Anaerobic Digestion of Livestock Manure for Pollution Control and Energy Production: A Feasibility Assessment

By Peter Ciborowski
Minnesota Pollution Control Agency

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Conversion Factors

Volume and Weight

1 cubic meter (m^3)	equals	35.315 cubic feet (ft^3)
1ft^3	equals	0.0283 m^3
1 liter (l)	equals	0.035 ft^3
1 l	equals	0.001 m^3
1 m^3	equals	1000 l
1 ft^3	equals	28.317 l
1 kilogram (kg)	equals	2.2046 lb.
1 lb. /ft^3	equals	16 kg/m^3
1 ft^3/lb	equals	0.062 m^3/kg

Manure

1 ft^3 manure	equals	62 lb.
1 kg solids/m^3	equals	0.1% manure solids content

Biogas

1 ft^3 biogas	equals	0.0716 lb. biogas
1 ft^3 biogas	equals	0.55 to 0.7 ft^3 CH_4
1 ft^3 CH_4	equals	0.04235 lb. CH_4
1 ft^3 CO_2	equals	0.1154 lb. CO_2
1 ft^3 biogas	equals	560 to 713 Btu
1 ft^3 CH_4	equals	1018 Btu

Energy

1 kWh	equals	3412 Btu
1 kWh	equals	0.03412 mmbtu
1 mmbtu	equals	293 kWh (thermal)
1 mmbtu	equals	61.5 kWh (electric-diesel generation)
1 kWh (electric-diesel generation)	equals	0.016 mmbtu or 26.67 ft3 biogas

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Executive Summary

Anaerobic digestion is the degradation of complex organic molecules to stabilized waste and two gaseous products, methane (CH_4) and carbon dioxide (CO_2). The process occurs in nature in swamps, wetlands, lake sediments, and in the gastrointestinal tract of ruminant animals. The conditions of anaerobic digestion can be recreated in an engineered structure specifically designed for the anaerobic treatment of organic wastes. Anaerobic digestion has been applied to the treatment of organic wastes for several decades. Livestock waste is among the waste types treated using anaerobic digestion.

Several types of anaerobic digesters are available for use in waste processing on-farm. These include the very ‘slow-rate’ covered anaerobic lagoon, and the ‘medium-rate’ plug flow digester, the continuously stirred tank reactor (CSTR), and the slurry loop digester. A slow-rate reactor like a covered anaerobic lagoon might take to 4 to 6 months to fully digest livestock waste, while a medium-rate reactor like a CSTR would require between 15 and 25 days for effective waste treatment. Various ‘fast-rate’ reactors are also in use in the processing of dilute industrial wastewater. It is possible that in the future fast-rate reactors might be available for the processing of dilute livestock wastes like dilute swine manure.

Due to its cold winter and cool spring and fall climates, the use of covered anaerobic lagoons is not recommended in Minnesota.

Anaerobic digestion works through the sequential degradation of complex organic molecules to smaller and smaller forms. The process depends on a unique biochemistry, which determines the rate at which organic wastes can be processed, and the design and operation of the digester.

The environmental benefits of anaerobic digestion include reduction of manure biological oxygen demand (BOD), odor reductions, the destruction of waste pathogens, and hydrogen sulfide and methane control. In addition, the anaerobic digestion of livestock waste produces substantial quantities of CH_4, which can be combusted for the production of energy. Combusted in a diesel engine adapted to use medium Btu gas, digester biogas can be used to generate electricity on-farm to meet on-farm electricity needs, as well as for sale onto the electrical grid. During combustion, CH_4 is destroyed. CH_4 is a greenhouse gas that has been implicated in global warming.

Because anaerobic digestion produces a commercially valuable product, electricity, it is possible to design an on-farm anaerobic digesters in a way that waste treatment using anaerobic digestion is economically self-sustaining or even a source of farm net profit.

Analysis has been performed to determine the conditions that contribute to the economic viability of on-farm anaerobic digestion. These include: large feedlot size, a high level of manure biodegradability and a low level of manure dilution, the presence of large on-farm electrical loads, and farm electric rates of at least $0.06 per kilowatt-hour. Also important is the prior existence of supporting manure collection systems and effluent storage capacity, and full on-farm use of any waste heat generated during biogas combustion for farm space heating and water heating. Through the use of waste heat, the purchase of high-priced liquid fuels like LPG can be avoided.

Herd sizes of at least 400 head of dairy cows seem to be required to insure the economic viability of on-farm digestion on dairy farms. Depending on manure dilution, it may be possible to anaerobically digest swine manure at herd sizes as low as 4,000 head, assuming that a non-dilute source of swine manure is available, or, if only highly dilute manure is available, assuming that the use of anaerobic covered lagoons is an option. Lacking the option of a covered lagoon, required herd sizes for the digestion of dilute swine manure in a medium-rate reactor like as CSTR are at least 3-fold higher than those necessary for a non-dilute swine manure treated in a CSTR.

Excessive dilution, it might be noted, acts to limit the economic viability of on-farm anaerobic digestion in two ways. Dilution adds large amounts of water to the waste. This extra water can be accommodated in the digester only by purposefully over-sizing the digester. This acts to increase the capital costs of the system, while adding nothing in the form of increased digester biogas or energy productivity. Dilution also raises the heating needs of the digester, thereby limiting the availability of waste heat for other on-farm uses.

The economic viability of anaerobic digester deployments on Minnesota feedlots was investigated using a decision-support evaluative software program for analysis. Assumptions that were utilized in the analysis included: $100 to 300 per cubic meter of digester volume total system capital costs, operating costs equal to roughly 3.5% of capital costs, farm electric rates of $0.06 to 0.07 per kWh, utility and electricity buyback rates of $0.01 to 0.04 per kWh. Also assumed were an 8% loan rate, two project discount rates, 10 and 14%, and a 3% per year rate of escalation in general price levels, including energy prices. No benefit from the use of the digested manure solids was included in the calculation, nor was any digester-derived benefit from odor reduction or pollution control assumed.

Using these assumptions, digester deployments appear to be economically viable on Minnesota feedlots with 400 to 800 head of milking cows. With tax incentives of $0.015 per kWh-generated, anaerobic digestion on dairy farms with as few as 250 to 300 head of cows appears to be economically feasible. It is estimated that within 10 years as much as 10 to 50% of the Minnesota dairy herd is likely to be housed on dairies of sufficient size to support the operation of an anaerobic digester, depending on the availability of governmental assistance.

Due to high levels of dilution of swine manure stored in below barn pits, the anaerobic digestion of swine manure in Minnesota is more problematical. Most swine manure in Minnesota is managed using slotted floors and below barn pits for storage. At high levels of dilution, little of the Minnesota swine herd is on feedlots large enough to support an anaerobic digestion project. Implicit in this understanding is the assumption that the digestion of swine manure in Minnesota requires the use of high capital cost medium-rate reactors. Covered anaerobic lagoons are designed to handle highly dilute waste. But, as noted above, the use of low-cost covered anaerobic lagoons is not an option in Minnesota.

It is possible that, with heightened attention to on-farm water management, anaerobic digestion could be economically viable on some Minnesota swine feedlots. The evidence is that at 4 percent manure total solids content and upward, the digestion of swine manure is economically viable. If managed without any dilution, swine manure can be digested even high-cost medium-rate reactors economically at relatively small herd sizes, e.g., 4,000 head.

The prospects for economically viable deployment of anaerobic digestion on Minnesota feedlots were evaluated assuming a continuation of current conditions in energy and electricity markets.

No effort was made to evaluate the prospects for digestion in light of possible future retail competition in electricity markets, a program of extensive green pricing of power, or ‘real-time’ time-of-day pricing in electricity markets. Any additional future assessment of on-farm digestion might address that potential under these potential alternative futures.

Additionally, future research might address the effect of fuller incorporation of environmental benefits of anaerobic digestion costs into in the calculation of digester viability.

Strategies for the development of the anaerobic digestion resource in Minnesota include:

- governmental subsidization of on-farm anaerobic digestion for the purposes of renewable energy development or rural economic development;
- targeted governmental expenditure on demonstration pilot projects and information dissemination; through the funding of a small number of strategically sited pilot projects around the state, the constraints to the development of anaerobic digestion that arise in the paucity of available technical information on digestion can be relaxed;
- private sector subsidization of anaerobic digestion through renewable energy development mandates;
- consumer choice pricing of renewable energy sources;
- and, the externalities pricing of energy production.

In addition, a pure market response without governmental intervention is possible. The economic analysis suggests the persistence of the condition of market failure with regard to anaerobic digester deployment. Under current conditions, the market would support a substantial number of anaerobic digester deployments, whereas in fact only one full-scale digester is operating in Minnesota on a dairy or a swine feedlot. This may suggest the funding of demonstration pilot projects and a broad-reaching information dissemination program as an appropriate policy response

Part 1. Technology Description and Literature review

Introduction and General Description of the Technology

Anaerobic digestion is the process of microbial degradation of complex carbohydrates to stabilized organic wastes, methane (CH_4), and carbon dioxide (CO_2) under conditions of anaerobiosis. Anaerobic digestion occurs naturally in oxygen-free conditions in swamps, marshes, and lake sediment. Four independent sets of bacteria are involved. The environmental requirements of the most sensitive of these four populations determine the conditions under which anaerobic digestion can occur.

The degree of degradation of complex organic wastes depends on the biodegradability of different waste polymers. Polymeric material that is high in lignin content is more resistant to microbial degradation than are sugars and starches.

The conditions of anaerobic digestion that are found in nature can be replicated or optimized under controlled conditions in different types of reactors. These conditions include an oxygen-free environment, digester temperatures near optimal for bacterial growth, and volatile fatty acids and ammonia concentrations and acidity levels below levels that are toxic to the most sensitive of the digester bacteria. In digester design, four digester parameters are optimized. These include reactor temperature, influent waste total solids content, retention time of the waste in the reactor, and digester organic loading rate.

