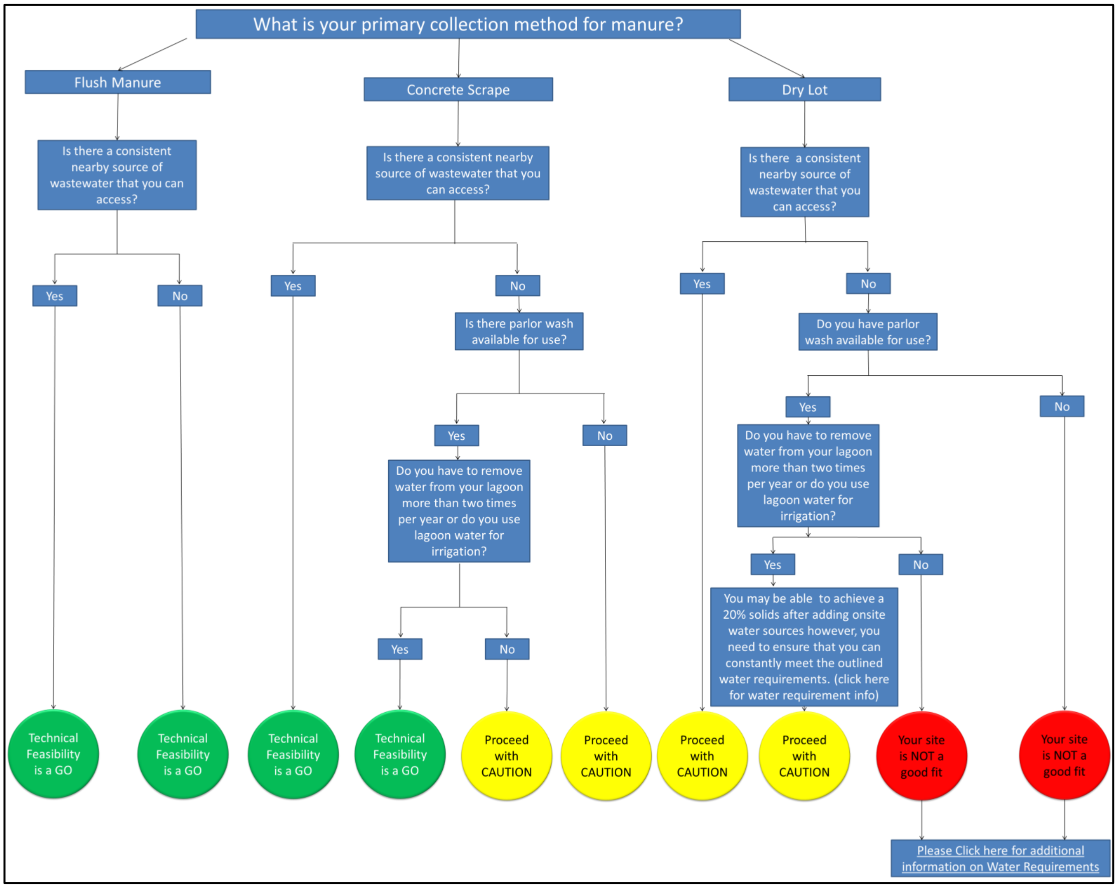


Figure 11: Decision Tree Flow Chart

Determining the Most Appropriate Technology

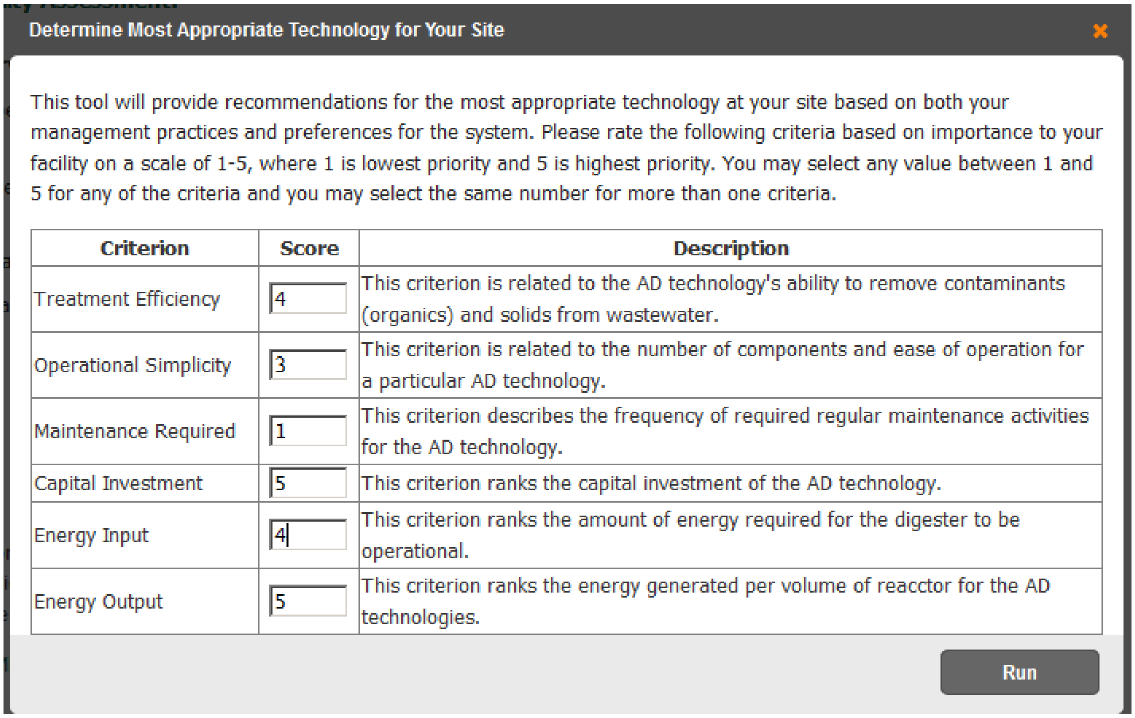
In the case that the preliminary feasibility assessment provided a result that your facility is not a good fit for AD or that feasibility is highly questionable based on your responses to the questions outlined in above section, you will be prompted with the following question.

Would you like to neglect water requirements and evaluate all AD technologies for your site? (Yes/No)

Answering "Yes" to this question will override appropriate technologies based on answers provided in the Preliminary Feasibility portion of the tool (Section 3.8) and consider all possible AD technologies. This option allows for further exploration of the tool and will give you the option to make a comparison of water requirements for all each technology.

Answering "No" to this question terminates the tool since installation of any conventional AD technology would require extensive water addition.

There are many AD technologies to choose from including; complete mixed, plug flow, fixed film, covered lagoon and upflow anaerobic sludge blanket. The purpose of the next component of the tool is to provide guidance on which technologies may be best suited based on your needs for the system in terms of treatment efficiency, operational simplicity, maintenance required, capital investment, energy input and energy output. The feasibility assessment tool will now ask you to rate criteria based on importance to your facility on a scale of 1-5 (Figure 12). Please note that these scores reflect personal preference of importance. Any value from 1-5 can be entered into the score section, where 1 is least important and 5 is most important. It is recommended that for the best results, a wide range of scores be chosen. Assigning the same rank to each one of the criteria will not provide a useful outcome as some technologies may receive the same score. If you are not sure of how you would like to rank these criteria and do not enter values, default values will be assigned as indicated in Figure 12.


Determine Most Appropriate Technology for Your Site

This tool will provide recommendations for the most appropriate technology at your site based on both your management practices and preferences for the system. Please rate the following criteria based on importance to your facility on a scale of 1-5, where 1 is lowest priority and 5 is highest priority. You may select any value between 1 and 5 for any of the criteria and you may select the same number for more than one criteria.

Criterion	Score	Description
Treatment Efficiency	4	This criterion is related to the AD technology's ability to remove contaminants (organics) and solids from wastewater.
Operational Simplicity	3	This criterion is related to the number of components and ease of operation for a particular AD technology.
Maintenance Required	1	This criterion describes the frequency of required regular maintenance activities for the AD technology.
Capital Investment	5	This criterion ranks the capital investment of the AD technology.
Energy Input	4	This criterion ranks the amount of energy required for the digester to be operational.
Energy Output	5	This criterion ranks the energy generated per volume of reacctor for the AD technologies.

Run

Figure 12: Default values for technology criteria scores.

<u>Treatment Efficiency:</u> Ranks the AD technology's ability to remove organics and solids from wastewater. This criterion is based on the performance of an AD technology to remove total solids (TS), volatile solids (VS), chemical oxygen demand (COD) and biological oxygen demand (BOD)

<u>Operational Simplicity:</u> This criteria is related to the number of components and ease of operation for a particular AD technology. The performance of a given technology for this criterion is based on the probability of upset, the probability of microorganism washout, frequency of component tuning and the complexity of startup.

Maintenance Required: This criterion describes the frequency of required regular maintenance activities for the AD technology. The performance of this criterion is based on the frequency of clogging, the frequency of sludge removal and the frequency of moving part replacements.

Capital Investment: Ranks the individual technologies based on estimated capital costs. The performance of this criterion is based on the footprint and components required for the AD technology.

Energy Input: Defined as the amount of energy required for the AD technology to be operational. This criterion is based on influent pumping energy, heating requirements and the energy use associated with recycle pumping if applicable.

Energy Output: This criterion ranks the amount of energy generated per volume of reactor for each of the AD technologies and is based on the amount of methane produced per pound of volatile solids added to the AD system.

The six distinct criteria have been selected because they represent the defining characteristics which identify key benefits and disadvantages of each of the AD technologies. The formulas which operate when the decision tool is run are based off of measurable metrics. These metrics were gathered using industry standards, literature reviews, case studies and performance contacts. Each of the metrics or "sub criteria" are compared to each other through a process referred to as multi criteria decision analysis (MCDA). A rank for each sub criteria between 1-5 was assigned for each technology based on performance data collected in the literature. When the ranks are summed and normalized it becomes possible to assign an overall score to each of the selected technologies Figure 13. The output is greatly dependent on the scores assigned to criteria outlined in Figure 12. It is recommended that the user makes use of the "Retry" button located at the bottom right hand corner of the graph as highlighted in Figure 13. This allows the user to change assigned values for each criteria and evaluate the impact to final scores for each technology.

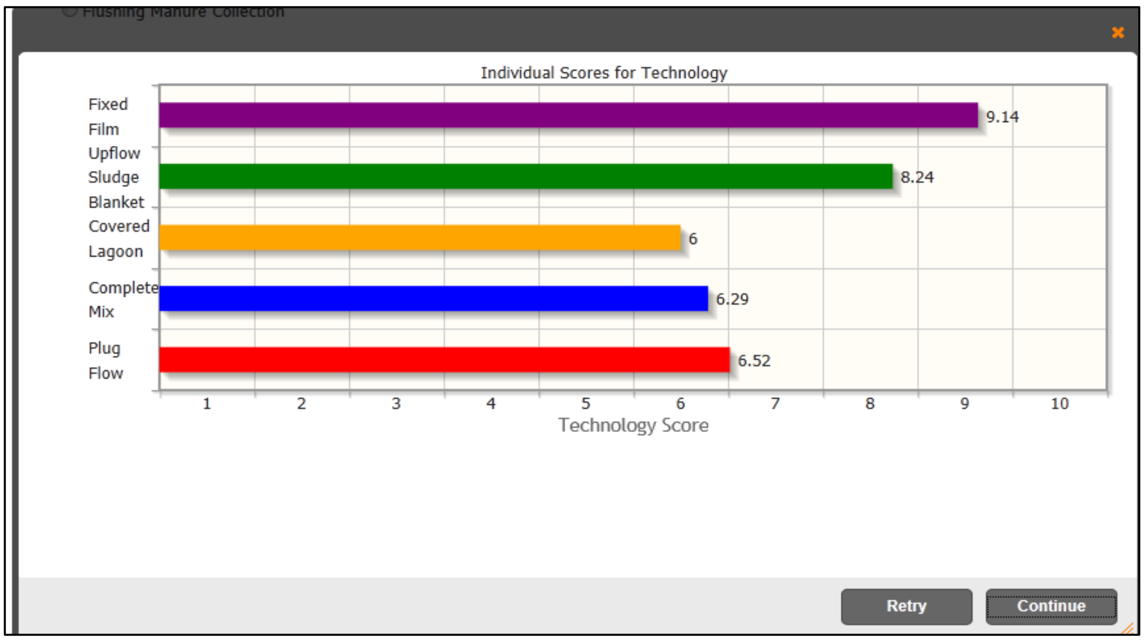


Figure 13: Example Overall Scores for Individual Technologies.

More Detailed Feasibility Analysis

After continuing beyond the technology recommendation output, another round of questions is asked involving the general characteristics of your site. The purpose of these questions is to obtain a more detailed assessment of feasibility than was previously provided (Section 3.8). The following is a list of the questions and summaries of possible answers.

Do you meet the definition of a CAFO: (yes / no)

CAFO's are defined based on the total number of animal equivalents you have onsite, use the related link on the website to find the exact criteria for CAFO definitions.

Bedding Material: (choose one)

Straw: Generally recommended as one of the best bedding material for AD systems, straw acts as a bulking agent which gives the manure better transportation and less clogging with in the AD tank. Straw can also add to the total organic stream of the waste and produce a portion of energy. The post digested product containing straw will have better bedding reuse quality as compared to use of other bedding materials.

Sand: Traditionally, sand is seen as a poor source of bedding when considering an AD system. Unless removed from the waste, sand can accumulate in the AD tank, consuming volume and decreasing treatment efficiency. Sand has also been known to clog AD tanks, damage pumps and corrode the interior of the tank.

Wood Chips: Wood chips, depending on size, will act as a bulking agent similar to straw. Wood chips will have low organic breakdown and thus will not substantially add to the organic waste stream converted to biogas.

Saw Dust: Sawdust exhibits the same qualities as wood chips.

Soil: Soil is seen as the worst source of bedding for AD systems since it often consists of sand and small rocks. Theses inorganics can seriously harm the efficiency of the tank and proper consideration must be given when considering the separation of manure from the soil.

Composted Manure: Manure, once properly treated and broken down by the composting process, is a great candidate for bedding material. One large advantage to installing an AD system is to utilize the end product as bedding.

None: If the cows are placed on concrete then the feasibility score for bedding is not calculated and re-normalized.

Dry Lot: If the cows are held in a typical dry lot setting ,select this option.

Other: If none of the above bedding options is given selecting other will give the average value for the bedding feasibility score.

Where do you Obtain Water? : (choose one)

Where the source of water comes from can greatly reduce or increase the cost of transportation and usage of water. If the source of water is a 50/50 split of any one of the three choices please select "other" as the answer.

Well: Water obtained from a privately owned well with established water rights will often have the cheapest per gallon cost and is easiest to access. However, excessive pumping can have major impacts on the surrounding area.

Municipality: Select if you obtain water from a city run government organization and pay based off of gallons used per month basis. This can be the most expensive per gallon option and the water can be difficult to obtain rights to.

Rural Utility Association (RUA's): Select if you obtain water from a RUA and pay a fixed per month price for water. You will need to consult with your representative at your RUA before proceeding with a AD system in order to ensure proper water rights are maintained.

Do you land apply wastewater from lagoons? : (Yes/No)

If you apply the wastewater from your lagoon onto fields at a higher rate than required for irrigation remove excess water please select yes to this question. Given the dry climate in Colorado , excess water from a lagoon can improve technical feasibility for installation of an AD system.

Do you consistently need to remove excess wastewater from lagoons? (Yes/No)

Please answer yes to this question is you remove water from the lagoon more than a few times per year.

Do you have any of the following equipment on site?

Solid Liquid separator: If you have a large scale solid liquid separator onsite used to process a majority of the wastewater select "yes" to this question. Solid liquid separators are required for processing for manure wastes going into a digester. The ability to lower or increase the total solids greatly expands the available options for AD systems.

Large Scale compost furrower: If you have a large compost furrower used to convert manure into compostable material which can later be sold or used for bedding please select "yes" to this question. While solids can be reduced in an AD system, the end products will contain solids requiring management.

Feasibility is improved when the infrastructure is already in place for composting solids.

Skip loaders: Select "yes" if you have smaller man powered skip loaders used to either scrape concrete pads of manure or used for general farm operations. Skip loaders help to transport manure to desired locations.

Estimating Methane Generation Potential and Water Requirements

The next section will cover the necessary information for estimating the methane and energy potential at your site as well as the purpose of each of the questions (Figure 12). Please note that the only required values here are the number of cattle, all other values are optional and only serve to provide more accurate results.

Number of Cattle: (Required Information)

Number of lactating cattle: If you operate a dairy, please enter the current number of lactating cattle.

Number of non-lactating Cattle: Also known as "dry cattle" this is the number of current non-lactating dairy cows onsite.

Number of Feedlot Cattle: if you operate a feed lot, please enter the total number of cattle onsite

Number of Heifers: Please enter the number of heifers and calves onsite.

The number of cattle is the primary value for determine the amount of water required to achieve the waste solids content required for AD. The number of cattle is applied to estimate total energy production. This value is required and a zero or blank value will result in a prompt from the tool to enter values.

Average Weight per Cow: (Defaulted at 1,400 lbs)

Please enter the average weight of all cows here excluding heifers and calves. The average weight per cow is used to determine the animal unit equivalent (AUE). The AUE calculation helps to determine the total amount of manure produced onsite, see Section 9, Terms and Definitions, for more information on AUE.

Cost of electricity ($/kWh): (Defaulted at $0.1 per Kwh)

Refer to your last utility bill and divide the total cost of the bill by the number of Kwh used for that month. The average electricity cost for northern Colorado is around 9.46 cents per Kwh. If you are unsure of your current electric cost, please use this value. *NOTE*: This tool assumes that you would be offsetting your current electricity bill in order to offset some of the costs of operating the tank. If you expect to offset more electricity than you use onsite, you will need to enter an average cost, which accounts for both offsetting energy costs onsite and what you can expect to receive for energy sold off-site. Typical electricity prices are negotiated around $0.02-$0.03 per Kwh in Colorado.

Total Milk production per day

If you r facility is a dairy, enter the average daily value of milk produced onsite. Otherwise, enter a 0 or leave the answer blank. The units for this value can be changed to gallons, cubic feet, cubic meters or pounds. Total milk production is used to further define the amount of manure produced onsite. Entering the amount of milk is not required, but will help to determine more accurate evaluation of onsite energy generation potential.

Manure Production per day

Enter the amount of manure produced per day at your facility. If you are unsure of a reasonable value for this, leave the cell blank.

Note Entering a value here will override the estimate for manure production based on number of cattle. Please only place a value here if you have a realistic value for manure production.

Feed Majority

Enter the majority constituent for your feed here. If you do not know or if your feed is not listed, please enter "corn" as the default option.

Feed Amount

Enter the amount of feed used per day for the entire facility, if you do not know or would not like to specify this amount leave the cell blank. The amount of feed will help to determine the total manure production for your site. This value is not required, but will improve methane estimates provided by the tool.

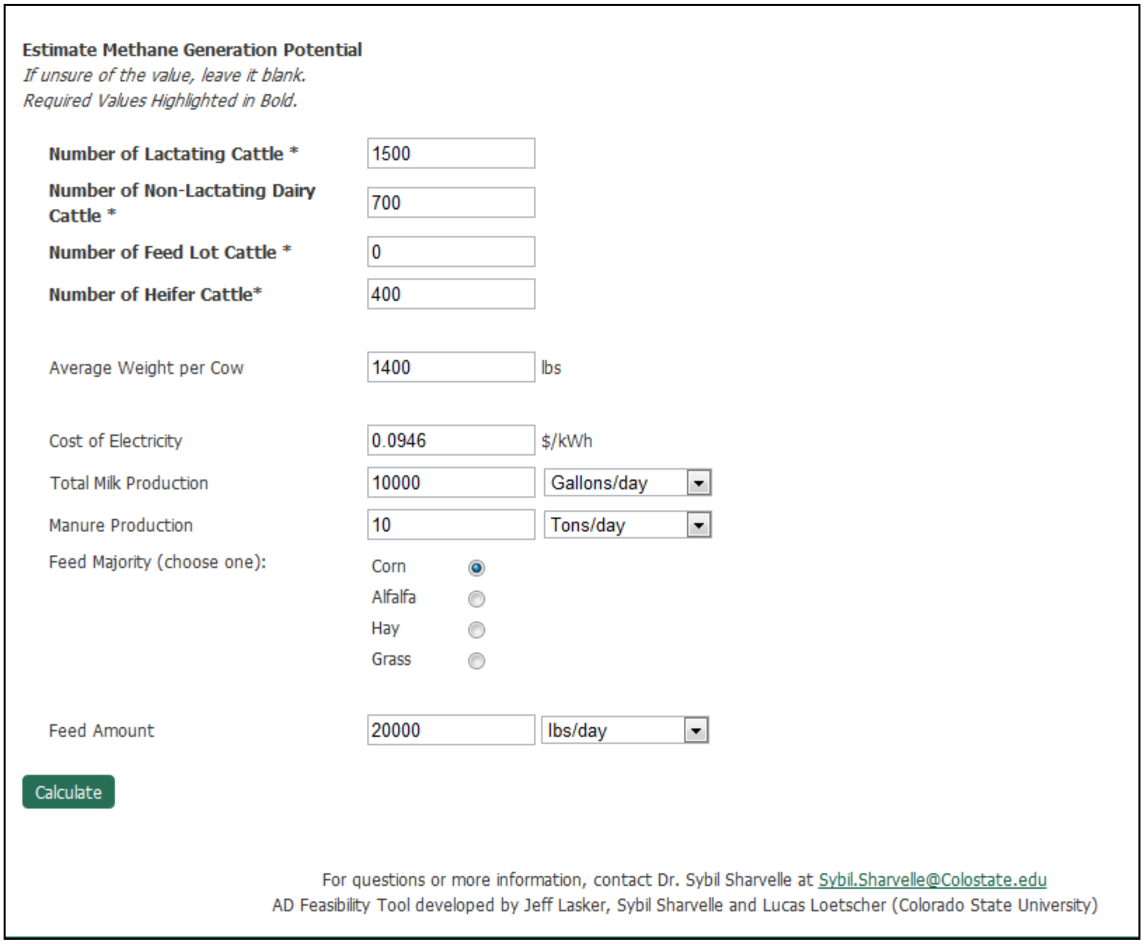


Figure 14: Methane Generation Potential Example Questions

Results Summary

Upon completion of data entry into the AD feasibility tool, the user will be supplied with a Results Summary (Figure 15). The specific components of the Results Summary are described below:

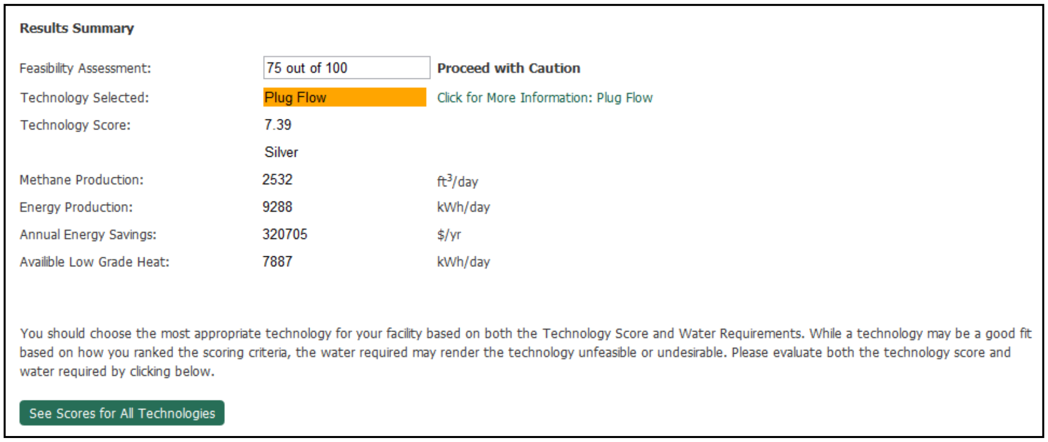


Figure 15: Example Results Summary

Feasibility Assessment Score:

The score represented in the first box shows the feasibility assessment on a scale of 1-100 where a higher the feasibility score means a high likelihood of success for installation of an AD system. The score is separated into three different possible ranges;

<u>Score 90-100</u>: “Feasibility looks good for your site”, you should strongly consider seeking further assistance with implementing an AD system.

<u>Score 70-89</u>: “Proceed with Caution”, AD may be feasible at your site, but there are some indicators that caution should be applied. You need to further evaluate your sites potential for an AD system.

<u>Score 0-69</u>: “Do not proceed”, your site does seem appropriate for an AD system and you should consider other options for manure handling.

Technology Selected:

This shows the technology which received the highest score based on criteria rankings you provided and also provides additional information about the technology. You can view scores for other technologies by clicking the" See Scores for All Technologies" button at the bottom.

