PG&E GAS R&D AND INNOVATION

Anaerobic Digestion Technical Analysis

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DEFINITION

A series of biological processes where microorganisms break down biodegradable material in the absence of oxygen to produce biogas and digested solids. The biogas can be used for electricity, heating, vehicles, and pipelines. The digested solids can be used as fertilizer.

EQUIPMENT

The anaerobic digestion system requires integrated tanks, mixers, covers, and heating systems. Digester tanks are typically constructed of concrete (precast or cast-in-place), stainless or carbon steel, and are internally coated with glass or painted epoxy. Typical microorganisms include fermenting bacteria, syntrophs, and methanogens.

DIFFERENT FEEDSTOCKS

Livestock manure, municipal wastewater solids (MWS), industrial wastewater, sewage sludge (biosolids), residuals, fats, oils, and grease. The basic AD process is the same for each feedstock. There might be slight modifications in the design.

BASELINE PROCESS DESCRIPTION

1) **Liquefaction/Bacterial hydrolysis** of feedstocks to break down insoluble long-chain organic polymers such as proteins, polysaccharides, fat and carbohydrates to produce simpler organic compounds such as peptides, saccharides, fatty acids, sugars and amino acids.
2) **Acidogenic** bacteria convert sugars and amino acids into carbon dioxide, hydrogen, ammonia, and organic acids.
3) **Acetogenic** bacteria turn the organic acids into acetic acid, and additional ammonia, hydrogen, and carbon dioxide. The main step is acid fermentation where no organic matter is removed, but rather converted to as substrate for the methanogenesis step.
4) **Methanogens** convert these products into methane and carbon dioxide by two groups of microbes known as acetoclastic and hydrogen-utilizing methanogens. The byproduct is a condensate liquid called digestate.

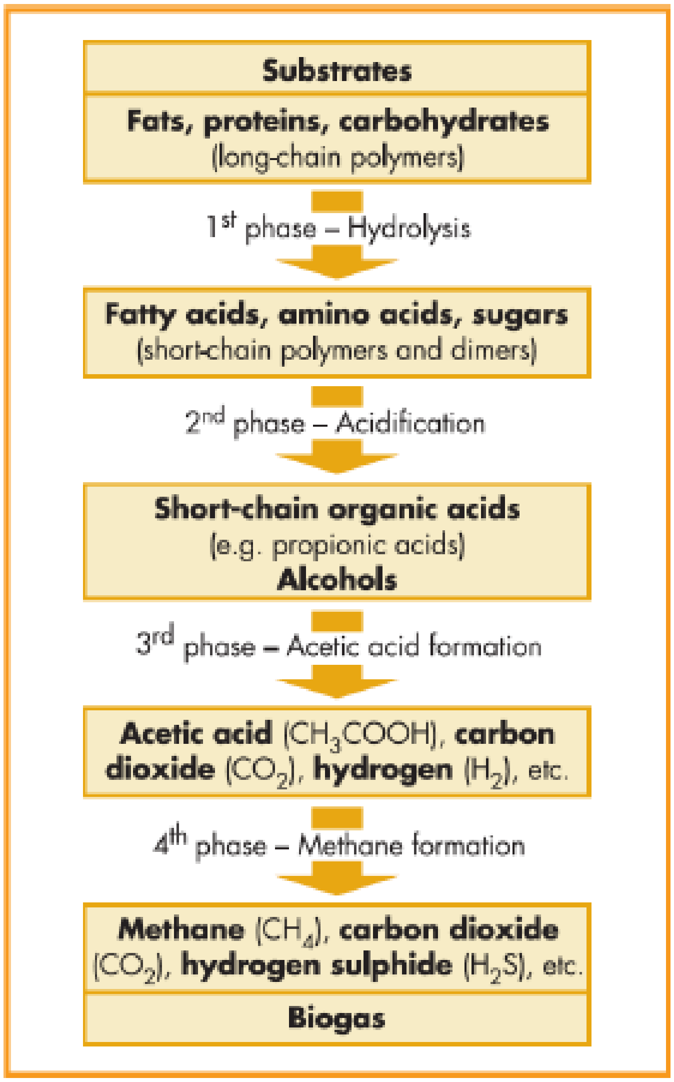

Figure 1: Anaerobic digestion flow chart (Chen, 2014)

