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An Analysis of Energy Production Costs from Anaerobic Digestion Systems on U.S. Livestock Production Facilities

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Preface

This technical publication reviews the potential of using manure anaerobic digestion (AD) systems on livestock production facilities to produce electricity or biogas to supply farm energy needs. An in-depth biogas production cost analysis is provided to assess the feasibility of utilizing an anaerobic digester for on-farm purposes.

The cost of electricity and biogas production using manure-based AD systems is presented based on an analysis of 38 installations in the United States. Both electricity and biogas costs from these systems were compared to the current U.S. cost of electricity, natural gas, and liquid propane (L.P.) in dollars per gigajoule of energy content. This analysis shows that AD system capital cost can be reduced by approximately 36 percent if no electrical generation system is installed. The economic advantage of using biogas at the point of generation is more apparent in remote locations where the costs of natural and L.P. gas are higher than standard markets. The cost analysis presented in this document suggest that lower cost AD systems currently employed on United States farms can provide biogas that is competitive or lower in cost than current United States commercial natural gas prices, if the biogas is used directly on site in space heaters or boilers without excessive additional gas upgrading (cleaning and conditioning) costs. Producers interested in manure AD systems should evaluate the potential of using biogas produced on site as an on-farm energy source alternative (e.g., heating water, heating animal housing, etc.) to generating electricity.

Lastly, general information relevant to AD system functionality, biogas production computations, and on-farm biogas use is provided for the landowner.

Acknowledgments

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I. Introduction

Anaerobic digestion (AD) is a natural process that converts a portion of the organic carbon in manure into methane (CH_4) and carbon dioxide (CO_2). Primary benefits of anaerobic digestion of manure include substantial odor reduction, production of a renewable energy source (biogas), reduction of greenhouse gas (GHG) emissions, and potential pathogen reduction in manure. Biogas produced from the AD of manure can be used for heat production to power generators or micro-turbines to generate electricity, or simply flared. Other direct use biogas options include cooking, cooling, and lighting (Balsam 2002).

While the authors estimate that more than 100 AD systems have been installed in the United States over the last two decades, it is difficult to obtain an accurate count of systems that are currently operating successfully. The installation of the majority of AD systems has been subsidized through assistance from the U.S. Department of Agriculture (USDA), U.S. Environmental Protection Agency (EPA); U.S. Department of Energy (DOE); and various state incentive programs. Historically, the failure rate for manure AD systems in the United States has been as high as 50 percent (Lusk 1998). Renewed interest in AD over the past 5 years has led to a number of vendors marketing systems that may have a higher potential for success.

Given the capital cost of AD systems relative to the cost of traditional manure management systems in the United States, digester technology is typically adopted by larger animal feeding operations (AFO). Despite lessons learned and recent technology advancements, the knowledge and funds needed to construct and install an AD system can seem out of reach for many producers. This coupled with the fact that many AD systems are unable to recoup the installation and operation costs through the sale of electricity has resulted in relatively low installation rates.

This technical note proposes using AD systems that directly use the biogas produced on site and do not include electricity generation. These simplified systems are less costly to install and maintain compared to systems that generate electricity. The target audience for this technical note is producers inquiring about the efficiency and practicality of AD systems for livestock operations. The economic analysis conducted for this publication does not include feedstock and digester effluent transportation costs. The technical note does not address the economics of centralized digesters where biomass is collected from several farms and then processed in a single unit.

II. Current status of anaerobic digestion technology in the United States

The limited long-term success of manure AD systems in the United States has been attributed to poor system design, improper system installation, and unsatisfactory system management (Lusk 1998). Drawbacks of AD systems include substantial capital costs, management and technical expertise needed to operate digesters, and potential safety issues with handling flammable biogas (Jones, Nye, and Dale 1980). Accurate data concerning the number of operating AD systems and the failure rate of these systems are difficult to obtain. For example, the AgSTAR Guide to Operational Systems reports 40 operating digesters as of 2002, including five digesters in Iowa (EPA 2007). However, only one dairy plug-flow digester constructed in 2004 is still in operation in Iowa, with the remaining four facilities having ceased operation prior to 2004 (Burns 2007). In many cases, AD systems that are no longer operational did not fail (defined as ceasing to operate) because of technology shortcomings, but because the farmer was unwilling to continue operating the AD system given the system operation and maintenance costs, whether they are experienced as a direct out-of-pocket cost or in the form of time demands on the farmer.

Data analyzed through 1998 indicates that the risk of having a U.S. farm-based AD system fail is approximately 50 percent (Lusk 1998). According to this same data set, the more complicated the AD system design, the higher the probability for failure; for example, a complete-mix system has a 63 percent failure rate, and a covered lagoon digester has a 12 percent failure rate. The reasons for digesters to cease operation were not reported on an individual basis by Lusk (1998). Other renewable energy systems have also had large numbers of systems that ceased to operate. For example, nearly 30 percent of biomass burning power plants built since 1985 are currently no longer in operation (Peters 2007).

The AgSTAR Digest Winter 2006 edition reports the number of installed manure digesters doubled from 2004 to 2006 (EPA 2006). No analysis is currently available that reports the success rates of manure AD systems since 1998. An analysis of manure digester numbers and status with the depth of the Lusk (1998) work has not been conducted for the period from 1998 to the present. It is possible that a higher percentage of manure AD systems constructed after 1998 are still in operation. Additionally, the AgSTAR Digest reports that "the success rate of installed systems has been extremely high." However, since many of these systems are supported by grant funding for a 2- to 3-year period, the time when systems would most likely cease operations is after the end of the financial support. It will be important to track the success rates of these systems over a longer period. In an effort to better analyze the performance of AD systems, *A Protocol for Quantifying and Reporting the Performance of Anaerobic Digestion Systems for Livestock Manures* was released and recommends a standard approach to evaluate and quantify AD system performance (Martin 2007). The AgSTAR program also provides assistance with its FarmWare 3.0 software, an analytical tool designed to provide a preliminary assessment on the benefits of integrating anaerobic digestion into an existing or planned dairy or swine manure management system. Additionally, the University of Minnesota has completed a tool to assist producers with initial calculations of annual costs and returns to be expected from owning and operating a methane digester on a dairy farm (*http://www.apec.umn.edu/faculty/wlazarus/tools.htm*).

While many U.S. producers hesitate to adopt AD systems, internationally, millions of small-scale anaerobic digesters have been implemented in rural landscapes across China, India, and Vietnam to provide biogas for direct use (An 2002). These countries are able to operate small digesters profitably due to their relative costs of labor and energy. Looking to our global counterparts and their success in using small anaerobic digesters to provide light and heat for multiple households in agrarian settings, it suggests the possibility that the direct use of biogas on site could provide an avenue for livestock operations to profitably implement AD systems on their operations. The numbers of AD systems installed in the United States, specifically on small- and medium-size animal operations, could grow substantially if AD systems capable of providing biogas as a lower cost alternative to natural gas are selected and implemented.

AD systems could also play a more prominent role in the manure management arena if their potential to mitigate global warming was fully explored and publicized. Biogas can range from approximately 55 to 80 percent CH_4, but biogas generated from animal manures is typically around 65 percent CH_4. The amount of CH_4 generated depends on the livestock type, frequency of waste collection, waste handling method, and climate. The biogas is flared (fig. 1) or used to produce heat or power. Either option reduces CH_4 emissions, the second most important GHG. CH_4 is 23 times more potent than CO_2 as a GHG.

III. Evaluation of manure-based biogas production costs

A database was compiled from case studies published in Kramer (2002), Lusk (1998), Lusk (1995), and Wright (2003). The 38 AD systems were grouped by digester configuration and manure type. Data from covered anaerobic lagoons, plug-flow digesters, and continually stirred tank reactors (mixed digesters) was included in the analysis. Three facilities did not fall into these categories and were included as "other." One of the facilities listed as "other" used an anaerobic sequencing batch reactor (ASBR) for swine waste. The remaining two facilities listed as "other" utilized an upflow sludge blanket reactor (UASB) and fixed-film for dairy waste treatment. Tables showing basic information for each facility are in appendix A.

Figure 1 Biogas flare

Capital costs

Review of the AD systems indicates that approximately 36 percent of the total capital cost is associated with electrical generation equipment. The average cost of digester construction, costs associated with electrical generation, and total costs for the 38 systems are provided in figure 2. All costs were converted to 2006 dollars using the Engineering News-Record (ENR) Construction Cost Index. Annual costs were determined assuming a 10-year lifespan with 8 percent interest.

The costs related to electrical generation as a percentage of the total system cost for covered anaerobic lagoons is a higher percentage than that reported for other types of digesters given the lower capital costs for lagoons compared to other digester types. Initial capital costs of electrical generation equipment ranged from $114,000 to $326,000 for the 38 case studies reviewed for this publication. In addition, the majority of the operation and maintenance (O&M) costs associated with farm AD systems is associated with the electrical generation equipment (Kramer 2002). The cost to produce electricity from the 38 case studies is presented in table 1.

The cost to produce electricity includes annualized capital costs for the digester, generator, and O&M costs. If O&M costs were not reported, they were estimated using the average O&M costs for other digesters of a similar type and species that were reported unless otherwise noted.

Figure 2 Digester and generator costs

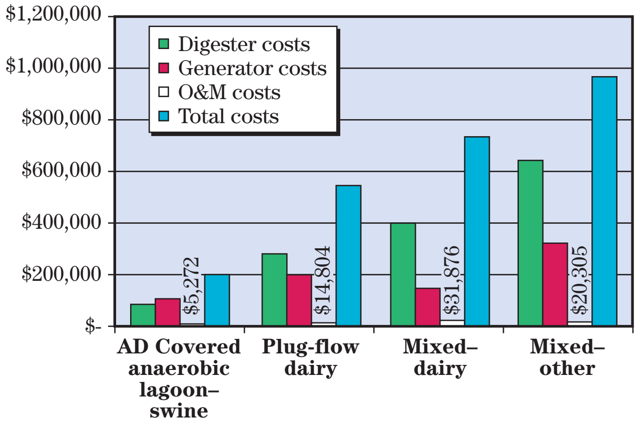


Table 1 Electricity production costs for AD case studies vs. average U.S. retail electricity cost

Manure anaerobic digester type by species	$/GJ	$ per kWh	No. of systems*	$/GJ O&M	$ per 1000 kWh O&M
Covered anaerobic lagoon—Dairy	12.59	0.05	2 (2)	1.06	3.82
Mixed—Swine	20.11	0.07	2	0.80	2.90
Electricity—average U.S. retail cost	**25.88**	**0.09**			
Other AD—Swine	27.16	0.10	1	2.09	7.57
Covered anaerobic lagoon—Swine	30.45	0.11	6 (1)	2.69	9.74
Plug-flow—Dairy	34.82	0.13	18 (10)	1.61	5.82
Mixed—Other species	40.05	0.14	2 (2)	1.81	6.55
Mixed—Dairy	52.39	0.19	4	3.54	12.79
Other AD—Dairy	139.55	0.50	2 (1)	12.07	43.64

* Average U.S. retail costs for electricity taken from DOE EIA (2007).
* A thermal efficiency of 30 percent was assumed for biogas to electrical energy conversion.
* When not reported, biogas production was estimated based on animal type and number. The number of systems that biogas production was estimated for are shown in parenthesis in the number of systems column.
* Biogas production for these systems was calculated on a theoretical basis and may not be representative of actual biogas production values on these farms.