Technology Score:

The value represented indicates the relative score of the technology selected for your site. The range of the technology scores is from 1-10 and based on the values assigned to the technology criteria as discussed in Section 4.2. The technology score is separated into five categories based on the score:

> <u>Score 9-10 (Platinum)</u>: The technology chosen is a great fit based on your criteria ranking, it is highly recommend that you follow through with a licensed AD consulting firm to learn more about the technology.
>
> <u>Score 8.0-8.9 (Gold)</u>: Technology chosen is a good match based on the criteria ranking you provided. You should evaluate other technologies within the tool to see which one you may have a preference of before consulting with an AD firm.
>
> <u>Score 7.0-7.9 (Silver)</u>: The technology chosen could work as a reasonable alternative for your site based on the criteria ranking you provided. It is recommended you evaluate other technologies as well to determine what will be best for your site.
>
> <u>Score 6.0-6.9 (Bronze)</u>: The technology was not a good fit for your facility and should be considered alongside with all other possible technologies.
>
> <u>Score 0-5.9 (Red)</u>: The technology assessment was not conducted, or not enough information was provided.

Methane Production:

The estimated amount of methane theoretically produced from an onsite AD system is provided. This value is variable and will change if co-digestion sources are added or if a different technology is chosen.

Energy Production:

The amount of energy produced by an onsite AD system is provided. This value is directly related to the amount of methane produced and will vary substantially if changes are made that affect methane production.

Annual Energy Savings :

This value is the amount of energy produced multiplied by the value selected for the cost of electricity. This does not provide an estimate for savings if the energy is sold offsite.

Available Low Grade Heat:

The amount of heat produced from a generator can be substantial and can also be used to help heat the AD tank during the colder months. It is strongly recommend that any project considering an AD system implement heat capture from the gen-set. Available low grade heat represents the expected amount of heat that could potentially be captured if a heat reuse were implemented. *NOTE* Kwh can be converted to BTU or joules with using conversion factors listed in Table 6: kWh Conversions.

Table 6: kWh Conversions

Kwh Conversions	
Kwh to BTU	3,412
Kwh to Joules	3,600,000

Daily Water Requirements

The water requirements for each technology are calculated (Figure 16)

Daily Water Requirements									
Technology	ft^3 per day			Acre feet per day			Gallons per day		
Complete Mix	1,403	-	2,494	0	-	0.1	10,494	-	18,655
Plug Flow	468	-	1,559	0	-	0	3,498	-	11,659
Covered Lagoon	7,950	-	9,041	0.2	-	0.3	59,463	-	67,625
Upflow Sludge Blanket	3,273	-	4,365	0.1	-	0.1	24,485	-	32,646
Fixed Film	7,950	-	9,041	0.2	-	0.3	59,463	-	67,625

Figure 16: Daily Water Requirements Table

Daily water requirements are calculated from the volume of manure estimated based on answers to previous questions. The range includes the lowest and highest values that may be expected for addition based on current waste management practices and the specified technology. (See Appendix E: Section 0 for more information on water requirement calculations) It would be expected that your specific water requirements would fall somewhere within this range and will vary seasonally. Estimates are provided in different units simply to meet user preferences. Water requirements are key when considering the overall feasibility of an AD system and should be given extended thought before pursuing any next steps.

NOTE One important aspect of the website is comparing the technology score with the water requirements. It is beneficial to observe the technology score in parallel with the water requirements in order to properly assess which technology is best suited for your site. This can be easily done by clicking on "See Scores for All Technologies" in the Result Summary.

Concluding the Feasibility Assessment

Printing can be done directly from the web browser, printing is the only way to save the results of the assessment given that no data is transmitted or stored from this assessment. Selecting print from file menu and the n print preview will give you an idea for how the assessment overall will look. This page can then be printed at 90% zoom in order to fit the entire assessment onto three pages.

If you are still considering AD after completed the technical feasibility assessment, it is advisable that you move on to the economic section of the tool in order to determine if there are financial incentives for you to pursue an onsite AD, (See Section 2.7).

AD Economic Tool

The following is a step by step guide for determining the economic feasibility of an AD system on your facility. This step by step guide will go through each question in the order in which it is asked, and provide additional information when needed.

Economic Feasibility Decision Tree

The economic feasibility assessment is broken up into several key questions which will determine the outcome of economic feasibility. The scoring for the feasibility is separated into three different levels, green (proceed), yellow (proceed with caution) and red (do not proceed). A red output indicates that the economics of your site are not supportive of an AD system and even when external funding provided and it is strongly recommended that you consider all funding criteria before pursuing an AD system.

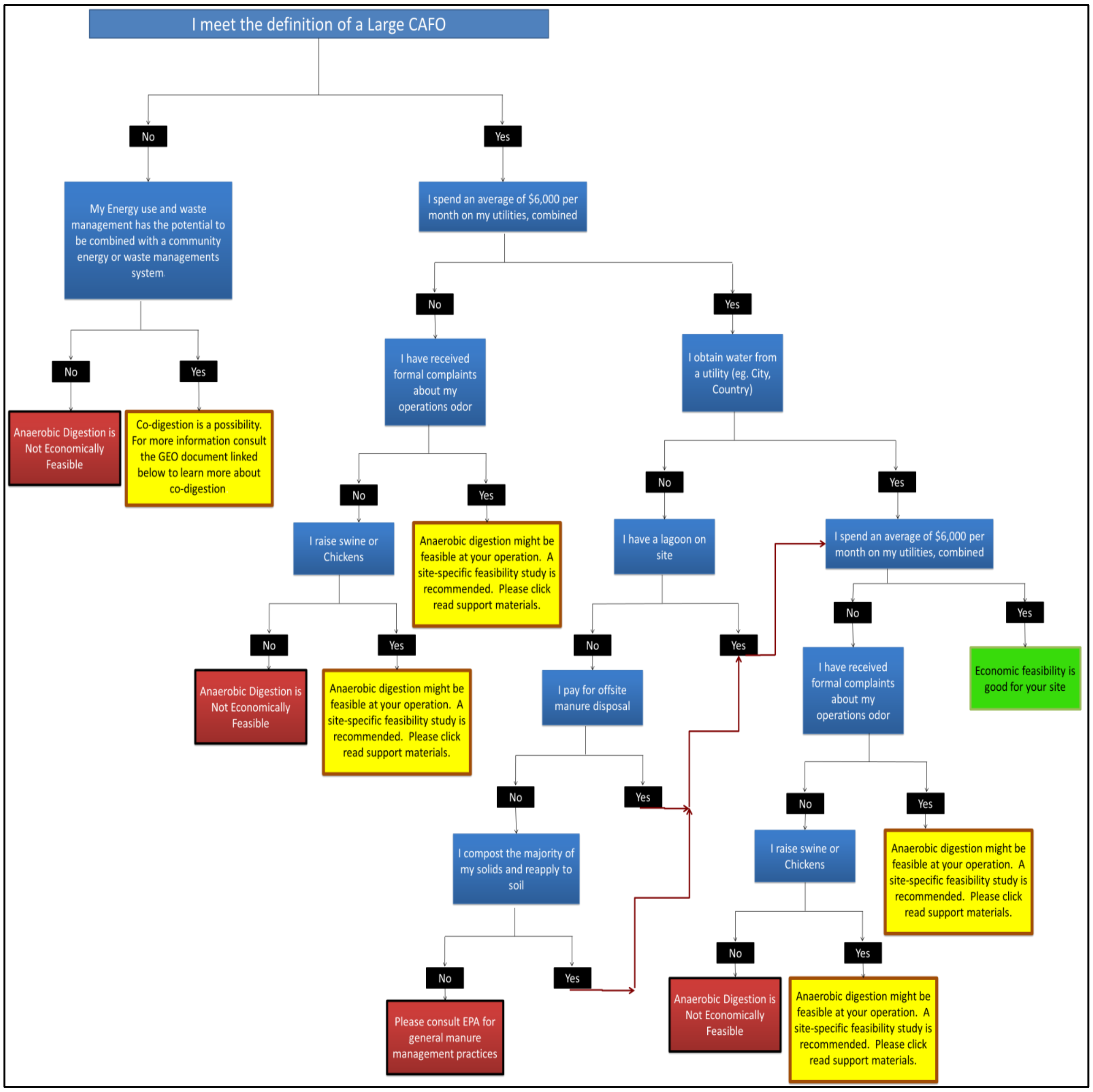


Figure 17: Economic Decision Tree

Questions for Determination of Economic Feasibility

The following section covers the varies topics and questions for determine the economic feasibility of AD systems.

Do you meet the definition of a large CAFO? (Yes/No)

The definition of a confined animal feeding operation or (CAFO) is defined by the number of cattle for a given site. Your site can meet the requirements for; a large CAFO, medium CAFO or Small CAFO, If you meet the requirements of any one of these CAFO you can often have certain regulations concerning waste management, consult EPA guidance on how this relates to AD implementation before proceeding: <http://www.epa.gov/npdes/pubs/sector_table.pdf >

Do you spend an average of $6,000 per month on utilities, (gas, electric and water?)

Combined utilities includes water, natural gas/propone and electricity. If your total monthly utility bill on average exceeds $6,000 select a yes for this question.

Do you have a lagoon onsite (Yes/No)

A lagoon on- site renders water storage and handling much easier.

Do you pay for offsite manure disposal (Yes/No)

Paying for offsite manure disposal adds substantial costs to the overall manure management strategy for the site. If you do pay for offsite manure disposal, a good rule of thumb is to not pay over $1/ton/mile. This is also a good indicator for economic feasibility of an AD system.

Do you obtain water from a utility (eg., City, County) (Yes/No)

The price of water can greatly affect the ability of a farm to recycle water or use excess water in order to lower the total solids of manure suitable for pumping. If you obtain water from a city or county and not from a well of rural utility association (RUA) please select “yes” for this question, otherwise select “no”.

Do you spend approximately $5,000 per month on electricity and natural gas? (Yes/No)

Excluding water from your monthly utility expenses, do you spend more than $5,000 on electricity and natural gas. The price of these energy sources can vary greatly from farm to farm, so it is more logical to estimate based on total cost rather than the cost per unit. Economic analysis has shown that when approximately $5,000 is spent per month on energy, AD may be economically viable.

Have you received formal complaints about odor? (Yes/No)

If you have received formal complaints about odor, AD installation can often be a great solution to the problem. AD systems can reduce ammonia emissions and since systems are sealed for biogas collection and use, release of odorous constituents is highly reduced compared to an open lagoon. Installing an AD system can mitigate potential lawsuits resulting from odor.

Do you raise swine or chickens? (Yes/No)

The OFADT tool has been developed for cattle operations such as feedlots or dairy farms, answering yes to this question will improve your economic feasibility but will disqualify you for using the technical feasibility guide as detailed in (Section 0: “AD feasibility Tool”).

***NOTE*:** After completing the economic feasibility tool, it is recommended that you talk with your local AG bank, the Colorado's Governor's Energy Office and a technology provider consulting firm.

Technology Provider Selection and Guidance for Maintenance

The OFADT website also contains several additional sections to help you better understand AD and to provide further assistance with follow up information support for selection of a technology provider and guidance for maintenance of an AD system.

<u>Technology Provider Selection</u>

This section covers each of the main technology provides, will provide general information about the company and gives links to each of their website. The technology provider section also covers a list questions that should be asked of a technology providers. This list can be used as a starting point for contacting AD technology providers and consultants. The information provided was updated as of December 2011.

<u>Guidance for Maintenance of an AD System</u>

This section covers general information regarding the maintenance and upkeep of an AD system and provides guidance for the time required for running an AD system. This section can also be used if you are trying to estimate what the maintenance costs may be for a given anaerobic technology.

CHAPTER 4: MULTI-CRITERIA DECISION ANALYSIS THEORY AND APPLICATION

A multi-criteria decision analysis (MCDA) tool was developed using Microsoft Xcel © and Visual Basic (VBA). The tool uses a weighted average method (WAM) approach to determine, based on user preferences, the Technology of Best Fit (ToBF) for a specified site. The different AD technologies included in the MCDA were chosen based on their uniqueness and included: plug flow (PF), complete mixed (CM), covered lagoon (CL), upflow anaerobic sludge blanket (UASB) and fixed film digesters (FF).

Two additional MCDA methods were used to compare results against the WAM. The methods used were, compromise programming (CP) and preference ranking organization method for enrichment evaluations (PROMETHEE). The resulting method for determining the appropriate technology was the weighted average approach. The following chapter explains the methodology, criteria and assumptions for selecting the WAM.

The MCDA tool begins with the assumption that there are no perfect AD technologies. The different technologies vary in regards to metrics such as water use, methane production, environmental impacts, and/or operational complexity. Based on results from the technical feasibility analysis, it became apparent that these metrics could be assigned sub-criteria and ranked in terms of personal preferences of importance. Thus, a customized decision making tool was created to determine the ToBF otherwise defined as the AD technology most feasible for the site of interest. These personal preferences offer a unique opportunity to create an MCDA tool capable of providing targeted, custom answers to the user as opposed to only providing information.

Terminology

Main Criteria – A set of six non-quantifiable characteristics which reflect the most common design specifications associated with AD technologies.

Sub Criteria – A set of 15 quantifiable AD metrics which can be classified and match with at least one of the main-criteria characteristics.

Data Value – A single quantifiable number found from either empirically tested values extracted from case studies or theoretical values from laboratory settings.

Sub Criteria Score – The mean of each data value for a given sub-criteria.

Sub Criteria Ranking – The assigned ranking on a discrete scale from 1-5 when each sub-criteria is compared across each AD technology.

Main Criteria Ranking – The ranking value established for the main criteria determined by summing each sub-criteria ranking and dividing by the number of sub-criteria within the same classification.

Confidence Margin – An interval scale from 60%-100% which is assigned based on the number of data values for a given sub-criteria.

Important Factors – An exponential value applied to the sub-criteria rankings ranging from 0.9-1.1.

Criteria Importance – A continuous user defined value from 1-5 applied to the main criteria in order to rate the relative personal importance of each main-criteria.

Technology Score – The number value associated with the multiplication of the criteria importance and the main criteria rating.

Combined Technology score – The sum of all the sub-criteria rankings for a given technology normalized to a continuous 0-10 scale.

MCDA Tool Objectives

The following chronological steps were taken for development of the MCDA tool:

1. Determine which criteria to consider: AD technologies can range in performance along multiple performance criteria. These criteria are often referred to as design metrics and are critical to consider before proceeding with an AD project. The criteria used for evaluation was chosen based on their importance for AD applications and by the ability of the criteria to be quantified. Data values for each of the sub-criteria were determined using a literature review of empirical values based from existing AD systems and theoretically based values from academic lab experiments (See Appendix B: MCDA scoring Criteria for further details on the values of the criteria.)
2. Quantify the confidence of data collected for each technology: In some cases data collected on a certain technology was either limited or highly variable. In particular, there were very few applications of some of the more advanced and recently developed AD technologies. Therefore, confidence in the data ranges needed to be addressed. By evaluating the range of values for each criteria and the total available number of data values, quantifiable confidence margins could be established. These confidence margins represent the accuracy of each sub-criteria's ranking and are used to interrupt the applicability of said sub-criteria to the chosen ToBF (See Section 4.3.4 for further details on confidence levels.)

3. Run an analysis on the outcome of the MCDA tool: To provide justification for the scale chosen during the confidence margin analysis and to categorize the results of the MCDA tool, an outcome analysis was preformed. The outcome analysis was conducted using a repeating loop program in Excel© VBA which calculated the outcome of the MCDA tool utilizing a set randomized user inputs. Results from the outcome analysis could then be graph to determine the total number of times a selected technology was rank as the ToBF. (See Section 4.4 for more information on the outcome analysis)
4. Quantify the importance of personal preferences: To understand the effects of how user defined ratings of sub-criteria importance affected the outcome of the MCDA tool an importance factor analysis was created. Important factors were used to quantify the relationship between sub-criteria and the impact's on the overall outcome. The importance factor analysis provided scenarios where each sub-criteria can be evaluated with a larger or smaller impact on the overall outcome. (See Section 4.8 for more information on importance factors)

MCDA Tool Classification

Each AD technology has a particular range of total solids (TS) percentages that result in stable operation. If a particular AD technology is outside of its total solids range it cannot function at a reasonable capacity. A major issue when construction the MCDA tool, was that TS percentage ranges can overlap between various AD technologies. Since the TS percentage solely determines if the AD technology will function properly, the outcome of the MCDA tool could not include an analysis incorporating TS percentage as a sub-criteria. Instead the user generated answers guided by the TS percentage flow chart remove non-relevant technologies (See Section 3.8 for more information on TS% flow chart). These non-relevant technologies are excluded from the MCDA tool. The MCDA then re-evaluates the final outcome excluding these technologies. The user can also choose to ignore water requirements and evaluate all technologies (See section 0 for further details concerning the evaluation of the TS percentages). Of note is that the user is always supplied information about water requirements for each technology evaluated so that this can be considered to guide decisions.

As the user answers questions relating to their onsite farm manure collection practices, five possible MCDA classifications are selected (see Section 0). The purpose of the different MCDA classifications is to eliminate those technologies which are not feasible from the analysis based solely on the determined TS percentage resulting from the manure management practice. The possible MCDA classifications are:

MCDA 1: 5-10% TS Technologies Considered: CM, PF
Collection Method: Concrete Scrape with water added

MCDA 2: 10-20% TS: Technologies Considered: PF
Collection Method: Concrete Scrape

MCDA 3: 80-90% TS: Technologies Considered: All Technologies considered
Collection Method: Dry Lot with water added

MCDA 4: 0-5% TS Technologies Considered: CM, UASB, FF, CL
Collection Method: Flush Manure with water added

MCDA 5: 5-9% TS: Technologies Considered: CM, UASB
Collection Method: Flush without water added

*Note the MCDA 2 classification does not conduct an MCDA analysis only the technology score

After the TS% is established, then the MCDA tool can designate which technologies are considered in the analysis.

MCDA Approach Considerations

Several MCDA approaches were considered when applying a scoring mechanism to the MCDA tool. The MCDA models considered were the WAM approach, the CP method and a PROMETHEE analysis. The selection criteria for the MCDA method chosen needed to included; the ability to rate each criteria on a scale of one-five, be easily understood, be completed in a ten minute period and collect enough information to provide customization for finding the ToBF. On It was determined that to simplify the tool, the total number of criteria selected by the user needed to be limited to allow the tool be to completed in a timely manner. Each of the selected MCDA methods was evaluated based on their ability to match the desired criteria. The following section details each MCDA method and their adherence to the criteria selection.

Weighted Average Method (WAM)

The WAM of MCDA is a value based method where the score assigned to each criteria is a value along a discrete pre-determine range. The "weight" or value of each criteria is determined using scores assigned by the user. The final scores are then normalized to produce a set of ranked criteria (Kevin, 2005). The overall scores for each criteria is determined by Equation 9:

$$S_j = \sum W_i * R_j$$

Equation 8: WAM score calculation

Where : S_j *= overall score for technology*

W_i *= Weight (tool defined)*

R_j *= Relative importance of criteria (user defined)*

Compromise Programming (CP)

CP is a value based method of MCDA. The method considered for the analysis can also be considered a discrete compromise programming (DCP). CP uses the following equation in order to determine the relative metrics.

$$R_{i,j} = \left\{\frac{Actual_j - Worst_i}{Best_i - Worst_i}\right\}^p$$

Equation 9: Compromise programming score evaluation

Where : R = CP rating metric

Actual = actual rating of technology

Worst = worst rating of any alternative for a specific criterion

Best = best rating of any alternative for a specific criterion

p = exponent determining the additional emphasis on the CP metric rating

The exponent *p* can be a value of either 1,2 or infinity. When *p* equals 1 the ranking is considered to have no additional weighting, a *p* value of 2 is considered an intermediate rating, a *p* value of infinite, adds the largest possible significance to the CP rating metric. The three *p* values are then evaluated on each of the separate MCDA outcome scenarios and compared to each other. The purpose of p value comparisons is to determine the worst sub-criteria and best sub-criteria for each technology. Worst sub-criteria's are assigned values of zero and best sub-criteria's are assigned values of one. The CP method then sums across sub-criteria, the technology with the highest score is then considered the ToBF. (Kevin, 2005).

Preference Ranking Organization Method for Enrichment of Evaluations (PROMETHEE)

The PROMETHEE method is based on the determination of preferences and indifferences; this is known as an outranking method. PROMETHEE functions by comparing each technology pair-wise to each other technology. A preference value of 1 is assigned if the technology is better than the performance of another, with respect to specific sub-criteria, without considering the difference in the performance of that criteria. A preference value (pV) is 0 if the technology is equal to or inferior to the other technology. Whereas, if the technology is better than the comparing technology the pV is 1 (CFHL, 2011). In PROMETHEE, the decision maker is considered to have a strict preference for the highest value. Preference values determined from the pair-wise comparisons are analyzed to develop an overall rating value for each alternative. These overall rating values are on a scale of +1 to -1. An overall rating of +1 means that an alternative is strictly preferred to all other alternatives whereas an overall rating of -1 implies that the technology is inferior to all other technologies.

Comparison of MCDA models

Each of the MCDA models were testing against the pre-set selection criteria and evaluated on a pass/fail scale. It was determined that the PROMETHEE method failed the test of user simplicity as significant confusion was caused by the pair-wise comparison analysis. The given output values of -1, 0 or 1 along with a lengthy data table proved to be too difficult for the lay user to interpret within a ten minute period. Additionally, the MCDA method of CP was also determined to fail the user simplicity test as the complexity associated with CP sub-criteria selection method required more time then was allotted. The final conclusion was that a WAM produced accurate results, passed each of the method criteria and would be suitable for conveying the necessary user information. (See Appendix B: MCDA scoring criteria for additional information)

MCDA Methodology

The procedure for evaluating the differing methods of MCDA followed a step by step technique as indicated in

Figure 18. This figure depicts the current MCDA approach.

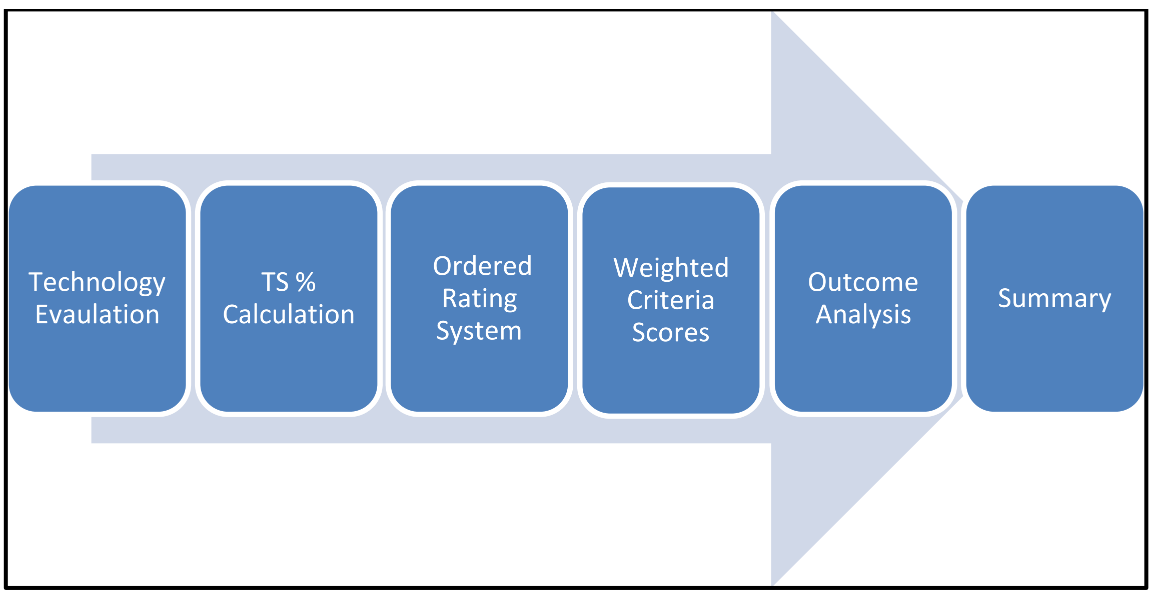


Figure 18: Flow chart of the MCDA tool

Technologies Specifics

Three of the five technologies are considered more conventional, including complete mix, plug flow and covered lagoons. The other two technologies, up flow sludge blanket and fixed film, are considered to be newer, more advanced AD technologies. The MCDA tool classified CM digesters as those meeting the definition of a completely stirred tank mixed systems. PF digesters with mechanical stirring modifications often called a hybrid system or modified PF digesters were not considered for this study.

Criteria Selection Process:

One of the major tasks for the MCDA tool included determination of the proper criteria that would be pertinent to AD systems. A series of sub-criteria were chosen based on the requirement that the data values could be quantified based on literature or case studies. Upon professional opinion the number of criteria which the user assigns criteria importances should be limited in number and easily understood. As such, six main criteria were chosen to represent the various classifications of the sub-criteria. The initial sub-criteria were in large part determined using a pre-existing literature sources (Predpall, 2005). Several sub-criteria were considered but eliminated due to the inability to find proper data on the corresponding metrics. Direct costs were not considered as a sub-criteria, since a separate economic feasibility tool was created in parallel with the MCDA tool to compensate for this.