OUTPUT

Biogas: Generated during the anaerobic digestion when microorganisms 'eat' the organic materials. It can be used for decentralized power and heat generation, for heat production by direct combustion, electricity production by fuel cells, or as a vehicle fuel. Typical breakdown (Williams, 2015):

50-75% Methane (CH_4)

25-45% Carbon Dioxide (CO_2)

2-7% Water (H_2O)

<2% Oxygen (O_2)

<2% Nitrogen (N_2)

<1% Ammonia (NH_3)

<1% Hydrogen Sulphide (H_2S)

<2% Trace Gases

Digestate: The material that is left over after the anaerobic digestion is a wet mixture that can be separated into a solid and a liquid. It is composed of water, minerals, nitrogen, phosphorus, potassium, and the build of the residual carbon from the original organic material.

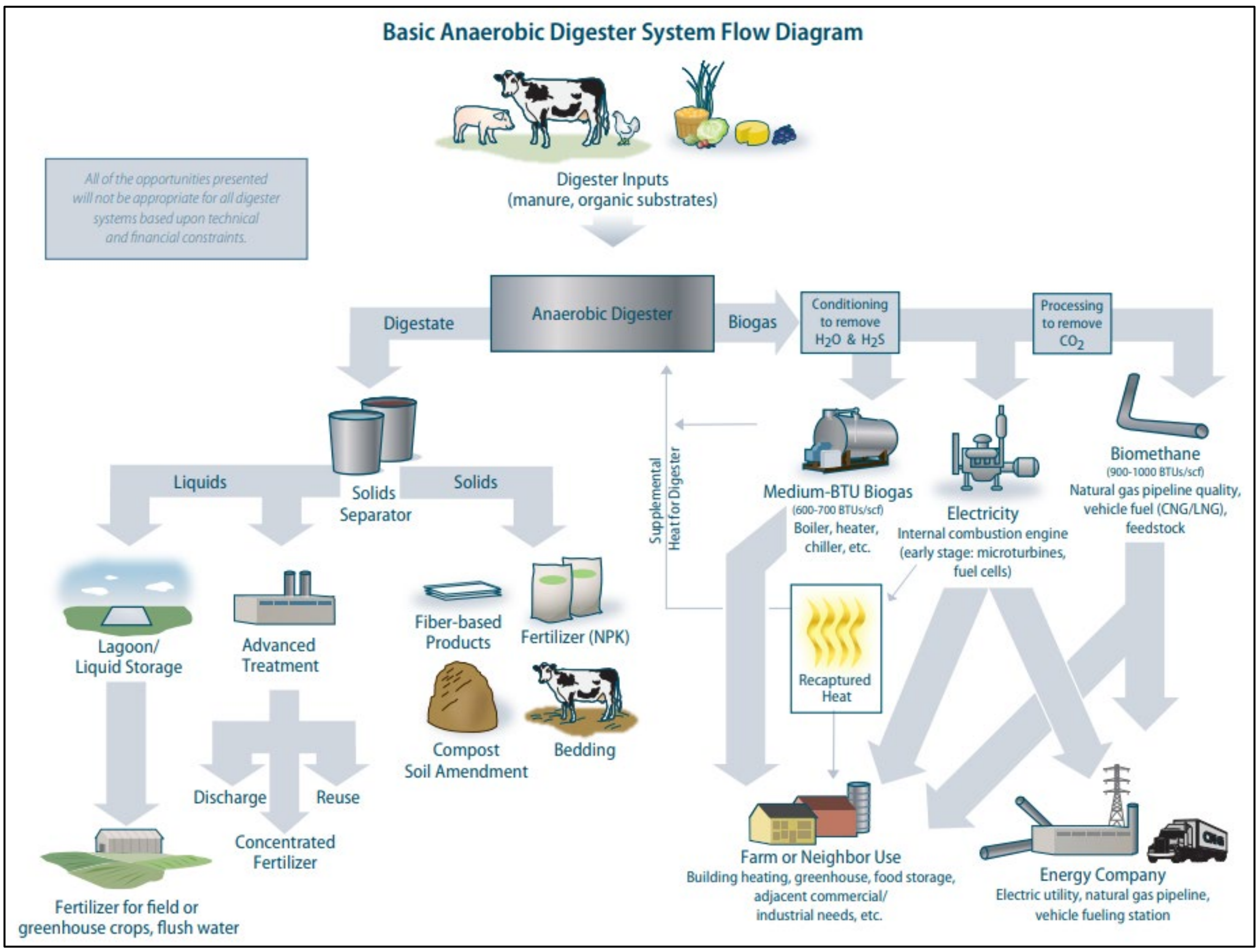

Figure 2: Anaerobic digestion process flow diagram

USES

- 85% of all anaerobic digestion used in electricity/cogeneration (20-30% energy efficient) (Banks, 2018)
- Biogas is captured from digester, scrubbed, and fed into an internal combustion engine. The internal combustion engine turns a generator which produces electricity.
- Sites utilizing cogeneration capture and reuse the heat created by the operation of the engine. Energy lost due to internal combustion engine heat loss is roughly 60% (Banks, 2018)
- Household and/or communities can use the biogas for water heating, cooking, and lighting.
- Medium-BTU fuel in on-site or adjacent furnaces, chillers, kilns, or boilers.
- If upgraded, the biogas can be used in vehicles or fed into distribution through natural gas pipelines.

ANAEROBIC DIGESTER VARIABLES

Single Stage vs. Multi-Stage Digester (USDA NRCS, 2007)

Single Stage System: All anaerobic process reactions take place inside a single reactor.

Pros: Cheaper to construct and operate.

Cons: Will not be optimal for the various trophic groups of microbes, lower gas production and organic conversion rate.

Multi-Stage System: Multiple reactors (usually two of them) are designed in series to optimize the process and enhance gas production.

Pros: Greater biological stability, greater ability to cope with fluctuations in feedstock type and amount, potential for higher output due to optimal conditions, higher volume reduction by volatile solids destruction, better odor control.

Cons: More complex requirements to control and operate, and higher capital costs.

Operating Temperature