O&M percentages are shown in table 2. Covered anaerobic lagoon—Dairy did not report O&M costs, so the O&M percentage from Covered anaerobic lagoon—Swine was used. Other AD—Swine did not report O&M costs, so the O&M percentage from Other AD—Dairy was used.

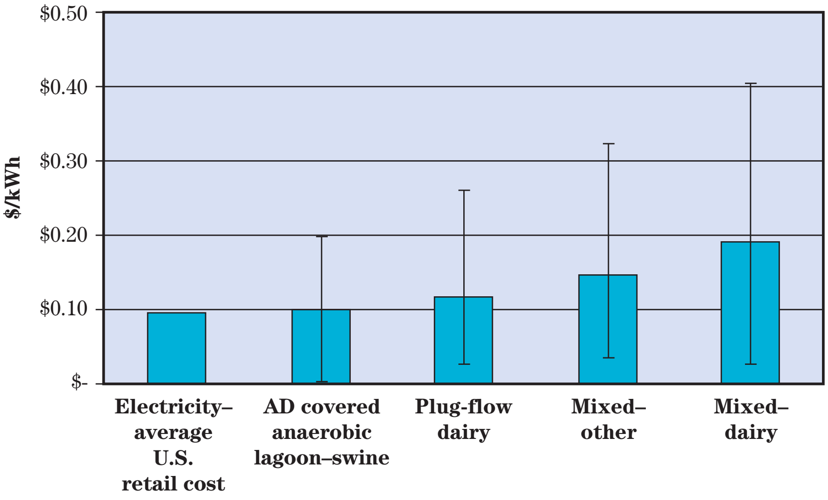
When available, biogas production was taken from the case study information. A thermal efficiency of 30 percent was assumed for biogas to electrical energy conversion (Jewell et al. 1997). Using this approach, the cost of electrical production from AD systems ranges from $0.05 to $0.50 per kilowatt hour. These costs suggest that the production of electrical power from an AD system to sell back to the utility company at a typical wholesale power rates hour would not be economically feasible. A review of the 2002–2005 wholesale power rates indicates a rate range from $0.02 to $0.06 per kilowatt (DOE EIA 2007c). Based on the DOE Energy Information Administration (EIA) reported average 2006 commercial electricity rate of $0.09 per kilowatt hour, the use of on-farm-generated electricity as cost-avoidance may or may not be feasible depending on the location and digester type in question (DOE EIA 2007b).

It should be noted that the values in table 1 shown for Covered anaerobic lagoons—Dairy ($0.05 per kilowatt hour) are based on limited data. Information from two case studies was available, but neither included biogas production data. As such, biogas production for these systems was calculated on a theoretical basis and may not be representative of actual biogas production values on these farms. Because of this, the confidence in the $0.05 per kilowatt hour value for anaerobic dairy lagoons is limited. The cost data for 2006 adjusted AD systems without the two outlying costs ($0.05 per kilowatt hour and the $0.50 per kilowatt hour dairy facilities) is shown in figure 3. The standard error bars added to the chart in figure 3 show one standard deviation of each data set mean.

Table 2 O&M costs shown as a percentage of total capital costs

Manure anaerobic digester type by species	% O&M cost of the total capital costs (digester and generator)
Covered anaerobic lagoon—Dairy	5.8
Covered anaerobic lagoon—Swine	5.8
Plug flow—Dairy	2.4
Mixed—Dairy	7.0
Mixed—Swine	2.3
Mixed—Other species	3.3
Other AD—Dairy	5.2
Other AD—Swine	5.2

Figure 3 Electricity production costs



The case study evaluation indicates that producing energy from swine facilities can be achieved at a lower cost than from dairy facilities. This is most likely due to the fact that the swine manure typically has a higher chemical oxygen demand (COD) to CH_4 conversion rate than dairy manure. The cost of electricity on a kilowatt-hour basis for the data where reported biogas production numbers were available is shown in table 3. Evaluating only the facilities with reported biogas production numbers decreases the cost of producing energy for plug-flow—dairy systems from \$0.13 per kilowatt hour to \$0.09 per kilowatt hour and Covered anaerobic lagoon—Swine from \$0.11 per kilowatt hour to \$0.09 per kilowatt hour.

Using a similar analytical approach, the cost for producing biogas from AD systems was calculated where the cost of the digester and generator components could be separated (table 4). Biogas production costs range from \$2.99 to \$28.98 per gigajoule (GJ). Note that the lowest cost option (AD Covered anaerobic lagoon—Swine) and the highest cost option (AD —Other dairy) are both based on a limited number of observations and should be used with caution.

Table 3 Electricity production costs for AD case studies with reported biogas production

Manure AD system type by species	$/GJ	$ per kWh	No. of systems	$/GJ O&M	$ per 1000 kWh O&M
Mixed—Swine	20.11	0.07	2	0.80	2.90
AD covered anaerobic lagoon—Swine	25.62	0.09	5	2.09	7.57
Plug flow—Dairy	25.78	0.09	9	2.69	9.74
Electricity	**25.88**			–	–
AD—Other swine	27.16	0.10	1	1.61	5.82
Mixed—Dairy	52.39	0.19	4	3.54	12.79
AD—Other dairy	79.33	0.29	1	12.07	43.64

* Average U.S. retail costs taken from DOE

* A thermal efficiency of 30 percent was assumed for biogas to electrical energy conversion.

Table 4 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 ft^3	1.90	6.00E+05	3.17	0.32	2.99	1
AD Covered anaerobic lagoon—Dairy	1,000 ft^3	2.40	6.00E+05	4.00	0.40	3.78	2
AD Mixed—Dairy	1,000 ft^3	2.60	6.00E+05	4.33	0.43	4.08	1
AD—Other swine	1,000 ft^3	3.52	6.00E+05	5.87	0.59	5.54	1
AD Plug flow—Dairy	1,000 ft^3	4.33	6.00E+05	7.22	0.72	6.82	12
Natural gas	**1,000 ft^3**	**11.60**	**1.03E+06**	**11.25**	**1.13**	**10.61**	
AD Mixed—Other	1,000 ft^3	6.97	6.00E+05	11.61	1.16	10.95	1
Gasoline	**Gallon**	**2.22**	**1.25E+05**		**1.78**	**16.78**	
Propane	**Gallon**	**1.66**	**9.13E+04**	**18.17**	**1.82**	**17.14**	
Heating oil	**Gallon**	**2.46**	**1.29E+05**	**19.03**	**1.90**	**17.95**	
Diesel fuel	**Gallon**	**2.71**	**1.39E+05**	**19.50**	**1.95**	**18.48**	
AD—Other dairy	1,000 ft^3	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

The cost of biogas production, excluding the low and high values based on limited data, is presented in figure 4. Other fuels including natural gas, propane, heating oil, and gasoline are also shown in the figure for comparison. The average cost of biogas production from anaerobic digestion of manure is $0.66 per therm when the lowest and highest cost systems are excluded and $0.96 per therm when all data is included.

Annual operation and maintenance costs

For small to medium size digesters with electrical generators, O&M costs include daily operator labor to pump the manure and perform routine maintenance; expenses for engine oil changes and minor repairs; and periodic major repairs and maintenance such as engine overhauls, sludge removal, and flexible cover repair or replacement. Annual O&M cost is estimated at 3 percent of the digester system turnkey cost (presumed to be capital cost) (Martin 2007).

Downtime and lost electricity revenue from an engine overhaul is an expense that should be considered. If waste engine heat is used to heat the digester, engine downtime may result in the digester cooling and reduced biogas output. A backup boiler may be useful to maintain digester output when the engine is shut down. A backup boiler could be purchased, or rented only when the engine is down. One drawback of renting a boiler is that the rental contract may require use of propane or natural gas fuel, while a purchased boiler could be operated on biogas. A second approach to minimizing downtime during an engine rebuild is to purchase a second engine in advance when an overhaul is due, and install this engine while the first unit is overhauled (Goodrich 2007).

IV. Discussion: Value of biogas as a replacement for propane or natural gas

Based on the average U.S. commercial price for natural gas of $1.13 per therm, using biogas on-farm can provide a cost-avoidance benefit. Similarly, with the commercial price of propane at $1.82 per therm, biogas can provide a cost effective replacement for propane. The potential cost advantage of on-farm produced biogas over natural gas or propane is a recent development. The cost of both natural gas and propane over the last decade is shown in figure 5.