Table 7 : Criteria and sub-criteria considered for evaluation

Main Criteria Ranking System	Sub-Criteria	Metric
Treatment Efficiency	Reduction of Volatile Solids	%
	Reduction of Contaminants	%
Operational complexity	Probability of Permanent Downtimes	# per year
	Probability of Washout	# per year
	Frequency of Component Tuning	# per year
	Downtimes due to Startup	# per year
Maintenance required	Frequency of Clogging	# per year
	Frequency of Sludge Removal	m^3 per year
	Frequency of moving part Replacement	# per year
Capital investment	Retention Time	Days
	Footprint	m^2 / # head
Energy input	Influent pumping	kWh / yr / # head
	Heating Requirements	kWh / yr / # head
	Recycle pumping	kWh / yr / # head
Energy output	Methane Production	m^3 / yr / # head

Sub-criteria Data Evaluation

Data values for the individual sub-criteria were evaluated based on a review of current literature. Only data from scholarly articles, professional journals, or case studies were considered. (See Appendix B: MCDA Scoring Criteria for further details regarding the literature review and the values for each sub-criteria)

Ordered Rating System

An ordered rating system otherwise referred to as the criteria importances, was utilized for the MCDA tool. After the sub-criteria ranking were determined the main criteria values could be established. Main criteria rankings were determined by summing the sub-criteria rankings and then dividing by the total number of sub-criteria. Values of 1-5 are assigned by the user for importance of each main criteria with 1 representing little to no importance of a criteria of 5 representing a very important criteria. The scale of 1-5 was chosen for the criteria importances since there are five technologies considered in the analysis and this scale is considered simple for users to understand. The main criteria ratings and the user defined relative importance of criteria are then multiplied together to produce the technology score. Technology scores are summed across all sub-criteria and normalized to a 0-10 scale. Applying this scale gave a simplified approach when considering the various MCDA models and added an additional layer of consistency between sub-criteria.

Sub-criteria Score Evaluation

The scoring system for the sub-criteria underwent several revisions before a final method was determined to be most effective. Namely, at the beginning of the study a rating system was evaluated that applied a non-discrete 1-5 scale to the sub-criteria. This method would create a continuous rating scale, for instance; if a data set of a determined sub-criteria score across all technologies were; 500, 490, 480, 300 and 150 the applied ratings would be 5.0, 4.9, 4.8, 3.0 and 1.5 respectively. Initially this method seemed to produce meaningful results, however after further analysis it was determined that a more consistent approach was necessary to reduce confusion. Additionally, when comparing sub-criteria which are not standardized on a single scale an MCDA between them becomes irrelevant. As such, this method was not used for the MCDA tool and instead a discrete ordered rating system was adopted. The discrete rating system when implemented would cause the above example to become 5,4,3,2,1 respectively.

Confidence Margins:

During the MCDA tool construction it was found that discerning between empirically established values for several of the sub-criteria was not feasible, due to the similarity of performance between the technologies and in particular, when data was limited for certain technologies. After an extensive data collection process, it became evident that the more traditional technologies of PF, CM and CL had lager sets of data and higher confidence in the data as opposed to the less established technologies of UASB and FF. To assign discrete rankings, a process hereby known as confidence margins was developed. Confidence margins are simply a percentage scale based on the maximum number of data values collected for any given sub-criteria. It should be noted that the percentages assigned are subjective and cause uncertainty within the MCDA tool, this uncertainty is resolved within the outcome analysis (See section 4.6 for further details on the outcome analysis). Table 8 shows the values associated with the number of data point and the corresponding margins of confidence.

Table 8: Confidence Margin Values

# of Data Points	Confidence Margin
7	100%
6	100%
5	100%
4	90%
3	80%
2	70%
1	60%

After the confidence margins were set, they were then applied using Equation 8. Equation 8 determines the modified data value range and represents a plus/minus of the confidence margin applied to an existing data point:

$$\textit{Modified Data Range} = \textit{Avg. Data Value} +/- (\textit{Average Data value} * (1 - \textit{Margin of Confidence}))$$

Equation 10: Modified Confidence Margin

Each modified data range was calculated for all of the sub-criteria, ranges which overlapped with other AD technologies were placed in one of two scenarios. The first scenario occurred when three or more technologies were within the same modified data range. An example of scenario one is as follows; if the non-modified rating for a sub-criteria was 5 for FF digester, 4 for UASB digester and 3 for CM digester and the number of empirically determined data values for FF and UASB were smaller than that of CM a confidence margin would be applied. If the modified data range caused FF, CM and UASB to be within the same data range the new rating for each sub-criteria would be 4. It is important to note that a sub-criteria would not be adjusted by more than one rating. The second scenario occurs when two sub-criteria are within the same modified data range, for this case the technology with the lower rating would be moved up one rating position. Tables 9-11 summarize the final outcome of the rating system with and without confidence margins, as well as the change in ratings.

Table 9: Final ordered ratings without confidence margins

Main/Sub Criteria	CM	Plug Flow	UASB	Covered Lagoon	Fixed Film
Treatment Efficiency	**3**	**2**	**5**	**1**	**5**
VS% Removal	2	2	4	1	5
Reduction of Contaminants	3	2	5	1	5
Operational Complexity	**3**	**4**	**2**	**4**	**3**
Probability of Permanent Downtimes	3	4	1	5	2
Probability of Washout	2	4	1	3	5
Frequency of Component Tuning	3	4	2	5	1
Complexity of Startup	4	2	3	1	5
Maintenance Required	**2**	**3**	**3**	**5**	**3**
Frequency of Clogging	1	5	2	5	3
Frequency of Sludge Removal	3	1	5	4	2
Frequency of Moving part Replacement	1	4	2	5	3
Capital investment	**3**	**2**	**3**	**2**	**5**
Retention Time	3	2	4	2	5
Footprint	3	2	2	2	5
Energy Input	**4**	**3**	**3**	**4**	**1**
Influent Pumping	4	3	2	5	1
Heating Requirements*	5	3	5	n/a	2
Recycle Pumping	3	4	3	4	1
Energy Output	**3**	**2**	**4**	**1**	**5**
Methane Production	3	2	4	1	5

Table 10: Final ordered rating with confidence margins imposed

Main/Sub Criteria	CM	Plug Flow	UASB	Covered Lagoon	Fixed Film
Treatment Efficiency	**3**	**2**	**5**	**1**	**4**
VS% Removal	3	2	4	1	4
Reduction of Contaminants	3	2	5	1	4
Operational Complexity	**4**	**4**	**2**	**3**	**3**
Probability of Permanent Downtimes	4	4	2	4	2
Probability of Washout	2	5	1	3	4
Frequency of Component Tuning	4	4	2	4	1
Complexity of Startup	4	2	3	1	4
Maintenance Required	**2**	**3**	**3**	**5**	**3**
Frequency of Clogging	2	5	1	5	3
Frequency of Sludge Removal	3	1	5	4	2
Frequency of Moving part Replacement	2	3	3	5	3
Capital investment	**3**	**2**	**4**	**2**	**5**
Retention Time	3	2	4	2	5
Footprint	3	2	3	2	4
Energy Input	**4**	**4**	**3**	**4**	**1**
Influent Pumping	4	3	3	4	1
Heating Requirements*	5	4	4	n/a	2
Recycle Pumping	3	4	3	4	1
Energy Output	**3**	**2**	**4**	**1**	**5**
Methane Production	3	2	4	1	5

Table 11: Change in rating when confidence margins applied.

Main/Sub Criteria	CM	Plug Flow	UASB	Covered Lagoon	Fixed Film
Treatment Efficiency					
VS% Removal	1	0	0	0	-1
Reduction of Contaminants	0	0	0	0	-1
Operational Complexity					
Probability of Permanent Downtimes	1	0	1	-1	0
Probability of Washout	0	1	0	0	-1
Frequency of Component Tuning	1	0	0	-1	0
Complexity of Startup	0	0	0	0	-1
Maintenance Required					
Frequency of Clogging	1	0	-1	0	0
Frequency of Sludge Removal	0	0	0	0	0
Frequency of Moving part Replacement	1	-1	1	0	0
Capital investment					
Retention Time	0	0	0	0	0
Footprint	0	0	1	0	-1
Energy Input					
Influent Pumping	0	0	1	-1	0
Heating Requirements*	0	1	-1	n/a	0
Recycle Pumping	0	0	0	0	0
Energy Output					
Methane Production	0	0	0	0	0

Note since Covered Lagoons are not heated the sub-criteria “heating requirements” was not evaluated for the MCDA tool. Instead only four technologies are ranked for that sub-criteria.

The rating systems could now be separated into two potential outcomes, one including confidence margins and the second without confidence margins. To conclude that the confidence margins produced accurate results an outcome analysis was conducted. (See section 4.4 for further details regarding the outcome analysis.) The fundamental difference between the rating systems is that, with confidence margins there is an established justification for two technologies receiving the same rating for a sub-criteria. The confidence margin approach eliminated the need to call one technology superior to another in cases where insufficient data was available to make such conclusions.

An evaluation of Table 10 shows an emerging pattern that, FF digesters while scoring high on individual data values had relatively large margins of confidence. When confidence margins were imposed the technology scores (ratings) for FF digester are considerably lower in several of the sub-criteria. When the analysis is run without confidence margins, FF is shown to have the highest overall rating based on the critera and sub-criteria scores. PF, UASB and CL have similar ratings and CM is the lowest rated technology. It is also important to note that the range between the lowest and highest score is only a 20% difference.

Outcome Analysis

An outcome analysis was conducted using a repeating loop in the Excel© VBA program. The outcome analysis took each user input for importance of a given criteria and assigned random values between 1-5. The VBA loop was conducted 1,000 separate times and results were recorded. After the results were computed the outcome analysis then determined the number of total times a technology was ranked as the ToBF and graphed the results. The outcome analysis has three primary goals; the first is to determine if a given technology had an unbalanced number of winning scenarios, second to visual display the randomized outcome results and three evaluate if the scaling of the confidence margins produced reasonable results. The following figures compare on a percentage basis, the outcome results without confidence margins (Figure 19) and with the inclusion of confidence margins (Figure 20).

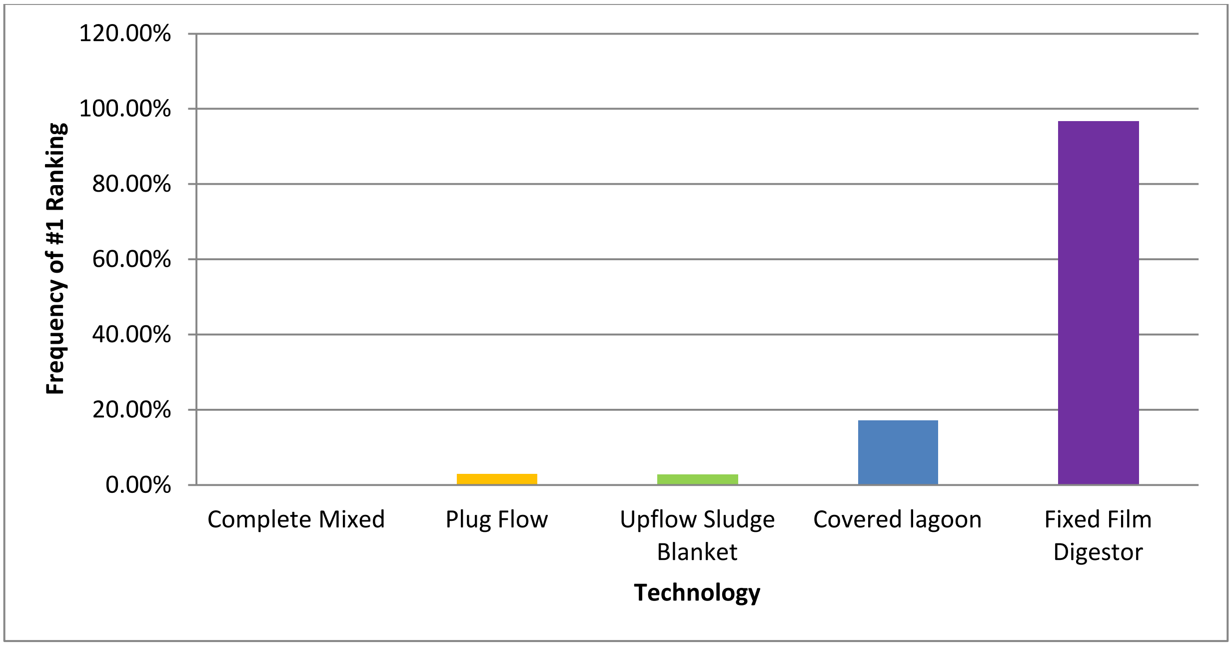


Figure 19: Outcome Analysis without the use of Confidence Margins

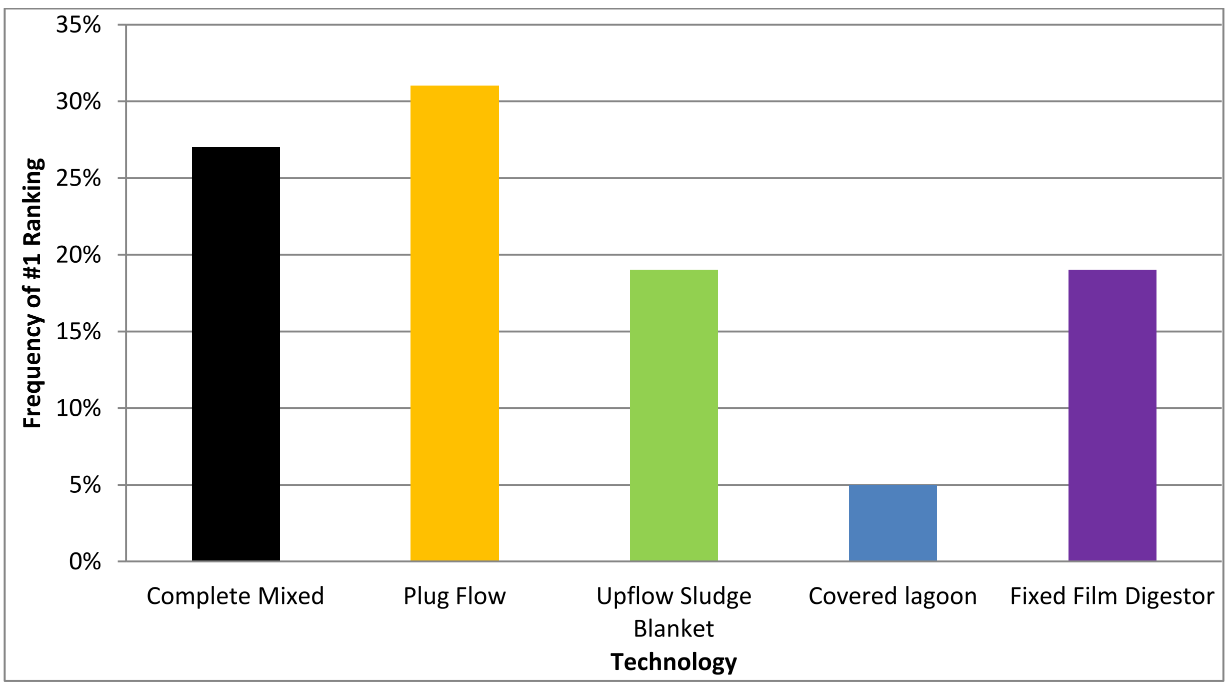


Figure 20: Outcome analysis with the use of Confidence Margins

A comparison of Figure 19 and Figure 20 gave rise to a clear indication that fixed film digesters are scored disproportionately higher than the rest of the remaining AD technologies when the MCDA tool was conducted without confidence margins. The issue of FF digester scoring disproportionately higher originates from the data value selection methodology, as the numbers of theoretically determined digester performance values for FF digesters were significantly greater than the other considered technologies. The number of data points for FF digesters was limited to academic papers with no empirically tested case studies resulting in a possibly inflated technology score for FF digester. The source of this problem was inherent within the literature review. As such, from a statistical standpoint this would be a first degree bias as the level of accuracy of the initial data values are questionable. Subsequently, with the use of direct experimentation it would not be possible to gain a full understanding of the performance capabilities of FF digesters. By integrating confidence margins the MCDA tool overcame this discrepancy, and the probability of the other AD technology receiving the ToBF became less skewed (Figure 20).

Additionally, based on professional opinion it was determined that the outcome of the MCDA tool needed to reflect real world design parameters associated with AD technologies. As such, the confidence margin scale was adjusted such that the outcome analysis would match these known AD design parameters. It is important to note that the confidence scale was adjusted unilaterally and in increments of 10%. In order to statistically verify the results a standard t-test was conducted on the outcome analysis. A two tailed, two sample, non-uniform variance t-tests was conducted and determined the average t value among each technology was negative 11. Using a standard t-test chart, this produces a confidence level of 99.99% indicating that there is only a 0.01% chance that the values of the two samples sets are interdependent.

Importance Factor Determination

A final analysis of the MCDA outcomes was necessary to resolve an issue resulting from the non-uniform number of sub-criteria associated within a given main-criteria. As seen in Table 7, the number of sub-criteria varies among main-criteria, with a maximum number of four sub-criteria for operational complexity and one sub-criteria for energy output. The main criteria ratings were determined by summing the sub-criteria ranks and then, dividing by the number of sub-criteria in each category. To observe the relationship between the user defined criteria importance and the number of sub-criteria per main criteria an importance factor analysis was created. The importance factor analysis served two critical functions the first was to ensure that the MCDA outcomes produced results which correspond to the design specification and to analyze the overall impacts on the MCDA outcome among all the sub-criteria. The importance factors were defined by the following equation.

$$Main\ Criteria\ Rating = \frac{\sum Sub\ Criteria\ Score^{\wedge} Importance\ Factor\ \ )}{Number\ of\ Sub\ Criteria}$$

Equation 11: Importance Factor Evaluation

The justification for the exponential nature of the importance factor equation is that, this approach resembles the CP MCDA method discussed in (Section 4.1.5). The CP method is an established MCDA methodology which assigns degrees of importance on sub-criteria. It is also critical to note that the assigned power factors were subjectively chosen such that they could be easily visualized on a graph. Because the purpose of the importance factor analysis is only to establish representative results between each sub-criteria, the actual power factor values are irrelevant. This MCDA analysis utilized the power factors of 1, -0.9 and 1.1. The value of 1 represents no power factor, -0.9 represents a low power factor and 1.1 represents a high power factor. An importance factor of one is used within the final MCDA analysis. The process for calculating the importance factors are as follows;

1.) Apply Equation 11 for each main-criteria and each AD technology at a power factor of 1.1 and rerun the outcome analysis.

2.) Apply Equation 11 for each main criteria and each AD technology at a power factor of negative 0.9 and re-run the outcome analysis.

3.) Record and graph the results.

Figure 21 shows the results from the importance factor graph for VS percent removal, which represents a typical importance factor results.

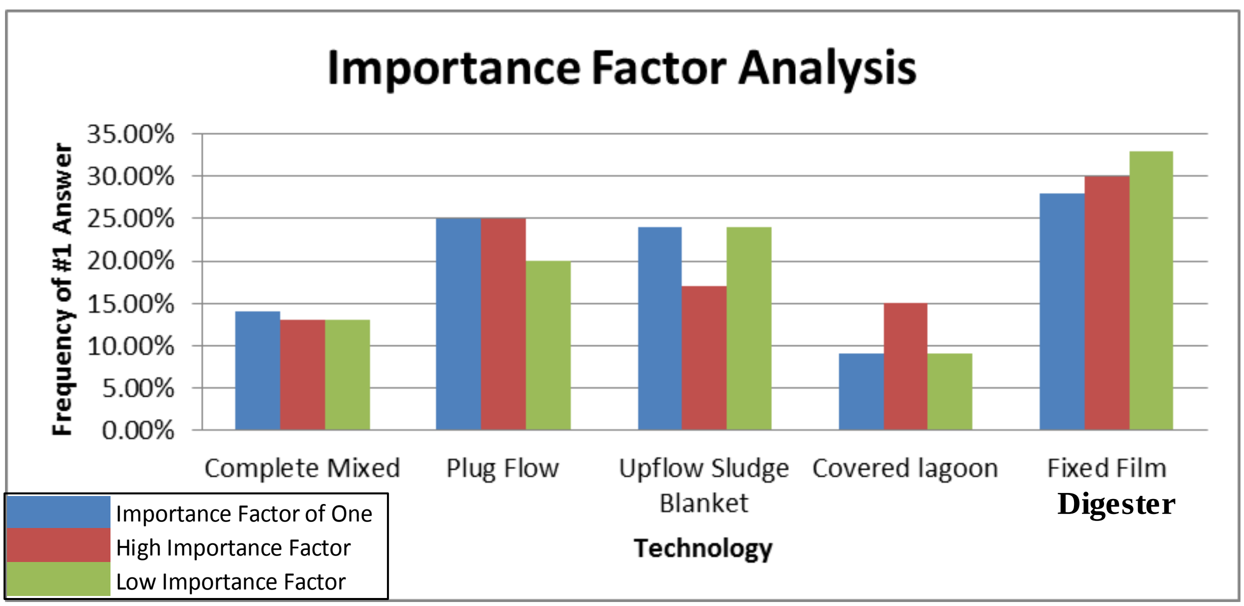


Figure 21: VS Percent Removal Importance Factor Graph

The comparison of each importance factor across all of the sub-criteria was then used to determine if any emerging trends occurred. After conducting the importance factor analysis, it was determined that methane production had the greatest impact among all the criteria for technology selection. Figure 22 illustrates the impacts that Methane production in regards to the importance of the overall outcome of the MCDA tool.

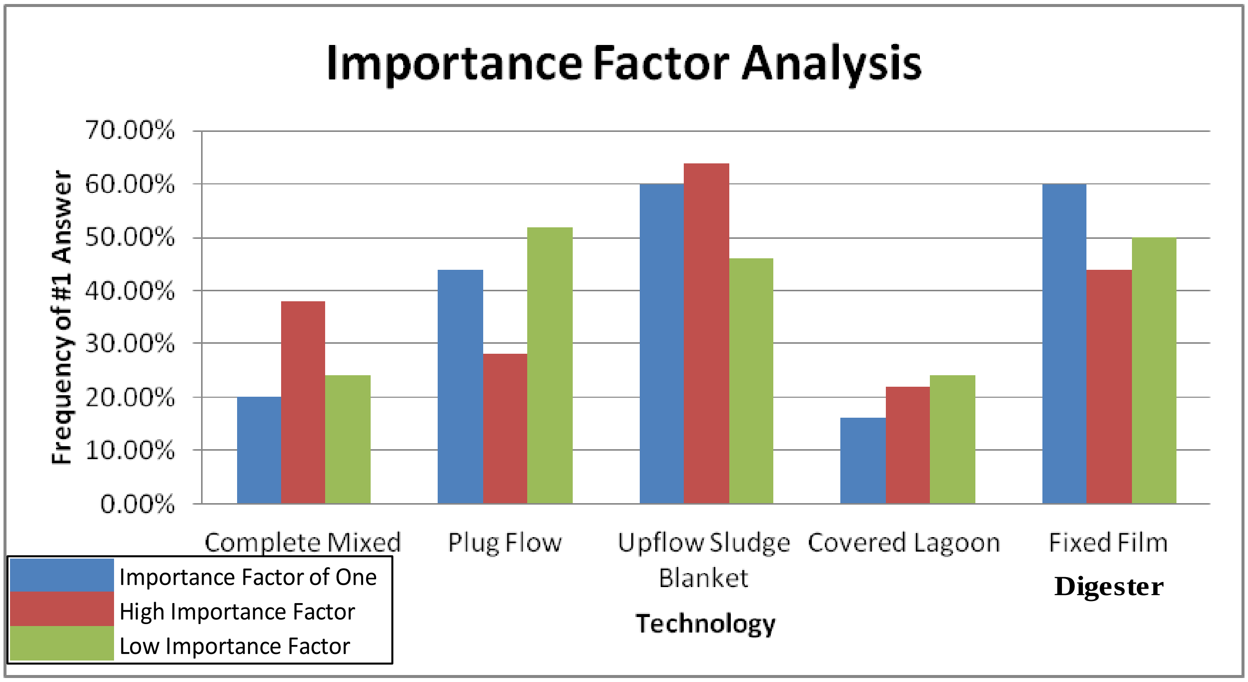


Figure 22: Importance Factor Analysis due to Methane Production.

Another distinction determined by the importance factor analysis is that the overall percentage change in the ToBF remained relatively consistent throughout each main criteria. This result indicates that a balance exists between each main criteria and the number of sub-criteria. Thus, the methodology of dividing each main criteria rating by the number of sub-criteria remains consistent among varying degrees of importance. Each of the sub-criteria importance factor graphs can be seen in Appendix B: Section 7.2.