Thermophylic (120-140°F) (EPA, 2018)

- Typical of large-scale digesters leading to higher efficiency. Reduces digester retention times to 3-5 days. Also requires more heat energy from external heat exchangers.
- Kill more pathogenic bacteria, but the cost to maintain a higher operating temperature is higher.
- This temperature develops “Class A Bio-solids” which is designated as dewatered and heated sewage sludge that meets US EPA guidelines for land application with no restrictions.

Mesophylic (95-105°F)

- Typically require digestion times longer than 20 days. Common for smaller, midsized operations.

Psychrophylic (60-75°F)

- Common for small-scale operations where production rates and retention times are less important. It is the least efficient system, but it is the simplest and least-expensive digester. Digestion slows down or stops completely below 60 or 70°F, so these digesters do not produce methane all of the time.

Wet vs. Dry

Whether an anaerobic digestion system is wet or dry is determined by the moisture content of the feedstocks. Wet digesters (low solids) generally have feedstocks with less than 15% solids content. It is more common to have a wet digestion system compared to a dry digester system. One of the advantages of having a wet digester is that the feedstock is usually in a slurry form, so it can be pumped for easier handling. Dry digesters (high solids) are systems that take in feedstocks greater than 15% solids content. (EPA, 2018)

Batch vs. Continuous Flow

An anaerobic digester can be either a batch flow or a continuous flow system. In a batch flow, the feedstock is loaded into the digester all at once, whereas for a continuous flow digester, the feedstock is constantly fed into the digester while digested material is continuously removed. For batch flow digesters, once a batch has been loaded, there is a set period of time for the digestion process to occur before the digester is emptied and reloaded with a new batch. (Lawson, 2018)

Hydraulic Retention Time (HRT)

The average amount of time that a given volume of sludge stays in the digester. It is a critical design parameter for anaerobic digesters.

- Typically, smaller digesters (lower capital costs) lead to shorter HRT.
- Shorter HRT also has the potential for not reaching the optimal results in biogas production, emissions of odor and GHG, chemical oxygen demand, total solids, volatile solids, and pathogens.