On-farm digester applications are limited to three types of continuous feed digester types, batch reactors, and covered anaerobic lagoons. The batch reactor has limited applicability on-farm due to the intermittent nature of batch reactor loading. Anaerobic lagoons are not suitable for cold northerly climates. The three continuous feed reactors are the continuously stirred tank reactor (CSTR), the plug flow reactor and the slurry-loop reactor.

Given sufficiently long residence times of the waste in the reactor vessel, farm digesters are quite stable.

The pollution control benefits of anaerobic digestion include: the reduction of manure biological oxygen demand (BOD), pathogen destruction, the destruction of volatile fatty acids and associated odorous compounds, reduced hydrogen sulfide emissions, and elimination of CH_4 emissions. CH_4 is a greenhouse gas that, once emitted to the atmosphere, contributes to greenhouse-induced global climate change.

Digester effluent contains the entire complement of nutrients of raw manure. No loss of manure fertilizer value results from anaerobic digestion. The effluent can be separated into its component liquid and solid parts. Most of the nutrient content of the manure is contained in the liquid portion, which is used in place of commercial fertilizer as a source of nutrients for plant growth. Manure solids can be composted, dried, and sold as compost or used for livestock bedding in place of purchased bedding materials.

The typical farm digester for a northern-tier state is a medium-rate digester like a Continuously Stirred Tank Reactor (CSTR), a Plug flow digester or a Slurry-Loop digester. The typical medium-rate farm digester produces about 60 to 80 cubic feet (1.7 to 2.3 cubic meters) of biogas per cow per day, 3 to 9 cubic feet of biogas per marketed hog per day, and 4 to 14 cubic feet per breeding sow per day. The typical medium-rate farm digester produces about 0.3 to 0.4 cubic meters of biogas per kilogram of volatile solids (VS) fed to the digester.

Medium rate farm digesters are designed to maximize volumetric productivity, or the biogas productivity per unit of digester volume, and digester net energy productivity. Digester net energy productivity is a measure of the energy productivity of the system that accounts for parasitic losses of energy for manure influent and digester heating. Minimum levels of digester volumetric productivity and net energy production for economic viability have been identified. Few conventional medium-rate farm digesters processing highly dilute manure with manure total solids content of less than 3% can meet these minimum design requirements.

At the digester design rules laid out in the literature, in the typical conventional medium-rate farm digester, waste is processed at an internal digester temperature of 35 degrees Celsius and a 20-day waste retention time in the digester. Manure is fed to the digester at an organic loading rate of 3 to 5 kilograms of VS per cubic meter of digester volume. Influent manure has a total solids content of 6 to 14%.

The economics of on-farm digestion are characterized by economies of scale and long-term declining capital costs. Minimum livestock herd sizes for economic viability are discussed in the literature. Based on the literature published since 1990, it appears that dairy herd sizes of 500 to 800 cows may be sustainable economically. The digestion of highly dilute swine manure in conventional medium-rate reactors appears to be economically infeasible, except at very large herd sizes. The minimum herd size for the economically viable digestion of high solids swine manure is near 4,000 head of market swine.

Anaerobic digestion in lagoons is economically viable at swine herd sizes of 2,000 to 3,500 head, but again this is limited to states in the southeastern or southwestern US.

Conditions are evolving that favor the continued economic viability of anaerobic digestion. These include, among others, the continuing consolidation of the livestock industry into larger herds, rising prices for liquid petroleum fuels, and the gradual evaporation of conditions of generation capacity surplus in the regional electricity grid. With excess capacity scarce, buyback prices for electricity generated on-farm and sold to the grid should rise. These evolving conditions promise enhanced economic viability for anaerobic digestion in the coming years.

Biochemistry of Anaerobic Digestion

Anaerobic digestion is a process of biological degradation of complex organic matter to stabilized organic waste, methane (CH_4) and carbon dioxide (CO_2) under oxygen-free conditions or conditions of anaerobiosis. The process occurs in nature in marshes, bogs, lake and pond sediments, and the gastrointestinal tract of ruminant livestock. (Hashimoto, *et al.,* 1980). During anaerobic digestion, a consortium of bacteria, many of which are strict anaerobes, catabolize complex organic polymers, degrading them to yield energy for bacterial maintenance and growth. The microbial degradation of organic polymers occurs in stages, each yielding intermediate products that are utilized as an energy source by bacteria in the next stage. During the final stage of anaerobic digestion, methanogenesis, most of the intermediate products are reduced to CH_4 and CO_2, which, under natural conditions, are lost to the environment in a gaseous form.

Four sets of bacteria are involved: hydrolytic, acidogenic, acetogenic, and methanogenic. Of these, methanogenic bacteria and acetogenic bacteria are strict anaerobes that cannot live in the presence of oxygen. Acidogenic and hydrolytic bacteria, which together are sometimes known as fermentative bacteria, can be either facultative bacteria, thus capable of living under both aerobic and anaerobic conditions, or strict anaerobes.

The bacteria involved in anaerobic digestion obtain energy through the transfer of electrons in the form of hydrogen (H_2^+) from one intermediate product of digestion to another. During this process, electrons are transferred from intermediate anaerobic digestion products with low affinities for electrons to intermediate products with higher electron affinities, making energy available to the bacteria.

The four sets of bacteria correspond to the four stages of anaerobic digestion: hydrolysis, acidogenesis, acetogenesis, and methanogenesis.

Hydrolysis is the process in which hydrolytic bacteria, using extra-cellular enzymes (or sometimes cell-associated enzymes), liquefy complex organic compounds to simpler forms, thus making them available for use by bacteria. Solubilized during digestion are such organic compounds as starch, pectin, cellulose, hemicelluose, lipids and proteins. The products of hydrolysis include simple sugars and groups of simple sugars (monomers and oligomers), amino acids, peptides, and long-chain fatty acids.

Acidogenesis is the process in which sugars, amino acids, peptides, long-chain fatty acids, and other low-molecular weight molecules are taken through the cell walls of acidogenic bacteria and metabolized to short-chain fatty acids, plus CO_2, H_2, ammonia (NH_3), sulfate and various alcohols. Short-chain fatty acids produced during acidogenesis include propionic acid ($C_3H_6O_2$), butyric acid ($C_3H_2CO_2H$), acetic acid (CH_3COOOH), and formic acid (HCOOH). The acidogenic stage is sometimes called the acid-forming stage.

Acetogenesis follows acidogenesis and utilizes the products of acidogenesis to produce acetate. Acetogenesis is the process in which syntrophic bacteria catabolize or degrade (with the release of energy) short-chain fatty acids like propionic and butyric acid, and homoacetogenic bacteria reduce CO_2 using hydrogen. Energy is made available to acetogenic bacteria during the reduction of CO_2, and the catabolism of propionic and butyric acid. The end product of both processes is acetate. Reduction is the process in which electrons are transferred from one molecule to another, resulting in an energy gain to the bacteria. During the catabolism of propionic and butyric acids, H_2 is reduced and propionic and butyric acids are oxidized. (Boone and Mah 1987)

Methanogenesis is the process in which methanogenic bacteria utilize the products of prior stages of anaerobic digestion to produce CH_4 and CO_2. During methanogenesis, acetate is cleaved and the resulting methyl group (CH_3) is reduced, forming CH_4 and CO_2. The CO_2 that is produced during acetogenesis and acidogenesis is reduced to CH_4 using hydrogen. Energy is gained from electron transfer during the reduction of CO_2 and the methyl group of the cleaved acetate molecule. (Ferguson and Mah 1987)

Of all of the CH_4 that is produced in the final methanogenic stage, about 70% derive from the catabolism of acetate, and the remainder from the reduction of CO_2. (Ferguson and Mah 1987) A small amount results from the catabolism of formate and methanol produced during acidogenesis. Of the acetate that is available for catabolism during methanogenesis, about 70% derive from the catabolism by acetogenic bacteria of volatile fatty acids other than acetic acid. (Colleran, *et al.*, 1982) The remainder is produced during acidogenesis. Most of the CO_2 that during methanogenesis is reduced to CH_4 derives from the catabolism by acidogenic bacteria of non-acetic volatile fatty acids like proprionic acid. The basic flow of the different processes is shown graphically in Figure 1.