Discussion of MCDA Outcome results:

The outcome of the MCDA tool is highly dependent on the TS% classification as the major deciding factor to determine the ToBF is whether the fixed water requirements can be met on-site. After extensive experimentation and adjusting the confidence margins, the overall outcome of the MCDA tool is that FF,PF, CM and UASB digesters are the most common ToBF while, CL digesters are only chosen under extremely specific conditions. Additionally, considerations for the applicability of on-site AD which are not considered in the MCDA tool include; type of equipment located on site, location near other waste streams, and on-site natural gas use.

The outcome analysis was highly valuable in determine if confidence margins adhered to real world AD design specifications. The final conclusion of the MCDA tool is that plug flow digesters offer the most advantages, over the largest variation of personal preferences. Also careful consideration must be used when determining the most appropriate technology, and one cannot simply assume that because a technology has been implemented before that it will offer the best solution for waste management issues. Instead a detailed and thoughtful analysis must be conducted and evaluated in order to establish the best solutions for the site specific case.

One critical piece of information which could not be integrated into the tool was specific costs. Integration of costs in to the MCDA tool would not yield a direct personal preference comparison but rather would be the sole determining factor for the technology selected. It is possible to construct a separate tool that considers a cost-benefit ratio. By analyzing risk associated with a particular investment and by calculating the perceived vs. real cost benefits added to the farm an extension of this tool could provide farmers with pareto-optimized curves and establish a cost benefit analysis. Additional extension to the tool could include a GIS databases to gather precipitation, land use, and waste water data. As well the addition of a co-digestion stream, energy potential analysis would yield more detailed AD technology benefits.

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APPENDIX A: LIST OF TECHNOLOGY PROVIDERS

This list includes technology providers who provided information on their services and/or products at the time of completion of this project (December 2011). Other technology providers may be available and it is suggested that the reader conducts a thorough search for technology providers.

Business Name	Number of employees (approximated)	Services provided	Number of Operational AD systems	Locations of AD systems	AD Technology Types	Works in Colorado / Northwest Region
RCM AD systems	35	Full service	Larger US firm with upwards of 30+ AD systems	AD systems are located in North East of USA, with a few international projects	Plug Flow, Complete Mixed, Covered Lagoon	Not Looking to expand at the moment
Environmental Energy and Engineering Co.	16	Full service	4	California, Indiana, Washington	Complete Mix	Could potentially expand
American BioGas	10	Design, Feasibility, and consulting	1 AD system in US, Have done support for multiple projects.	Germany, USA	Complete Mixed	n/a
Andigen	5	Full Service	At least 4 operational with design assistant on more	Canada and USA	Induced Blanket Reactor (IBR)	n/a

GHD Inc.	100+	Full Service	Largest firm in US with 40+ operational AD systems	USA	Plug Flow with Linear Mixing Components	Have not yet
Avatar Energy	20-30	Full Service including feasibility studies	7 (With three more in design phase)	All in California	Plug Flow	Depends on project
Bekon	55	Full service in Europe. Does	17 (none directly in USA)	All in Germany	Dry AD system (Batch/leachate)	No
Stewart Environmental	30	Consulting only	Feasibility studies only	Work in Colorado and Northern USA	Range of systems including Complete missed and plus flow	Yes
BioFerm	40	Full service	28 (world Wide projects) BioFerm is owned by Viessman Group which does projects all over the world	Most projects in Germany several located in Wisconsin	Dry AD system (Batch/leachate)	Most project located in WI region would like to expand out to rest to country
Applied Technologies	35	Full Service	Worked on at least 100 projects in US	One of the Leading AD design firms in USA	Complete Mixed, Plug Flow and UASB	None in CO. Most located in Wisconsin, Minnesota, Illinois and Iowa

Ecovation	15-20	Full Services	Subsection of ECOlab ™ Currently have 6 AD systems	All Current AD systems are in Minnesota	UASB, Complete mixed and Fixed Film	Depends on Project
Environmental Fabrics	6	Specialized Tech	Has implemented 200 plus covers worldwide	USA / Mexico and other part of the developing world	Covered Lagoon	no case studies in Colorado
* This list does not represent a comprehensive list of all biogas technology providers and is subject to change.						

* For a complete list of all biogas technology providers please visit

http://www.epa.gov/agstar/documents/agstar_industry_directory

Appendix B: MCDA Scoring Criteria

Technical Feasibility Scores

The following appendix lists each value attributed to the respective sub-criteria for that technology. Please see section 5.0: References for specific locations of references listed in the tables.

Table 9: Scoring criteria for complete mixed reactor

Complete Mixed Reactor

Sub Criteria	Description of Ranking	Units of Ranks	Farmware v 3.4	Mass natural Feasability Study	A.C. Wilkie, 2003	An Assessment of the Performance of the Colorado LLC	Dairy Waste Anaerobic Digestion Handbook	(Zhiyou, Shulin 2006)
Ability to Treat High Solids	Total Solids %	%	10.00%	10.50%	11.00%	9.50%		8.00%
Volatile Solids % Removal	% Destruction of VS	%	45.00%	52.00%	42.00%	64.00%		
Probability of Upset	Frequency of permanent Downtimes per year	#		2				
Probability of Washout	Frequency of Washouts per year	#		2.1				
Frequency of Component Tuning	# of Adjustments per year	#		2.5				
Complexity of Startup	# of Startup's per year	#		1.5				
Frequency of Clogging	# of non-operational clogging	#		6				
*Frequency of Sludge Removal	Number of Times removed per year	#	2	3				
Frequency of Moving Part Replacement	# Replacements of parts	#	4					
*Retention Time	Amount of HRT	days	20.00	25.00		36.00		15.00
*Footprint	Area of Land used Per # of Cows	m^2	0.48	0.53		1.04	3.00	
*Influent Pumping	Energy of influent pumping per year per # of Cows	kWh		130			2	
*Heating Requirements	Energy of heat required per year per # of Cows	Therms		193.33		135.8	3	
*Recycle Pumping	Energy required for recycle pump per year per # of Cows	kWh		221			1	
Reduction of Contaminants	% reduction of BOD/COD	%	75.00%			74.75%	3.00%	48.00%
*Methane Production	Volume of Methane produced per # of Cows per day per HRT	m^3	2.09	2.03		1.77	3	2.89

Table 10: Scoring criteria for plus flow reactor

Plug Flow Reactor

Sub Criteria	Description of Ranking	Units of Ranks	Farmware v 3.4	(Nelson, Lamb 2002)	(Sharvelle, Loetscher 2008)	(Dvorak 2001)	(J. H. Martin, Jr., P. E. Wright, 2003)	(J.H. Martin, Jr.1 and K.F. Roos, 2007)
Ability to Treat High Solids	Total Solids %	%	12.00%	12.50%	14.00%	13.00%		
Volatile Solids % Removal	% Destruction of VS	%	27.00%			50.00%	29.70%	34.00%
Probability of Upset	Frequency of permanent Downtimes per year	#		1				0.5
Probability of Washout	Frequency of Washouts per year	#		1.25				
Frequency of Component Tuning	# of Adjustments per year	#		1				
Complexity of Startup	# of Startup's per year	#		5.1				
Frequency of Clogging	# of non-operational clogging	#		1.25				
*Frequency of Sludge Removal	Number of Times removed per year	#	3.5					
Frequency of Moving Part Replacement	# Replacements of parts	#	1.00					
*Retention Time	Amount of HRT	days	30		30			34
*Footprint	Area of Land used Per # of Cows	m^2	0.981					
*Influent Pumping	Energy of influent pumping per year per # of Cows	kWh		260				
*Heating Requirements	Energy of heat required per year per # of Cows	Therms		150				
*Recycle Pumping	Energy required for recycle pump per year per # of Cows	kWh		17				
Reduction of Contaminants	% reduction of BOD/COD	%	28.50%			33.00%	41.90%	30.00%
*Methane Production	Volume of Methane produced per # of Cows per day per HRT	m^3	1.36				2.27	1.3

Table 11: MCDA Scoring Criteria for Up Flow Anaerobic Sludge Blanket

Up Flow Anaerboic Sludge Blanket

Sub Criteria	Description of Ranking	Units of Ranks	(Gaval, H.N 1999)	(Ramasamy, Gajalakshmi 2004)	(Sharvelle, Loetscher 2008)	(Case study concering Jer-Lindy system) (01/20/11)
Ability to Treat High Solids	Total Solids %	%	4.50%	5.50%	7.00%	
Volatile Solids % Removal	% Destruction of VS	%	55.00%			
Probability of Upset	Frequency of permanent Downtimes per year	#				3.5
Probability of Washout	Frequency of Washouts per year	#				3.75
Frequency of Component Tuning	# of Adjustments per year	#				5
Complexity of Startup	# of Startup's per year	#				1.75
Frequency of Clogging	# of non-operational clogging	#				4.25
*Frequency of Sludge Removal	Number of Times removed per year	#				0.25
Frequency of Moving Part Replacement	# Replacements of parts	#				3.50
*Retention Time	Amount of HRT	days	6	5	10	
*Footprint	Area of Land used Per # of Cows	m^2		0.30		
*Influent Pumping	Energy of influent pumping per year per # of Cows	kWh				355
*Heating Requirements	Energy of heat required per year per # of Cows	Therms				375
*Recycle Pumping	Energy required for recycle pump per year per # of Cows	kWh				254
Reduction of Contaminants	% reduction of BOD/COD	%	90.00%	92.00%		
*Methane Production	Volume of Methane produced per # of Cows per day per HRT	m^3	1.4	1.5		

Table 12: MCDA Criteria Scoring Covered Lagoon

Covered Lagoon

Sub Criteria	Description of Ranking	Units of Ranks	Farmware v 3.4	Biogas production from A covered Lagoon	(Sharvelle, Loetscher 2008)	An Assessment of the Performance of the Colorado LLC	Email exchange with leland Saele at USDA	(Dennis A. Burke 2001)
Ability to Treat High Solids	Total Solids %	%	3%	2.50%	3%			5%
Volatile Solids % Removal	% Destruction of VS	%	22.00%	40.00%				
Probability of Upset	Frequency of permanent Downtimes per year	#		0			0.25	
Probability of Washout	Frequency of Washouts per year	#					1.5	
Frequency of Component Tuning	# of Adjustments per year	#		1			0	
Complexity of Startup	# of Startup's per year	#					10	
Frequency of Clogging	# of non-operational clogging	#					1	
*Frequency of Sludge Removal	Number of Times removed per year	#	0.25				0.3	1
Frequency of Moving Part Replacement	# Replacements of parts	#	0.00	0.5			0.25	
*Retention Time	Amount of HRT	days	63	40	45			
*Footprint	Area of Land used Per # of Cows	m^2	1.43	2.88				
*Influent Pumping	Energy of influent pumping per year per # of Cows	kWh		100				
*Heating Requirements	Energy of heat required per year per # of Cows	Therms						
*Recycle Pumping	Energy required for recycle pump per year per # of Cows	kWh	0					
Reduction of Contaminants	% reduction of BOD/COD	%	25.00%	59.00%		26.23%		
*Methane Production	Volume of Methane produced per # of Cows per day per HRT	m^3	0.76					1

Table 13: MCDA Scoring Criteria for Fixed Film Digester

Fixed Film Digester

Sub Criteria	Description of Ranking	Units of Ranks	(Srinivasan, Subramaniam 2009)	Operational Complexity Guidelines	(Sharvelle, Loetscher 2008)
Ability to Treat High Solids	Total Solids %	%	3.00%		3.00%
Volatile Solids % Removal	% Destruction of VS	%	58.00%		
Probability of Upset	Frequency of permanent Downtimes per year	#		2.5	
Probability of Washout	Frequency of Washouts per year	#		0.5	
Frequency of Component Tuning	# of Adjustments per year	#		7	
Complexity of Startup	# of Startup's per year	#		1	
Frequency of Clogging	# of non-operational clogging	#		4	
*Frequency of Sludge Removal	Number of Times removed per year	#	3		
Frequency of Moving Part Replacement	# Replacements of parts	#	3.20		
*Retention Time	Amount of HRT	days	3		5
*Footprint	Area of Land used Per # of Cows	m^2	0.23		
*Influent Pumping	Energy of influent pumping per year per # of Cows	kWh	410		
*Heating Requirements	Energy of heat required per year per # of Cows	Therms	475		
*Recycle Pumping	Energy required for recycle pump per year per # of Cows	kWh	301		
Reduction of Contaminants	% reduction of BOD/COD	%	77.00%		
*Methane Production	Volume of Methane produced per # of Cows per day per HRT	m^3	1.57		

Table 14: Compromised Programming Values

Sub- Criteria	Compromised Programming Values
Total Solids range	n/a
Reduction of Volatile Solids	0.87
Reduction of Contaminants	0.87
Probability of Permanent Downtimes	0.76
Probability of Washout	0.76
Frequency of Component Tuning	0.76
Complexity of Startup	0.76
Frequency of Clogging	0.8
*Frequency of Sludge Removal	0.8
Frequency of moving part Replacement	0.8
Retention Time	0.5
Footprint	0.87
Influent pumping	0.8
Heating Requirements	0.8
Recycle pumping	0.8
Methane Production	1