Figure 5 Average commercial cost for natural gas and propane from 1996 to 2006

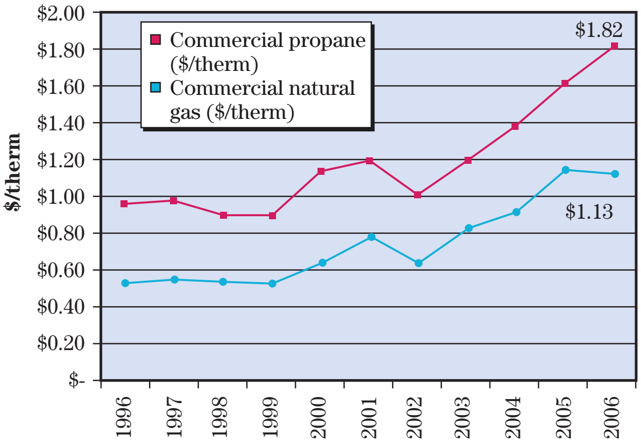
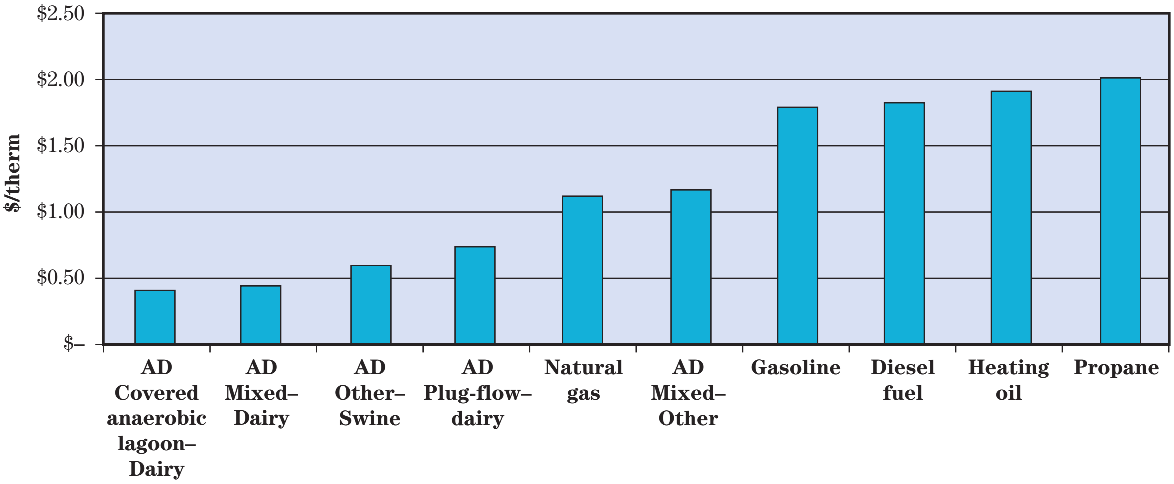


Figure 4 Biogas production costs



The significant increase in both natural gas and propane cost over the past 5 years has made the use of on-farm-produced biogas economically attractive as a replacement for natural gas and liquid propane. It is important to note that producing biogas as shown in table 2 assumes that the digester feedstock (manure) is available at no cost. Additionally, the analysis does not include the cost for biogas cleaning (hydrogen sulfide (H_2S) removal) and conditioning (removing water (H_2O) and CO_2 and compressing) to natural gas standards. The cost to clean biogas ranges from \$0.03 per cubic meter for H_2S removal to \$0.14 per cubic meter to clean gas to pipeline quality (\$0.88 to \$3.88/1,000 ft^3) (BABA 1987). These reported cleaning costs were converted from British pounds to dollars using a 1987 conversion rate and then converted to 2006 dollars using the Engineering News-Record (ENR) Construction Cost Index (BABA 1987). Given the cost to clean and condition biogas, the direct on-farm use of unconditioned biogas offers the greatest economic advantage for producers. Some level of biogas cleaning and conditioning prior to use may reduce maintenance of equipment and be economically feasible depending on the specific situation.

The main question that arises with using biogas on site for heating is how much heat is needed and how can the heat be used productively. Heat from burning the biogas has little economic value unless it replaces a fuel that otherwise would need to be purchased (or unless it can be sold). Anecdotal information suggests that few commercial livestock farms will be able to productively use all of the biogas from a digester for heat, if the digester is sized to utilize all of the farm's manure. Additionally, because space heating is generally needed only in the late fall and winter, biogas supply may exceed demand in the warmer months.[1] For example, consider a dairy farm that uses propane for space heating the milking parlor and cow holding area. A digester is installed that is expected to produce 66 cubic feet of biogas per cow per day. At 600 Btu per cubic foot of biogas and 91,600 Btu per gallon of propane, each cow for a 365-day year could potentially replace around 158 gallons of propane per year. This would typically provide more fuel than would be required to heat the dairy and the system would provide this level of biogas in the warmer months, as well as the cooler months. It is important that any producer considering AD-produced biogas as a replacement for other fuels carefully consider fuel demand with biogas supply. If only 50 percent of the biogas produced can be used on the farm, then the true cost of the biogas used would be doubled.

V. Typical manure anaerobic digestion systems

This section describes typical manure anaerobic digester types, digester construction materials, the associated range of organic loading rates (OLR), hydraulic retention times (HRT), and appropriate total solids (TS) input levels. OLR is an expression of the waste strength introduced into a unit volume of a digester per unit of time. The OLR of an anaerobic digester is typically expressed in terms of COD per digester volume per unit time, typically represented as kilogram COD per cubic meter per day (kg COD/m^3/d). While animal manures have a high waste strength (i.e., manures have a high COD) as compared to municipal wastewaters, the OLR for manure anaerobic digesters is typically lower than many industrial AD systems. This is due to the fact that many of the industrial AD design configurations that achieve high organic rates are not capable of handling high solids waste streams, such as manure. As such, manure digesters typically have longer HRTs, which translate into lower OLRs.

The HRT of a system is defined as the digester volume divided by the flow rate into the digester. The HRT expresses the average time it takes manure to pass through the anaerobic digester, and is typically expressed in days. There is a direct correlation between digester OLR and HRT. For a waste stream of constant composition, the lower the HRT, the higher the OLR.

The TS content of the manure will affect the physical movement and settling characteristics of manure through the AD system. The TS content of manure is expressed as a percentage representing the mass of solids divided by the total mass of a manure sample. Knowledge and management of manure TS content is important to ensure proper digester operation because different digester types require different manure TS content to function optimally. The impact of manure TS content on an AD system varies by digester type and is discussed by digester type. Both the COD and

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[1] Data on farm propane use is limited. Minott and Scott report propane expenses for one 500-cow New York dairy farm of 10 gallons per cow per year. Fuel expense data reported for 2006 in the University of Minnesota's FINBIN farm business summary program would be 42 gallons per dairy cow per year if all of the fuel expense were for propane costing \$1.50 per gallon. This is likely an over-estimate because the fuel expense likely includes other fuel such as diesel fuel for feed and manure handling. Farrow-to-finish swine enterprise fuel expenses would be 2.7 gallons per head per year (in inventory) if it were all for propane, assuming 4.5 head in inventory per litter farrowed per year. See *http://www.finbin.umn.edu/*

TS of manure can be determined through laboratory analysis or estimated using values published by the USDA Natural Resources Conservation Service (NRCS) and the American Society of Agricultural and Biological Engineers (ASABE). Typical operating parameters for various manure AD configurations are shown in table 5.

AD systems that are cost effective and easily managed are needed for feasible integration into AFOs, especially for smaller operations. Successful AD systems are those that have been designed to meet the specifications of the manure source and management of the facility. Construction of successful digesters is completed by skilled and knowledgeable contractors following sound designs that were planned to minimize system O&M requirements. Digesters have a better chance of providing an economic return if they combine income from various system outputs including utilization of the biogas, digested solids, effluent, and carbon credits. System types that have been successfully integrated on multiple livestock operations to date include covered anaerobic lagoons, plug-flow digesters, and continually stirred tank reactors (mixed digesters). Other promising designs, such as induced blanket reactors and fixed-film reactors, currently are installed on smaller numbers of farms.

Covered anaerobic lagoon

Covered anaerobic lagoons are designed to collect biogas produced from stored animal manures. Typically, they are earthen structures and may or may not include heat addition. Biogas production increases with increasing temperature, making biogas production seasonal. Because of this limitation, heated covered anaerobic lagoon systems are preferred to maximize biogas production. The applicability of these systems is limited to temperate and warmer climates, allowing for more efficient systems that reduce retention time and lagoon volume. These systems may use full or partial covers. A partial cover allows for biogas collection from the majority of the lagoon surface area while maintaining a simple system to allow collected rainwater to be drained from the covered area (fig. 6).

Covered anaerobic lagoons can utilize high manure TS concentrations that might plug other AD systems because they include large dilution volumes that result in very low OLRs that range from 0.05 to 0.2 kilograms COD per cubic meter per day (3.1 and 12.5 lb COD/1,000ft^3/d). The HRT for covered anaerobic lagoons can vary from 60 to 360 days, depending on the management of the facility. Typically, heated lagoons will have a much shorter HRT than ambient temperature lagoons.

Figure 6 Partially covered anaerobic swine lagoon

Table 5 Typical AD system characteristics

AD system	OLR Kg COD/m^3/d	HRT days	% TS operational range
Covered anaerobic lagoon	0.05–0.20	60–360	Variable*
Plug-flow digester	1–6	18–20	11–14
Mixed	1–10	5–20	Variable*
Fixed-film	5–10	0.5–4	<1
Induced blanket reactor	5–10	3–5	<8

* These systems utilize a wide range of TS, including high TS manure

The main advantages of covered anaerobic lagoons are the low capital cost compared to other digester types, fairly simple construction design, and ease of management. The disadvantage of covered anaerobic lagoons is the large footprint (land area requirement), solids settling issues, and the dependency of biogas production on climate. Solids introduced into a lagoon are prone to settle and require removal at some interval because of the large dilution volume and long HRT associated with covered anaerobic lagoons. Solids removal requires removing the lagoon cover and may require removal of heat exchangers used with heated systems.

Covered anaerobic lagoons are usually built with an earthen or geosynthetic liner. Facilities on sites with high ground water will need to be avoided or tile-drained. Facilities using a geosynthetic liner will need to vent the subgrade to avoid gas build-up floating of the liner. Lagoon gas collection covers are typically constructed of flexible geosynthetic materials including high density polyethylene (HDPE), linear low-density polyethylene (LLPE), ethylene propylene diene monomer rubber (EPDM), polypropylene (PP), or reinforced polyethylene (RPE). Biogas is collected in pipes along the top of the cover and moved using a low vacuum to the point of use. In many cases, excess biogas is flared (burned off without being used for other energy needs) from covered anaerobic lagoons. Biogases from covered anaerobic lagoons have been utilized to fuel boilers and generate electricity.

Plug-flow digester

A plug-flow system digests manure as it moves through the system in a “plug.” As manure enters a plug-flow digester, it also displaces a like volume of manure from the system. Plug-flow digesters are designed to minimize mixing through the vessel. Untreated waste is pumped into one end of the digester, and digested waste exits at the other end of the digester. Plug-flow digesters require high TS manures in order to avoid short-circuiting or mixing of the manure as it passes through the digester.