In the acidogenic stage proper, about one-quarter of the short-chain acids production is in the form of acetic acid, and the remainder is in the form of volatile fatty acids (VFAs) other than acetic acid, mostly propionic acid. (Colleran, *et al.*, 1982) Other minor products include butyric acid and formic acid. Intermediate products include pyruvic acid ($CH_3COCOOH$), lactic acid ($CH_3CH(OH)COOH$), and succinic acid ($HOOCCH_2COOH$). Most of the carbon flow during anaerobic digestion is in the form of acetic acid and propionic acid. (Fischer, *et al.*, 1986)

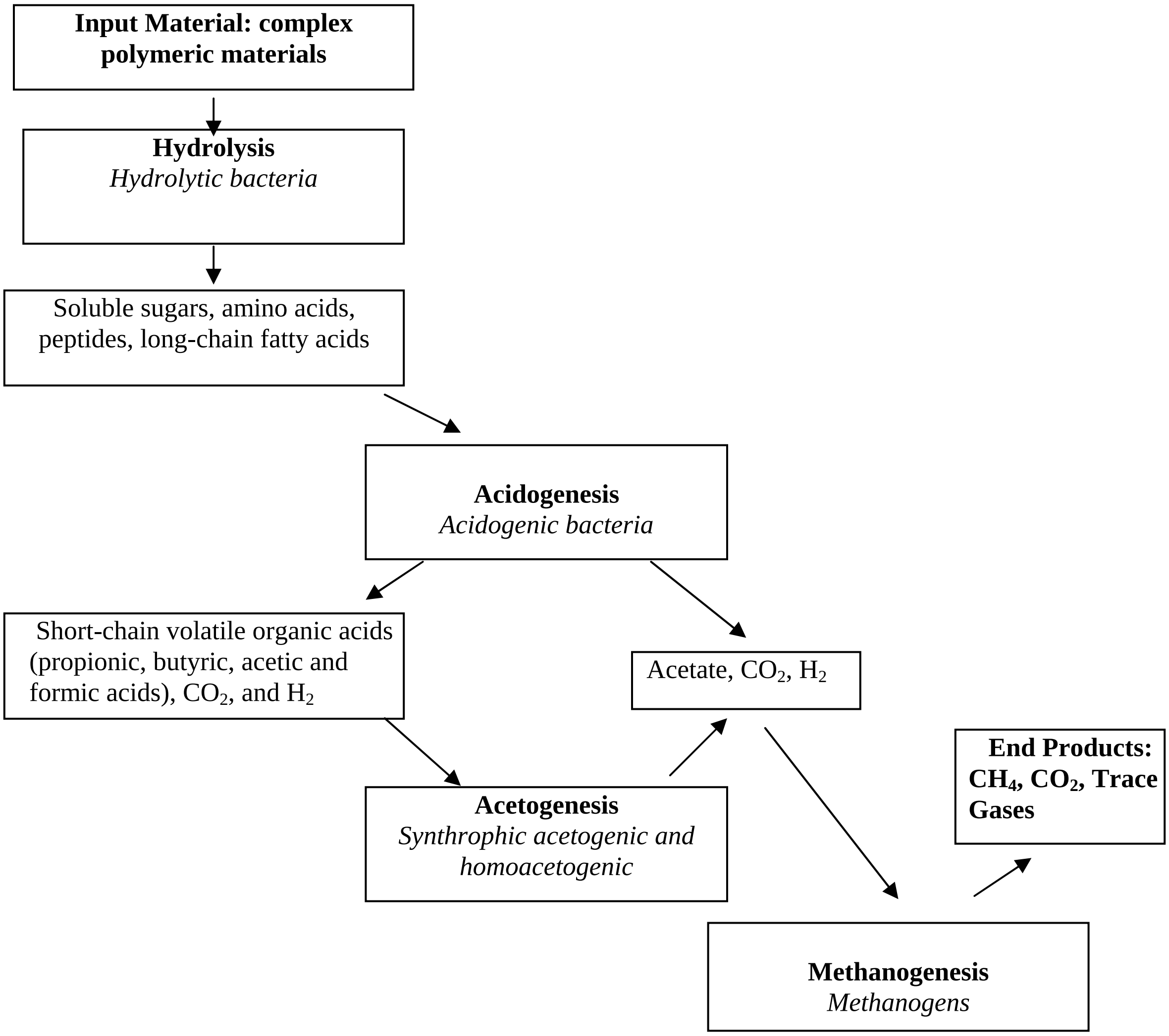
In the hydrolytic stage of anaerobic digestion, the enzymes that are employed include amylases (starches), cellulase (polysaccharides), lipases (lipids), and proleases and peptidases (proteins). (Breure and van Audel 1987).

The four bacterial populations are tightly coupled metabolically. The early stages of digestion provide the reduced products necessary for the growth of the bacterial populations of the acetogenic and methanogenic phase. In removing volatile fatty acids from the digesting substrate, acetogens maintain the conditions necessary for the survival of the methanogenic populations involved in the final stages of anaerobic digestion. Methanogens are intolerant of VFA levels higher than 4,000 to 5,000 milligrams per liter (mg/l).

The interrelationships, particularly between the acetogenic and methanogenic populations, are complex. Acetogenesis depends on the hydrogen concentration of the digesting material. At low hydrogen concentrations, which are maintained by the functioning of a healthy population of methanogenic bacteria, acetogenesis is unhindered, resulting in the continued conversion of proprionic acid to acetate. However, at high partial pressures of hydrogen, the acetogens cease to operate as efficiently, resulting in reduced removal of propionate and other VFAs, and their progressive accumulation in the digesting substrate. (Stevens 1980) Without removal of these compounds, methanogenic activity ceases, leading to failure of the anaerobic digestion process. (Boone and Mah 1987) As noted above, the methanogens use hydrogen to reduce CO_2, thereby removing it from the digesting environment.

The most sensitive of the four populations acting during anaerobic digestion are is the methanogenic population. The conditions necessary for the maintenance of a healthy population of methanogenic bacteria are listed in Table 1. Methanogenic populations are especially sensitive to acidity, volatile fatty acid concentration, and concentrations of free ammonia and ammonium ion in the digesting substrate. The optimal temperature for naturally occurring methanogenesis is about 35 to 37 degrees Celsius (95 and degrees Fahrenheit). The optimal temperature for methanogenesis, it might be noted,

Figure 1. Anaerobic Digestion



is slightly lower than the optimal temperature for hydrolysis, which is nearer 40 degrees Celsius. (Rivard 1996)

The conditions necessary for anaerobic digestion are met when the necessary conditions for the survival and growth of the most sensitive of the bacterial populations that are involved in anaerobic digestion—the methanogens-- are met. Suboptimal conditions for growth of the methanogenic population short of methanogen death result in a slower pace of anaerobic digestion, leading to slower production of CH_4 and CO_2.

Table 1. Necessary Conditions for Mesophilic Digestion

Environmental Factor	**Inhibition Threshold**	**Optimal Level**	**Operating Range**
Temperature	15C[a]	35-37	30-35
pH	6.0-6.5[a]	7-7.2	6.8-7.6
Alkalinity	NA	2,500-3,000 mg/l[b]	NA
Volatile fatty acids	4,000-5,000 mg/l[b]	300 mg/l[b]	200-2,000 mg/l[b]
Ammonium ion (NH_4^+-N)	1,500-3,000 mg/l[b]	NA	< 1,500 mg/l[b]
Free ammonia (NH_3)	1,500-3,000 mg/l[b]	NA	< 1,500 mg/l[b]

[a] complete inhibition

[b] milligram per liter

Sources: Fischer, *et al.,* (1986), Hashimoto, *et al.,* (1980), Hill (1983), Hill (1983), Horton (1979), Jones, *et al.,* (1982), NAS (1977), Rivard (1996, Stafford, *et al.,* (1978), Van Velsen and Lettinga (1979)

Digester temperature is important. Fermentative bacteria can achieve catabolism at lower temperatures than methanogenic bacteria. This leads to generally higher volatile fatty acid concentrations in the digesting waste and some suppression of methanogenic activity, leading to reduced biogas production and reduced levels of waste stabilization. At too low a digestion temperature, failure of anaerobic digestion occurs. (Jewell, *et al.,* 1982)

During anaerobic digestion, the onset of fermentation is rapid. The level of volatile fatty acids (VFAs) in the digestion organic waste rises rapidly during the first one to four days of digestion. (Gunnerson and Stuckey 1986) Under optimal environmental conditions, the slower growing acetogens and methanogens begin to remove substantial quantities of VFAs after the fifth day of digestion. At suboptimal environmental conditions, the onset of substantial VFA removal is delayed by slower growth of the acetogenic and methanogenic bacterial populations, and the degree of removal is lower, resulting, as noted above, in suppressed rates of biogas production.

Suboptimal conditions for anaerobic digestion include: waste pH less than 6.8, digestion temperature lower than 35 degrees Celsius, VFA levels more than 600 mg per liter, and ammonia and ammonium ion levels above 1,500 mg per liter (see Table 1). Under suboptimal environmental conditions, bacterial populations are weighted toward the acidogenic and hydrolytic types.

The specific bacterial colonies that are favored during anaerobic digestion depend on the composition of the waste being digested and the environmental conditions of digestion. (Fischer, *et al.*, 1986) For instance, the bacteria *Ruminococcus* and *Bacteroid*es utilize cellulose and hemicellulose as an energy source. (Marty 1986) During digestion of an organic waste high in available cellulose and hemicellulose, the populations of these two bacteria expand in response to the availability of suitable substrate. The total mass of bacteria that is involved in anaerobic digestion is small, equal to about 5% of the digesting total solids. (Fischer and Ianotti 1981) The methanogenic part might comprise only about 1 to 5% of these bacteria by weight.

The limits to anaerobic digestion are discussed extensively in the literature. These include: the limits posed by the sensitivity of the methanogenic population involved in anaerobic digestion, particularly to VFA concentration and pH; and the limits to the biodegradability of complex polymers through enzymatic hydrolysis. (Colleran, *et al.*, 1982, Fischer, *et al.*, 1986, Klass 1998) The first of these was just discussed. The biodegradability of many organic wastes is influenced by the 100% non-degradability of lignin during anaerobic digestion. (Fischer and Ianotti 1981) Many organic wastes include a substantial cellulose and hemicellulose component. In themselves, cellulose and hemicellulose are readily catabolized during anaerobic digestion. However, in many organic wastes, much of the cellulose and hemicellulose content of the waste is structurally bound-up with lignin, which forms a barrier that partially protects the cellulose and hemicellulose form enzymatic hydrolysis. (Van Velsen 1981, Tsao 1985)

The degree of non-degradability increases with increasing lignification of the waste. About 50% of lignified cellulose is available to enzymatic hydrolysis. (Hashimoto, *et al.*, 1980) For a typical farm organic waste, 30 to 60% of the organic part of the waste is protected from enzymatic hydrolysis by this lignin barrier. (Mosey 1998)

In practice, this means that for most complex polymeric materials, only about 50 to 65% of the organic part or volatile solids part of the waste ultimately is available for conversion to biogas. The rest is refractory material that is unavailable to bacteria.