MCDA Importance Factor Analysis across Each Sub-Criteria

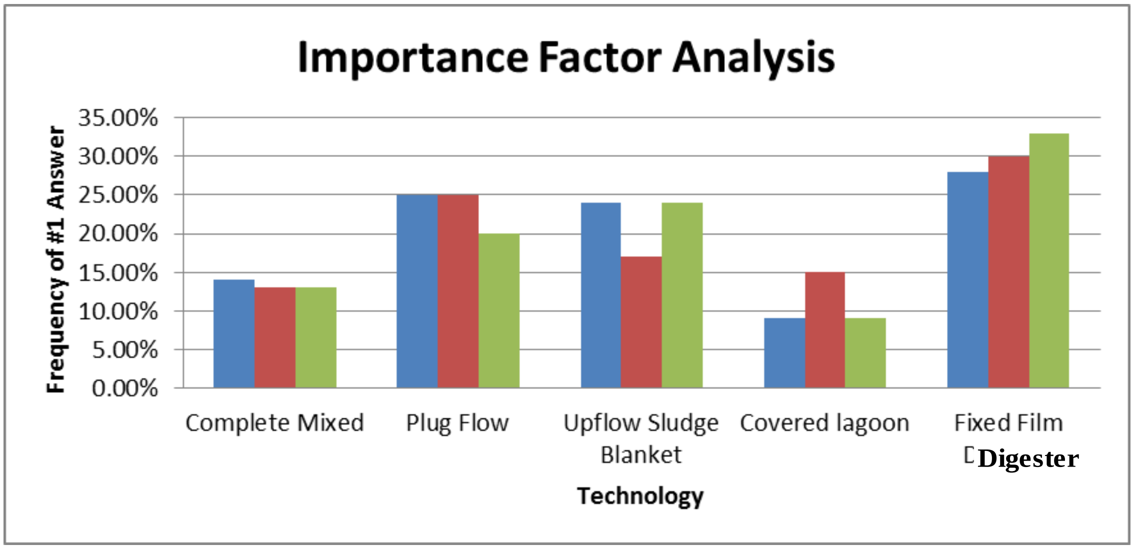

Figure 22: Importance Factor of VS% Removal

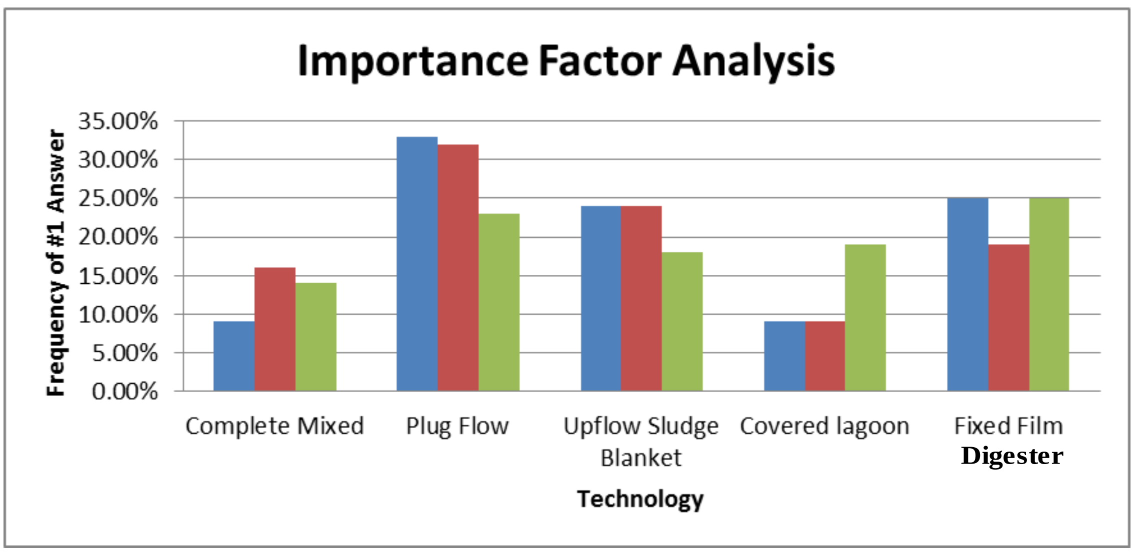

Figure 23: Importance Factor Analysis for Probability of Upset

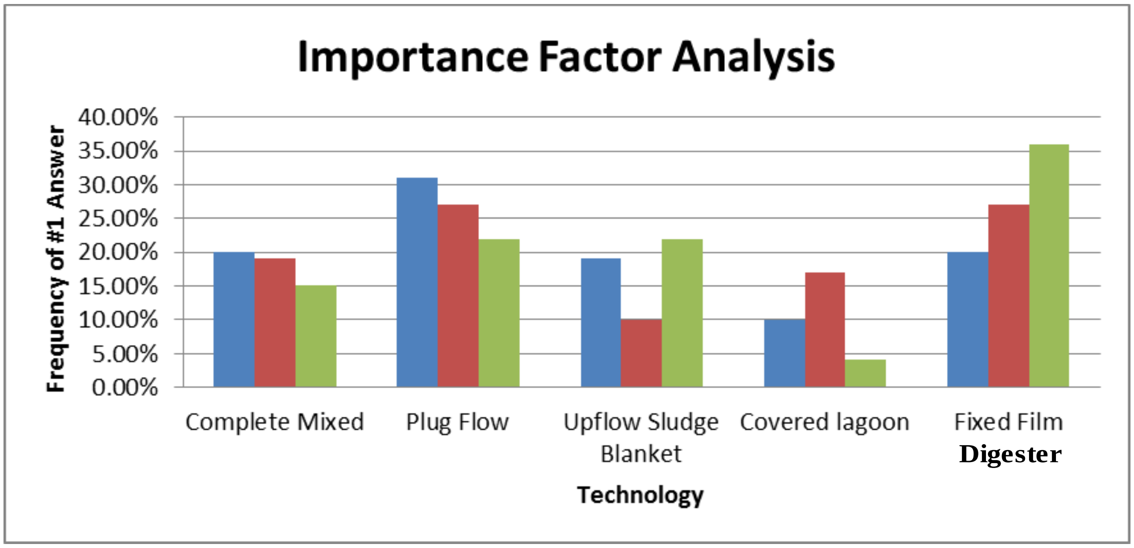

Figure 24: Importance Factor Analysis of Probability of Washout

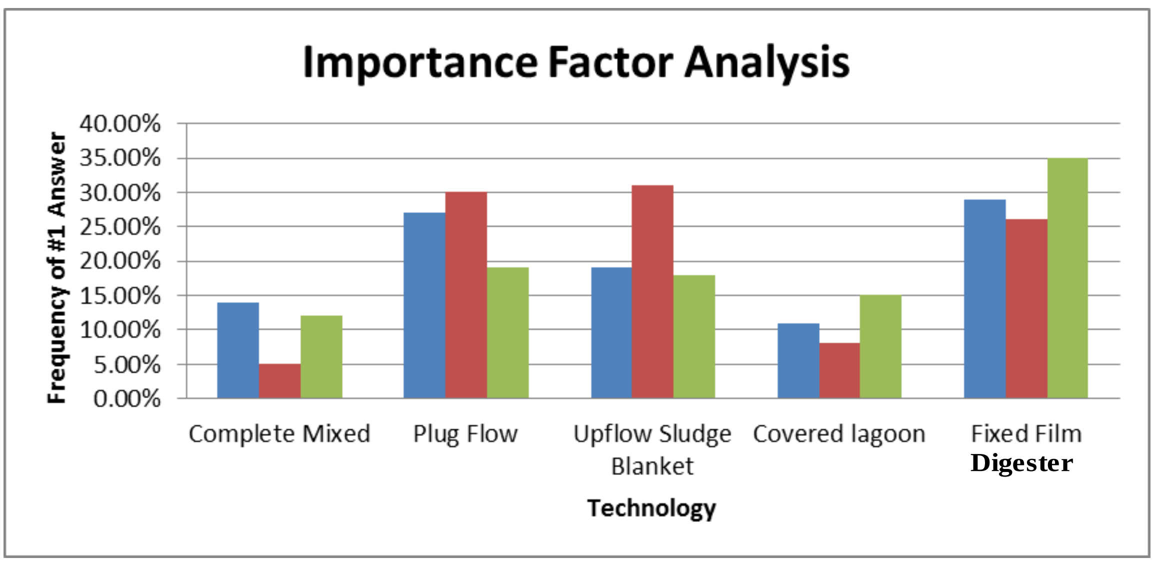

Figure 25: Importance Factor Analysis for # of downtimes due to Adjustments

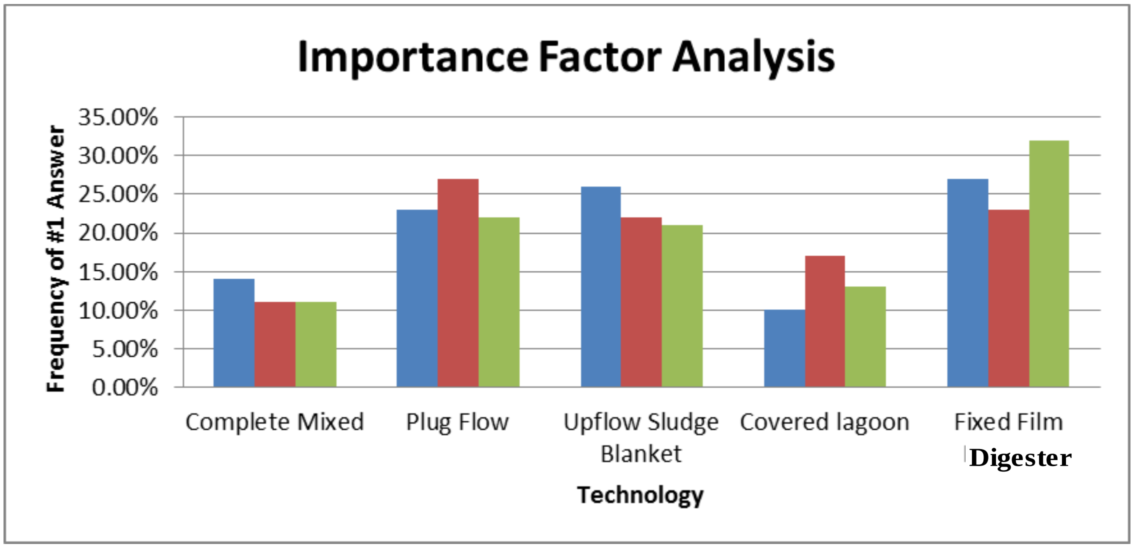

Figure 26: Importance Factor Analysis due to Number of Startups

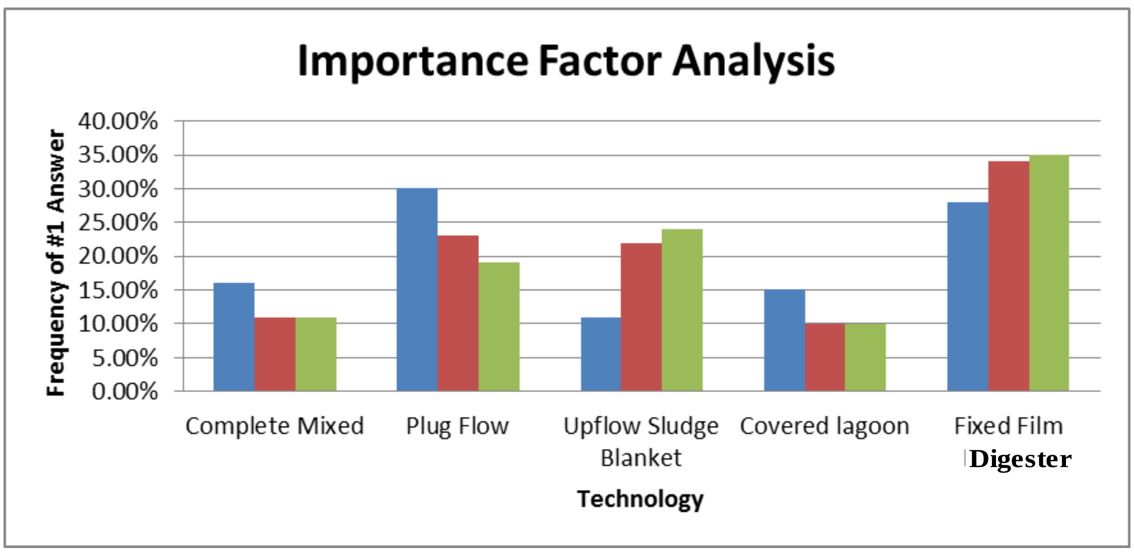

Figure 27: Importance Factor Analysis due to Frequency of Clogging

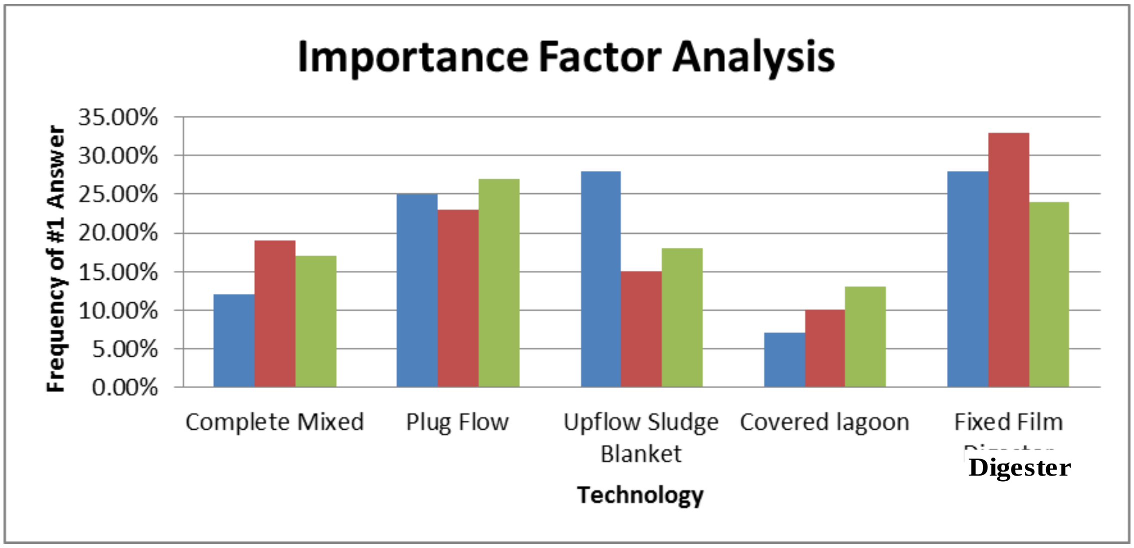

Figure 28: Importance Factor Analysis due to Frequency of Sludge Removal

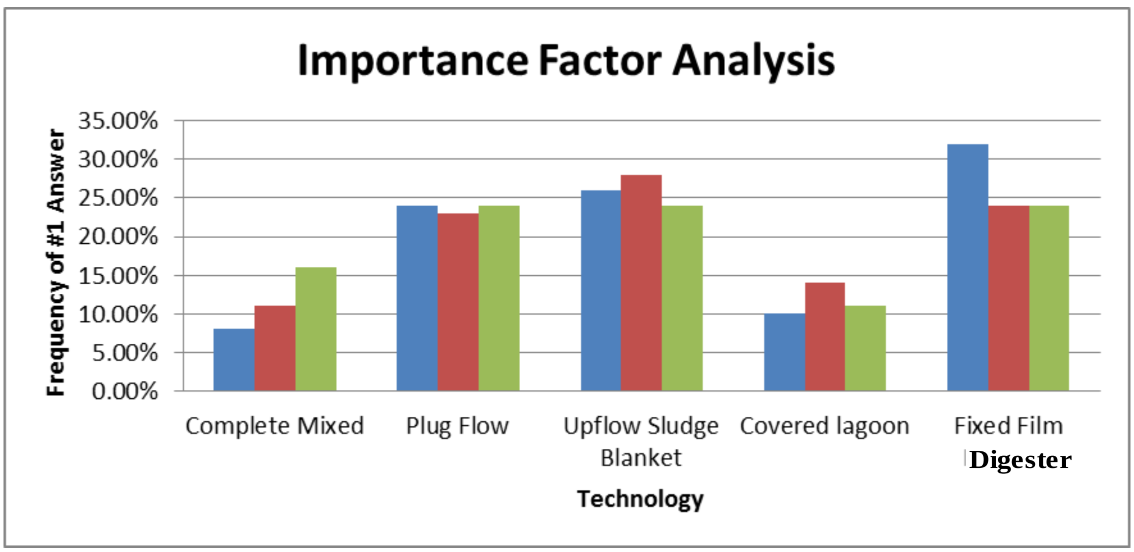

Figure 29: Importance Factor Analysis due to Frequency of Moving Parts Replacement

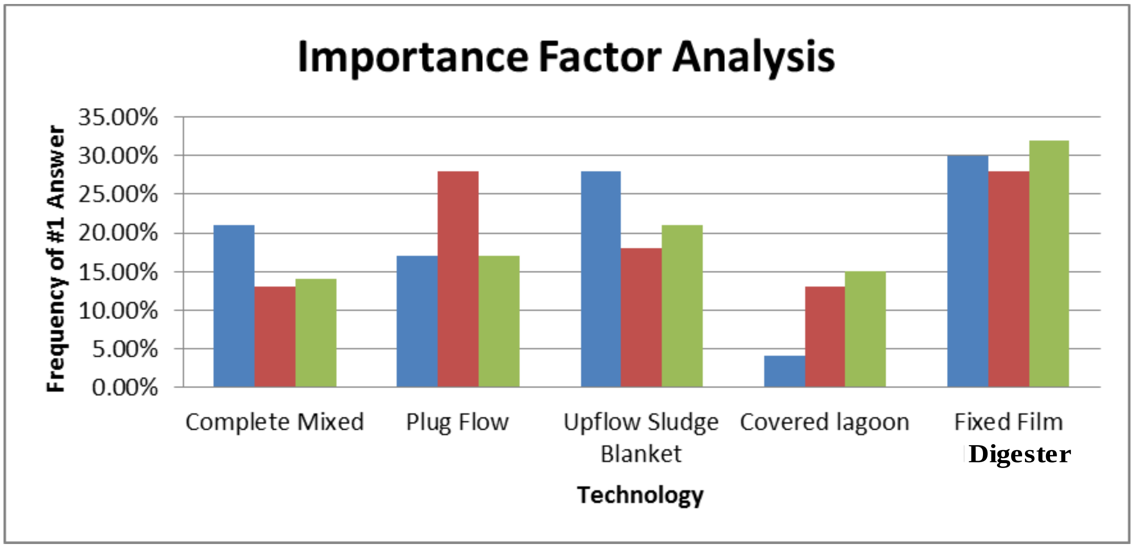

Figure 30: Importance Factor Analysis due to Retention Time

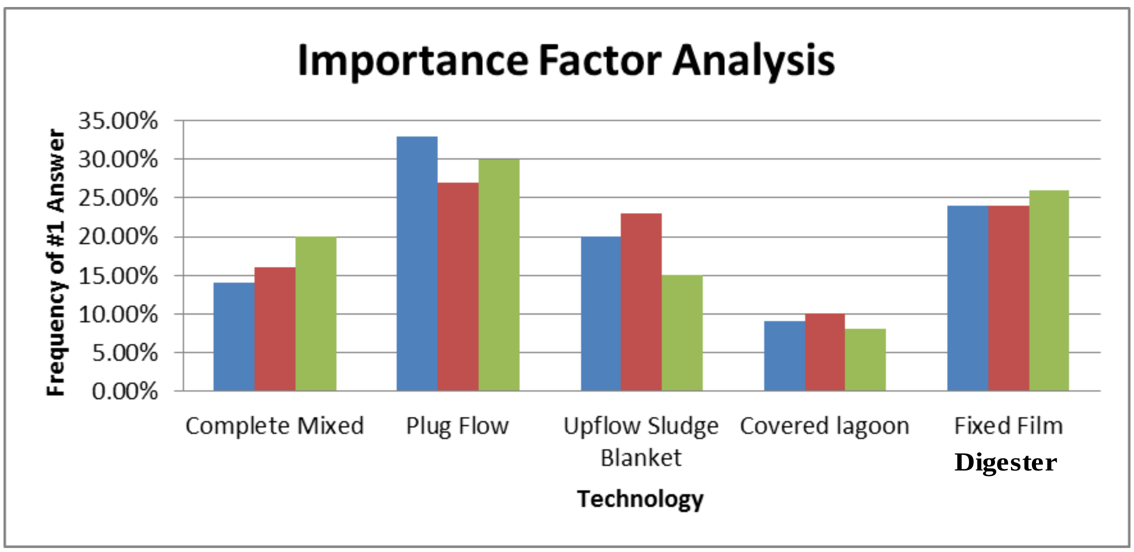

Figure 31: Importance Factor due to Footprint

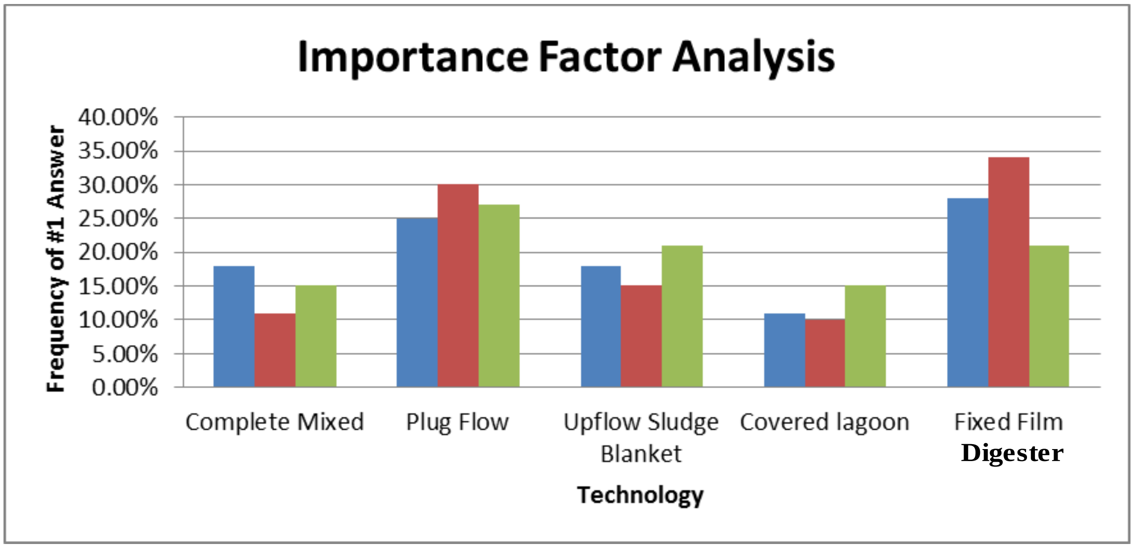

Figure 32: Importance Factor Analysis due to influent pumping

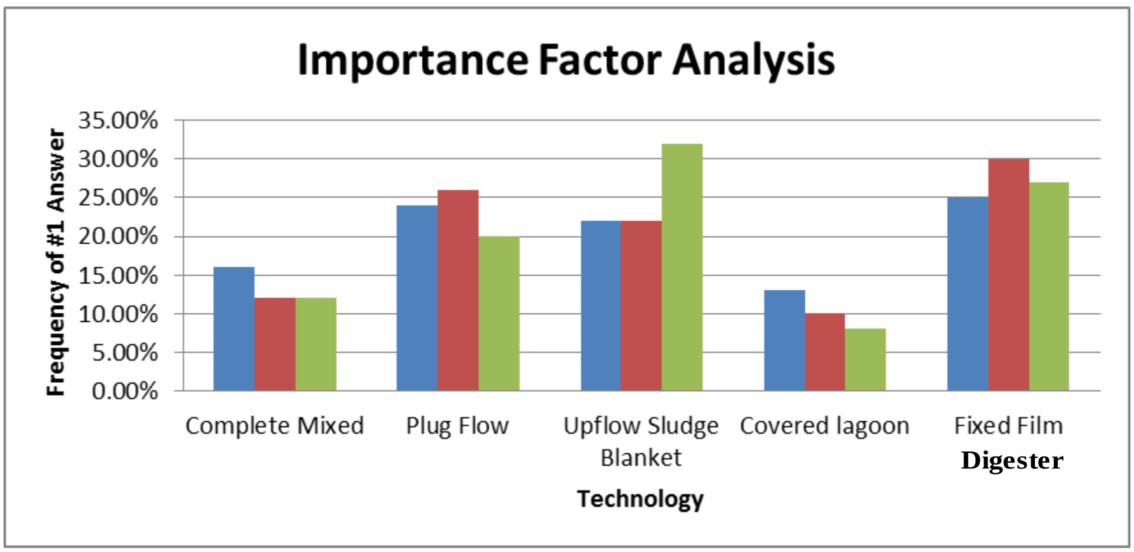

Figure 33: Importance Factor Analysis due to Heating Requirements

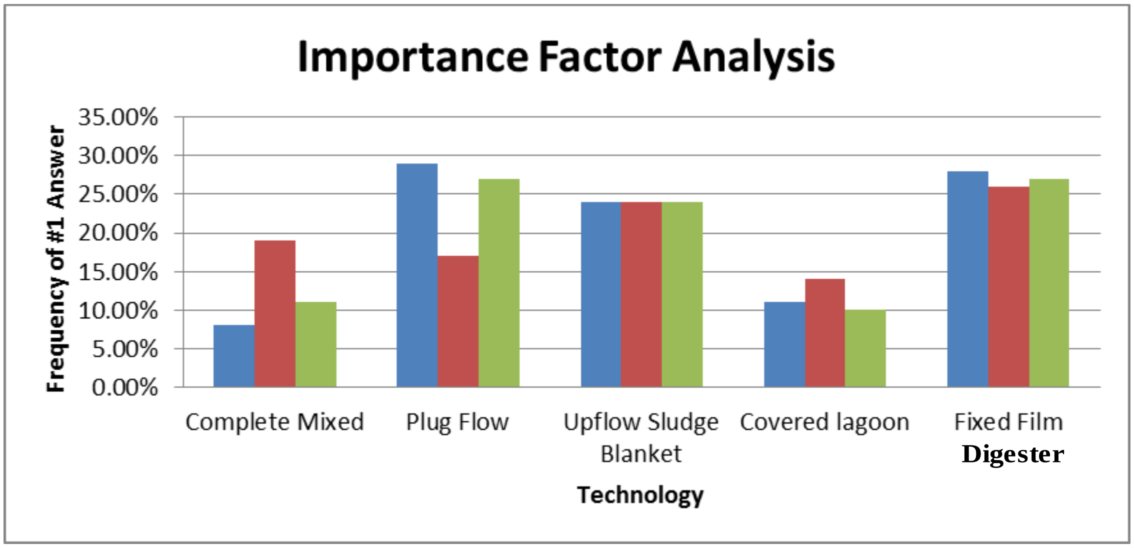

Figure 34: importance Factor Analysis due to Recycle Pumping Requirements

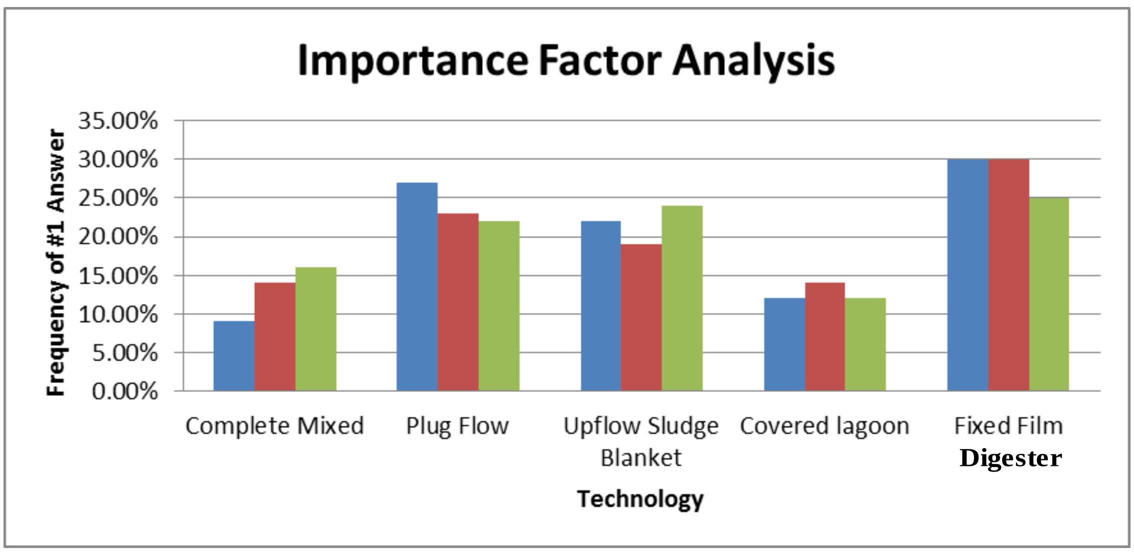

Figure 35: Importance Factor Analysis due to Reduction of BOD

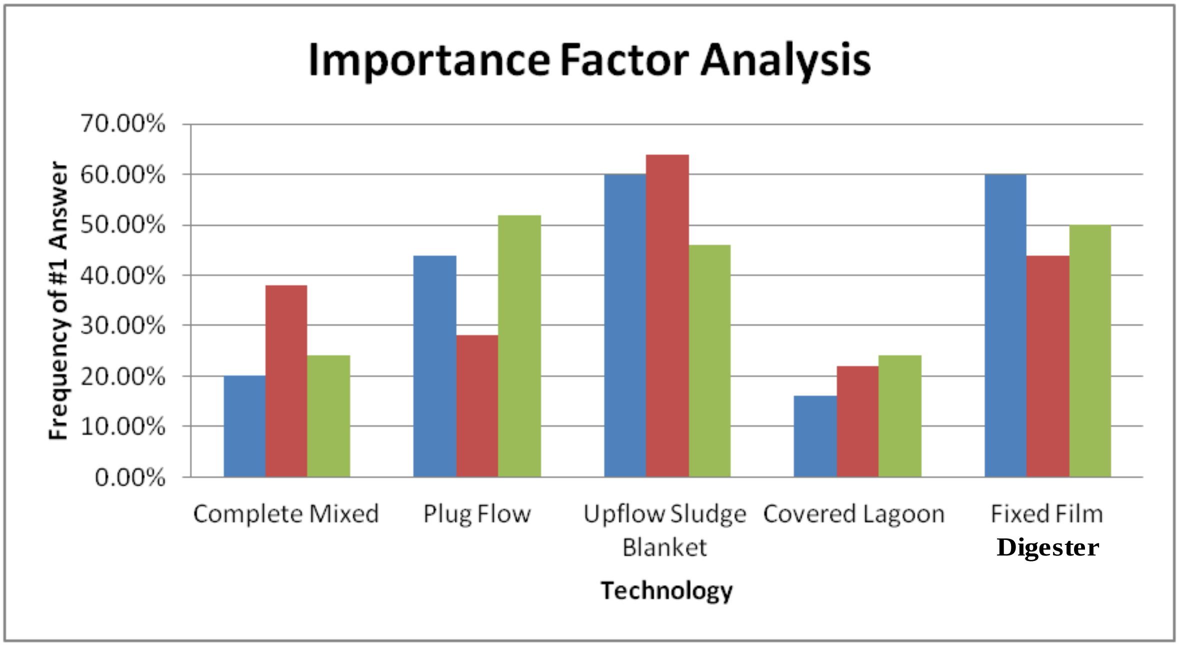

Figure 36: Importance Factor Analysis due to Methane Production.

Compromised Programming Data

During the analysis of the comparison of the different MCDA tools the relative values and data associated with the discrete compromised programming data was recorded. The following tables and graphs show the results of the analysis. They include the R values associated with each different p value and there subsequent sensitivity graphs.

Table 15: R values of each sub-criteria with the associated p value of (1) with confidence levels

Main/Sub Criteria	CM	Plug Flow	UASB	Covered Lagoon	Fixed Film
Treatment Efficiency					
VS% Removal	0.6667	0.3333	1	0	1
Reduction of Contaminants	0.5	0.25	1	0	0.75
Operational Complexity					
Probability of Permanent Downtimes	1	1	0	1	0
Probability of Washout	0.25	1	0	0.5	0.75
Frequency of Component Tuning	1	1	0.3333	1	0
Complexity of Startup	1	0.3333	0.6667	0	1
Maintenance Required					
Frequency of Clogging	0.25	1	0	1	0.5
Frequency of Sludge Removal	0.5	0	1	0.75	0.25
Frequency of Moving part Replacement	0	0.3333	0.333	1	0.3333
Capital investment					
Retention Time	0.3333	0	0.6667	0	1
Footprint	0.5	0	0.5	0	1
Energy Input					
Influent Pumping	1	0.6667	0.6667	1	0
Heating Requirements*	1	0.6667	0.6667	n/a	0
Recycle Pumping	0.6667	1	0.6667	1	0
Energy Output					
Methane Production	0.5	0.25	0.75	0	1

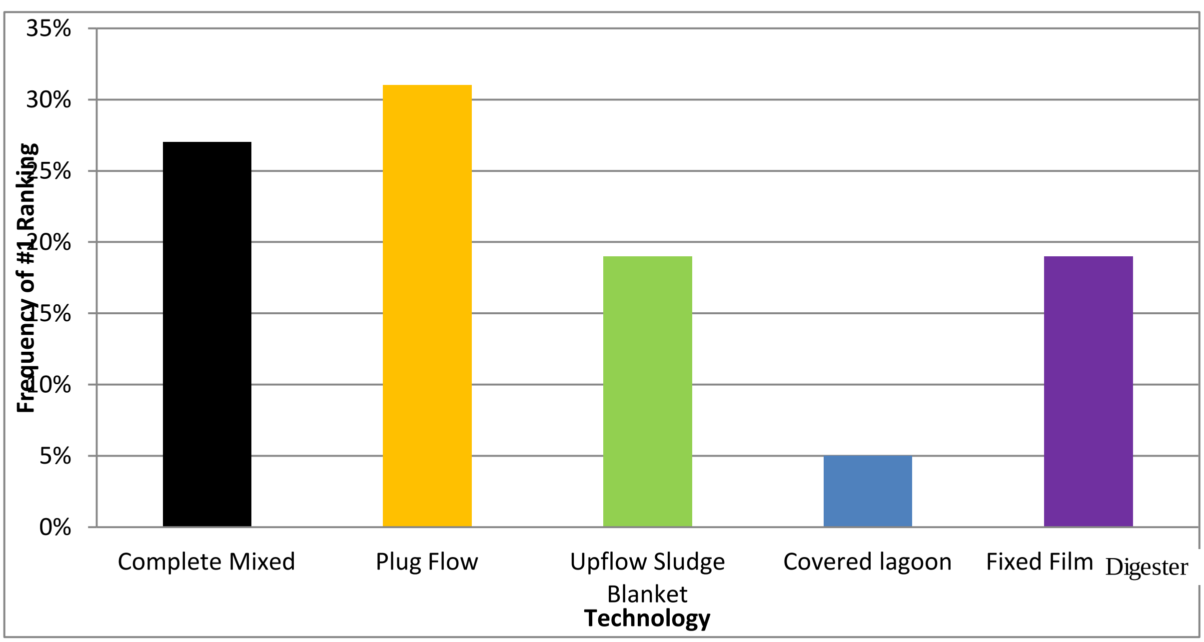

Figure 37: Sensitivity Analysis of CP with CL for a p value of (1)

Table 16: R values with confidence levels for a p value of (2)

Main/Sub Criteria	CM	Plug Flow	UASB	Covered Lagoon	Fixed Film
Treatment Efficiency					
VS% Removal	0.4444	0.1111	1	0	1
Reduction of Contaminants	0.25	0.0625	1	0	0.5625
Operational Complexity					
Probability of Permanent Downtimes	1	1	0	1	0
Probability of Washout	0.0625	1	0	0.25	0.5625
Frequency of Component Tuning	1	1	0.1111	1	0
Complexity of Startup	1	0.1111	0.4444	0	1
Maintenance Required					
Frequency of Clogging	0.0625	1	0	1	0.25
Frequency of Sludge Removal	0.25	0	1	0.5625	0.0625
Frequency of Moving part Replacement	0	0.1111	0.1111	1	0.1111
Capital investment					
Retention Time	0.1111	0	0.4444	0	1
Footprint	0.25	0	0.25	0	1
Energy Input					
Influent Pumping	1	0.4444	0.4444	1	0
Heating Requirements*	1	0.4444	0.4444	n/a	0
Recycle Pumping	0.4444	1	0.4444	1	0
Energy Output					
Methane Production	0.25	0.0625	0.5625	0	1