Dilute manure streams (those with low TS content) are not appropriate for plug-flow digesters because they tend to separate into a floating crust with solids settled in the bottom leaving a narrow band in the middle that in effect “short circuits” the digester. Plug-flow digesters require input manures with 11 to 14 percent TS. The OLR for a plug-flow system is typically between 1 and 6 kilograms COD per cubic meter per day (62.3–374 lb/COD/1,000 ft^3/d), with a HRT between 18 and 20 days. The NRCS Conservation Practice Standard for Anaerobic Digesters—Controlled Temperature requires an HRT of 20 days for plug-flow systems.

Potential disadvantages of plug-flow systems are the high TS manure requirement and the incompatibility with some types of bedding, particularly sand. More than 50 percent of the ADs evaluated in this paper are concrete plug-flow digesters for treating dairy waste. Dairy facilities that bed with sand and/or large wood chips should consider changing their bedding source or consider separation of these materials before digestion.

Plug-flow digesters have traditionally had a higher success rate than other digester configurations used for manure digestion (Lusk 1998). Plug-flow digesters are typically long rectangular tanks constructed of concrete with a flexible geosynthetic cover for gas collection. Rigid concrete ceilings have been used to collect biogas with limited success. Most plug-flow digesters are heated by running hot water through pipes in the digester itself or through the concrete walls. Water should not be heated above 60 degrees Celsius (140 °F) to minimize reduced heat transfer caused by manure buildup onto the outside of the pipes at higher temperatures.

Figure 7 shows parallel plug-flow digester cells under construction prior to cover installation.

Continually stirred tank reactor

A continually stirred tank reactor (mixed digester) is classified as a contact process where the influent is mixed to maintain a uniform substrate concentration throughout the system. Traditionally, these systems have been used in industrial settings. However, the mechanical mixing requirement for a mixed digester increases the initial capital costs, as well as the O&M costs of the system.

Figure 7 Parallel plug-flow digester cells under construction prior to cover installation

Mixed digesters can process manure over a wide range of TS. Continually stirred tank reactors used for manure digestion typically have OLRs between 1 to 10 kilograms COD per cubic meter per day (62–623 lb COD/1,000 ft^3/d). The HRT of these systems treating manure is typically between 5 to 20 days. The NRCS Conservation Practice Standard for Anaerobic Digesters—Controlled Temperature requires an HRT of 17 days for mixed digester systems.

Mixed digesters handle shock loading and toxicity issues better than plug-flow digesters. The main advantage of a mixed digester system is that it can function over a wide range of TS. The technology is not limited to scrape or flush manure collection systems or to specific animal manure. One disadvantage of a mixed digester is the poor anaerobic biomass immobilization provided by the system. Because of the mixing, the influent substrate is continually in contact with the system anaerobic biomass, and some influent substrate is discharged from the system without being digested. This can reduce the system treatment efficiency. Mixed digesters are typically constructed using cylindrical concrete or steel tanks because of the mixing efficiency (fig. 8).

Figure 8 Continually stirred tank reactor (mixed digester)

Fixed-film digester

A fixed-film digester uses an attached growth process that digests waste as it moves through a system that contains some type of fixed media. Anaerobic biomass attaches to the fixed media and comes in contact with the substrate as it flows past the fixed film of biomass. Because the biomass is attached to the media inside the digester, biomass immobilization is excellent with properly operating fixed-film digesters. Due to the excellent biomass retention, these systems operate at higher efficiencies and can therefore have shorter HRTs than many other system designs. Fixed-film digesters are sometimes called anaerobic “filters” because of the media they contain. Anaerobic filters are constructed in either an upflow or downflow configuration.

Fixed-film digesters require low influent TS content, typically less than 1 percent, to minimize plugging the system. When used with manures, these systems typically treat a medium to high OLR, between 5 and 10 kilograms COD per cubic meter per day (312–623 lb COD/1,000ft^3/d), with a short HRT of 0.5 to 4 days. Systems designed to meet the NRCS Conservation Practice Standard for Anaerobic Digesters—Controlled Temperature require an influent TS concentration of less than 5 percent and a HRT of 1 to 6 days. In industrial settings on very high COD wastewaters that have very low solids contents, fixed-film systems are operated with much higher OLRs and very short HRTs.

The anaerobic fixed-film process can be considered with flush manure management systems where the diluted manure has low TS content. While the NRCS Conservation Practice Standard for Anaerobic Digesters—Controlled Temperature, for fixed-film systems requires a TS concentration less than 5 percent, it has been the authors’ experience that TS concentrations of less than 1 percent are required for reliable performance. Anaerobic filter processes exhibit excellent biomass immobilization and have short HRTs. Anaerobic filter processes have a high potential for plugging problems and their use is limited to low TS manure.

Fixed-film digesters are typically constructed in tanks and gas is collected in the same vessel as shown in figure 9.

Solids will tend to settle in the bottom of the tank. A fixed-film digester design should allow solids removal without disrupting the anaerobic process.

Induced blanket reactor

An induced blanket reactor (IBR) digester is a contact process where the anaerobic biomass forms a sludge blanket that digests the waste as it moves through the reactor. Influent is introduced at the bottom of the reactor and flows up through the sludge blanket. Digestion occurs as manure flows up through the sludge blanket and comes in contact with the anaerobic biomass. As biogas is produced it adheres to the sludge blanket causing it to rise. At the top of the tank, the biogas is released and the sludge blanket will fall towards the bottom of the reactor.

Figure 9 Fixed-film digester

IBR digesters are designed for influent with 6 to 8 percent TS. This system will treat a medium to high OLR, between 5 to 9.1 kilograms COD per cubic meter per day (312–567 lb COD/1,000ft^3/d), with a short HRT of 3 to 5 days. Systems designed to meet the NRCS Conservation Practice Standard for Anaerobic Digesters—Controlled Temperature (366) require an influent TS concentration of less than 5 percent and a HRT of 1 to 6 days.

IBR digesters can handle a large range of OLRs. Problems have occurred in IBR digesters with gas collection due to foaming. Biomass can be “washed out” with the effluent, which will reduce available biomass to treat the waste in the reactor. IBR digesters are typically constructed in tanks and gas is collected in the same vessel. Gas is screened before collection to minimize foam or sludge entering the gas collection system. Solids will tend to settle in the bottom of the tank. IBR digester design should account for solids removal without disrupting the anaerobic process.

VI. Estimating biogas production through anaerobic digestion

The amount of biogas produced from animal manure can be theoretically or empirically estimated. At a minimum, laboratory testing of animal manure to determine the COD and TS should be conducted when considering anaerobic digestion as a treatment alternative. This information can be used to estimate potential biogas production and to evaluate applicable anaerobic digester configurations.

Given the stoichiometric relationship between COD and CH_4 in the anaerobic digestion process, 0.39 cubic meters of CH_4 will be produced for every kilogram of COD digested at 35 degrees Celsius (6.3 ft^3/lb COD @ 95 °F) (Speece 1996). Keep in mind that not all the COD entering the digester in the manure will be converted into CH_4. The amount of COD actually converted is proportional to the COD conversion, or removal efficiency of the digester. Digestion efficiency will vary with manure type and amount, bedding material, and dilution water, as well as with digester type and design. COD removal efficiency for manure anaerobic digesters will range from 10 to 70 percent (10–50% dairy, 30–70% swine) based on manure type and digester efficiency. Theoretical biogas production calculated for dairy, beef, swine, and poultry is shown in tables 6 and 7.

The calculation for biogas produced per animal per day is shown in equation 1. COD production derived from a laboratory analysis will increase the precision of this calculation. The percentage of CH_4 in the biogas can range from 55 to 80 percent, depending on the digester type and the influent source (eq. 1).

The COD excreted in the manure per AU per day was estimated using the ASAE D384.2 MAR2005 Standard for Manure Production and Characteristics for Dairy and NRCS Agricultural Waste Management Handbook, Chapter 4, Agricultural Waste Characteristics for Beef, Swine, and Poultry. CH_4 produced for each kilogram of COD was based on 0.39 cubic meters of CH_4 produced for every kilogram of COD digested.

The volume of biogas generated from the anaerobic digestion of manure can be theoretically predicted based on the COD of the manure and the COD to CH_4 conversion efficiency. If the COD content of the manure is

$$\frac{\text{Biogas}\left(\text{ft}^3\right)}{\text{Animal}\times\text{Day}}=\frac{\frac{\text{lb COD}}{\text{Animal}\times\text{Day}}\times\%\text{ Manure Collected}\times\%\text{ COD Conversion}\times\frac{\text{Methane}\left(\text{ft}^3\right)}{\text{lb COD}}}{\%\text{ Methane in Biogas}} \qquad \text{(eq. 1)}$$

not available from a laboratory analysis, the manure volatile solids (VS) content can be used as an approximation of COD because of the nearly 1:1 relationship between COD and VS (fig. 10).

Note that the COD and VS estimates shown in figure 10 are taken from the ASAE 384.1 Standard for Manure Characteristic and Production for as excreted manure (ASAE 2000).