TYPES OF DIGESTERS

Plug Flow Digester

Plug flow digesters are long, narrow concrete enclosures with either a rigid or flexible cover that pushes manure from one end to the other as more manure is introduced on the front end. Common inputs include drier (11-13% solids content) and thicker organic matter such as manure. The final output is biogas, compost, and liquid digestate. Typical components include a mix tank, a digester tank with heat exchangers a biogas recovery system, an effluent storage system, and a biogas utilization system. One main benefit is the ability to optimize energy production in any climate. (AgStar, 2022)

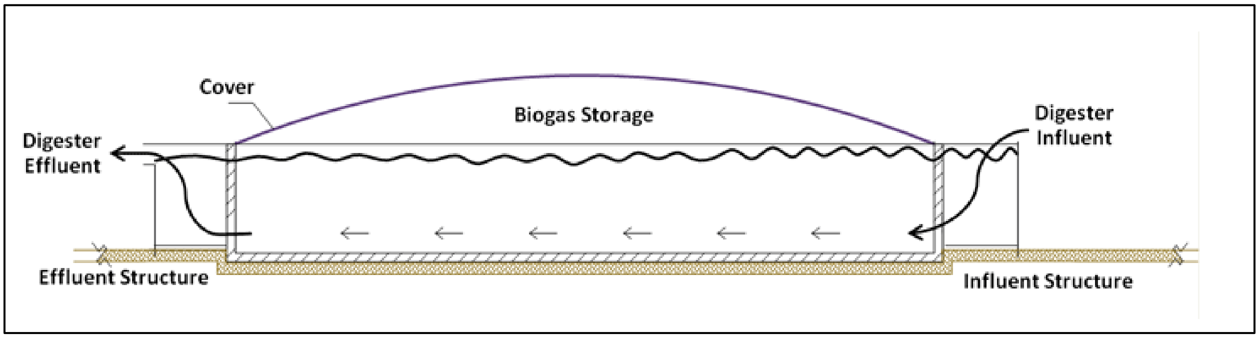

Figure 3: Layout of a plug flow digester

Complete Mix Digester

Complete Mix Digesters, typically constructed from steel or concrete, are technologically advanced systems designed to maximize the quantity and the quality of biogas that is produced. These are also known as continuously stirred tank reactors (CSTR). Some of the main benefits are biological stabilization of the effluent and odor control. The feedstocks, which are mainly slurry form, will be mixed with bacteria. The incoming feedstock will displace an equal amount of output. The typical components of a complete mix system are a sealed mix tank, a digester tank with mixing, heating and biogas recovery systems, an effluent storage structure, and a biogas utilization system. Dozens of complete mix digesters have been constructed globally.