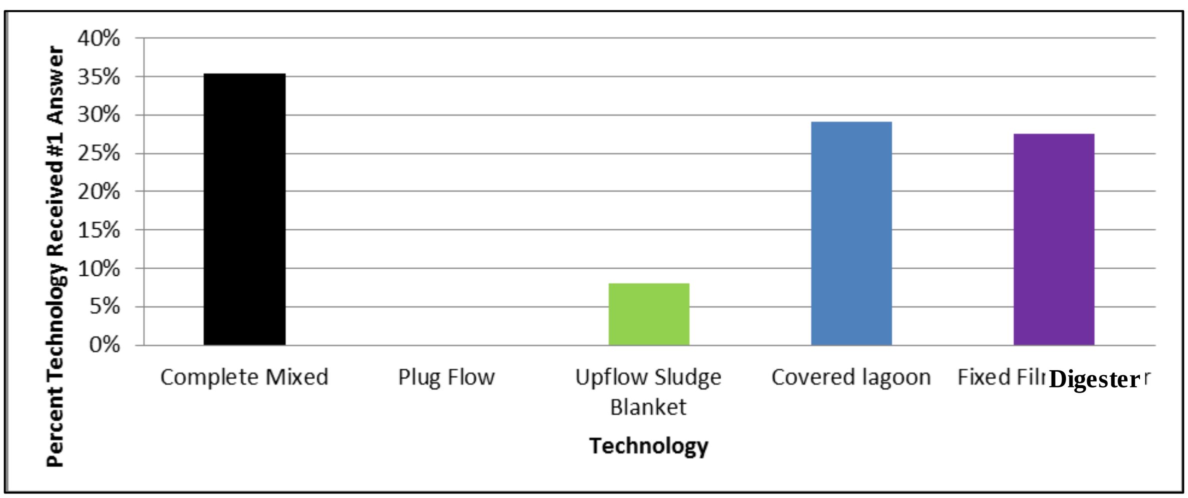

Figure 38: Outcome analysis of CP with CL for a p value of (2)

Table 17: R values with confidence levels for a p value of (Infinity)

Main/Sub Criteria	CM	Plug Flow	UASB	Covered Lagoon	Fixed Film
Treatment Efficiency					
VS% Removal	0	0	1	0	1
Reduction of Contaminants	0	0	1	0	0
Operational Complexity					
Probability of Permanent Downtimes	1	1	0	1	0
Probability of Washout	0	1	0	0	0
Frequency of Component Tuning	1	1	0	1	0
Complexity of Startup	1	0	0	0	1
Maintenance Required					
Frequency of Clogging	0	1	0	1	0
Frequency of Sludge Removal	0	0	1	0	0
Frequency of Moving part Replacement	0	0	0	1	0
Capital investment					
Retention Time	0	0	0	0	1
Footprint	0	0	0	0	1
Energy Input					
Influent Pumping	1	0	0	1	0
Heating Requirements*	1	0	0	n/a	0
Recycle Pumping	0	1	0	1	0
Energy Output					
Methane Production	0	0	0	0	1

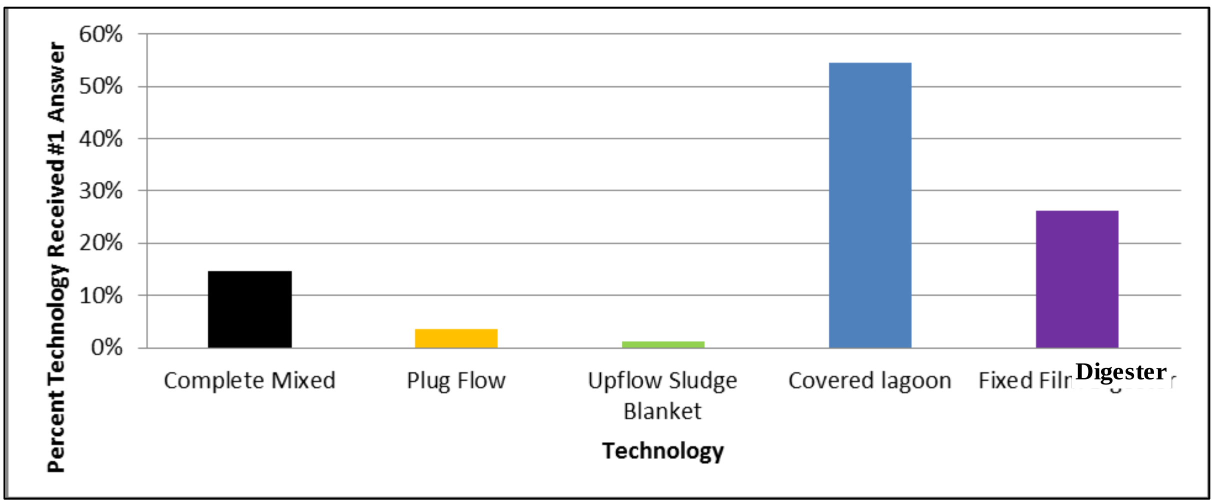

Figure 39: Outcome analysis of CP with CL for a p value of (infinity)

APPENDIX C: INDEPENDENT STUDY "MANURE WASTE CHARACTERIZATION STUDY

Summary:

The following study covers two major topics of interest concerning manure waste characterization in the northern Colorado area. The first topic covered involves a series of tests designed to measure basic properties of the manure which include total solids, volatile solids, bulk density and the chemical oxygen demand and biochemical methane potential tests. The purpose of the tests is to gather the total amount of biogas produced under varying digester conditions. The second major objective of the study is to determine the efficiency of thermophilic digestion of manure. The efficiency of increased temperature can be made by a comparison of the energy created in biogas production under varying temperatures, subtracted by the energy required for increase in temperature. All waste characterizations made on the manure samples were conducted using calibrated testing equipment provided by Colorado State University under the supervision of Dr. Sybil Sharvelle. The results of the study will be used to gain a better understanding of the potential for installation of biomass conversion technology in Colorado. The study will provide with an approximation of the total estimated value contained for each unit of manure specifically for dairy and feedlot farms. Manure samples were collected from several dairy farms located in the northern Colorado area. Manure samples were selected based on the total solids content in order to define a range of gas production. Each waste sample was tested for total solids, volatile solids, and chemical oxygen demand using standard methods and practices. Methods of manure collection include but are not limited

to dry scrape, wet scrape and concrete scrape. Sets of samples were conducted at two varying temperatures set at (35^{O}C) for Mesophilic conditions and at (55^{O}C) for thermophilic conditions.

Introduction

Advancements in the areas of renewable energy sources have allowed for an explosion of studies in the energy generation field. One potential source of renewable energy comes from the conversion of biomass to methane also known as anaerobic digestion (Cantell et al.,2008). One of the largest sources of potential biomass comes from the agricultural industry specifically there care and operations of livestock. Manure digesters have proven to be both an alternative energy source, economically viable and have positive benefit for the environment. One questions concerning biomass scientist is how much total potential energy is held within a certain volume of manure and how much can be extracted from bacteria in a certain amount of time. The goal of the study is to provide another data point relative to the second question. Biochemical methane potential test were initially designed in the late 1970's to determine the anaerobic degradability of a given waste. Using BMP's to estimate actual digester gas is a relative recent exercise and was not the originally intention of the test, however an extensive array of literate has compiled enough data to be able to determine the comparison of BMP test to real world digesters and are now standard practice for any upcoming anaerobic digester. Part of this study will include both an analysis of the results given during the BMP test and how they would relate to an operation digester.

Background Information:

Samples of manure were collected from sounding dairy farms in Northern Colorado; the primary selecting characteristic for the manure was total solids. Samples of inoculum were collected from two locations both thermophilic digesters one located in Wisconsin and the other located in Texas. Table 18 provides a list of the digesters and information about them.

BMP tests were conducted for a total of 25 days with samples of gas taken every two to three days. Gas was measured for total volume and for percent methane. Results were compiled in MS EXCEL© and analyzed using appropriate statistical methodology. A BMP bottle assay contained three separate components; the first ingredient is the nutrient solution corresponding concentrations and compounds in the nutrient solution are listed in Table 18. Nutrient solutions are used to ensure the microbial communities have the proper trace elements.

Table 18: List of Compounds in Nutrient Solution

Compound	Chemical Form in Solution	Concentration (g/L)
Nitrogen (N)	NH_4Cl, $(NH_4)_2SO_4$, N_2, KNO_3	0.216
Phosphorus (P)	KH_2PO_4, Na_2HPO_4	1
Sulphur (S)	$NaSO_4$, KH_2SO_4,NaS_2O_3,Na_2S	0.156
Potassium (K)	KCL, KH_2PO_4	0.59
Magnesium (Mg)	$MgCL_2$,$MgSO_4$	0.81
Sodium (Na)	NaCl	0.1
Calcium (Ca)	$CaCL_2$	0.11
Iron (Fe)	$FeCL_3$,$FeSO_4$	1.7
Micronutrients	Cr, Co, Cu, Mn, Mo, Ni, Se, V, Zn	~0.1

The second ingredient added to the biochemical methane potential test is the manure sample. The manure is the most important constituent to the BMP test and also includes the largest amount of variability for total energy production. Manure samples were initially measured for COD using standard Hawk outlined protocol (See Appendix "COD procedure"). Manure samples were also tested for Total solids and Volatile solids as well. Results for the waste characterization analysis are listed in Table 19.

Table 19: Manure Sample Characterization

Sample Description	TS (%)	VS* (%)	COD (g/L)	Amount of Sample Added (g)	Amount VS Added (g)
Farm #1 Concrete Scrape (C1)	25.82%	11.50%	78	32.38	3.72
Farm #1 Flush (F1)	11.45%	5.48%	33	78.32	4.29
Farm #2 Dry (D2)	84.08%	24.46%	512	5.27	1.29
Farm #3 Concrete Scrape (C3)	19.94%	11.27%	109	23.51	2.65
Farm #3 Flush (F3)	6.09%	4.13%	59	42.53	1.76
Farm #4 Dry (D4)	83.90%	26.39%	413	6.29	1.66

* VS% is measured as percent of total sample.

The final ingredient for the BMP test is the addition of the inoculum. Samples of inoculum were collected from around the country under the basis that each digester be both a manure treatment facility and run at thermophilic temperatures ~55^{0}C. Several digesters were contacted in order to facility gathering of samples. Two digesters responded willing to assist in the research project there information is listed below in Table 20.

Table 20: Inoculum Digester Information

Dairy Name	Location	Digester Type	HRT (days)	Avg. pH	Avg. Temp C^0	Co-Digestion Streams
Huckabee Digester	Texas	Complete Mix Tank Reactor	15	8.3	55	Paunch, Food Wastes, Feed, Corn by-products
Five Star Dairy	Wisconsin	Complete Mix Tank Reactor	20	8.1	55	Glycol , Sugar beet wastes

Inoculum samples were collected from the primary effluent of the digester and shipped using the United States post office. A plastic cooler filled with ice packs and three one liter

Nalgene© bottles was sent to each of the digester. Samples were then collected and ship at first class priority mail while remaining in refrigeration. Each digester provided three separate 1 liter samples of inoculates. Upon receiving, the inoculum samples were purged with nitrogen gas for 30 minutes in order to remove any excess oxygen that may have accumulated during the shipping process.

Methodology

The primary purpose of the BMP study was to determine the total energy contained in manure. Please note that this study is not meant to serve as a data point for digester operations. The limiting energy source in the study is intended to be the manure sample. To determine the appropriate rate of methane generation expected from full sized digester further tests would be required with differing nutrient concentrations and inoculum concentrations.

Variable parameters of BMP test:

- Manure total solid percentages
- Inoculum source
- Temperature
- Constant parameters of BMP tests:
- Amount of manure added (grams of COD per Liter)
- Amount of nutrient solution (ml)
- Amount of inoculum (ml)
- Retention time (days)

Step by Step Procedure

The methodology for the study can be best understood using a step wise format where each step is laid out in chorological order.

Step 1: Combining ingredients

After the inoculum samples were purged with nitrogen the next step for conducting the BMP test is to combine the three ingredients (manure sample, nutrient solution and the inoculum) into a single container. Each of the three ingredients were placed in a pressure inducing case which achieved a pressure of over 600psi for 30 seconds removing any gases left in the solutions. The ingredients are then placed in an anaerobic environment. 700 ml of nutrient solution, 300 ml of inoculum and 5 g COD/L of manure sample is poured into a 1000ml flask.

Step 2: Sealing the sample for outside air

A rubber stopper is then placed on top of the flask in which a metal needle is stabbed through the rubber into the flask. The end of the needle is connected to a duel value syringe. The syringe itself has two possible positions open and closed. When open the methane produced by the BMP test is collected into the syringe. When closed the gas is allowed to go to the atmosphere. Each syringe also contains volume based measuring increments.

Step 3: Incubation

After the ingredients are placed into the flask they are taken out of the anaerobic environment and placed on a temperature controlled enclosed incubator. The enclosed incubator is capable of reaching $100C^{o}$ and contains a shaking table which was run at approximately 60 RPM. To be clear the incubator uses air to heat the vials and is not heat plate driven. After the samples are placed in the incubator they are allowed to shake for one to two days.

Step 4: Collection

One the samples have incubated and a noticeable amount of gas is produced they are now ready for gas collection. The syringe is placed to the closed position and a secondary syringe is place on the open end of the valve. The gas is then transferred to the secondary syringe and measured for total volume. The syringes handles are allowed to expand and then contract in order to best simulate atmospheric pressure this ensures an accurate volume reading of the biogas.

Step 5: Gas chromatography (GC)

The sample of gas is now taken to the gas chromatography machine and runs thru a 90 second gas phase analysis, please see Appendix A: GC machine protocol for a detailed analysis of the GC step. After the gas sample has been tested for percent methane the results are logged and entered into a computer spreadsheet.

Step 6: Repeat

Steps 3-5 are now repeated every one to two days for a total of 25 days.

Results

The final results of the study are contained into two sections, Biochemical methane potential sections covers the results of the BMP test and the specific methane production. Each of the BMP test were normalized to 5 grams of COD per trails assay, thus for total ml production of methane multiply the number given in the result graphs by five. The second section of the results contains the equations used to find the difference in total temperature energy for 35°C to 55°C.

Biochemical Methane Potential Test-

The following graphs represent the cumulative methane production of both temperature trials in ml of Methane per gram of Chemical Oxygen Demand (COD) vs. Time. Figure one shows the cumulative Methane production for the Thermophilic flush manure sample with error and the Mesophilic flush manure samples with error.

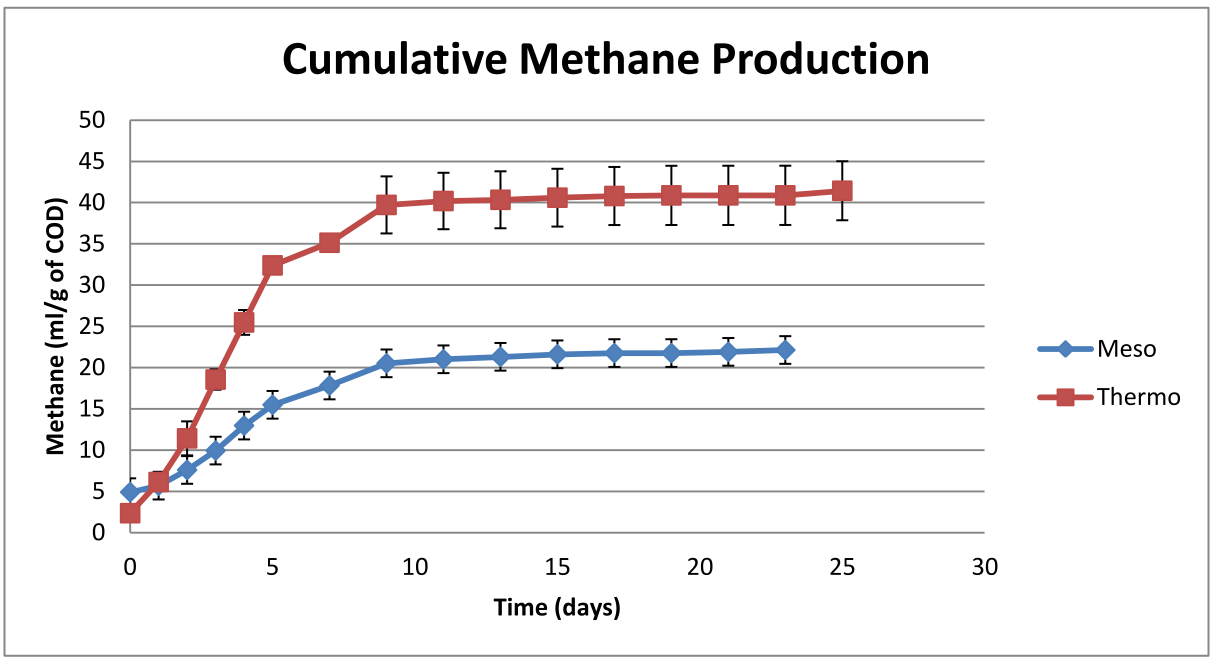

Figure 40: Comparison of Thermophilic vs. Mesophilic ml of CH4 per gram of COD

Figure 40 represents the total methane production for mesosphilic bacteria vs. thermophilic bacteria on grams per volatile solid

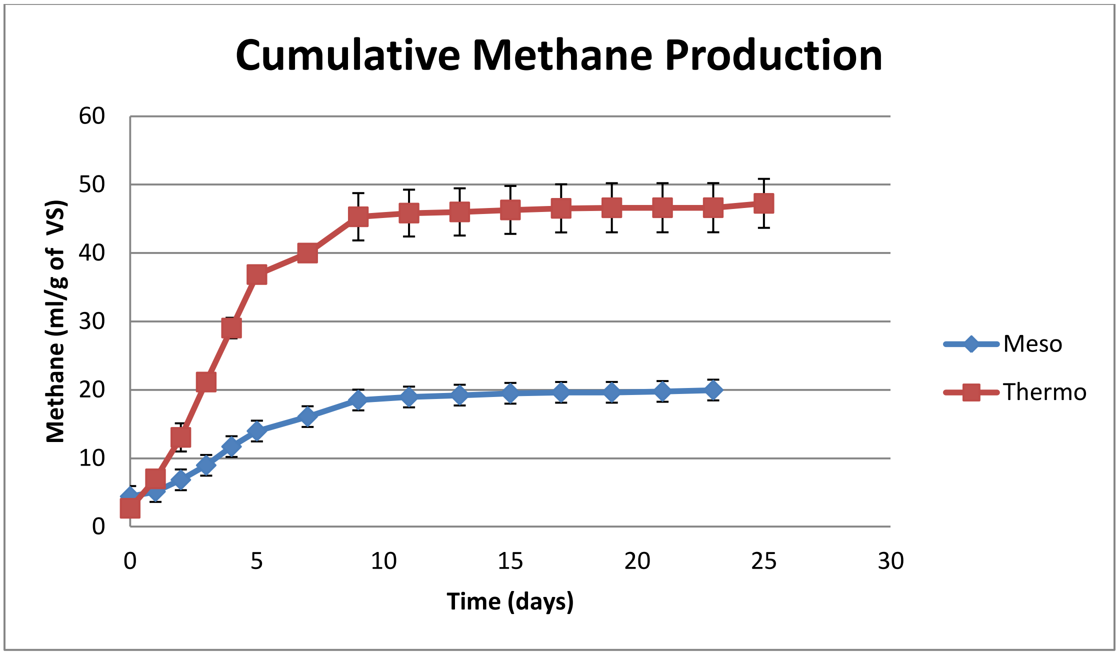

Figure 41: Cumulative Methane Production Meso Vs. Thermo

Figure 41 shows the individual sample results for each of the thermophilic methane potential tests, each of the samples match with the above waster characterization table. Each of the values is an average of two samples taken with error bars shown.

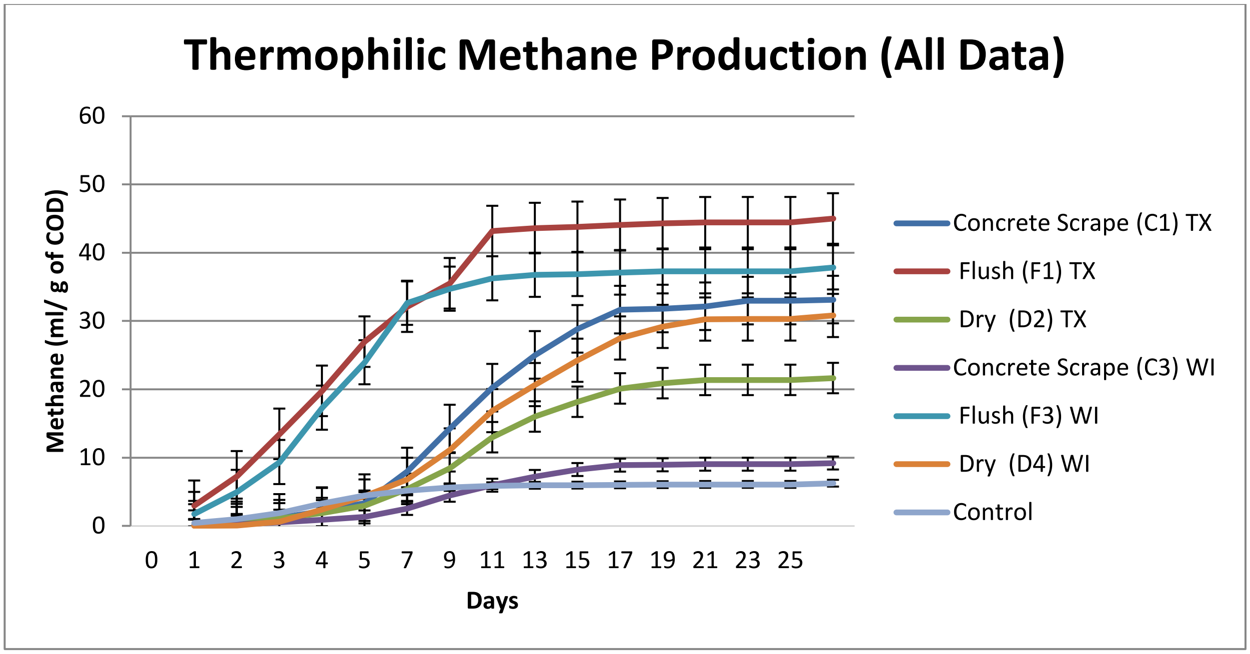

Figure 42: Thermophilic BMP Raw Data

Heat Equations

In order to determine the amount of energy required to heat thermophilic bacteria vs. the amount of energy to heat mesosphilic bacteria the follow calculation step process explains the calculations.

Calculated Heat Loss Over One HRT -

Step 1 – Calculate Delta T (Design Temperature):

Delta T is a difference between indoor design temperature (T1) and outdoor design temperature (T2), where indoor design temperature is typically 35-55^{o}C depending on the trial, and outdoor design temperature is the ambient room temp estimated at 22^{o}C.

Step 2 – Calculate surface area:

The calculation for surface area heat loss is done by assessing the average volume requirements for thermophilic digesters vs. mesosphilic digester. The average percent change in total surface area will be used to find the surface heat loss. Since it is assumed that the U-values for the two digesters are the same the insulation on the two tanks are equal. This step calculation also assumes that the heat produced within the digesters is non-important. The system boundaries are assumed to be closed with heat loss to the atmosphere by the surface area the only form of energy dissipation. *The assumed surface area decrease is 2X for thermophilic digesters.

Step 3 – Calculate U-value:

Assuming that the digester of mesosphilic and thermophilic have the same insulation requirements. The U-values for each are assumed to be the same.

Step 4 – Calculate wall surface heat loss:

Surface heat loss can be calculated using the formula below:

$$\text{Surface Heat Loss} = \text{U-value} \times \text{Wall Area} \times \text{Delta } T$$

Step 5 - Total Wall heat loss over time

The equation for the total wall heat loss over time is as follows:

$$\text{Surface Heat Loss} \times \text{Total Time of One Hydraulic Retention} = \text{Total Heat Loss}$$

Calculated Heat difference from Surface area loss –

Given that the above equations and assumption for the heat loss the remaining dependent variables are the delta in temperatures, and change in surface area, and the change in hydraulic retention time. With these is becomes possible to determine the total heat loss given the similar conditions. One the calculations are run it was determined that thermophilic temperatures would require 1.12 times the amount of energy then for the Mesosphilic conditions.

Ratio of Thermophilic vs. Mesosphilic digesters over one HRT = 112%

Heat required for incoming material

The required heat difference from Mesosphilic to Thermophilic digesters is also related to the amount of volume incoming into the digester. The loading rates for each temperature differ significantly as well the incoming material must be heated to a either the 35 ^{o}C or 55 ^{o}C degree range.

Step 1 – Calculate Delta T (Design Temperature):

Delta T is a difference between indoor design temperature (T1) and outdoor design temperature (T2), where indoor design temperature is typically 35-55^{o}C depending on the trial, and outdoor design temperature is the ambient room temp estimated at 22^{o}C.

Step 2 – Calculate the mass incoming into each digester type:

Using literature provided on the internet it is possible to estimate the average amount of incoming material into a thermophilic digester and for a mesosphilic digester. The amount of incoming mass into the digester is known as the substrate loading rate. For this analysis it was assumed that only manure counted for this material and that co-digestion stream were not considered in this study.