Figure 10 VS and COD comparison

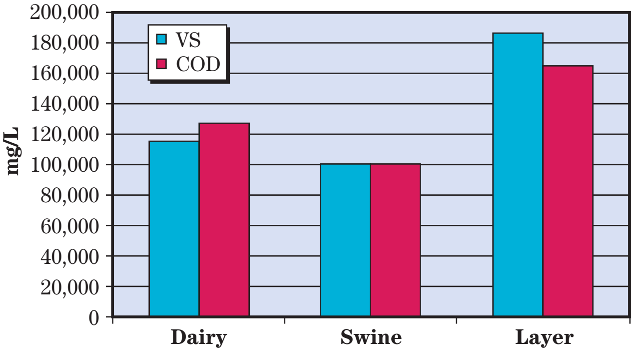

Table 6 Theoretic biogas production (metric)

Animal type	Average weight (kg)	COD kg/animal/d	Manure collected (%)	COD conversion (%)	Biogas/animal/d (m^3) [5]	Biogas/AU/d (m^3) [6]
Dairy	625	8.1 [1]	90	30	1.3	0.95
Beef	447	2.0 [2]	90	30	0.32	0.33
Swine	70	0.39 [3]	100	60	0.14	0.91
Poultry	1.2	0.022 [4]	100	70	0.0092	3.6

1/ ASAE D384.2 MAR2005, Table 1.b, Dairy-Lactating Cow
2/ ASAE D384.2 MAR2005, Table 1.a, Beef-Finishing cattle divided by assumed finished time period of 153 days
3/ ASAE D384.2 MAR2005, Table 1.a, Swine-Grow–finish divided by assumed finished time period of 120 days
4/ ASAE D384.2 MAR2005, Table 1.a, Poultry-Broiler divided by assumed finished time period of 48 days
5/ Assuming 0.39 m^3 of CH_4 for every kilogram COD converted and CH_4 is 65 percent of biogas
6/ 454 kg per animal unit (AU)

Table 7 Theoretic biogas production (English)

Animal type	Average weight (lb)	COD lb/animal/d	Manure collected (%)	COD conversion (%)	Biogas/animal/d (ft^3) [5]	Biogas/AU/d (ft^3) [6]
Dairy	1,375	18 [1]	90	30	47	34
Beef	983	4.4 [2]	90	30	11.5	12
Swine	154	0.87 [3]	100	60	5.1	33
Poultry	2.6	0.048 [4]	100	70	0.33	125

1/ ASAE D384.2 MAR2005, Table 1.b, Dairy-Lactating Cow
2/ ASAE D384.2 MAR2005, Table 1.a, Beef-Finishing cattle divided by assumed finished time period of 153 days
3/ ASAE D384.2 MAR2005, Table 1.a, Swine-Grow–finish divided by assumed finished time period of 120 days
4/ ASAE D384.2 MAR2005, Table 1.a, Poultry-Broiler divided by assumed finished time period of 48 days
5/ Assuming 6.3 ft^3 of CH_4 for every pound COD converted and CH_4 is 65 percent of biogas
6/ 1,000 pounds per animal unit (AU)

Figure 11 illustrates the theoretical biogas production and the average reported biogas production of the 38 case studies by digester type and animal species.

Biogas production numbers were not reported for Covered Anaerobic Lagoon—Dairy and Mixed—Other.

Manure AD OLR can also be reported in pounds of VS added per day per cubic foot of digester capacity per unit time. The COD conversion efficiency can also be measured by the percent reduction in VS. Biogas production can also be estimated using VS destroyed. Table 8 provides estimates of the biogas that will be created for every kilogram of VS consumed in the anaerobic digestion process, assuming a 1:1 ratio with COD. Typically, between 30 to 60 percent of the VS in animal manures can be converted to biogas (Wright 2003). The conversion depends on temperature of the digester and the manure type. Table 9 shows the biogas production per AU.

Figure 11 Biogas production

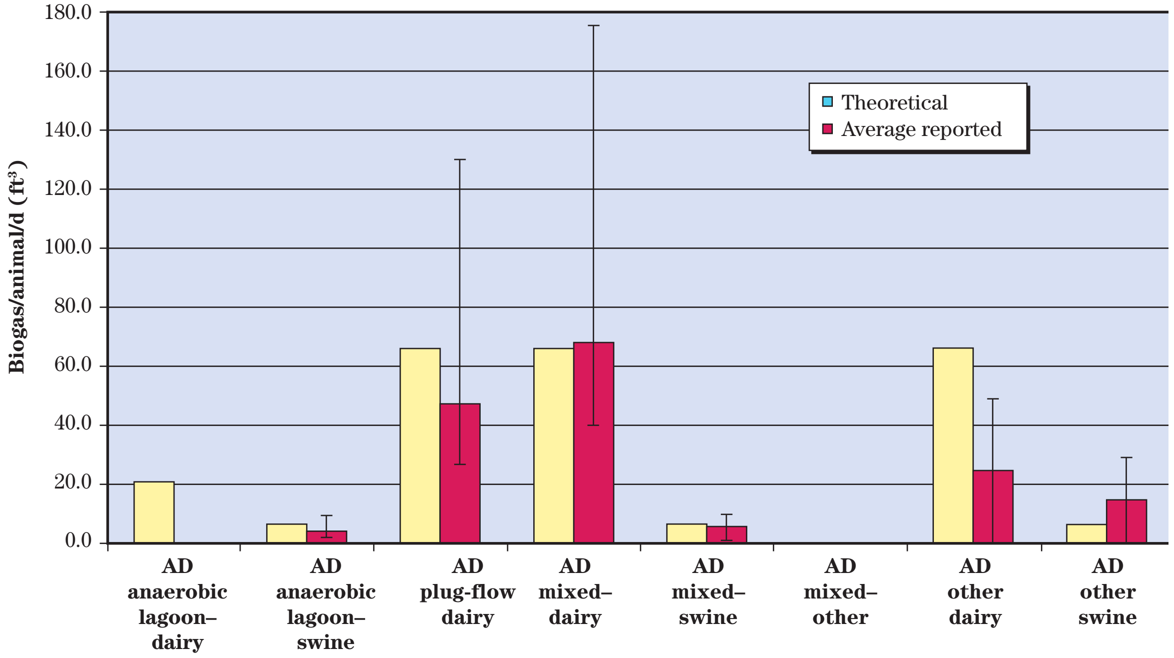

Table 8 Biogas production per pound of VS

Animal type	Biogas/kg VS (in m^3)	Biogas/lb VS (in ft^3)
Dairy	0.18	2.9
Beef	0.18	2.9
Swine	0.36	5.8
Poultry	0.42	6.8

Table 9 Biogas production per AU

Animal type	Biogas/1,000 lb of LAW/d* (in m^3)	Biogas/1,000 lb of LAW/d (in ft^3)
Dairy	1.3	47.1
Beef	0.4	13.6
Swine	1.0	35.5
Poultry	2.6	92.9

* Live animal weight

VII. Biogas collection, upgrading, and on-farm use

Power generation is not always cost effective for small or medium-scale anaerobic digestion facilities (Tanaka 2002). The increased capital cost of generators and the subsequent O&M costs may have restricted the use of AD systems to large animal operations. Utilization of biogas on-farm without electricity generation will benefit producers by lowering capital and O&M costs. Potential savings could be achieved by using biogas as a fuel for heating, lighting, and for both stationary and mobile engines. The following section discusses the basics of biogas as a fuel and potential on site biogas use.

The CH_4 concentration in biogas will determine the heating value of the gas. Natural gas has a heating value of approximately 31,800 to 35,300 British thermal units (Btu) per cubic meter (900–1,000 Btu/ft^3) (Walsh et al. 1998). One Btu will raise 1 pound or 1 pint of water by 1 degree Fahrenheit. Biogas heating values typically vary between 17,700 to 28,300 Btu per cubic meter (500–800 Btu/ft^3), with 21,200 Btu per cubic meter (600 Btu/ft^3) for an average biogas with 65 percent CH_4. A medium Btu gas is one with 17,700 to 21,200 Btu per cubic meter (500–600 Btu/ft^3), where a high Btu gas will contain between 21,200 to 35,300 Btu per cubic meter (600–1,000 Btu/ft^3). The higher the percent CH_4 found in the biogas, the higher the heating value.

The parasitic heating requirements as a percentage of biogas produced from an AD system were calculated for both swine and dairy manure assuming the use of both as excreted manure and manure diluted 1:1 with water for both a 20 degrees Celsius and 30 degrees Celsius temperature rise. For dairy, the parasitic heating requirements range from 15 to 45 percent and for swine range from 12 to 36 percent. These calculations assume 30 percent COD conversion efficiencies for dairy and 60 percent COD conversion efficiencies for swine. For example, a plug-flow dairy digester operating with as excreted manure that required a 30 degrees Celsius temperature rise to reach a 35 degrees Celsius operating temperature would require 23 percent of the biogas to heat the influent manure. For a swine mixed digester utilizing manure diluted 1:1 with water that required a 30 degrees Celsius temperature rise to reach a 35 degrees Celsius operating temperature would require 36 percent of the biogas to heat the influent manure. The percentage of biogas required to heat is heavily dependent on the COD content of the influent and the temperature rise required. Also note that this calculation does not account for the heat loss from the digester, just the heat required to raise the temperature.

Anaerobic digester heating is accomplished through preheating manure influent before digestion or heating the digester itself. Temperatures of influent should correspond with the operating temperature of the digester, usually 35 degrees Celsius (95 °F) for mesophilic digestion. Most anaerobic digesters are heated by running hot water through heat exchangers or pipes inside the digester along the walls and floor of the system. The remaining biogas can be flared to the atmosphere or utilized for heating and/or electricity production. The greatest economic payback will be realized on facilities that have a uniform and continuous need for heat used on farm.

Biogas collection

Biogas is collected in the headspace of the anaerobic digester under a floating or fixed biogas collection cover. Covers can typically function as reservoirs for biogas storage for a few hours at low pressures. It is particularly important to ensure that excessive amounts of air do not enter the gas collection system. Depending on the methane concentration of the biogas, explosive mixtures are created when air is mixed with biogas such that 6 to 12 percent of the mixture is CH_4. Safety precautions including adequate flame traps and pressure reducers should be used on biogas delivery lines.

Biogas upgrading

Biogas consists of CH_4, CO_2, and trace amounts of H_2S, and other components. The composition is determined by the raw material being digested. The higher the degradable carbon content of the raw material, the higher the CH_4 concentration in the biogas and consequently the more energy produced. Digester temperature and retention time also affects biogas composition to a lesser extent (Marchaim 1992). Biogas produced on agricultural facilities typically contains between 60 to 70 percent CH_4 by volume. CO_2 concentrations vary between 30 to 40 percent by volume. CH_4 concentrations must be at least 50 percent for biogas to burn effectively as fuel. In addition to CO_2, biogas also contains moisture and smaller amounts of H_2S, ammonia (NH_4), hydrogen (H_2), nitrogen gas (N_2) and carbon monoxide (CO). For direct use, only H_2S and moisture require some level of removal. CO_2 will not cause complications during combustion. However, if a high Btu fuel is needed, CO_2 removal may be considered to increase the percentage of CH_4 in the gas and thereby increase the Btu value of the biogas.