The amount of time that is required to yield this level of digestion varied with temperature, the other environmental conditions of digestion, and the degree of polymerization of the waste being catabolized. Under optimal conditions, for heavily lignified wastes, upwards of 120 days is required for maximum conversion of organic waste to CH_4 and CO_2. (Gunnerson and Stuckey 1986) With less lignified wastes, less than 30 days may be required for digestion.

As a biological process, anaerobic digestion is a slow process. Most of the energy of catabolism ultimately is unavailable to the bacteria involved, but rather is contained in the evolved biogas. (Hashimoto, *et al.,* 1980) The resulting yield of bacterial biomass is small. However, the amount of waste that is degraded during anaerobic digestion is considerable. Because of this, it is possible to utilize the unique metabolism of anaerobic digestion to process organic wastes on an industrial scale, reducing them to a stabilized conditions, while generating commercially valuable CH_4 gas as a byproduct. Most engineering of the anaerobic digestion process involves continuous waste processing under controlled conditions.

Anaerobic Digestion in Waste Processing

In waste processing in industry and agriculture, anaerobic digestion is designed as a continuous process. Waste is treated as it is produced, thereby avoiding the need for interim storage. The process is usually designed to accommodate a continuous flow of waste. The anaerobic digestion process itself is, to various degrees, optimized to result in the maximum degree of waste stabilization with the least commitment of resources. Conditions for balanced bacterial growth are created and maintained in the controlled conditions of an engineered structure, called a waste-processing reactor. The processing of the waste is standardized, both in terms of the conditions within the reactor and in terms of daily operations.

The minimum conditions necessary in the processing reactor or lagoon include: anaerobiosis, temperatures of at least 25 degrees Celsius, and volatile fatty acids and ammonia levels below threshold levels for toxicity to methanogenic populations in the digester.

Anaerobic digesters processing organic wastes are designed around four basic parameters: digester temperature, influent waste total solids content, waste retention time, and organic loading rate.

Reactor Temperature: Temperature in a working reactor optimized for waste processing is set at or near the optimal temperature for maximum bacterial growth. For the bacteria that are present during anaerobic digestion, two temperature optima are evident: 35 to 40 degrees Celsius; and 55 to 60 degrees Celsius. It is also possible to process organic wastes at ‘psychrophilic’ temperatures, near 25 degrees Celsius.

Waste processing at thermophilic temperatures is rapid, complete in a few days. Waste processing in the 35 to 40 degree Celsius ‘mesophilic’ range proceeds at slower rates than digestion at reactor temperatures in the 55 to 60 degree Celsius range or ‘thermophilic’ range. The rate of digestion declines at reactor temperatures between these two temperature optima and at reactor temperatures below 35 degrees Celsius. At psychrophilic temperatures, waste processing is very slow, taking many months to complete. In practice, this means that waste processed in a reactor operating at psychrophilic temperatures needs to be retained in the reactor for long periods of time, months, which results in the need for reactors with very large working volumes. By contrast, waste processed in a reactor operating at thermophilic or mesophilic temperatures needs to be retained in the digester vessel for shorter periods of time, which results in the need for smaller digester vessel sizes.

Hydraulic Retention Time: Given a reactor temperature, waste is retained long enough in the reactor to result in a significant degree of volatile solids destruction. At a given temperature, the degree of volatile solids destruction depends on the length of time that the waste is kept in contact with the hydrolytic, acidogenic and other bacteria that comprise the bacteria population of the reactor. For design purposes, retention time is optimized near the level of organic waste retention where marginal rates of VS degradation are maximized and where further lengthening of retention times yields only small incremental increases in organic waste degradation. Anaerobic reactors are designed to handle dilute wastes high in water content. In a well-mixed waste, the solid degradable part of the waste is held in suspension. For such a well-mixed organic waste, a single waste retention time is defined, called the hydraulic retention time (HRT).

For well-mixed wastes with substantial amounts of total solids, a 10- to 25-day waste retention time is typical at mesophilic temperatures. At thermophilic reactor temperatures, HRTs for well-mixed wastes are shorter, about 5 days.

In most waste processing, waste is continuously fed to the reactor. As it enters, it displaces an equal amount of largely digested waste. However, also exiting the reactor are bacteria, including the slow growing methanogenic and acetogenic bacteria. At mesophilic temperatures, at HRTs of less than 10 to 12 days, the removal rate of methangens from the tank through displacement by newly fed manure exceeds the rate of bacterial growth, resulting in net methanogen washout and digester failure. (Aubart 1983, Hill 1983, Smith 1980) This effectively establishes the minimum length of waste retention in the reactor.

Influent Total Solids: The total solids content of the influent waste determines the amount of organic matter to be digested. At any given waste retention time, the total solids content of the waste influent is limited by the processing capacity of the bacteria involved in anaerobic digestion. The presence of too much organic material can, if hydraulic retention times are too short, lead to the production of volatile fatty acids at rates that exceed the ability of the acetogenic and methanogenic bacterial populations to remove them. This results in depressed rates of anaerobic digestion or even to outright digester failure.

The level of influent solids also determines the level of dilution of the waste in the reactor. By adding water to the organic part of the waste, dilution acts to increase the volume of the waste, thereby increasing the size of the reactor vessel and its costs.

Organic Loading Rate: Organic loading rate is the rate of volatile solids feed to a reactor per unit of reactor volume. The organic loading rate is set to realize a desired digester hydraulic retention time, given an influent waste of some known total solids content. Extensive analysis of loading rates for different influent wastes at different hydraulic retention times has resulted in agreement on a suite of recommended loading rates for the typical reactor configurations that are used in reactor design and operation.

The controlled anaerobic treatment of organic wastes has been in use for decades. Anaerobic digestion reactor types that have been developed and are either in commercial use or are in the experimental stage of development are listed in Table 2. These are grouped by

Table 2. Anaerobic Digester Types

Continuous Feed

Liquid

Agricultural Waste
Covered Anaerobic Lagoon
Anaerobic Sequencing Batch Reactor

Industrial and Municipal Wastewater

Upflow Anaerobic Sludge Blanket Reactor
Anaerobic Filter Reactor
Anaerobic Packed Bed Reactor
Anaerobic Fluidized Bed Reactor
Anaerobic Sequencing Batch Reactor
Anaerobic Fixed Film Reactor
Expanded Bed Reactor
Anaerobic Contact Reactor

Slurry

Agricultural Waste

Continuously Stirred Reactor (CSTR)
Plug Flow Reactor
Slurry-Loop Reactors

Continuous Feed

Solid

Agricultural Waste
Dry CSTR

Batch Feed

Solid

Agricultural Waste

Batch Reactor
Sequential Batch Reactor

Mixed Municipal Solid Waste

MMWS Landfill
Sequential Batch Reactor

Psychrophilic: Anaerobic lagoons, MMSW landfills
Mesophilic and Thermophilic: CSTR, Batch, Sequential Batch Upflow Anaerobic Sludge Blanket Reactor, Anaerobic Attached Filter Reactor, Anaerobic Packed Bed Reactor, Anaerobic Fluidized Bed Reactor, Suspended Particle Reactor, Anaerobic Contact Reactor

Sources: Biljetina (1987), Fannin and Biljetina (1987), Hobson and Wheatley (1993), Lusk (1996), Sax and Lusk (1995), Whittier, *et al.*, (1993)

degree of water dilution, and also by type of waste and waste treatment.

Most industrial and municipal waste is highly dilute wastewater. These typically are treated in what are known as ‘high-rate’ reactors. These include: the Upflow Anaerobic Sludge Blanket Reactor, the Anaerobic Filter Reactor, the Anaerobic Packed Bed Reactor, the

Anaerobic Fluidized Bed Reactor, the Anaerobic Sequencing Batch Reactor, the Anaerobic Fixed Film Reactor, the Expanded Bed Reactor, and the Anaerobic Contact Reactor. In such high rate reactors, waste is retained in the reactor for 1 to 5 days, before exiting the reactor as stabilized waste.

Livestock waste can be in a highly dilute liquid form, the form of a slurry, or in a solid form. Highly dilute livestock waste is digested in anaerobic lagoons and, potentially, depending on further technological development, in the future may be digester in high-rate Anaerobic Sequencing Batch Reactors. Anaerobic lagoons are very slow-rate reactors, with waste retention times of greater than 120 days.

Livestock waste that is in a less dilute slurry form is digested in what can be called ‘medium-rate’ reactors. These include the Continuously Stirred Tank Reactor, the Plug Flow Reactor, and the Slurry-Loop Reactor. Waste is retained in the digester typically between 10 and 25 days. Relatively little livestock manure is digested in a solid form.

Conventional covered landfills are a form of extremely slow-rate of digesters, processing waste over periods of 20 years or more. Investigations are underway to determine whether the rate of waste processing in landfills can be accelerated through leachate recirculation through the waste. It is also possible to digest waste in a sequential batch reactor.

In practice, most digesters operate at mesophilic temperatures (35 to 40 degrees Celsius). Covered landfills and lagoons operate at lower psychrophilic temperatures (25 degrees Celsius). Anaerobic digestion at thermophilic temperatures (55 to 60 degrees Celsius) is rare in waste treatment applications.

The engineering of anaerobic digestion as a waste processing technology is organized around the effort to optimize the mix of reactor temperatures, hydraulic retention times, influent total solids and organic waste loading rates. The purpose of this optimization is to achieve the maximum degree of waste stabilization with the least commitment of resources. The biochemical conditions necessary for anaerobic digestion to begin and be sustained set the limits on what may be done with digester design. Other limits arise from the nature of the waste streams in question, prospective biogas uses, and climate.