Average Themo. Substrate Loading rate = 64,570 Kg per day

Average Meso. Substrate Loading rate = 55,100 Kg per day

Step 3 – Calculate the Specific heat for Manure:

The specific heat for manure can be found using the equation below [Abdellatif, Begdouri 2003]

$$C_p = 4187{\cdot}5 - 28{\cdot}9\,(TS) \qquad (12)$$

where

C_p = specific heat (J kg^{-1} °C^{-1}),
TS = Total Solids (%)

and adjusted $R^2 = 0{\cdot}98$, $F = 147$ (R = coefficient of correlation, F = F-Statistic).

Figure 43: Specific heat for manure

It was assumed for each type of digester that the total solids is around 8%, and that the manure is originally at 4^{o}C when entering the digester.

Step 4 – Calculate the Heat added per day

Using the following equation it is possible to find the amount of heat added to the incoming manure on a daily basis.

$$Q = cm\,\Delta T$$

c = Specific heat capacity

m = Mass

ΔT = Change in temperature

Step 5 – Calculate the heat added over one HRT

The amount of total heat added over one HRT can be found by multiplying the heat added per day by the HRT of each digester type.

*Total Heat added Thermo. = (Q) * (0.000947 Joules/BTU) *(20 days) = 266,000,000 BTU*

*Total Heat added MESO. = (Q) * (0.000947 Joules/BTU) *(28 days) = 184,000,000 BTU*

Step 6 – Calculate the heat ratio

The amount of heat added for mesosphilic digesters divided by the amount of heat added for thermophilic digesters is equal to the following equations.

Heat added ratio for Meso vs. Thermo = 145%

Calculated Energy in bio gas production

The amount of heat gained from additional gas production is equal to the total amount of methane produced for each digestion temperature over the HRT of a typical digester setting. The difference in the total bio gas production on a ml of methane when comparing the mesosphilic conditions vs. the thermophilic conditions is a calculated as follows.

Step 1 – Calculate average amount of methane produced:

Methane (ml) Thermophilic = 207 ml

Methane (ml) Mesosphilic = 110 ml

Step 2 – Find the heat energy of each digestion type:

The amount of heat energy for the gas produced is equal to the volume of gas times the BTU equivalent. For methane one cubic foot of gas at standard pressure is equal to 1027 BTU's of heat energy when burned. This analysis does not take into consideration the efficiency associated with generators when converting methane to electricity since we are only observing the total heating requirements.

Step 3 – Find the heat ratio of Thermophilic to Mesosphilic gas production:

In order to find the ratio of heat produced for the gas production we must divide the total BTU's produced under thermophilic conditions by the gas production BTU's under mesosphilic conditions.

Thermophilic Gas production heat = 6.00 BTU's

Mesosphilic Gas production heat = 4.00 BTU's

Equates to a 50% increase in gas production

Discussion:

The end results of the analysis are that under worst case scenario thermophilic digestion is not energy efficiency when compared directly to mesosphilic conditions. Taking the ratios of each heat equation we find the following results

Total energy equivalency in %= (Energy loss %) +(Energy Added %) – (Energy of Gas produced %)

Total Heat % = (12%) + (45%) –(50%)

Total Energy % Increase in Thermophilic vs. Mesophilic Digester = 7%

The total heat equation represents the amount of additional heat required for thermophilic digestion under the conditions listed above. The biogas productions rate is provided in milliliter (ml) of bio gas produced. These values are corrected for the blank assay which contained no manure only nutrient solution and the inoculum. **Figure 40** and Figure 41 clearly shows the impacts of temperature on the BMP test as there is a large difference both in the rate of production and the total amount of gas produced overall. Two major trends emerged overall for the BMP tests in regards to the thermophilic analysis in that the manure used did not have that large of an impact on the total methane produced. The rate of the methane production is significantly changed over the different water concentrations of manure. The hypothesis behind these results is that the manure when in a more dissolved form is readily available for use by the bacteria. Where manure types that contains more cellulose material take longer to convert to methane.

The total heat requirement equations should be taken as a worst case scenario as such the results listed are highly variable. Due to the relative small difference in heat generation it is possible that changing any one of the variables could cause the heat difference to swing in favor of thermophilic.

Conclusion:

Due to complex nature of the equations and the variability of prevailing assumptions it is recommended that anyone considering anaerobic digestion for a dairy farm should gain a deep understand of the variables associated with heat input. It is also recommended that potential digester implementers also understand the additional advantages of thermophilic digestions. These additional advantages include, lower capital costs due to less volume required, one log removal of pathogens over mesosphilic digestions and larger substrate loading rates. It is mainly because of these reasons that thermophilic digestion is becoming more and more popular with AD system even in colder climates.

Procedural explanations for testing

<u>Hach ® Procedure COD analysis:</u>

The Chemical Oxygen Demand (COD) test measures the oxygen equivalent consumed by organic matter in a sample during strong chemical oxidation. The strong chemical oxidation conditions are provided by the reagents used in the analysis. Potassium dichromate is used as the oxygen source with concentrated sulfuric acid added to yield a strong acid medium. Several reagents are added during the setup of the analysis to drive the oxidation reaction to completion and also to remove any possible interferences. Vials are then placed in a Hach certified Colorimeter which measures the change in color occurring in the vial due to the reagents consuming the organic matter.

GC Machine Procedures:

In gas chromatography, the *mobile phase* (or "moving phase") is a carrier gas, usually an inert gas such as helium or an unreactive gas such as nitrogen. The *stationary phase* is a microscopic layer of liquid or polymer on an inert solid support, inside a piece of glass or metal tubing called a column (a homage to the fractionating column used in distillation). The instrument used to perform gas chromatography is called a *gas chromatograph* (or "aerograph", "gas separator").

Surface Area Comparison Data

Table 21: Table of Surface Areas for Various digesters

	Surface Area comparison					
	Digster Name	Size (Volume) Gallons	Biogas production (ft^3/day)	Dimensions	Surface Area (ft^2)	Surface Area to Bio Gas Ratio
Thermophilic	Huckabay	900,000	342,465	D= 55 H =50	13,391	25.57
	Norwiss	750,000	290,800	d= 50 H=50	11,781	24.68
Mesophilic	Green Meadow	2,700,000	329,000	D = 85 / H= 24	53,274	6.18
	Scenic View	870,000	108,000	D = 85 / H= 24	17,758	6.08
	Patterson	1,200,000	173,300	104' x 30' x 19'	14,860	11.66
	Roach Dairy	1,501,900	113,230	D = 120 / H=18'	29,405	3.85

Average Ratio of Meso to Themo Surface Area

2.0

Incoming Heat Comparison

Table 22: Table of Incoming heat comparison

	Name	Loading Rate Gallons per Day	Delta T	Mass per day (kg)	Specific heat @ 8% solids ($J\ kg^{-1}\ C^{-1}$)	Heat added Per day (Joules)	Heat Added BTU's per day	HRT	Total heat (BTU's)	Cows	Heat % change
Thermo	Huckabay	17,125	55	64,575	3956.3	14,051,293,988	13,306,575	20	266,131,508	**10,000 dairy @ 13.7 Gallons per cow**	**145%**
Meso	Green Meadow	14,613	35	55,104	3956.3	7,630,278,432	7,225,874	28	183,931,330	**3,200 dairy @ 13.7 Gallons per cow**	

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APPENDIX D: RESULTS OF ON-SITE FARM SURVEYS

The name and locations of the surveys have been removed in order to protect the privacy of those who participated in the survey. Answers to the surveys are placed in italics.

Farm # 1

I) **Technical questions for producers-**

() Considering Solar thinks it's a better option need a regional digester in his area 5-6 dairies in the area goal is to cover hauling costs.

2) How many of the following animals do you have?
   a) Lactating cows: *1,800*
   b) Feed lots Cows: *200*
   c) Steers or Bulls? *None*
3) Manure Collection practices: *Dry Lot*
   a) What are you current manure collection practices, and with what frequency?
      () Harrow 2-3 Days

      - (i.e dry scrape, concrete scrape, vacuuming, flushing, etc.)

      () Scrape when dry ~ 1/mo. Lanes with slurry cleaned every other day and mixed with dry manure

   b) When do you collect manure?
      () When the manure is dry
   c) How does this change with variations in weather if at all?
      () Winter when wet, we bed and haul into stock pens.
      () Milk Barn goes to lagoon, weeping wall 1st to remove solids

3) What are your current manure management practices?

(ie managed composting, land application, on-site, hauled off)

() Local Farmers haul off manure in fall and winter/ Some composting it gets mixed but not fully composted.

4) What are the perceived issues with current manure management system (either in collection, treatment, or regulation), or goals for improvement?

() Need not to move it twice- to stockpile and then to load

How could these issues be addressed satisfactorily?

() Try to coordinate with a farmer to do that especially when manure goes to plowing areas to hold it in place.

II) Economic-specific questions for producers-

1) How much natural gas do you use on the farm or in the home/office for heating?
   a) Would like answer in units used/prices per unit/ or typical total bill across seasons
      () No, use propane
2) How much electricity do you use on the farm or in the home/office?
   a) Would like answer in units used/prices per unit/ or typical total bill across seasons
      () $10,000/ month up a little during summer months
3) Has your operation ever been involved in or may be at risk of a nuisance lawsuit (or a normal complaint) involving odor?
      () Never Neighbors are happy
   b) If yes, what was the outcome? (Management plan and/or settlement) –try to get order of magnitude of the settlement or costs associated with it.
      () Don't flush with water, keeps odors down, dust becomes a big issues from plowing.
   c) What do you estimate to be the like hood (probability) of this type of lawsuit occurring in the future?
      () LOW
4) Describe your water rights and/or how much do you pay per acre/foot?
      () City Water $4,000-5,000 / month
5) Do you currently have land allocated towards carbon trading (or have you in the past)?
      () Possibly helpful but doesn't think it will improve sustainability.
   b) If yes, what price do you receive per acre or per metric tone?
   c) How much would the price need to rise before you would be willing to engage in carbon trading? Recent prices have ranged from $0.10 to 6.00/metric tone.
      () Doesn't trust the politics
6) Are you located near a community natural gas pipeline? How far away is the distance if known?
      () There is one (a transmission line not a delivery line) goes right thru the property.

7) Open to Sampling?
      () He thinks so, was interrupted before question could be asked.

<u>Farm # 2</u>

1) **Technical questions for producers-**
2) How many of the following animals do you have?
   a) Lactating cows: *660 total*
   b) Dry Cows: *included in 660*

c) Steers?/ Bulls? : *None*

3) Manure Collection practices: *Dry Lot*
   a) What are you current manure collection practices, and with what frequency?
      () Harrowing and mounding

      - (i.e dry scrape, concrete scrape, vacuuming, flushing, etc.)

   b) When do you collect manure?
      () Clean mounds 1/yr, Haul for ~1/month onto rowed land in fall

   c) How does this change with variations in weather if at all?

4) What are your current manure management practices?
   () Scrape with tractor in barn goes to ceavent, hauled up. Pumped and hauled weekly.

   (ie managed composting, land application, on-site, hauled off)

   () No land application

4) What are the perceived issues with current manure management system (either in collection, treatment, or regulation), or goals for improvement?

   How could these issues be addressed satisfactorily?

   () Haul weekly from barn to neighbors, but it's a pain.

II) Economic-specific questions for producers-

1) How much natural gas do you use on the farm or in the home/office for heating?
   a) Would like answer in units used/prices per unit/ or typical total bill across seasons
      () Winter -$2000/ month heat water and parlor
      () In Summer $700-$800

2) How much electricity do you use on the farm or in the home/office?
   a) Would like answer in units used/prices per unit/ or typical total bill across seasons
      () $1,200-$1,300/month year round

3) Has your operation ever been involved in or may be at risk of a nuisance lawsuit (or a normal complaint) involving odor?
      () No lawsuits or nuisance complaints.
   b) If yes, what was the outcome? (Management plan and/or settlement) –try to get order of magnitude of the settlement or costs associated with it.
   c) What do you estimate to be the like hood (probability) of this type of lawsuit occurring in the future?

4) Describe your water rights and/or how much do you pay per acre/foot?

- () *~$700/ month*
- () *Cows on a well- pumped cost associated with in electric bill, use domestic water in barn for clean up*

5) Do you currently have land allocated towards carbon trading (or have you in the past)?
   a) If yes, what price do you receive per acre or per metric tone?
   b) How much would the price need to rise before you would be willing to engage in carbon trading? Recent prices have ranged from $0.10 to 6.00/metric tone.
      - () *Understands concept but doesn't know much about it*
6) Are you located near a community natural gas pipeline? How far away is the distance if known?
   - () *There is one directly on the farm*
7) Open to Sampling?
   - () YES

Farm # 3

1) **Technical questions for producers-**
2) How many of the following animals do you have?
   a) Lactating cows: *1300*
   b) Dry Cows: *120*
   c) Steers? *A few Babies*
3) Manure Collection practices: *Dry Lot and Free stall*
   - () *Flush with recycled water and then scrape*
   - () *Pretty thick and dirty water*
   - () *No management just sits*
   - () *Separator and settling basins prior to lagoon*
   - () *Haul in spring and fall to local farms, never fully evaporated.*

   b) What are you current manure collection practices, and with what frequency?
      - () *Been thinking about AD recently since algae project over, concerned about costs.*

      - (i.e dry scrape, concrete scrape, vacuuming, flushing, etc.)

      () Scraped weekly, (Every two days for heifers and dry cows)

   c) When do you collect manure?
      - () *Flushed 3 times per day / no mounds or accumulation*
   d) How does this change with variations in weather if at all?
      - () No change during the year, same every day
4) What are your current manure management practices?
   - () *Sell manure to local farmers (contracts etc.)*

(ie managed composting, land application, on-site, hauled off)

() Dry manure used for bedding including sawdust

() Compost dead animals, only due to permit process. (Dry manure is turned but not composted)

5) What are the perceived issues with current manure management system (either in collection, treatment, or regulation), or goals for improvement?
    - *() Issue with lagoon – solid mat, acts as a cover on top*
    - *() Inadequate solid separation*
    - *() Solids overload lagoon.*

How could these issues be addressed satisfactorily?

II) Economic-specific questions for producers-
1) How much natural gas do you use on the farm or in the home/office for heating?
    a) Would like answer in units used/prices per unit/ or typical total bill across seasons
        - *() Varies quite a bit $1,000-$1,500 / month a little less in summer*
2) How much electricity do you use on the farm or in the home/office?
    a) Would like answer in units used/prices per unit/ or typical total bill across seasons
        - *() $6,000 / month a little more in winter*
3) Has your operation ever been involved in or may be at risk of a nuisance lawsuit (or a normal complaint) involving odor?
    - *() Yes, complaints when 1st expanded the farm*
    b) If yes, what was the outcome? (Management plan and/or settlement) –try to get order of magnitude of the settlement or costs associated with it.
        - *() Made some changes: 1) filled in old lagoon, 2) Keep manure moving out 3) stopped flushing for a year but labor was enormous.*
    c) What do you estimate to be the like hood (probability) of this type of lawsuit occurring in the future?
        - *() Possible, would hate to declare victory*
        - *() Have not had any complaints lately.*
4) Describe your water rights and/or how much do you pay per acre/foot?
    - *() Have a well used for flushing in barn*
    - *() Also on city water $2,000/month*
5) Do you currently have land allocated towards carbon trading (or have you in the past)?
    a) If yes, what price do you receive per acre or per metric ton?
    b) How much would the price need to rise before you would be willing to engage in carbon trading? Recent prices have ranged from $0.10 to 6.00/metric tone.
        - *() To him on farm ground just bought up $1/acre*

() Inadequate to change farm practice

6) Are you located near a community natural gas pipeline? How far away is the distance if known?

   () Delivered directly to farm

7) Open to sampling?

   () Would be open to sampling wants to learn more.

Farm # 4

1) **Technical questions for producers-**

   () Doesn't like to participate in these things probably only would work on large free stall dairies financial viability a huge limitation 5/130 dairies in Co currently viable solar on free stall roofs or shades seems more promising didn't ask the survey questions

2) How many of the following animals do you have?
   a) Lactating cows
   b) Feed lots Cows
   c) Steers?
3) Manure Collection practices: *Dry Lot*
   a) What are you current manure collection practices, and with what frequency?

      - (i.e dry scrape, concrete scrape, vacuuming, flushing, etc.)

   b) When do you collect manure?

   c) How does this change with variations in weather if at all?

   3) What are your current manure management practices?

      (ie managed composting, land application, on-site, hauled off)

   () Land application and hauled off

4) What are the perceived issues with current manure management system (either in collection, treatment, or regulation), or goals for improvement?

   How could these issues be addressed satisfactorily?

II) Economic-specific questions for producers-

1) How much natural gas do you use on the farm or in the home/office for heating?
   a) Would like answer in units used/prices per unit/ or typical total bill across seasons
2) How much electricity do you use on the farm or in the home/office?

a) Would like answer in units used/prices per unit/ or typical total bill across seasons

3) Has your operation ever been involved in or may be at risk of a nuisance lawsuit (or a normal complaint) involving odor?
   a) If yes, what was the outcome? (Management plan and/or settlement) –try to get order of magnitude of the settlement or costs associated with it.
   b) What do you estimate to be the like hood (probability) of this type of lawsuit occurring in the future?
4) Describe your water rights and/or how much do you pay per acre/foot?
5) Do you currently have land allocated towards carbon trading (or have you in the past)?
   a) If yes, what price do you receive per acre or per metric tone?
   b) How much would the price need to rise before you would be willing to engage in carbon trading? Recent prices have ranged from $0.10 to 6.00/metric tone.
6) Are you located near a community natural gas pipeline? How far away is the distance if known?

Farm # 5

1) **Technical questions for producers-**
2) How many of the following animals do you have?
   a) Lactating cows*: 2,500*
   b) Feed lots Cows: *~500*
   c) Steers?
3) Manure Collection practices:
   a) What are you current manure collection practices, and with what frequency?

      - (i.e dry scrape, concrete scrape, vacuuming, flushing, etc.)

      () 12 pens, three times per day – slurry- mixed with straw and use for horse bedding also adds branched and wood chips.

      () Hoping that Hartland will come and will take his manure.

   b) When do you collect manure?
      () Piled and scraped or bedding as needed.
   c) How does this change with variations in weather if at all?
      () Hauled out in spring and mixed with slurry.

3) What are your current manure management practices?

   (ie managed composting, land application, on-site, hauled off)

() Yes, plus give it away has a hard time getting rid of the manure.

4) What are the perceived issues with current manure management system (either in collection, treatment, or regulation), or goals for improvement?

How could these issues be addressed satisfactorily?

() Relocate, improve composting practice and distribution to farmers.

II) Economic-specific questions for producers-

1) How much natural gas do you use on the farm or in the home/office for heating?
   a) Would like answer in units used/prices per unit/ or typical total bill across seasons
      () Propane
2) How much electricity do you use on the farm or in the home/office?
   a) Would like answer in units used/prices per unit/ or typical total bill across seasons
      () Doesn't know has to look up.
3) Has your operation ever been involved in or may be at risk of a nuisance lawsuit (or a normal complaint) involving odor?
      () Has received a few complaints
   b) If yes, what was the outcome? (Management plan and/or settlement) –try to get order of magnitude of the settlement or costs associated with it.
      () We try to be neighborly but we were here first.
   c) What do you estimate to be the like hood (probability) of this type of lawsuit occurring in the future?
      () Probably
4) Describe your water rights and/or how much do you pay per acre/foot?
      () #1 user of water in fort Collins/Loveland water district, all on city water.
5) Do you currently have land allocated towards carbon trading (or have you in the past)?
   a) If yes, what price do you receive per acre or per metric tone?
      () New to him does not know much about it.
   b) How much would the price need to rise before you would be willing to engage in carbon trading? Recent prices have ranged from $0.10 to 6.00/metric tone.
6) Are you located near a community natural gas pipeline? How far away is the distance if known?
      () Yes, 1 mile away
7) Open to Sampling?
      () *Can grad student come sample? "Did he vote for Obama? If he did, I don't want him on the place." Otherwise fine.*

On-Site Farm Assessments Guideline and Questionnaire

The Following outline was used to determine the equipment structure and guide conversions for the on-site farm assessments.

Farm Name:__________________________Contact Person:_____________ Contact Phone #________________Visit Date:_________ Visit by_______

General Information:

Renovations planned for the farm within future? ☐ No ☐ Yes Notes:

Total Number of Cattle: Feed Lot________ Dairy_________ Lactating___________ Non-Lactating_________ Calves__________

Equipment Checklist:

☐ Parlor ☐ Heating Equipment ☐ Cooling Equipment ☐ Solid/liquid Separator ☐ Harrow Maker ☐ Tractors

☐ Sprinkler Equipment (pens) ☐ Well ☐ Other Equipment of concern __________________________________

Equipment Description

Insert Make-Model-Serial

Equipment	Description	Make	Model #	Water use (units)
Heating				
Refrigeration				
Waste Water Equipment				
Other				

Manure Collection Method ☐ Picture of farms ☐ Does Manure collection change with time? Total Manure Production:___________________

Manure Collection Area	Description	# of cows on avg per area	Manure storage method	Manure Removal	Notes
Dry Lot					
Feed Lot					
Parlor					
Free Stalls					
Pastor					

Figure 44: Page 1 of the on-site farm assessment questionnaire

Building Name:________________________ Visit Date:_________

Economic Information

1. Gas Usage: (Natural Gas, Propane, Other): ($) ___________ (Units) ___________ Are you located near Gas Pipeline: (Y/N)
2. Water Usage: (Well, City, Other): ($)___________ (Units)_____________
4. Electricity Usage: ($)___________ (Units)__________
5. Describe your Water Rights: ____
6. Do you have any land allocated to Carbon Trading (Y/N)
7. Have any formal complaints been taken against the farm operations: (Y/N) description (outcome):________________________________

Challenges

1. What do you consider is the feasibility of Anaerobic Digestion of manure for your farm: ____________________________________
2. What are your biggest issue with manure management: ____
3. What in your opinion is biggest challenge for your farm in the next few years:____

Feed Stock

1. What is the amount of feed you use per day/month/year: ($)____________ (Units)_________________
2. What is the % concentration of feed constituents that you use? __________% _______________% ___________% ___________%

NOTES:

____
____
____
____
____

Figure 45: Page 2 of the on-site farm assessment questionnaire

APPENDIX E: EQUATIONS INVOLVED WITH FEASIBILITY TOOL

The feasibility tool uses several major equations in order to determine the output from the executive summary. These equations include: Methane production, manure production, electricity production and water requirements. The following appendix will outline each of these methods an detail the relevant equations involved.

Methane Production Equations

Over the course of the study it several methods for calculation the amount of methane produced per cow per day for a given type of digester was found to be applicable for the tool. It was determined that each method should be considered and then averaged among one another to determine a likely daily gas output from the digester.

Method One: Ohio Live Stock Manure Management Guide

The guide for livestock management is a collection of aggregated values collected from the Ohio livestock association. One portion of the table publishes the amount of total solids and volatile solids in pounds produced per day by a 1,000 lbs cow as shown in Table 23.

Table 23: Total and Volatile solids produced per day per 1,000 pound cow

Type of Cow	Total Solids (kg/day/1000)	Volatile Solids (kg/day/1,000)
Feedlot	3.44	2.68
Lactating Dairy Cow	6.98	5.93
Dry Dairy Cow	4.47	3.82

Once the amount of volatile solids per day is known this can be multiplied by the number of cows to find the total amount produced per day. It was then assumed that a typical digester would operate at %60 efficacy of converting the volatile solids directly to biogas. Applying the above ratio of biogas production to volatile solids amount yields approximately 6.3 m^3 of methane per day per 1,000 pound cow.

Method Two: Dairy Waste Anaerobic Digestion Handbook

The second method evaluated for methane production was the one outlined in the 2004 copy of the anaerobic digestion handbook. This method begins by assuming that the average volatile solids production per cow per day is approximately 8.0 lbs per day for lactating and dry dairy cows. The dairy waste handbook does not have a volatile solids estimate for feedlot cows so the Ohio study was used to determine an appropriate value. The next step in the process was determining the amount of volatile solids destruction. The dairy waste handbook is unique in that it considers the difference in technology performance when estimating the amount of expected gas production. Table 24 shows the volatile destruction percentages used for each technology as it related to the methane production.

Table 24: Retention times and Volatile Destruction % for each technology

Digester Technology list	Retention Time Days	VS% destroyed
Plug Flow	25	35.18%
Covered Lagoon	45	31.00%
Completely Mixed	25	50.75%
UASB	5	55.00%
Fixed Film	3	58.00%

The amount of methane is now found by multiplying the number of cows by a conversion factor for the rate of methane production (5.62 ft^3 of biogas per pound of volatile solids destroyed) and by the % VS destroyed.

<u>Method Three: Mass Natural Feasibility Study:</u>

The third evaluation for the amount of methane produce came from an empirically derive study as detailed in the Massachusetts natural feasibility study for anaerobic digestion implementation (2008) and from the source Steve Brunner at the Brendle Group. The estimate assumes that the total amount of methane produce is directly related to the content of the manure in question the considerations for methane production include fat, protein, glucose and cellulose.