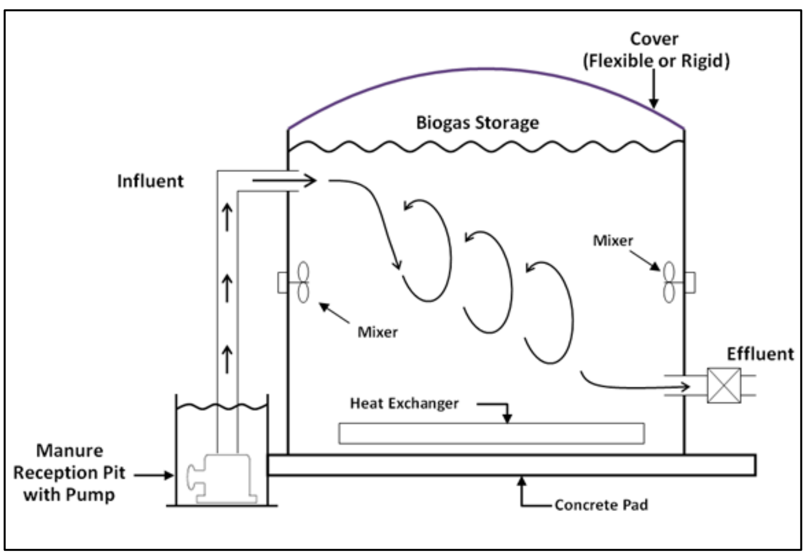

Figure 4: Configuration of a complete mix digester system

Covered Lagoon

Covered Lagoon anaerobic digesters produce biogas at ambient temperatures from diluted manure with less than 3% solids. In order to trap biogas, an impermeable cover floats on top of a lagoon filled with flush manure. These systems are typical in warmer climates. The components of the system include a solids separator, one or more lagoons, a floating lagoon cover, and a biogas utilization system. Often a variable volume one-cell lagoon designed for both treatment and storage will be utilized to recover biogas. A second lagoon can be used for variable volume storage to receive effluent from the primary lagoon and contaminated runoff which will be stored and used for irrigation, recycle flushing, or for other purposes. Dozens of covered lagoon anaerobic digestion systems have been implemented globally. Lagoon cover materials should be ultraviolet resistant, hydrophobic, tear and puncture proof, non-toxic to bacteria, and have a bulk density near that of water. (RCM Digesters, 2018)

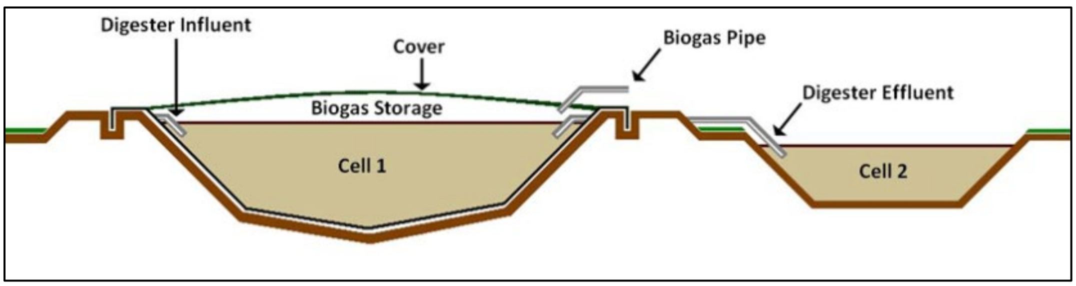

Figure 5: A covered lagoon system containing two cells

Up-Flow Anaerobic Sludge Blanket Reactor (UASB)

UASB reactors are also called "three-phase separators because they separate gas, water, and sludge mixtures under high turbulence conditions, which allows for cheaper and more compact designs. Extremely large gas/water interfaces reduce turbulence, making high loading rates of 10-15 kgm^3 possible. Substrate will pass through an expanded sludge bed which contains a high concentration of biomass. Then the substrate passes through a dense layer of biomass called the sludge blanket. The reactor has multiple gas hoods which allows for the separation of biogas.

The main objective of the design is to facilitate sludge return without the help of external energy. After the treated wastewater is collected by the effluent collection system via numerous launders distributed over the entire discharging area, the biogas generated will be collected as fuel output.

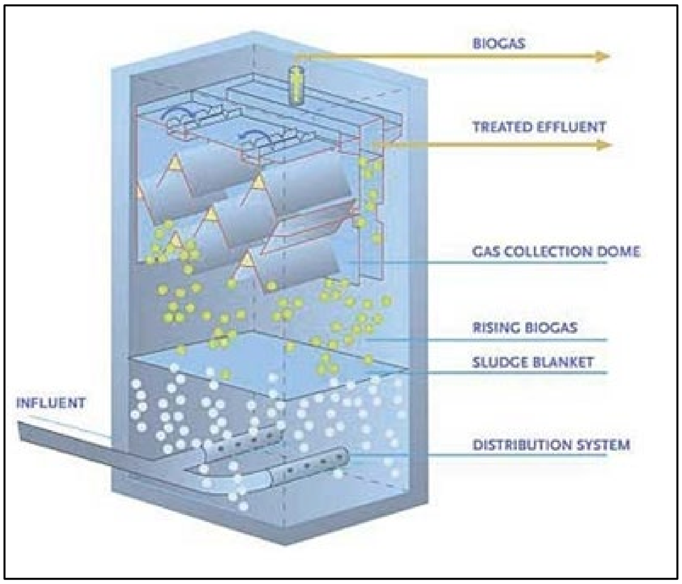

Figure 6: Diagram showing an up-flow anaerobic sludge blanket reactor

Fixed Film

Fixed film digesters are columns packed with media such as wood chips. Methane-forming microorganisms, called biofilm, grow on the media. Manure liquids pass through the media. Usually effluent is recycled to maintain a constant upward flow. There is a risk when using fixed film digesters because the manure can clog the media. For this reason, a solid separator will be needed to remove particles from the manure before feeding the digester. There is a direct correlation between the system efficiency and the efficiency of the solid separator. The system is most effective with manure with lower percent solids. Another downside is that when the manure solids are removed, some of the biogas potential is lost. (Lo, 1985)