Finally, in 1996 in the US, about 25 digesters were in operation processing farm wastes. (Lusk 1996) An additional 4 to 5 have been constructed since then. On the order of several hundred anaerobic digestions are in operation processing municipal and industrial wastewater elsewhere in the US economy. (Klass 1990)

Farm Digester Applications

Feedlot livestock produce a large amount of digestible volatile solids on a continuous basis. A 500-cow dairy farm produces about 3 to 3.5 tons of VS per day, and a 5,000 head finishing swine feedlot about 2.5 tons of VS per day.

As noted above, five farm digester types are commercially available: the continuously stirred tank reactor (CSTR), the plug flow digester, the slurry-loop digester, the batch reactor, and the covered anaerobic lagoon.

The batch reactor is a periodic feed reactor, which is batch loaded, sealed for digestion, and then unloaded as a batch 40 days after the initiation of digestion. Due to the batch nature of the waste processing with this type of reactor, batch reactors are not widely used on feedlots, where the production of waste is continuous. (Thornton 1978) It has been suggested that batch digestion might be useful in the processing of poultry manure. Poultry manure is managed predominantly as a solid in deep pit stacks. The removal of the manure is periodic, timed to coincide with the turnover of the flocks. It has been suggested that a batch digester be run to coincide in digester loading and unloading with this periodic deep pit stack clean-out. (Minnesota Department of Agriculture 1993)

The covered anaerobic lagoon is a continuously fed digester with no waste mixing and heating and very long waste retention times, 120 days or more. The waste is usually very dilute and is collected and moved to the lagoon through hydraulic flushing. Due to the virtual cessation of digestion at temperatures below 15 degrees Celsius (59 degrees Fahrenheit), the use of anaerobic lagoons for digestion is generally limited to more southerly states, especially of the southeast and southwest. As noted above, it is considered a very slow-rate reactor.

The CSTR, plug flow and slurry-loop designs are medium-rate, continuous-feed reactors, processing waste over periods of 10 to 25 days. Almost all farm digesters operated in northern cold climates are of this variety.

In addition to the five conventional reactor types, there also are a number of high-rate reactors that have been applied to farm digestion on an experimental basis. These were listed above in Table 2. None is yet in commercial use on-farm.

The general fit of manure collection and storage systems to digester design type is shown in Table 3. With its high manure solids content, as currently managed, dairy manure is well suited to digestion in any of the three medium rate reactors, e.g., CSTR, plug flow, or slurry-loop. Due to large pre-digestion losses of volatile solids on drylots, drylot storage of beef or dairy manure is a poor fit to any of these reactor types. (Ward 1983)

In general, unless managed as a solid or unless special efforts are taken to limit dilution, the digestion of swine manure is limited to lagoon processing and, possibly, depending on future technological developments, high rate third-generation reactors. The CSTR design is poorly suited to the digestion of dilute swine manure. (Edelman 1984, Zhang, *et al.*, 1997) Hydraulic flush collection systems and below barn swine manure storage in particular result in substantial dilution of livestock manure. As excreted, dairy manure is about 12% total solids and swine manure about 8%. Hydraulic flush systems typically lower this to the 0.5 to 1.5% range.

(Fischer and Ianotti 1981, Sweeten, *et al*., 1984) Due to heavy use of high pressure hoses, incidental spillage during swilling, and leakage of groundwater below barn, the total solids content of swine manure in below barn pits is typically in the 1.5 to 3% range. (Friman, *et al*., 1986, Moser 1998, Nielson 1985, Roos and Moser 1997, Zhang, *et al*., 1998, Zhang and Day 1996)

By contrast, managed as a thick slurry, swine manure is well suited to digestion in a CSTR.

As will be discussed below in the section on the economics of anaerobic digestion, the economic viability of anaerobic digestion also depends on the existence of large on-farm electrical loads. (Hobson and Wheatley 1993) Electrical loads on beef feedlots are quite small. This acts to additionally limit the potential for digester deployments on beef feedlots. (Smith 1978)

Table 3. Digester Type Suitability Based on Housing and Manure Management

Animal Type and Housing	**Manure Collection**	**Characteristic Total Solids (%)**	**Digester Type**
Dairy			
Drylot	Periodic Scrape	30	None
Freestall or Stanchion	Hydraulic Flush	1 to 2	Lagoon
Freestall or Stanchion	Mechanical Scrape	8 to 14	Plug Flow, Slurry-Loop

			or CSTR
Swine			
Confinement Barns	Mechanical Scrape	6	CSTR
Confinement Barns	Slatted Floor/BBP[a]	2	Lagoon
Confinement Barns	Slatted Floor/BBP, Pit Recharge or Hydraulic Flush	1	Lagoon
Confinement Barns	Slatted Floor/BBP, Heightened Water Management	3	CSTR or Lagoon
Beef			
Drylot	Periodic Scraping	30	None
Turkeys and Layers			
Confinement Barns	Deep Pit Stacks	high	Batch

[a] BBP = below barn pit storage

Practicality for on-farm use is an important consideration in digester applications. Given the many demands on a feedlot owner’s time, farm digesters must be able to tolerate occasionally irregular feeding and temperature variations in the digester vessel. It also must be sufficiently stable to tolerate irregularities in feed content, for instance, occasional feeding with high ammonia feeds or manure laced with antibiotics, other feed additives, or detergents. This is a concern with conventional medium-rate farm reactors. Safety margins are built usually built into the design of medium-rate digesters, usually in the form of lengthened waste retention times.

Anaerobic digestion at thermophilic temperatures (55 degrees Celsius) is rare in US agriculture. Digestion at these temperatures is less stable than at mesophilic temperatures (35 degrees Celsius), particularly in response to even small temperature fluctuations in the reactor vessel and to the presence of small amounts of farm antibiotics. (Fannin 1987, Hashimoto, et al., 1981, Sandvist 1985) Anaerobic digestion at high temperature is also limited by the energy demands of influent and reactor heating. (Hobson 1990, MacKie and Bryant 1995) For this reason, most farm reactors operate at mesophilic temperatures.

In stabilizing the organic part of livestock waste, anaerobic digestion acts to reduce the biological oxygen demand (BOD) of manure, which is a key determinant of its potential to contribute to water pollution. Digestion also destroys many of the odorous compounds that form in manure during storage and contribute to odor complaints. A complete listing of the environmental benefits of the farm digestion of manure is given in Table 4.

Table 4. Environmental Benefits of Digestion

Environmental Advantages

Reduced Biological Oxygen Demand
Reduced Chemical Oxygen Demand
Odor Reduction
Pathogen Destruction
Reduced Fly and Rodent Problems
Increased Nitrogen Availability for Crop Growth
Improved Manure Physical Quality
Greenhouse Gas Emission Reduction

Environmental Drawbacks

Possible Increased Ammonia Volatilization
Possible Increased Nitrate Leaching Rate

Sources: Chessire (1986)**,** Clanton (1991), Lusk (1998), Moser (1998), National Academy of Sciences (1977)**,** Nielson (1985), Olson (1985), Roos (1992)

Finally, about 30 farm digesters are in operation in the US. Of digesters of the CSTR, plug-flow and slurry-loop variety, most deployments are at dairy farms. (Lusk 1997) Only a few working digesters are located on swine feedlots. Of the dairy deployments, these are nearly equally divided between the three commercially available reactor designs.

Most anaerobic digestion on swine farms in the US takes place in anaerobic lagoons. A growing number of these have received covers and are capturing biogas for purposes of energy production.

About 470 digesters, most farm digesters, are in operation in western Europe, up from about 200 in 1980 and nearly the same as in the late 1980s and early 1990s. (Klass 1998, Coombs 1990) Anaerobic digestion is heavily subsidized throughout the European Union.

Digester Applications in Minnesota

Due to it’s cool spring and fall climates and cold winters, anaerobic lagoons are not recommended for use in Minnesota. As a result, potential digester applications in Minnesota are limited to conventional medium-rate digester types like the CSTR, plug flow and slurry-loop designs. In the future, it is possible that third generation retained biomass reactors could be used to digest highly dilute swine wastes, but this will depend on future technological development.