Biogas produced from swine and dairy manures has been reported to contain from 300 to 4,500 parts per million of H_2S (Chandrasekar 2006; Safley 1992). Moisture is present as both water vapor and water droplets. H_2S removal is usually referred to as “cleaning” the biogas, while "conditioning" is used to describe the removal of the moisture and CO_2, as well as possibly compressing the gas if required. Adjusting BABA's 1987 biogas cleaning costs to 2006 values, it is estimated that the cost to clean biogas ranges from \$0.03 to \$0.14 per cubic meter (\$0.88–\$3.88 per 1,000 ft^3) of biogas (BABA 1987). For the on-farm use of biogas to be economically feasible, the biogas must be used directly or the cost of any required biogas cleaning and conditioning prior to use must be less than the incremental difference between the biogas and natural gas cost. Depending on the planned use for the biogas, different cleaning options may be feasible.

Contaminants in biogas can be reduced through several different methods including physical and chemical absorption, adsorption, conversion to a different chemical form and membrane separation (Walsh et al. 1988). Other contaminants found in biogas: particles, halogenated hydrocarbons, NH_4, nitrogen (N), oxygen (O), organic silicon compounds, etc., can be removed through available commercial processes using filters, membranes, activated carbon, and absorption media.

On-farm biogas use

Direct combustion is the simplest method for biogas consumption (Walsh et al. 1988). The cost of cleaning the biogas for storage, handling, and transport is eliminated by using biogas directly on the facility. There are several options for direct utilization of biogas produced through anaerobic digestion. These include combustion to provide space heating, combustion in a boiler to provide hot water, or use as fuel for either stationary or mobile engines. The use of biogas in mobile engines will require compressing the gas. Prior to compression biogas must be completely cleaned and conditioned. If a CH_4 pipeline is within a reasonable distance, biogas can be sold as CH_4 if cleaned of all impurities and pressurized to a level equal of that in the commercial delivery pipelines. This publication focuses on direct use options for biogas and does not consider the economics of biogas sold as CH_4 to commercial gas systems.

Direct combustion in boilers

Biogas can be burned directly through boilers to produce hot water for the facility and to heat the anaerobic digester and/or manure influent. To date, the primary direct use of biogas on farm settings has been to fire boilers used to heat water. These systems have primarily been employed on dairies due to the year-round requirement for hot water to clean and sanitize milking pipelines and equipment on the dairy. Since dairies will typically milk two to three times daily and clean after each milking, there is a consistent requirement for hot water on these facilities. Swine farrowing operations also provide a good fit for biogas-fired boilers since the water can be used to heat the farrowing floors if the facilities are constructed with hot water pipes in the floors. Boilers require very little biogas cleaning and conditioning prior to use, and boiler efficiency has been reported to average 75 percent when burning biogas (NETL 2000).

Boilers will operate on very low gas pressures in the range of 5 to 10 inches of water. While burning biogas with large amounts of H_2S will decrease the useful life and increase the operation and maintenance of the equipment, it is commonly done. The cleaner the biogas in relation to H_2S, the longer the boiler life. To successfully burn biogas that has not had the H_2S removed, the boiler should be operated continuously. When biogas containing H_2S is burned, the H_2S is converted into oxides of sulfur (S) (primarily sulfur dioxide (SO_2) and sulfur trioxide (SO_3)). These sulfur compounds are regulated as air pollutants in the United States, and air emission permits are required depending on the amount released by a facility. When exhaust gases containing SO_2 and SO_3 cool below the dew point temperature, the moisture that condenses in the gas stream will combine with these compounds to form highly corrosive sulfuric acid (H_2SO_4). It is the formation of H_2SO_4 following the combustion of biogas that contains H_2S that results in severe equipment corrosion. A method commonly employed when operating boilers on biogas containing H_2S is to operate the boiler continuously at a temperature above dew point. By maintaining the boiler temperature above the dew point of the gas steam, H_2SO_4 is not formed inside the boiler and corrosion is avoided. Since SO_2 will reduce the dew point of the gas stream, the greater the H_2S level of a biogas, the higher the boiler temperature that must be maintained to avoid H_2SO_4 formation. Biogas with a 1,000 parts per million H_2S concentration will require exhaust gas stream temperatures of around 150 degrees Celsius (302 °F) to remain above dew point (IEA Bioenergy 1999). Of course, wherever the exhaust gas stream cools to dew point outside of the boiler, H_2SO_4 will be formed. Thus, it is very important to direct exhaust gases away from any equipment, personnel, or livestock. Since H_2SO_4 will form when the boiler is shut down, cautionary measures must be taken to avoid any cycling of the boiler on and off when burning H_2S-laden biogas to avoid corrosion.

Direct combustion in heaters

The on-farm use of unconditioned biogas in space heaters for heating animal facilities, such as swine finish floors, appears to be economically feasible, but has not been widely practiced to date. Like boilers, space heaters will function on biogas containing H_2S and have low biogas pressure requirements. Consideration must be given to the H_2SO_4 that will be produced when uncleaned biogas is combusted and the exhaust cools below dew point temperature. The formation of H_2SO_4 will certainly reduce life of the heaters due to corrosion.

Swine and broiler poultry operations in the United States commonly use direct-fired (unvented) space heaters to heat animal housing during the winter. Additionally, the formation of H_2SO_4 in the exhaust of an unvented space heater could potentially cause complications with animal health inside the facility, as well as damage the housing materials. As such, H_2S cleaning would be required to utilize biogas as a fuel for direct-fired heaters inside animal housing areas. Another option would be to use indirect-fired heaters (vented) inside animal housing areas and exhaust the combustion products outside of the animal buildings. If a producer is willing to switch to a hot water heating system, a boiler could be employed rather than traditional heaters. While biogas has been burned as a fuel for boilers for many years in the United States, a literature review found no publications regarding the use of biogas as a fuel for space heating in animal facilities. One disadvantage of using biogas for space heating is that the requirement for biogas would only exist in the winter months. This requirement could possibly extend into the fall if the biogas could also be used to fire heaters to dry grain after harvest.

VIII. Summary

Most manure AD systems built to date in the United States have included electrical generation capacity with the intent of enabling the producer to directly sell electricity to a utility company. Historically, high up-front capital requirements and O&M costs required to reliably produce electricity coupled with the low wholesale electricity rates has resulted in a choice by many producers who have installed anaerobic digesters to discontinue their use within 2 to 3 years following installation. An analysis of 38 existing U.S. AD systems indicates that the omission of electrical generation equipment would lower the initial digester capital cost by approximately 36 percent. Given the increase in natural gas prices over the past 5 years, the direct use of biogas as a replacement for natural gas or propane for onsite heating purposes (e.g., heating water, heating animal housing, etc.) would provide economic benefits to animal producers with a consistent year-round requirement for the biogas. When generator sets are removed from the digester system design, costs, as well as maintenance measures, are reduced. The cost analysis presented in this document suggests that the lower cost AD systems currently employed on U.S. farms can provide biogas that is competitive or lower in cost than the current $0.41 per cubic meter ($11.60/1,000 ft^3) U.S. natural gas price if the biogas can be used directly in space heaters or boilers without excessive gas cleaning costs.

The total costs and projected benefits of an AD system should be fully considered before making a decision to install an anaerobic digester. The required capital cost of an AD system and the amount of biogas produced will vary based on livestock production facility type and the digester technology selected. System success rates and operation and maintenance expense are dependent upon digester type and technical knowledge of the operator. Typically, the value of the energy alone produced by a manure anaerobic digestion system will not provide a positive cash-flow given current U.S. energy costs. The combination of multiple benefits including energy value, odor control, by-product sales, carbon credit value, and possible tipping fees for taking other materials (such a food waste) is the best approach to operating a manure digestion system with overall benefits that exceed system installation and operation costs. Producers should also consider the use of cost-share, grant monies, or other support for the development of renewable energy sources that may be available to assist with the installation of manure AD systems. The offset of a portion or all of the digester capital costs can result in the ability to operate a digester system with a positive cash-flow from energy sales alone. Based on the analysis completed in this study, the direct use on the farm for biogas produced via a manure AD system appears to be economically feasible when the on-farm heating requirements are high enough to utilize the biogas produced by the system.

Abbreviations

AD	Anaerobic digestion
AFO	Animal feeding operation
ASABE	American Society of Agricultural and Biological Engineers
ASBR	Anaerobic sequencing batch reactor
C	Celsius
CH_4	Methane
CSTR	Continually stirred tank reactor
CO	Carbon monoxide
CO_2	Carbon dioxide
COD	Chemical oxygen demand
EPDM	Ethylene propylene diene monomer rubber
F	Fahrenheit
GHG	Greenhouse gas
HDPE	High-density polyethylene
HRT	Hydraulic retention time
H_2	Hydrogen gas
H_2S	Hydrogen sulfide
H_2SO_4	Sulfuric acid
LLPE	Linear low-density polyethylene
L.P.	Liquid propane
N_2	Nitrogen gas
NaOH	Sodium hydroxide
NH_4	Ammonia
NRCS	Natural Resources Conservation Service
OLR	Organic loading rate
PP	Polypropylene
RPE	Reinforced polyethylene
SO_2	Sulfur dioxide
SO_3	Sulfur trioxide
TEC	Triethylene glycol
TS	Total solids
UASB	Upflow anaerobic sludge blanket digesters
U.S.	United States
VS	Volatile solids

Units

AU	Animal units
Btu	British thermal units
d	Day
ft^3	Cubic feet
kW	Kilowatt
kWh	Kilowatt hours
m^3	Cubic meter

Glossary

AgSTAR	A program sponsored by the U.S. Environmental Protection Agency (EPA), the U.S. Department of Agriculture (USDA), and the U.S. Department of Energy (DOE) that advocates the use of methane recovery technology for enclosed operations that manage manure as liquid or slurries.
Anaerobic digestion (AD) system	A system utilizing tanks or vessels for the biological treatment of organic waste by anaerobic micro-organisms that produce biogas by converting organic carbon into methane and carbon dioxide.
Anaerobic lagoons	Large pond like basins sized to provide biological treatment and storage of animal waste. Anaerobic micro-organisms present in the manure produce biogas by converting organic carbon into methane and carbon dioxide.
Anaerobic organisms	Micro-organisms naturally present in manure that convert organic carbon into methane and carbon dioxide in an oxygen free environment.
Anaerobic sequencing batch reactor (ASBR)	An anaerobic digester configuration that is operated in a four-step batch mode. These steps are: 1) fill, 2) react, 3) settle, and 4) decant.
Biogas	Refers to the gas produced through anaerobic digestion of organic material (manure, sewage, sludge, etc.). Biogas contains methane and carbon dioxide, and typically has an energy content of approximately 650 Btu per cubic foot of gas.
Biomass	In the anaerobic digestion process, the anaerobic micro-organisms that grow and reproduce within the digester are referred to as biomass.
British thermal unit (Btu)	A unit of energy commonly used to quantify the energy content of fuels. By definition, 1 Btu is the energy required to raise the temperature of 1 pound of pure liquid water by 1 degree Fahrenheit. 3.41 Btu per hour is equivalent to 1 watt of power.
Carbon credits	A value per ton of carbon emissions whose release to the environment is sequestered by methods that include the capture and combustion of biogas. These credits are purchased and traded as a way to reduce the amount of GHGs released into the atmosphere.
Chemical oxygen demand (COD)	COD is a measure of the capacity of wastewater to consume oxygen during the decomposition of organic matter and the oxidation of ammonia and nitrate in the water. COD values are used as an indicator of wastewater strength.
Continually stirred tank reactor (CSTR)	An anaerobic digester configuration where the system is continuously mixed and the manure in the digester is uniformly distributed. This digester type is also known as a Complete Mix system.
Dew point	The temperature at which water vapor condenses to liquid water (dew) if air with a given water vapor content were cooled at a constant pressure.
Effluent	Digested material (such as digested manure) leaving a digester.
Fixed-film digester	An anaerobic digester configuration where anaerobic microbes (biomass) are grown on a fixed structure within the digester. This digester configuration has excellent biomass retention and can therefore be operated at low hydraulic retention times. Manure contacts biomass attached to a structural surface in the reactor when it flows through the reactor. These systems are also known as Anaerobic Filters and may be designed to operate in either an upflow or downflow mode.