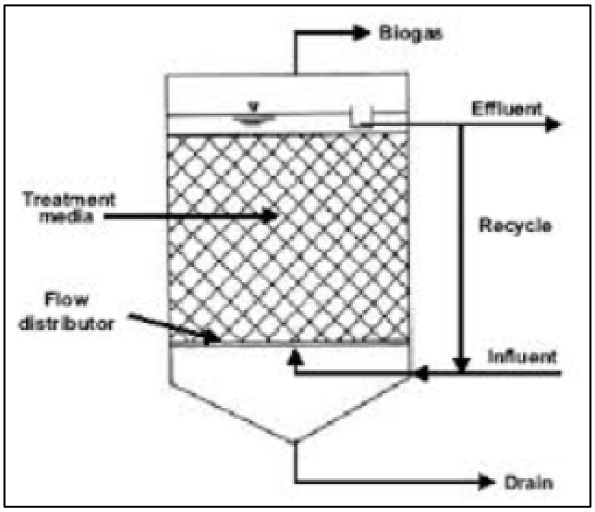

Figure 7: Design of a fixed film digester

Anaerobic Sequencing Batch Reactor

Anaerobic Sequencing Batch Reactors operate in a cycle with four main steps: feed, reaction, settling, and discharge (decant). Microorganisms are exposed to variable substrate concentrations over the duration of the cycle, resulting in high rates of substrate conversation and efficient biomass flocculation and settling. The cycles should be as frequent as possible, which is why operating in batches enables solids residence time to be independent of the hydraulic retention time. Typically, oxygen is bubbled through the mixture of wastewater and activated sludge to reduce the organic matter.

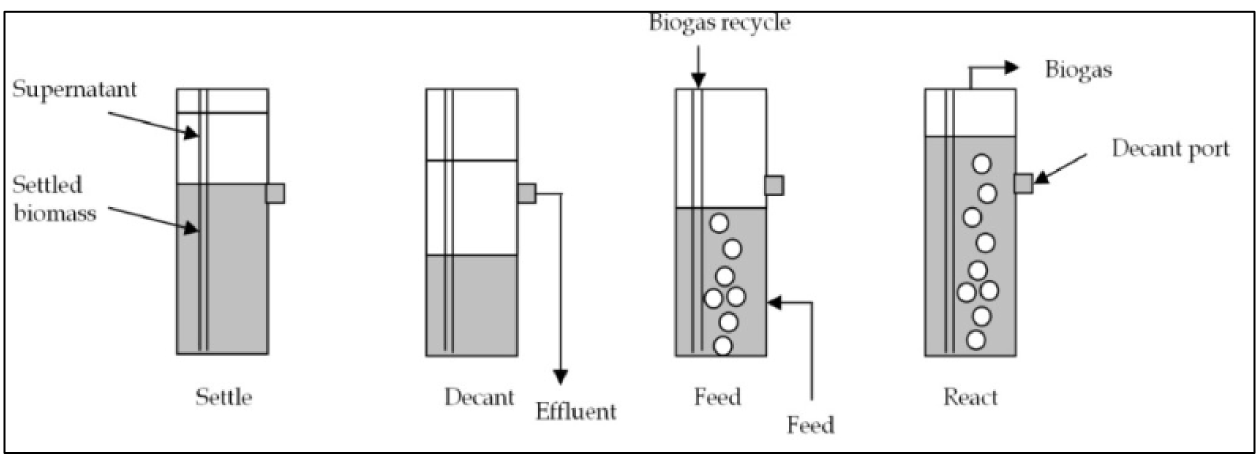

Figure 8 The main steps in the anaerobic sequencing batch reactor process

High-Solids Fermentation

High-solids fermentation typically uses a batch-style approach where waste material remains stationary during the anaerobic digestion process. Thus, there are no moving parts in the system, and the process can recover energy from numerous types of organic waste. Biomass is loaded into large fermentation chambers where it will remain for ~28 days (EPA, 2018). Biogas that is produced is collected in a flexible storage bag and then fed into a biogas utilization source.