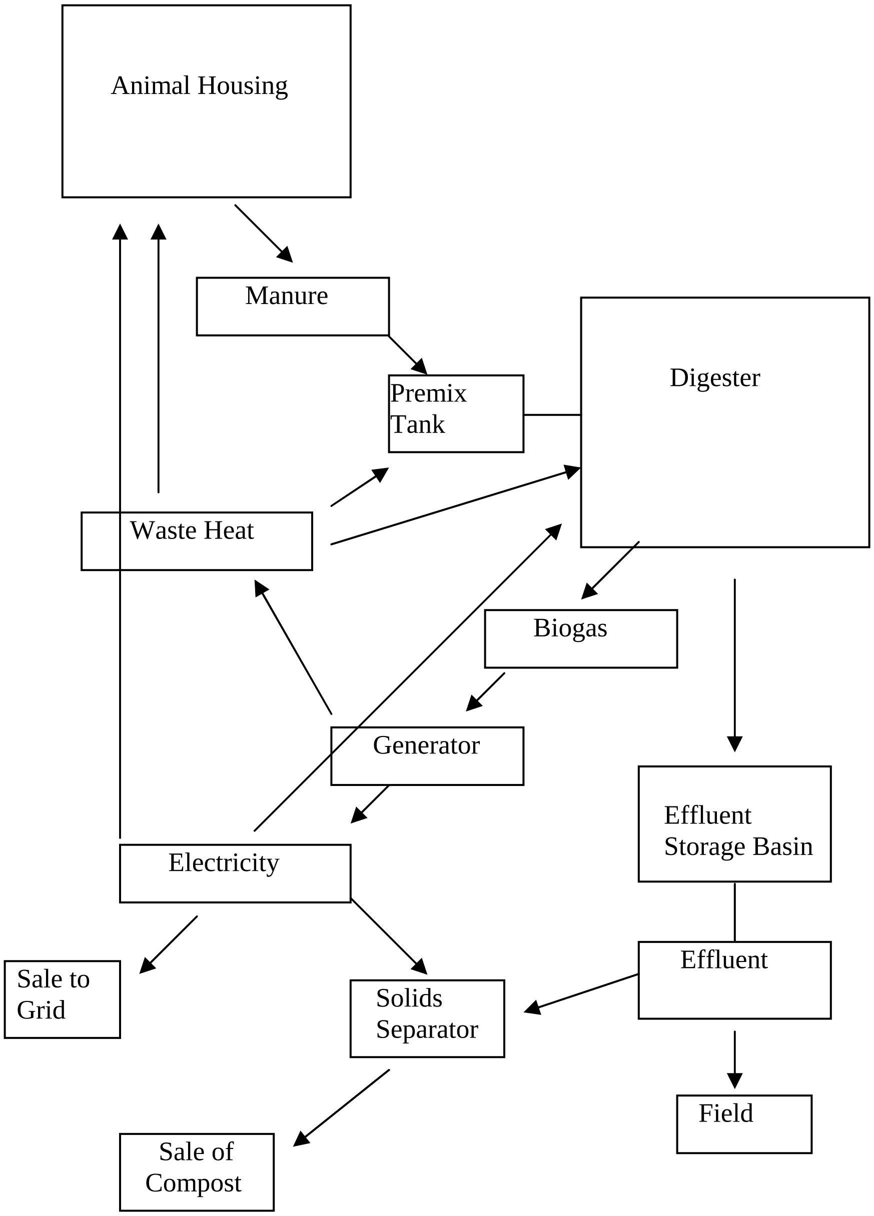
One on farm digester is currently in operation in Minnesota on the Haubenschold farm near Princeton, Minnesota. (Nelson and Lamb 2000)

Physical Make-Up of a Farm Digestion System

A medium-rate farm digester is comprised of a series of components, including the digester vessel, a mixing tank, pumps and piping to move the manure into and out of the digester, an outdoor effluent storage basin or tank, and either a flare, an engine or a boiler in which to combust digester biogas.

Manure is collected in confinement barns or buildings and is moved to the digester site through gravity drain gutters or mechanical scraping (see Figure 2). It is fed to the mixing tank, where it is mixed and heated. It is then pumped into the digester or reactor vessel, where it is retained and processed for 15 to 25 days, exiting through a displacement system in which entering manure displaces an equal volume of digestate or digested manure. Exiting digester effluent is then pumped to an outdoor storage basin or tank to await field application as a fertilizer and soil amendment. Some systems add an intermediate solid separation phase prior to outdoor storage in which effluent solids are removed using a vibrating screen or screw press, and are either used as bedding on-farm or are sold commercially as compost.

Figure 2. Schematic Representation of Digester Set-up for A Conventional Medium-Rate Farm Reactor



Supporting systems for a farm digestion system include: the confinement barns or buildings, the electric grid and its on-farm components, pipelines for delivery of biogas off-site, if that is the chosen use, and piping for on-farm space and water heating utilization of waste heat produced during biogas combustion.

The reactor vessel of a conventional medium-rate farm digester is typically configured in a squat silo form, an elongated tubular form, or in a horseshoe form, depending on reactor design. Construction is usually of concrete, with heating components fixed to the walls. Hot water is circulated through the piping to these heating components or heat exchangers inside the digester, which maintain a constant digester temperature in the range of 30 to 40 degrees Celsius. The vessel is sealed to maintain anaerobic conditions. Mixing through mechanical means (paddle wheels) or gas injection may or may not be used, again depending on reactor type. The CSTR design employs active gas mixing, while the slurry-loop and the plug flow designs rely on convection inside the digester vessel, solids settling, and the friction of the manure moving against the digester walls to promote manure mixing.

The digester vessel contains a head-space to accommodate accumulating biogas. Biogas is removed from this headspace for use as gaseous fuel in engines or boilers, or is flared. Biogas typically is removed from the digester as it is produced. Some CSTRs incorporate an interior floating roof under the permanent roof that allows for the temporary pressurized storage of biogas for up to 24 hours.

Gas use is typically in the form of combustion for electricity generation using stationary diesel engines. No gas clean-up is required for diesel uses of digester biogas. Electricity is used primarily on-farm in place of electricity purchased from the grid typically costing $0.06 to 0.07 per kilowatt-hour. Excess generation is sold back to the grid at rates that are contractually determined.

Waste heat from combustion is captured by the water jacket of the engine and from the diesel exhaust and is used for digester heating and, if there is a surplus, for water and space heating on-farm.

Pumping is handled through the use of reversible pumps. Piping must be oversized and specially designed to avoid sharp right angle turns where clogging by high TS slurries can occur.

Up to six months of manure storage is necessary to accommodate the digester effluent produced during the late fall, winter and early spring, when land application of manure should be avoided and, in some locales, is illegal. The pre-mix tank, where used, is typically sized for 2 days storage.

In the dairy industry, manure collection in confinement buildings is typically in the form of mechanical scrape gutter systems, aisle scrape systems in free-stall barns using farm tractors, flush systems, or a combination of the two e.g., hydraulic flush for the milking parlor and mechanical scrape for the barns. Most swine operations utilize slotted floors and either below barn pit storage or transport from shallow below barn pits to outdoor storage using mechanical gutter scraping or hydraulic flushing. With below barn pit storage, manure collects below barn and a portion of it daily is removed to the digester for processing.

As discussed above, three medium-rate reactor designs are commercially available for on-farm use: the plug flow, the CSTR and the slurry-loop designs. The plug-flow digester is configured as an elongated tube through which high TS manure enters at one end as a plug, is retained for 20 to 25 days, and exits at the other end as stabilized organic waste. The plug is maintained by the viscosity of the manure. Most hydrolytic and acidogenic activity occurs near the front end of the tube, most methanogenic activity near the rear end prior to exit from the digester. The digester is insulated to limit heat losses. Movement of the plug through the digester is accomplished through the daily feed of the fresh manure to the digester. The feed of fresh manure results in the displacement of an equal volume of digester manure down the length of the tube.

The plug flow-type digester usually is limited in its applications to the digestion of high total solids manure like non-dilute dairy manure with manure total solids of 12 to 14%. Below this level, problems often develop in the reactor involving liquid-solid separation, leading to scum formation on the surface of the liquid and the suppression of biogas production.

The CSTR is configured as a squat cylindrical silo, with a large volume to surface area ratio to minimize digester heat losses. Four to ten percent total solids manure is fed to the digester daily, resulting in the displacement from the digester of an equivalent volume of largely, though not wholly, digested manure from the reactor’s interior. For very high TS manure, some dilution in the mixing tank is required. The manure is well mixed in the digester through the use of mechanical mixing or gas injection, which limits the settling of solids, maintains the bacteria in constant contact with the manure substrate, and maintains an optimal temperature for digestion throughout all parts of the digester. This results in faster biological degradation of fed organic waste than is true with plug flow digestion.

Since it can tolerate a wide range of manure total solids content (4 to 10%), the CSTR design is generally more forgiving of periodic variations in the TS content of fed manure than the plug flow reactor, and more versatile.

The slurry-loop reactor is laid out in a loop or horseshoe arrangement with no mixing. A high total manure solids content of at least 8% is recommended. As with the other reactor designs, the slurry-loop reactor is well insulated to limit heat losses to the environment. The horseshoe configuration increases the ratio of volume-to-surface-area, thereby also limiting heat losses. Along with its ability to tolerate lower total solids manure, this constitutes its principal advantage over the plug flow design. Mixing is accomplished through convection within the digester vessel. This acts to limit the complexity of the system and its vulnerability to mechanical breakdown. These is constitutes its principal advantage over the CSTR reactor design, an advantage it shares with the plug flow design. The capital costs associated with the slurry-loop reactor design also are generally lower than those associated with the CSTR design.

Regardless of reactor design type, all components of the digestion system are closely interrelated. The physical set-up of digestion system determines its efficiency and economic attractiveness.

In an efficient system, to limit the amount of digester biogas needed to raise the temperature of the manure influent to necessary levels, fresh manure is expeditiously transported to the digester after excretion. Pumping energy uses are minimized through the use of gravity feed gutters to move manure to and from the digester, and by the topography of the farmstead. Manure total solids contents are maintained close to optimal levels for peak digester net energy performance. Peak net energy performance in a heated medium-rate reactor requires that manure total solids be maintained at level of at least 4%, and more generally, as high as possible consistent with manure pumping capabilities of the system (see below). This requires close attention to water management in confinement barns and levels of dilution during influent mixing.

The heat exchange components of the system are maintained close to optimal levels of efficiency for the same reason, and are appropriately sized. The diesel engine is periodically serviced. In cold climates, precautions are taken against gas line freeze-up, which will reduce the efficiency of the entire system.

Finally, waste heat is utilized to maintain barn temperatures above freezing. This eliminates the danger of frozen manure in gutters, and reduced the loss of heat from the excreted manure. At reduced rates of influent heat loss, the digester operates at higher levels of net energy production, which increases the economic viability of the system.

As noted above, in addition to medium-rate reactors, high-rate reactor designs also exist, as do slow-rate lagoon designs. The physical set-up of high-rate second and third-generation reactors is little different from that of CSTRs. High dilution to 1 to 2% total manure solids is necessary, but because the reactors are designed to retain microbial biomass in the reactor even in the face of high loading rates and short waste retention times, reactor volumes are much smaller than is true for conventional farm digesters. Second- and third-generation reactors are discussed in more depth below. Suffice it here to say that it has yet to be demonstrated that that are suited to on-farm use due to their high levels of complexity, required day-to-day management, and capital costs.