Geosynthetic	A variety of flexible manmade materials that can be used as liners in waste storage ponds or lagoons and for the construction of biogas collection covers for anaerobic digesters or manure storage structures.
Gigajoule	An SI unit of energy equivalent to one billion (10^9) joules. One joule is equivalent to 1 watt of power expended over 1 second. Approximately 1,055 Joules equal 1 Btu.
Greenhouse gas (GHG)	Gases that when released into the Earth's atmosphere contribute to the warming of the Earth's surface. GHGs include water vapor, carbon dioxide, methane, nitrous oxide, and ozone. Methane is a particularly powerful GHG and has 23 times more impact as a GHG than carbon dioxide.
Hydraulic retention time (HRT)	The average time that a discrete volume element of manure introduced into an anaerobic digester stays in the digestion system. HRT is calculated by dividing the volume of the digester by the influent (manure) flow rate into the digester. The HRT of manure digesters is typically measured in days.
Induced blanket reactor (IBR)	An anaerobic digester contact process that uses a layer (called a blanket) of anaerobic biomass to digest manure as it moves through the digester.
Influent	Material (such as manure) entering a digester.
Kilowatt-hour (kWh)	A unit of energy equivalent to a 1 kilowatt (1 kW) power load over a 1 hour (1 h) period of time. The kilowatt-hour is commonly used in electrical applications. One kWh is equivalent to 3.6 megajoules.
Mesophilic digestion	Digestion that takes place using microorganisms over a temperature range between 30–38 degrees Celsius (85–100 ºF).
Mixed digester	An anaerobic digester configuration where mixing occurs, but where the system is not continuously mixed as in a Complete Mix (or CSTR) system.
Organic loading rate (OLR)	The rate at which organic material is introduced into an anaerobic digester per unit volume of digester per unit time. The OLR for anaerobic digestion systems is typically expressed as kilograms of COD per cubic meter of digester volume per day (kg COD/ M^3/d). Note that the strength of the waste alone does not determine if a digester has a high or low OLR, but rather the combination of waste strength, digester volume, and HRT.
Plug-flow digester	A manure anaerobic digester configuration that typically uses a concrete horizontal tank with a flexible gas collection cover. Manure is pumped into one end of the digester and is displaced down the digester where it exits at the far end. A high solids manure is required to achieve plug-flow (no mixing) conditions within the digester. Plug-flow systems are commonly used with scrape collected dairy manures.
Substrate	The organic material that is digested within an anaerobic digester. The substrate (in this case, manure) is the food source for the anaerobic bacteria inside the digester.
Therm	A unit of energy commonly used to quantify the energy in fuels such as natural and L.P. gas. One therm is equivalent to 100,000 Btu.
Total solids (TS)	A measure of the mass of both dissolved and suspended material in a liquid. For manures, TS refers to the material remaining after all water has been evaporated from a sample at 100 degrees Celsius for a 24-hour period. Manure TS is typically

	reported as a percentage of the wet-based sample mass. TS are sometimes referred to as dry matter (DM).
Turnkey cost	The complete initial cost that must be incurred to have a unit or project ready to operate, not including operation and maintenance costs.
Upflow anaerobic sludge blanket digesters (UASB)	An anaerobic digester design that passes influent through a granulated sludge bed. This bed is composed of anaerobic micro-organisms (biomass) that digest the substrate as it passes through the bed.

References

American Society of Agricultural Engineers. 2000. ASAE D384.1: Manure production and characteristics. The Society for Engineering in Agricultural, Food and Biological Systems. St. Joseph, MI.

American Society of Agricultural and Biological Engineers. 2005. ASAE D384.2: Manure production and characteristics. The Society for Engineering in Agricultural, Food and Biological Systems. St. Joseph, MI.

An, B. 2002. Biogas technology in developing countries: Vietnam case study. Proceedings Biodigester Workshop. University of Agriculture and Forestry.

BABA, Ltd. 1987. A Survey of Existing Methods of Biogas Scrubbing and Utilization. Report No: ETSU B 7006. United Kingdom.

Balsam, J. 2006. Anaerobic digestion of animal wastes: factors to consider. ATTRA–National Sustainable Agriculture Information Service. Publication #IP219. *http://attra.ncat.org/attra-pub/anaerobic.html.*

Burns, R. 2007. Personal interview. January 27, 2007.

Chandrasekar, A., V. Maston, and N.R. Scott. 2006. Demonstration of Hydrogen Production from Dairy Manure Derived Biogas. ASABE Paper No. 067065. St. Joseph, MI.

Goodrich, P. 2007. Personal communication, April 9, 2007.

Great Lakes Regional Biomass Energy Program Council of Great Lakes Governors. 2002. Agricultural biogas case study. Chicago, IL.

IEA Bioenergy. 1999. Biogas upgrading and utilisation. Task 24: Energy from biological conversion of organic waste.

Jewell, W.J., P.E. Wright, N.P. Fleszar, G.Green, A. Safinski, and A. Zucker. (1997). Evaluation of anaerobic digestion options for groups of dairy farms in Upstate New York. Department of Agricultural and Biological Engineering, Cornell University. Ithaca, NY.

Jones, D.D., J.C. Nye, and A.C. Dale. 1980. Methane generation from livestock waste. Publication #AE–105. Purdue University Cooperative Extension Service, West Lafayette, IN. 15 p. *http://pasture.ecn.purdue.edu/%7Eepados/swine/pubs/methane.htm*

Kramer, J.M. 2002. Agricultural biogas casebook. Resource Strategies, Inc. Madison, WI.

Lusk, P. 1998. Methane recovery from animal manures: a current opportunities casebook. 3rd Edition. NREL/SR–25145. Golden, CO: National Renewable Energy Laboratory. Work performed by Resource Development Associates, Washington, DC.

Lusk, P. 1995. Methane recovery from animal manures: a current opportunities casebook. U.S. Department of Energy, Regional Biomas Energy Program, National Renewable Energy Laboratory. Washington, DC.

Marchaim, U. 1992. Biogas Process for Sustainable Development. Food and Agriculture Organization of the United Nations, Viale delle Terme di Caracalla, 00100 Rome, Italy. *http://www.fao.org/docrep/T0541E/T0541E00.htm*

Martin, J.H. 2007. A Protocol for Quantifying and Reporting the Performance of Anaerobic Digestion Systems for Livestock Manures. Hall Associates, Georgetown, DE.

Minott, S.J., and N.R. Scott. 2001. Feasibility of fuel cells for energy conversion on dairy farms. Paper number: 01–7015. 2001 ASAE Annual International Meeting, July 29–Aug. 1, 2001. Sacramento, CA.

National Energy Technology Laboratory. 2000. Pleasant Hills Sewage Treatment Plant Project on Alternative Energy Generation. *http://www.netl.doe.gov/energy-analyses/pubs/PHA%20Final%20Report.pdf*

Peters, J. 2007. Debt financing. Oral Presentation. Biomass Finance & Investment Summit, January 18–19, 2007. San Diego, CA.

Safley, L.M. Jr., and P.W. Westerman. 1992. Performance of a dairy manure anaerobic lagoon. Bioresource Technology, vol. 42, pp. 43–52.

Speece, R.E. 1996. Anaerobic Biotechnology for Industrial Wastewaters. Archae Press. TN.

Tanaka, Y. 2002. A dual purpose packed-bed reactor for biogas scrubbing and methane-dependent water quality improvement applying to a wastewater treatment system consisting of UASB reactor and trickling filter. Bioresource Technology, vol. 84, pp. 21–28.

U.S. Department of Agriculture. Natural Resources Conservation Service. 1992. Agricultural Waste Management Field Handbook. National Engineering Handbook, Part 651.

U.S. Department of Energy, Energy Information Administration. 2006. Report #: DOE/EIA-0573(2005): Emissions of Greenhouse Gases in the United States 2005.

U.S. Department of Energy. Energy Information Administration. 2007a. U.S. Natural Gas Summary. Washington, DC. *http://tonto.eia.doe.gov/dnav/ng/hist/n3020us3m.htm* (Accessed 1/28/07).

U.S. Department of Energy. Energy Information Administration. 2007b. Average Retail Price of Electricity to Ultimate Customers by End-Use Sector. Washington, DC. *http://www.eia.doe.gov/cneaf/electricity/epa/epat7p4.html* (Accessed 1/28/07).

U.S. Department of Energy. Energy Information Administration. 2007c. Average Wholesale Electric Price by NERC region, 2001–2005. Form EIA–861, Annual Electric Power Industry Report. Washington, DC. *http://www.eia.doe.gov/cneaf/electricity/wholesale/wholesalet2.xls* (Accessed 6/09/07).

U.S. Environmental Protection Agency. AgSTAR Guide to Operational Systems. Washington, DC. *http://www.epa.gov/agstar/operation/bystate.html* (Accessed 1/28/2007).