Figure 9: An example of a high-solids fermentation facility (BIOFerm, 2018)

Table 1 Comparison of different types of anaerobic digester systems (EPA, 2018)

	Optimal Feedstocks	Percent Solids	Hydraulic Retention Time (HRT)	Co-Digestion	Temperature	Efficiency (VS reduced %)	% CH_4
Plug Flow Digester	Dairy manure	11-13%	15+ days	Not Optimal	Mesophilic or thermophilic	68 - 72	68
Complete Mix Digester	Diluted manure – slurry, other slurry organic wastes	3-10%	15+ days	Yes	Mesophilic or thermophilic	50	58
Covered Lagoon	Manure from flush/pit recharge collection systems	0.5-3%	40-60 days	Not Optimal	Psychrophilic	Not available	40 – 80 (dependent on temperature)
Up-flow Anaerobic Sludge Blanket (UASB) / Induced Blanket Reactor (IBR)	Consistent, homogenous waste streams, sewage sludge	>3% UASB 6-12% IBR	>5 days	Yes	Mesophilic or thermophilic	73 - 86	78
Fixed Film/Attached Media Digester/ Anaerobic Filters	Manure in temperate and warm climates	1-5%	>5 days	Yes	Mesophilic or thermophilic	60	62.1 – 69.3
Anaerobic Sequencing Batch Reactors	Diluted waste/ Manure in slurry form	2.5-8%	>5 days	Yes	Mesophilic or thermophilic	87	68.5 – 76.7
High-Solids Fermentation	High solids manure and other organic substrates (silages, food waste, distiller grains)	18%+	2-3 days	Yes	Mesophilic or thermophilic	71.6	59

PERFORMANCE/EFFICIENCY (FAN, 2017)

- Efficiency is typically measured by calculating the reduction of volatile solids after digestion. Varies between 20-70%
- Generally, for every 1 kg of waste that is converted by anaerobic digestion, 0.35 m^3 of CH_4 is produced. This equates to 12 x 10^6 BTU for every 1000 kg of waste material. This means that for solid wastes, concentrated manure, and high-strength wastewater, the potential biogas that can be produced will be much greater than the energy required for the process.
- One cubic meter of methane has the energy content of 9.97 kWh
- Methane production efficiency is roughly 50%. AD produces biogas with a methane content of 50-60% (but will depend on substrate)
- Biogas typically has a thermal value of 22 MJ m^{-3}, and methane has a thermal value of 36 MJ m^{-3}
- The energy conversion efficiency for anaerobic digestion can be limited due to the lignocellulosic composition during the hydrolysis process. The hydrolysis of biomass is highly energy inefficient within full-scale biogas digesters. They have tried to increase the energy conversion efficiency by applying pre-treatment, but the results have not shown that they increase the energy efficiency.

ECONOMICS

The capital cost to construct anaerobic digesters varies greatly depending on the type digester system. Each digester can be constructed with different capacities, so this will also have an effect on the overall cost of a given project. The operations and maintenance costs are typically consistent for different types of digesters and are between 2.3-7.0% of the capital costs.

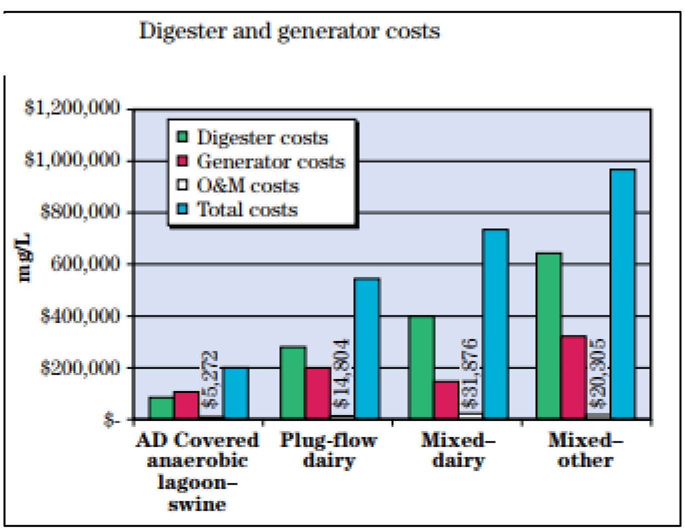

Figure 10: Approximate cost breakdown for various types of anaerobic digester systems (Fan, 2017)