The physical set-up of a covered anaerobic lagoon is similar to that of a CSTR, plug-flow or slurry-loop system. The principal difference is that the manure is moved directly to the lagoon without mixing or heating, and waste retention times are 4 to 10 times as long in the covered lagoon as in the conventional farm digester. Given the long retention times, lagoons are much larger than conventional farm digesters. As noted above, anaerobic lagoon use in cold climates is limited by the 15 degrees Celsius (65 degrees Fahrenheit) temperature threshold required for the on-set of anaerobic digestion.

Farm Digester Stability: Medium-Rate Farm Reactors

As discussed above, digester instability in a conventional medium-rate farm digester results from digester washout of bacteria, the accumulation of toxic substances in the digester through high rates of and variations in digester feeding and antibiotic use, and large rapid variations in digester temperature.

At characteristic manure total solids and characteristic reactor temperatures, all these sources of instability can be and typically are addressed during reactor design by lengthening digester hydraulic retention time (HRT). An attenuated HRT relaxes the constraint imposed by digester wash-out around 8 to 10 days and constraints imposed by antibiotic effects and effects of temperature fluctuations or fluctuations in feeding rates on methanogenic populations at HRTs near this critical level. This is accomplished by reducing the organic loading to the digester.

The typical medium-rate farm digester operates at an HRT of at least 15 days, and more often than not, 20 to 25 days. This can be shortened somewhat by raising the temperature of the digester to 37 to 40 degrees Celsius, but this comes at a price of increased energy consumption for digester heating.

Theoretical calculations of optimal waste retention times are lower than either the retention times employed in practice in working farm digesters or those that are recommended for use in working digesters. (Chessire 1986) At characteristic design, theoretical calculations suggest an optimal period of waste retention in a conventional medium-rate farm digester of 10 to 11 days. (Hill 1983, Hill 1983) The difference between these estimates and retention times actually in use represents the safety factor built into digester design to remove the potential for digester upset.

With this safety factor built-in, medium-rate farm digesters are quite stable in operation and able to tolerate variations in organic loading rates, irregularities in digester feeding, and fluctuations in reactor temperature. (Hawkes 1979, Hobson 1990, van Velsen and Lettinga 1979, van Velsen and Lettinga 1981) In practice, farm digesters, with their large heat capacities, are protected against most short-term fluctuations in digester heating. (Hobson 1990) Digester stability can be enhanced by adding buffering capacity to the reactor in the form of bicarbonate or sodium hydroxide. (Fannin 1987)

In general, medium-rate digesters processing dairy manure are most stable; in these reactors, lower levels of biodegradability of complex manure carbohydrates allows methanogenic bacteria to more easily keep pace with acidogenic bacterial populations, thus contributing to enhanced digester stability. (Hill 1983) With their long HRTs, plug flow digesters are very stable. (Fischer, *et al.,* 1986) While employing shorter waste retention times, and utilizing a more biodegradable feedstock, CSTRs processing swine manure also are quite stable. (Hobson and Wheatley 1993)

Finally, as noted above, at mesophilic temperature and typical waste retention times (15 to 20 days) and organic loading rates (3 to 5 kg VS per m^3 digester volume), antibiotic inhibition of digestion in a conventional medium-rate farm digester is limited by dilution. (Ianotti and Fischer 1982, Poels, *et al.,* 1984, Varel 1983) Inhibition arising from the occasional feeding of high NH_4-N waste is limited by the large mass of waste processed at waste retention times of 15 to 20 days in relation to total NH_4-N inputs of a more purely daily nature. (Hobson 1990)

Farm Digester Volatile Solids Degradability

Assuming that there are no inhibitory substances in the waste, the biodegradability of volatile solids (VS) in a farm digester depends: on the feed rations given livestock, the temperature of the digesting manure in the reactor, and the retention time of the waste in the reactor. Other factors include the manure age and the conditions of manure storage, and the VS or organic content of the manure.

The biodegradability of organic wastes was discussed above. The biodegradability of farm wastes is influenced by the 100% non-degradability of lignin by anaerobic digestion. (van

Velsen and Lettinga 1979) As a rule of thumb, the degree of non-degradability is a factor of 2.5 to 3 times the lignin content of the waste. (Fischer, *et al.*, 1986) With a lignin content of 14%, dairy manure is 58% to 65% degradable, and swine manure, with an 8% lignin content, is 75 to 80% biodegradable. (Gunnerson and Stuckey 1986, Hobson 1990) The corresponding level of biodegradability of feedlot beef and poultry manure is 65 to 70% and 85%, respectively.

In practice, in a working medium-rate farm reactor with short waste or hydraulic retention times (15 to 25 days), rates of VS destruction of 20 to 45% for dairy manure and 50 to 65% for swine manure are common (see Table 5 below).

The degree of lignification of manure components in influenced by animal diet. Diets high in forages contain a much greater amounts of lignin complexed with cellulose and hemicellulose than do high energy diets of grains. (Nielson 1985) In general, biodegradability increases as high-energy grain diets are substitutes for diets high in roughage like corn silage, alfalfa or other hay. (Hashimoto, *et al*., 1981)

Volatile solids biodegradability in a farm reactor depends on manure age and pre-digestion storage conditions. If substantial quantities of the most easily degraded components of VS (e.g., the starches, free cellulose, lipids) are lost while in extended storage, leaving only the more refractory materials, digester biodegradability will be low. Substantial amounts of VS can be lost from the dirt and paved surfaces drylots through drying and oxidation. (Ward 1983, Williams and Hills 1981) Losses also can occur during below barn pit storage, due to partial digestion of settled manure solids at the bottom of the pit prior to removal to the farm reactor. (Zeeman, *et al.*, 1985, Hobson 1990)

VS biodegradability depends on reactor temperature. Digester VS destruction increases linearly between 27 and 37 degrees Celsius. (di Bernardina and Oliviera 1994) Biogas productivity, which is an indirect measure of VS destruction, increases linearly over the same range of internal reactor temperature. At waste retention times that are characteristic of conventional medium-rate farm digesters, biogas productivity per kg of VS added to the reactor increases by one-half to two-thirds as the reactor temperature is increased from 20 to 30 degrees Celsius, reaching a maximum at 35 and 40 degrees Celsius. (Fischer and Ianotti 1981, Hashimoto, *et al*., 1979, Hawkes, *et al*., 1979) Anaerobic digestion ceases completely below 15 degrees Celsius. (Hobson and Wheatley 1993)

As noted, VS degradation in a conventional medium-rate farm reactor varies with waste retention time, increasing for dairy manure about 50% as the waste or hydraulic retention time is lengthened from 15 to 30 days, and doubling at the waste retention period is lengthened from 15 to 120 days. (Gunnerson and Stuckey 1986) For dilute manure, a similar although somewhat smaller percentage reduction in VS content results as the retention time of the waste in the reactor is lengthened from 10 to 20 days. (Powers, *et al*., 1997)

Finally, the VS content of dairy manure is about 80%, and that of swine and poultry manure is about 85%. (Hill and Bolte 1988, Ritchie 1983)

Pollution Control with Anaerobic Digestion

As noted above, anaerobic digestion for waste treatment results in substantial environmental benefits. These include reductions in biological oxygen demand, human pathogens, hydrogen sulfide, and the various odor-related components of manure. It is possible that digestion may also contribute to reduced nitrogen leaching to ground water, but this has yet to be firmly demonstrated.

Biological Oxygen Demand: If spilled into waterways, organic wastes act biologically to remove oxygen from lakes, streams and other surface waters, leading to fish kills and declining fish populations. Biological oxygen demand (BOD) is a measure of this potential to negatively impact aquatic systems. Manure BOD declines substantially during anaerobic digestion. BOD reductions of 40 to 75% are reported in the scientific literature for the digestion of dairy manure in conventional medium-rate farm digestions; a 55 to 85% range has been reported for swine manure (see Table 5).

Pathogens: Various pathogens of concern to human health are present in livestock manure and can persist for weeks to months after excretion. Upon digestion, many of these are destroyed or greatly reduced in concentration. (Cheng 1999) Examples of pathogens that are destroyed during digestion include Streptococcus faecalis, Staphylococcus aureus, Escherichia coli, Salmonella typhimirium, and Mycobacterium praetuberculosis. Ninety percent reduction in the numbers of these pathogens per unit volume of manure is typically realized within 1 to 6 days of digestion at mesophilic temperatures, depending on the pathogen in question. (Olson 1985)

Odors: The principal organic odorants in anaerobically stored manure include skatole, indole, phenol, p-cresol, mercaptans, and fatty volatile acids (VFA). Many of these compounds are destroyed during digestion, and the remaining carbon substrate in the effluent is largely unavailable for bacterial growth. (National Academy of Sciences 1977) During digestion at mesophilic temperatures, by the 15th to 20th day of anaerobic digestion, VFA destruction is about 75% for swine manure, reaching 90% at very long retention times in the digester (40 to 50 days). (Summers, *et al.*, 1979, Hobson, *et al.*, 1979, Poels, *et al.*, 1985) Similar values are reported for VFA destruction during the anaerobic digestion of dairy manure. Maximum destruction of skatole, indole, and p-cresol occurs within about 15 days of anaerobic digestion for manures with 6% total solids content or less, with little gained from further time in the reactor. (van Velsen and Lettinga 1979)

In terms of actual odor, at 16 hours after placement on an agricultural field, digested swine manure is as odoriferous as spread undigested swine manure in-place in the field and exposed to the atmosphere for 3 days, which implies a substantial level of odor control. (Voermans 1985).