U.S. Environmental Protection Agency. Office of Air and Radiation. 2006. AgSTAR Digest Winter 2006. Washington, DC.

Walsh, J., C. Ross, M. Smith, S. Harper, and W. Wilkins. 1988. Handbook on Biogas Utilization. Prepared for U.S. Department of Energy, Southeastern Regional Biomass Energy Program. Prepared by Georgia Institute of Technology, Engineering Technology Branch. Atlanta, GA.

Wright, P. 2003. Anaerobic digester design and operational considerations. *In* Anaerobic Treatment of Agricultural Wastes Short-Course Proceedings. November 3–5, 2003. The University of Tennessee, Nashville, TN.

Appendix A
Case Study Data

Table A–1 Covered anaerobic lagoon

Facility	Digester type	Farm type	Animals	Reported ft^3 biogas produced/ head/d	Produce energy? Sell to grid?	Heat recovered?	Biogas flared?
Swine	N = 6						
AS	Covered lagoon	Swine	8,300	4.3	No	Yes	Yes
BS	Covered lagoon	Swine	1,150	0.0	No	No	Yes
CS	Covered lagoon	Swine farrow to finish	11,500	2.5	Yes/No	Yes	Yes
DS	Covered lagoon	Swine farrow to feed	3,500	0.7	No	No	Yes
ES	Covered lagoon	Swine farrow to feed	3,000	3.9	Yes/No	Yes	Yes
FS	Covered lagoon	Swine farrow to wean	8,800	4.9	Yes/No	Yes	Yes
Dairy	N = 2						
GD	Covered lagoon	Dairy	1,100	0	No	No	Yes
HD	Covered lagoon	Dairy	1,600	0	No	No	Yes

Table A–2 Plug-flow digester

Facility	Digester type	Farm type	Animals	Reported ft^3 biogas produced/head/d	Produce energy? Sell to grid?	Heat recovered?	Biogas flared?
Dairy	N = 19						
AD	Plug-flow	Dairy	420	0.0	Yes/No	No	Yes
BD	Plug-flow	Dairy	120	38.3	No	Yes	Yes
CD	Plug-flow	Dairy	700	0.0	Yes/Yes	Yes	Yes
DD	Plug-flow (2)	Dairy		0.0	Yes/Yes	No	Yes
ED	Plug-flow	Dairy	500	0.0	Yes/Yes	Yes	Yes
FD	Plug-flow	Dairy	725	0.0	Yes/Yes	Yes	Yes
GD	Plug-flow	Dairy	1,000	0.0	Yes/No	Yes	Yes
HD	Plug-flow	Dairy	840	102.4	Yes/Yes	Yes	Yes
ID	Plug-flow	Dairy	1,200	0.0	Yes/No	No	Yes
JD	Plug-flow (2)	Dairy	2,285	52.5	Yes/No	Yes	Yes
KD	Plug-flow (2)	Dairy	600	46.7	Yes/No	Yes	Yes
LD	Plug-flow	Dairy	700	42.9	Yes/No	Yes	Yes
MD	Plug-flow (3)	Dairy	15,000	8.0	Yes/No	No	Yes
ND	Plug-flow	Dairy	300	0.0	Yes/No	Yes	Yes
OD	Plug-flow	Dairy	750	64.6	Yes/No	Yes	Yes
PD	Plug-flow	Dairy	350	25.7	No	Yes	Yes
QD	Plug-flow	Dairy	1,000	42.0	Yes/No	No	Yes
RD	Plug-flow	Dairy	236	0.0	Yes/No	Yes	Yes
SD	Plug-flow	Dairy	850	0.0	Yes/Yes	Yes	Yes

Table A–3 Mixed digester

Facility	Digester type	Farm type	Animals	Reported biogas produced/ head/d (in ft^3)	Produce energy? Sell to grid?	Heat recovered?	Biogas flared?
Swine	N = 2						
AS	Complete mix	Swine farrow to finish	13,000	4.6	Yes/No	Yes	Yes
BS	Complete mix	Swine farrow to finish	14,600	5.1	Yes/No	Yes	Yes
Dairy	N = 4						
CD	Complete mix	Dairy	750	38.7	Yes/No	Yes	Yes
DD	Complete mix	Dairy	490	48.2	No	Yes	Yes
ED	Complete mix	Dairy	600	70.4	Yes/Yes	No	Yes
FD	Complete mix	Dairy	675	113.2	Yes/No	Yes	Yes
Other	N = 2						
GO	Complete mix	Duck	500,000	0.0	Yes/No	Yes	Yes
HO	Complete mix	Poultry	70,000	0.0	Yes/No	Yes	Yes

Table A–4 Other digesters

Facility	Digester type	Farm type	Animals	Reported biogas produced/ head/d (in ft^3)	Produce energy? Sell to grid?	Heat recovered?	Biogas flared?
Swine	N = 1						
AO	ASBR	Swine	2,800	14.3	No	No	Yes
Dairy	N = 2						
BO	UASB	Dairy	500	24.0	Yes/No	Yes	Yes
CO	Fixed-film	Dairy	100	0.0	0	0	Yes

Table A–5 AD systems cost data

Farm name	Digester type	Farm type	Animals	State	Startup date	Biogas/d/head (in ft^3)	ENR construction costs index	Digester cost (in 2006 dollars)*	Generation cost (in 2006 dollars)	O&M (in 2006 dollars)	Total cost (in 2006 dollars)	Revenue (biogas) (in 2006 dollars)
Agricultural biogas casebook												
Crawford Farm	ASBR	Swine	2,800	IA	1999	14	6059	214,659	59,194		377,279	
Futura Dairy	Plug-flow	Dairy	420	IA	2002		6538	159,146	196,521		355,666	
Northeast IA CC Farm	Plug-flow	Dairy	120	IA	2002	38	6538	186,876	48,226		271,271	
Top Deck Holsteins	Plug-flow	Dairy	700	IA	2002		6538	303,221	301,412		604,633	
Wholesome Dairy	Plug-flow (2)	Dairy	3,000	WI	2002		6538				1,567,343	
Apex Pork	Covered lagoon	Swine	8,300	IL	1998	4	5920	88,812	113,977		202,789	
Fairgrove Farms	Plug-flow	Dairy	500	MI	1981		3535	334,478	111,493	2,676	445,971	
Gordondale Farms	Plug-flow	Dairy	725	WI	2002		6538	349,638	277,299		626,937	27,730
Maple Leaf Farms	Complete mix	Duck	500,000	WI	1988/2002		6538	643,816	325,525	36,169	969,341	21,702
Baldwin Dairy	Covered lagoon	Dairy	1,100	WI	1998		5920	93,206			93,206	
Emerald Dairy	Covered lagoon	Dairy	1,600	WI	1999		6059	162,620			162,620	
Double S Dairy	Plug-flow	Dairy	1,000	WI	2002		6538	602,824			602,824	
Haubenschild Farms	Plug-flow	Dairy	840	MN	1999	102	6059	162,750	204,902	4,814	461,842	50,738
Stencil Farm	Plug-flow	Dairy	1,200	WI	2002		6538				602,824	
Methane recovery from animal manures												
McCabe Farms	Covered lagoon	Swine	1,150	IA	1972		1753	89,932		11,241	89,932	
Mason Dixon Farms	Plug-flow (2)	Dairy	2,285	PA	1979	53	3003	472,479	209,991		682,470	
Agway Farm	UASB	Dairy	500	NY	1981	24	3535			8,139	390,224	
Foster Brothers Farm	Plug-flow (2)	Dairy	600	VT	1982	47	3825	381,247	236,991	20,608	618,238	
Langerwerf Dairy	Plug-flow	Dairy	700	CA	1982	43	3825			0	412,158	
Arizona Dairy Company	Plug-flow (3)	Dairy	15,000	AZ	1983	8	4066			29,080	1,744,780	
Darrell Smith Farm	Complete mix	Poultry	70,000	NC	1983		4066			11,360	484,661	
Oregon Dairy Farm	Plug-flow	Dairy	300	PA	1983		4066			7,755	232,637	
Grant Amen Dairy	Complete mix	Dairy	750	CA	1984	39	4146			22,815	351,729	
Cooperstown Holstein Corporation Farm	Complete mix	Dairy	490	NY	1985	48	4195			7,751	939,515	
Rocky Knoll Farms	Complete mix	Swine farrow to finish	13,000	PA	1985	5	4195			15,032	610,685	

Table A–5 AD systems cost data—Continued

Farm name	Digester type	Farm type	Animals	State	Startup date	Biogas/d/head (in ft^3)	ENR construction costs index	Digester cost (in 2006 dollars)*	Generation cost (in 2006 dollars)	O&M (in 2006 dollars)	Total cost (in 2006 dollars)	Revenue (biogas) (in 2006 dollars)
Valley Pork	Complete mix	Swine farrow to finish	14,600	PA	1986	5	4295			9,176	458,820	
Carroll's Foods, Inc.	Covered lagoon	Swine farrow to finish	11,500	NC	1992	3	4985			15,812	302,809	
Lou Palmer Farm	Covered lagoon	Swine farrow to feed	3,500	AR	1992	1	4985			791	25,300	
Martin Farms	Covered lagoon	Swine farrow to feed	3,000	VA	1993	4	5210			3,782	128,795	
Methane recovery from animal manures the current opportunities casebook												
Craven Dairy Farms	Plug-flow	Dairy	750	OR	1997	65	5826				294,885	
Barham Farms	Covered lagoon	Swine farrow to wean	8,800	NC	1997	5	5826				357,831	
Cushman Dairy	Complete mix	Dairy	600	CT	1997	70	5826			16,236	608,846	
Freund Dairy	Plug-flow	Dairy	350	CT	1997	26	5826	207,684		2,029	207,684	14,071
AA Dairy	Plug-flow	Dairy	1,000	NY	1998	42	5920			19,973	282,013	
Anaerobic treatment of agricultural waste												
Spring Valley Dairy	Plug-flow	Dairy	236	NY	2003		6695	68,641	31,789	9,445	169,130	
DDI	Plug-flow	Dairy	850	NY	2001		6334	435,568	292,453	36,860	1,285,298	7,467
JJ Farber Dairy	Fixed-film	Dairy	100	NY	1997		5826	79,827		32,472	397,780	
Matlink Dairy Farm	Complete mix	Dairy	675	NY	2003	113	6695	388,534	151,800	136,470	732,940	