Table 25 indicate the values associated with each constituent and its expected gas production per kilogram of volatile solids.

Constituent	Theoretical gas Potential (m^3 CH_4/kg VS)	Expected Decomposition %	Expected Gas Potential (m^3 CH_4/kg VS)	Biogas (m^3/kg VS)
Fat:	1.014	80%	0.811	1.248
Protein:	0.537	60%	0.322	0.496
Glucose:	0.373	95%	0.354	0.545
Cellulose:	0.415	30%	0.125	0.192

Table 25: Expected Gas Potential on a Fat/Protein/Glucose and Cellulose basis.

In addition to the above table another literature source was needed to confirm the average makeup of typical cow manure. The source used was the dairy waste handbook as it detailed the specific make up of average manure collected. Figure 46 represents the percent make up of volatile solids for cattle manure.

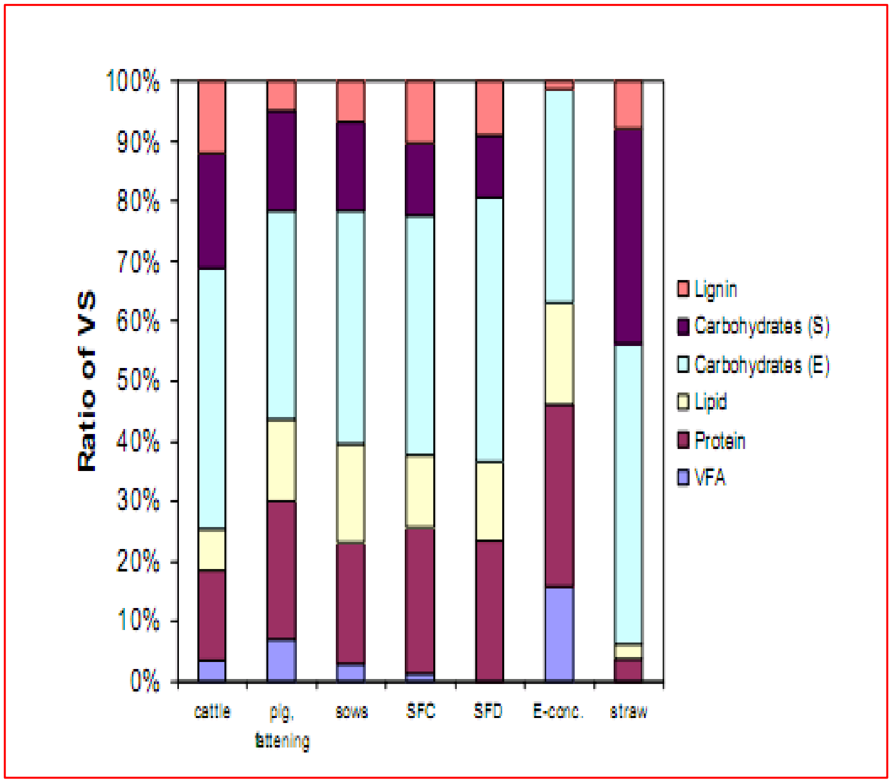


Figure 46: Average composition of VS in freshly excreted cattle manure.

Method Four: Farmware v 3.4 Methane production Estimates

Part of the project was determining what additional sources already existed for AD technology decision tools. One such tool is the EPA Agstar Farmware software. This software allows user to gain in depth understanding of AD feasibility, and also had a built in methane production estimation tool. In order to gather another data point for the amount of methane produce the equation involving in methane production were back calculated from the

Farmware software. Figure 47 and Figure 48 outline a step wise process of that analysis.

Main Equation

$$Y_v = \left(\frac{B_O * VS}{\emptyset}\right) * [1 - \left(\frac{K}{\emptyset * u_m - 1 + K}\right)]$$

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

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

K= kinetic parameter, dimensionless

Equation for Um

$$u_m = 0.013(T) - 0.129$$

Where: T is the temperature in °C

Equation for K

$$K_{dairy} = 0.8 + 0.016 * \exp(0.06 * VS_0)$$

Where:

VS_0= influent total volatile solids concentration per influent volume, kg/m^3

K_{dairy} less than or equal to 1.64

Figure 47: Outline of Equations associate with Farmware methane production estimates.

FARMWARE Methane calcs Step by step.

1.) Calculate the influent VS
    a. VS is in terms of (kg/m^3)
2.) Identify the B_0 Term
    a. Dairy = 0.304
3.) Define the hydraulic retention time
    a. Plug flow = 20 days
    b. Covered Lagoon = Climate Dependent
    c. Complete Mixed = 20 days
4.) Calculate the K value
    a. Using step one for VSo
5.) Calculate um
6.) Calculate the monthly methane production from the system:
7.) For Dairy operation 57.5% of biogas is considered to be Methane
8.) Estimate Biogas Btu production per month
    a. Btu per month= Methane per month (ft^3/month) *923 Btu/ft^3

Figure 48: Step wise process for determine methane production from farm ware tool

Once each of the methods is calculated the feasibility tool then takes the average of each of the methods to produce the final results. The relative methane production from a 1,000 cow dairy farm is shown in Figure 49 and illustrates how different each calculation can be. These values range from 2,000 m^3 per day to 171 m^3 per day of methane. The justification for the difference is that the mass natural feasibility study is based off of completely differing metrics than the farmware software, these difference can lead to significant changes in total methane production.

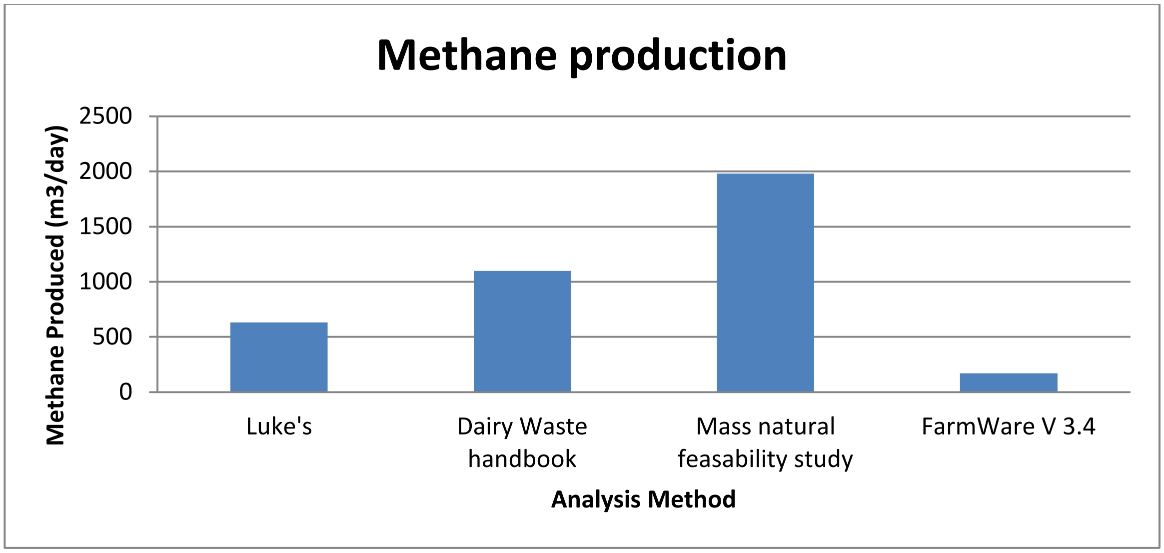


Figure 49: Relative Methane production from a 1,000 cow farm for each method.

Electricity Production Equations

In order to estimate the amount of possible electricity produce per day for an onsite AD system the following assumption were made.

- 35 % efficient gen-set
- 1,000 BTU per m^3 of biogas produced
- For each kBTU created 3.41 Kwh can be produced
- Gen–set has a 95% operational time per year

Manure production Equations

Similar to the methane production equations the amount of manure generated for on-site is averaged over three different methods. Each method is based off of fundamentally different parameters, the first method id a milk to manure correlation as provided by Steve Brunner at Brendle Group, the second is a correlation between the number of cows and manure production as provided by the anaerobic dairy waste handbook and the third is a feed to manure correlation as provided by chapter seven of the EPA manure handling guideline.

Milk to manure correlation

$$y=0.023x+0.931$$

Where: y = manure production in ft^3 / day

X = Milk production in lbs/day

Conversion for Milk production:

1 Gallons = 8.6 lbs

1 Ft^3 = 64.32 lbs

1 m^3 = 2271.86 lbs

In order to get total manure production in feet cubed per day take the total amount of milk produced apply an if statement such that each is converted to lbs/day. Then apply the above equation to result in manure production in ft^3 / day.

Number of cows to Manure production

Each type of cow has a different amount of total manure production per day.

Types of cows:

Lactating (Avg. Weight 1,200 lbs)

Dry (Avg. Weight 1,400 lbs)

Feedlot (Avg. Weight 1,000 lbs)

Heifers (Avg. Weight 700 lbs)

Manure Production for each cow type:

*Manure production (ft^3/day) = # Number of Lactating Cows * 1.47 ft^3 of manure * (Average cow weight / 1000)*

*Manure production (ft^3/day) = # Number of Dry Cows * 1.3 ft^3 of manure * (Average cow weight / 1000)*

*Manure production (ft^3/day) = # Number of feedlot Cows * 1.3 ft^3 of manure * (Average cow weight / 1000)*

*Manure production (ft^3/day) = # Number of heifers * 85 lbs of manure * 0.7 animal weight equivalency * (1/62.2) lbs to Ft^3*

Equation 12: Manure production based on type of cow

Each of the above equations can now be summed in order to find the total manure production per day as based by the number of cattle on site.

<u>Feed Conversion to total manure production</u>

$$Total\ Manure\ = Feed\ amount\ (lbs) * Total\ organic\ matter\ digestability\ (OMD) * (1 - Acivity\ Coeffiecnt\ (AC)$$

<u>Feed Conversions</u>

1 ton = 2,000 lbs

1 kg = 2.2 lbs

<u>OMD possible units</u>

Corn

Alfalfa

Hay

Grass

<u>OMD Unit conversions</u>

Corn = 73%

Alfalfa = 87%

Hay = 67%

Grass = 93%

Activity Coefficients possible units

Inside = 0

Outside = 0.17

Water Requirement Calculations

The following is a step by step process for determining the amount of water needed for an individual site based on the initial starting conditions of the manure, the manure collection process and the amount of total manure collected.

Where the Starting Conditions are:

V_{tot} = Volume of manure found see previous section 10.3

Total Solids % = As determined from feasibility analysis see section 2.9

Step 1 (As Excreted)

$$Bulk\ Density_{1} = IF\ TS_{1} < 16\ Than\ [= 998\ (1-(0.00345\ X\ TS_{1})\text{^}-1\ ]$$

$$TW_{1} = 1- (TS_{1}/100)$$

*Note**TW is total water percentage*

$$W_{tot1} = V_{tot1}\ X\ Bulk\ Density_{1}$$

$$\text{Weight of Manure}_{1} = W_{tot}\ X\ (TS_{1} / 100)$$

NOTE V_{tot1} *obtained from user input*

$$IF\ TS_1 > 16\ Than = [16.02\ (20.41 - (0.3648\ X\ TW_1) + (0.01972\ X\ TW_1\text{^}2) + (0.0.0001036\ X\ TW_1\text{^}3)-(0.000001304\ X\ TW_1\text{^}4) / 16.018)]$$

Step 2 (As Collected)

$$Weight\ of\ Manure_1 = Weight\ of\ Manure_2$$

$$Weight\ ofManure_2 = W_{tot}\ X\ (TS_2 / 100)$$

$$Volume_{tot2} = W_{tot2} / Bulk\ Density_2$$

$$Bulk\ Density_2 = IF\ TS_2 < 16\ Than\ [\ = 998\ (1-(0.00345\ X\ TS_2)\text{^}{-1}\ ]$$

$$TW_2 = 1-(TS_2 / 100)$$

$$IF\ TS_2 > 16\ Than\ = [16.02\ (20.41 - (0.3648\ X\ TW_2) + (0.01972\ X\ TW_2\text{^}2)+ (0.0.0001036\ X\ TW_2\text{^}3\ )-(\ 0.000001304\ X\ TW_2\text{^}4) / 16.018)]$$

$$Volume\ of\ Water_2 = Weight\ of\ Water / (62.2\ {*}lbs/ft\text{^}{3})$$

$$Weight\ of\ Water_2 = W_{tot2} - Dry\ Weight$$

Step 3 (As Treated)

$$Weight\ of\ Manure_2 = Weight\ of\ Manure_3$$

$$Weight_{tot3} = Weight\ of\ Manure_3 / TS_3\%$$

$$Volume_{tot3} = Weight_{tot3} / Bulk\ Density_3$$

$$Volume\ of\ Water_3 = Weight\ of\ Water_3 / (62.2\ {*}lbs/ft\text{^}{3})$$

$$Weight\ of\ Water_3 = Weight_{tot2} - Dry\ Weight$$

$$Bulk\ Density_3 = IF\ TS_3 < 16\ Than\ [\ = 998\ (1-(0.00345\ X\ TS_3)\text{^}{-1}\ ]$$

$$TW_3 = 1-(TS_3/100)$$

$$Else\ IF\ TS_3 > 16\ Than = [16.02\ (20.41 - (0.3648\ X\ TW_3) + (0.01972\ X\ TW_3\text{^}2) + (0.0.0001036\ X\ TW_3\text{^}3\ )-(\ 0.000001304\ X\ TW_3\text{^}4) / 16.018)]$$

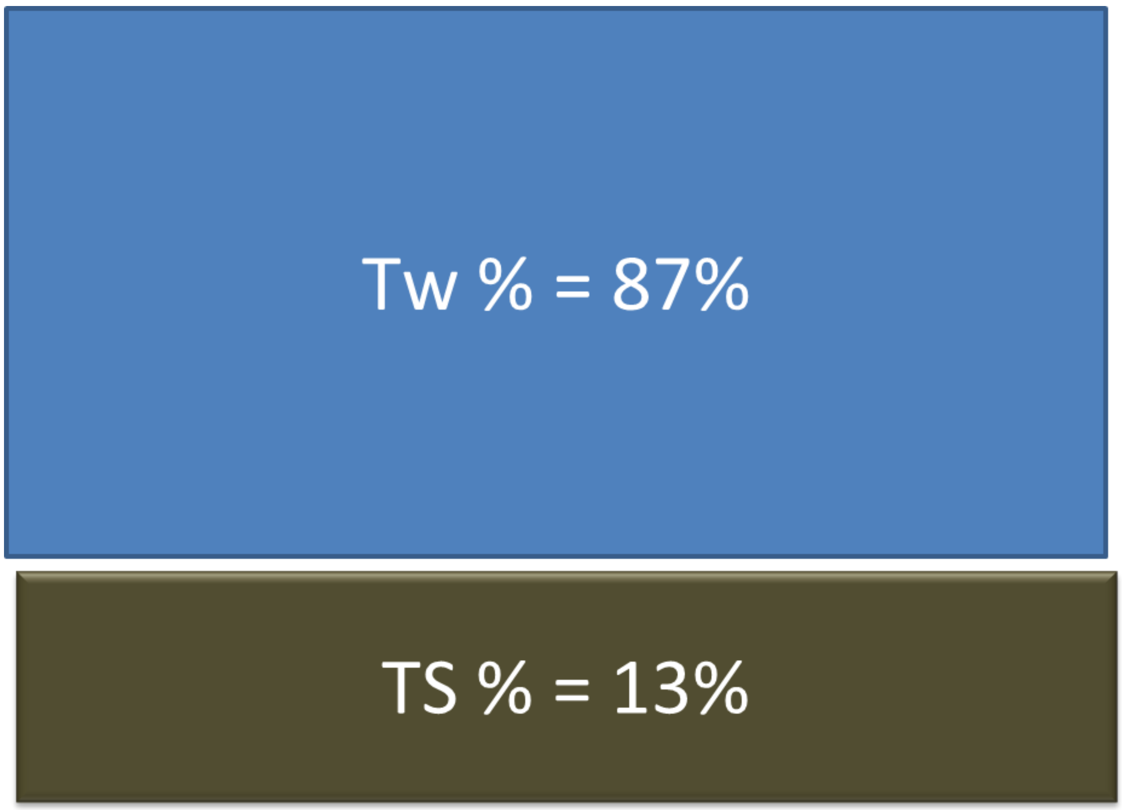
Step 4 (Water Cal)

Total Water Required = *Volume* $Water_3$ - *Volume* $Water_2$

*NOTE*IF Water Required is Equal to a Negative Value than 0

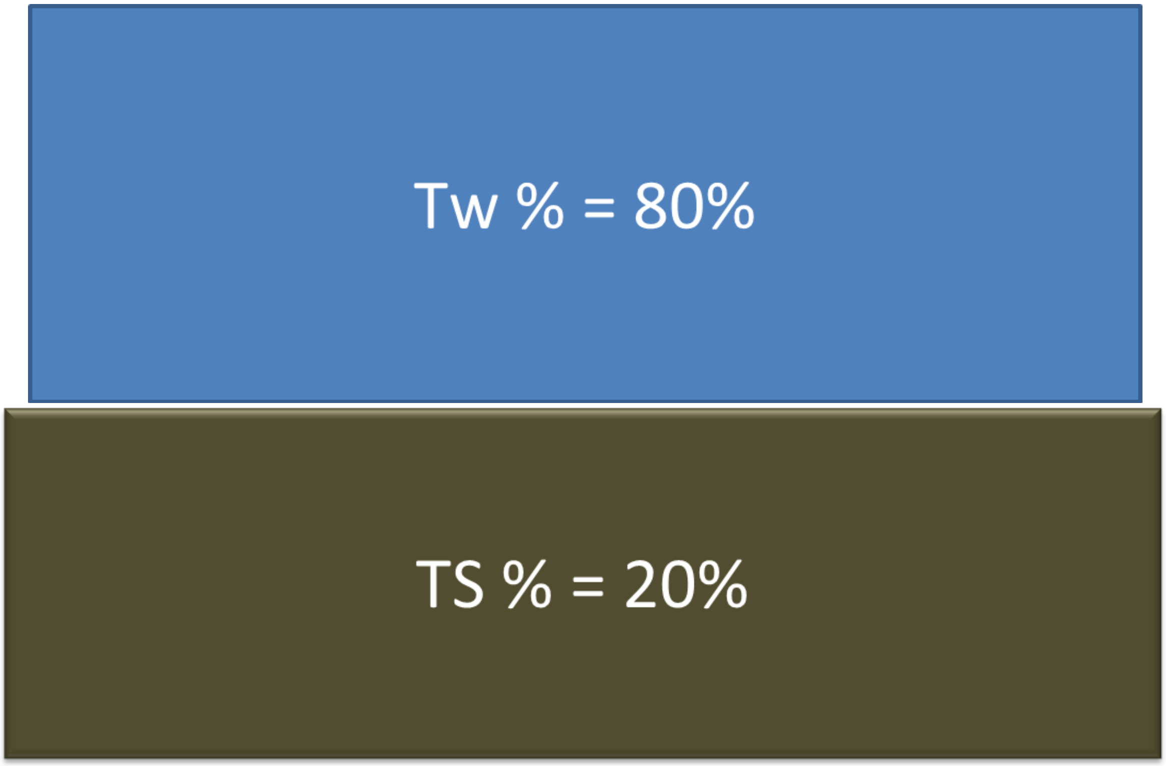
Visual Representation of Water Requirements

Manure as Excreted



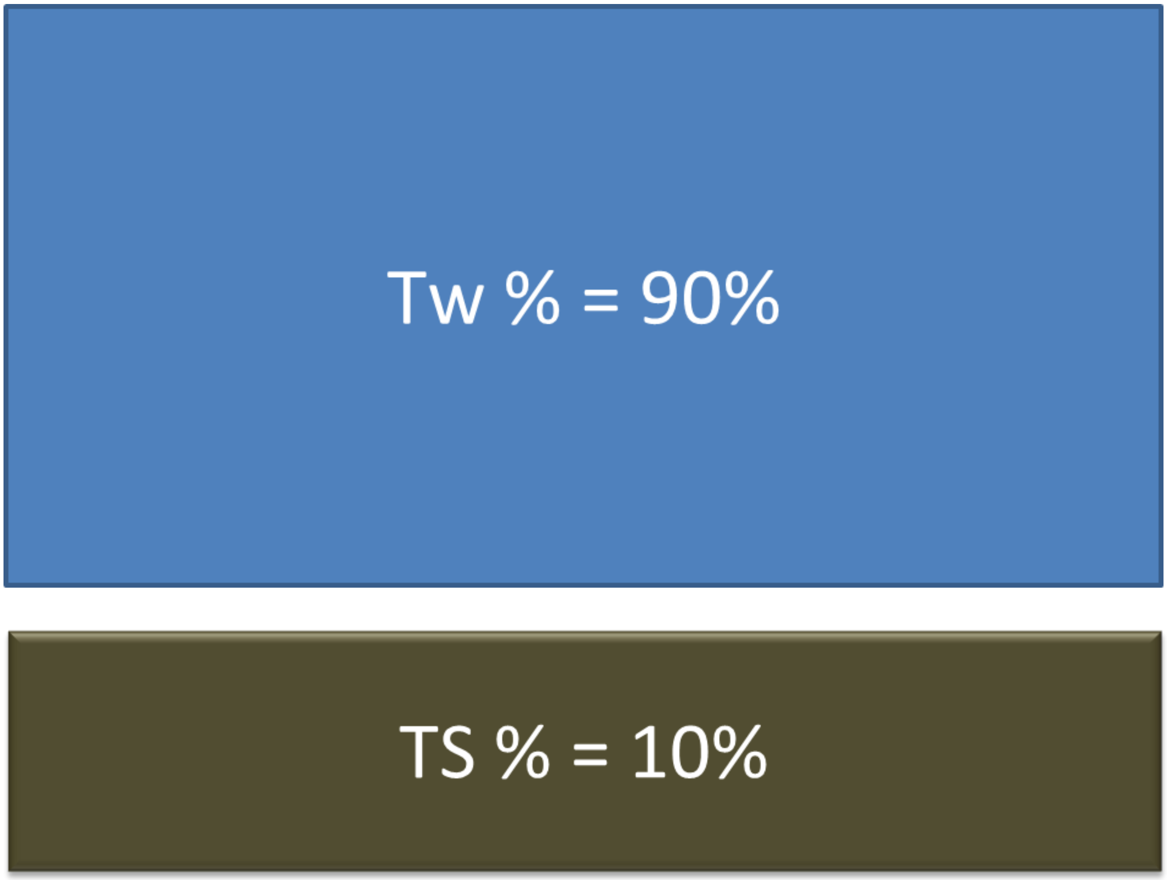
Data	Value	Units
TS%	13	%
TW%	87.00	%
Volume	2,058	ft^3
Bulk Density	65.22	lbs/Ft^3
Weight	134,240	lbs
Volume of Water	1,790	ft^3
Weight of Water	116,789	lbs
Weight of Manure (dry)	17,451	lbs
Volume of manure	268	ft^3

Manure As Collected



Data	Value	Units
TS%	5	%
TW%	95.00	%
Volume total	5,505	Ft^3
*Bulk Density	63.39	lbs/Ft^3
Weight	349,025	lbs
Volume of Water	5,331	ft^3
Weight of Water	331,574	lbs
Weight of Manure (dry)	17,451	lbs
Volume of Manure (dry)	275	ft^3

Manure As Treated



Data	Value	Units
TS%	3.00	%
TW%	97.00	%
Volume	9,240	Ft^3
*Bulk Density	62.95	lbs/Ft^3
Weight	581,709	lbs
Volume of Water	9,072	ft^3
Weight of Water	564,257	lbs
Weight of Manure (dry)	17,451	lbs
Volume of Manure (dry)	277	ft^3

Total Water Requirement Calculation

TW = 9,072 ft^3 - 5,331ft^3 = 3,741 ft^3

APPENDIX F: TERMS AND DEFINITIONS

Animal Units Equivalent (AUE) – For cattle the animal equivalent unit is description in the following equation

$$Animal\,Unit\,Equivalents = \frac{(Live\,Animal\,Weigth)^{0.75}}{1000^{0.75}}$$

Biochemical Oxygen Demand (BOD) – Is the amount of dissolved oxygen needed by aerobic biological organisms in a body of water to break down the organic material present in a given water sample.

Organic Matter Digestibility (OMD) – the measurements of the percentage of digestible organic matter per total dry weight. OMD changes according to the type of animal digesting the material and is determined by imperial testing.

Organic Matter (OM) - Any piece of matter that comes from once living organisms and is capable of decay or is the product of decay .

Total solids (TS) – The percent of solids which is left after the water for the material has been evaporated at 212 degrees Fahrenheit for at least 24 hours. Total solids are the reciprocal of moisture content .

Volatile Solids (VS) – The percent of solids left after the material has been incinerated at 550 degrees Celsius or 1022 degree F for more than one hour.