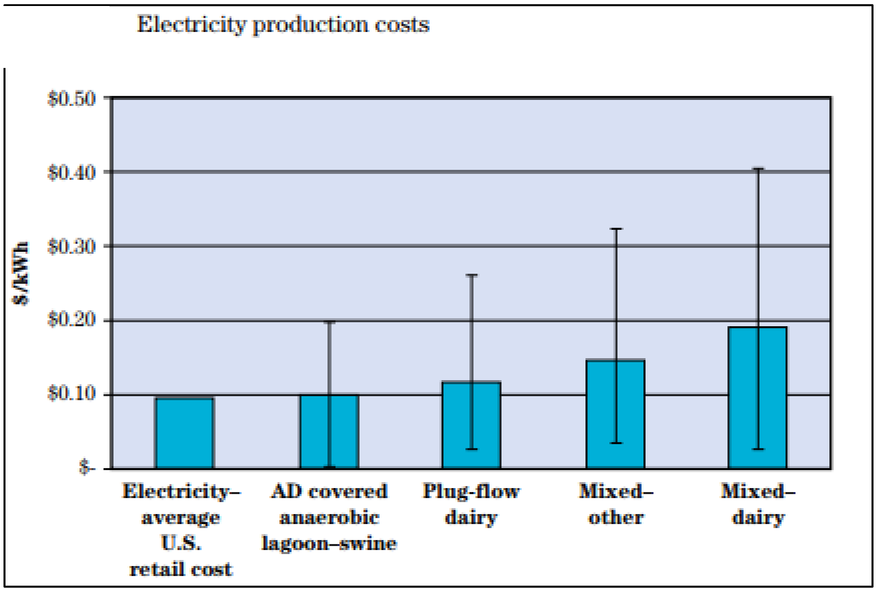

Figure 11: Comparison of electricity production costs for anaerobic digestion systems (Fan, 2017)

Table 2 Comparison of anaerobic digester costs to fossil fuels (Williams, 2015)

Biogas production costs for AD case studies that reported digester costs vs. U.S. average fossil energy retail costs

Manure AD system by species	Unit of measurement	Cost per unit ($)	Btu per unit*	$ per M Btu	$ per therm	$ per GJ	No. of observ.
AD Covered anaerobic lagoon—Swine	1,000 ft³	1.90	6.00E+05	3.17	0.32	2.99	1
AD Covered anaerobic lagoon—Dairy	1,000 ft³	2.40	6.00E+05	4.00	0.40	3.78	2
AD Mixed—Dairy	1,000 ft³	2.60	6.00E+05	4.33	0.43	4.08	1
AD—Other swine	1,000 ft³	3.52	6.00E+05	5.87	0.59	5.54	1
AD Plug flow—Dairy	1,000 ft³	4.33	6.00E+05	7.22	0.72	6.82	12
Natural gas	**1,000 ft³**	**11.60**	**1.03E+06**	**11.25**	**1.13**	**10.61**	
AD Mixed—Other	1,000 ft³	6.97	6.00E+05	11.61	1.16	10.95	1
Gasoline	**Gallon**	**2.22**	**1.25E+05**		**1.78**	**16.78**	
Diesel fuel	**Gallon**	**2.52**	**1.39E+05**	**18.17**	**1.82**	**17.14**	
Heating oil	**Gallon**	**2.46**	**1.29E+05**	**19.03**	**1.90**	**17.95**	
Propane	**Gallon**	**1.85**	**9.13E+04**	**20.26**	**2.03**	**19.12**	
AD—Other dairy	1,000 ft³	18.43	6.00E+05	30.72	3.07	28.98	1

* Average U.S. retail costs for natural gas taken from DOE EIA Natural Gas Summary, 2007

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