Digestate just out of the digester is equivalent in terms of associated odors with undigested swine manure that has been out in the field and exposed to the atmosphere for 16 hours.

Table 5. Estimates of Anaerobic Digester Effects on Various Measures of Water and Air Pollution for Conventional Medium-Rate Farm Reactors

	Approximate % Reduction After Digestion[a]	
Pollution Measure	**Dairy Manure**	**Swine Manure**
Biological Oxygen Demand	40 to 75	55 to 85
Total Manure Solids	20 to 40	30 to 60
Manure Volatile Solids	20 to 45	50 to 65
Chemical Oxygen Demand	20 to 50	40 to 75
Volatile Fatty Acids	high	75 to 95

[a] Digestion at mesophilic temperatures across a range of typical HRTS (15-25 days), total solids content, and organic loading rates.

Sources: VS reduction-Campbell, *et al.*, (1997), Fischer, *et al.*, (1981), Gunnerson and Stuckey (1986), Hashimoto (1983), Hawkes, *et al.*, (1984), Hayes, *et al.*, (1979), Hill 1980, Hill (1993), Hills and Roberts (1980), Jewell (1984), Jewell and Loerh (1977), Lorimor (2000), Martin and Lichtenberg (1981), Mattcks (2000), Rorick, *et al.*, (1980), Sasscer and Morgan (1988), Singh, *et al.*, (1984), Smith (1978), Summers and Bousfield (1980), Whittier, *et al.*, (1993), Zhang, *et al.*, (1990)
TS reduction-Aubart (1983), Campbell, *et al.*, (1997), Fabian (1989), Fischer, *et al.*, (1981), Hobson, *et al.*, (1979), Hobson and Wheatley (1993), Jewell, *et al.*, (1981), Jewell, *et al.*, (1981), Mattocks (2000), Powers, *et al.*, (1997), Sasscer, and Morgan, (1988), Singh, *et al.*, (1984), Summers and Bousfield (1980), Summers, *et al.*, (1979), Zhang, *et al.*, (1990)
COD reduction- Fernandez, *et al.*, 1989, Fischer, *et al.*, (1977), Hills and Roberts (1980), Hobson, *et al.*, (1979), Kiely and Taluntais (1984), Lorimor (2000), Nielson (1985), Powers, *et al.*, (1997), Sasscer and Morgan (1988), Summers and Bousfield (1980), Summers, *et al.*, (1979), Zhang, *et al.*, (1990)
BOD reduction-Fischer, *et al.*, (1977), Hobson, *et al.*, (1979), Kiely and Taluntais (1984), Nielson (1985), Summers and Bousfield (1980), Summers, *et al.*, (1979)
VFA reduction-Fischer, *et al.*, (1977), Hashimoto (1983), Kiely and Taluntais (1984), Poels, *et al.*, (1983), Summers and Bousfield (1980), Summers, *et al.*, (1979), Zhang, *et al.*, (1990)

Percentage reductions in the various odor-related components of livestock manure as a result of anaerobic digestion in conventional medium-rate farm digesters are shown in Table 5. During mesophilic digestion, manure volatile solids levels are reduced 20 to 40% for dairy manure and 30 to 60% for swine manure. Of the VS that remains, most of it is refractory material resistant to further degradation. Percentage VFA reductions that are reported in the scientific literature approach the 70 to 95% level. Chemical oxygen demand (COD) reductions of 20 to 50% are reported for dairy manure and 40 to 75% for swine manure. COD is a measure of the stability of organic waste under high temperatures and strongly acidic conditions.

Hydrogen Sulfide: Hydrogen sulfide (H_2S) is produced by sulfate-reducing bacteria during the storage of manure under anaerobic conditions, and is released to the atmosphere upon manure agitation and pit or tank clean-out. At concentrations of 100 ppmv, H_2S is an eye and nose irritant, and at higher concentrations can cause dizziness, headaches and other more significant negative health effects. During anaerobic digestion, high levels of H_2S are produced in the highly reducing conditions in the digester vessel. But these are retained in the digester, and are not released the environment. Combustion of digester biogas for energy production converts H_2S to SO_2, thereby eliminating much of it from the waste stream. H_2S emissions from then digestate itself are minor in comparison to those from untreated raw manure. (Lorimor 2000)

Nutrient Management: The situation is more ambiguous with regard to nutrient management. In itself, anaerobic digestion results in little or no loss of nitrogen from livestock manure. Ninety to one-hundred percent of total manure nitrogen is retained in the manure after digestion. (Fischer, *et al.,* 1977, Lorimor 2000, Mattocks 2000, Pigg 1977, National Academy of Sciences 1977) However, a substantial amount of manure nitrogen is converted to ammonium ion (NH_4^+) and free ammonia (NH_3). (Fischer, *et al.*, 1981, Ward 1983) In the form of NH_3, it is more readily available for plant uptake and growth upon land application. However, in the form of NH_3, nitrogen is also subject to significant losses through ammonia volatilization. Volatilization losses occur during manure storage and upon manure land applications. Once volatilized to the atmosphere, NH_3-N is eventually deposited on land, where after nitrification it can contribute to plant growth or to leaching to ground and surface waters.

Unless the manure is chemically treated or a storage cover is utilized, much of the NH_3-N that is produced during anaerobic digestion probably will be lost during extended outdoor open-air storage following digestion. Without digestion, typical feedlot losses of manure nitrogen prior to land application are estimated to be about 30% of excreted nitrogen, much of this in the form of free ammonia. The one study on nitrogen losses that treated pre-digestion and post-digestion losses of nitrogen, a 30% loss of effluent nitrogen was noted in post-digestion storage. (Sharp 1985)

Given this condition, the environmental consequences of greater nitrogen availability from anaerobic digestion at best are uncertain, and depend critically on measures taken to control volatilization through manure storage covers and manure incorporation during land application. The limited literature on yield response to digested effluent that is available is ambiguous. (Dahlberg, *et al.,* 1988, Fischer, *et al.,* 1984)

Greenhouse Gas Control Aspects of Anaerobic Digestion

Greenhouse gases are infrared-absorbing compounds that, in substantial accumulations in the atmosphere, act to increase the resistance of the atmosphere to the radiation of heat to space by the surface and lower atmosphere, leading to increased heating of the surface and lower atmosphere of the earth. These gases have long atmospheric lifetimes, which allows substantial long-term accumulations. Substantial atmospheric accumulations have occurred over the last 150 years, and an intensification of this rate of accumulation is forecast for the next 100 years. At projected future rates of accumulation, mean global surface temperature—surface air temperature averaged across all points across the earth's surface—will rise 1.5 to 6 degrees Celsius, leading to rising sea levels, contraction of the earth's permanent snow and ice cover, and global redistribution of surface climates. (IPCC 2001)

To date, mean global surface temperature has risen about 0.8 degrees Celsius. The recent rate of increase is about 0.2 degrees Celsius per decade. By contrast, the range of total natural variability in mean global surface temperature is about 0.4 or 0.5 degrees Celsius over periods of 100 to 300 years. (Mann, *et al.*, 1999)

The greenhouse gases of most concern include carbon dioxide (CO_2) from fossil fuel combustion, methane (CH_4), nitrous oxide (N_2O), tropospheric ozone (O_3), chlorofluorocarbons (CFCs), and hydrofluorocarbons (HFCs).

Global climate change resulting from greenhouse gas emission and atmospheric accumulation is subject to an international convention, the United Nations Framework Convention on Climate Change, which requires that its signatories, including the United States, implement policies to stabilize their domestic emissions at 1990 levels. Negotiations to make emissions reductions legally binding in the developed industrialized economies have been underway since 1997, and continue today.

Manure management is a source of emissions of two greenhouse gases: CH_4 and N_2O. CH_4 is created in liquid manure storage tanks, pits, basins and lagoon by the processes of anaerobic digestion discussed above. N_2O is produced in manure stockpiles and upon manure land application by various soil nitrifying and denitrifying bacteria.

By stabilizing the non-refractory part of manure volatile solids, and capturing and destroying the resulting CH_4, anaerobic digestion acts to eliminate most CH_4 emissions to the atmosphere from liquid manure storage. N_2O emissions from the feedlot appear to be unaffected.

In 1998 in Minnesota, livestock excretion at feedlots and manure storage resulted in an estimated emission of 99,000 tons of CH_4 and 3,000 tons of N_2O, an amount equal on a weighted basis to about 2% of all greenhouse gases emitted from Minnesota. Emissions of CH_4 and N_2O from feedlots and solid and liquid manure storage comprise a similar percentage of US greenhouse gas emissions. (USEPA 2000)

Digester Effluent: Fertilizer Value and By-product Use

Most digester effluent is used as a nutrient source and soil amendment. Uncertainties about the claims made about greater nutrient availability were discussed above. At this time, it is impossible to conclude that digestion increases the fertilizer value of nitrogen. (Nielson 1985)

Digestion does result in a more homogenous, more easily handled manure that is more amenable to incorporation into the soil during land application. As a liquid, digestate should be less costly to manage than raw manure. (Campbell, *et al.*, 1997, Roos 1992)

Effluent solids can be separated from the liquid component of the digester waste employing vibrating screens, centrifugal separators, filters, screw presses and sedimentation ponds. (Blaha 1997) About 23 to 30% of manure solids can be removed from digested effluent using mechanical screens and screw presses. (Powers, *et al.*, 1995, Fulhage and Pfost 1993) With settling basins, up to two-thirds might be removed for use. (Powers, *et al.*, 1995) Costs range from $5,000 for a sedimentation pond to $25,000 for a screw press. (Bicudo 2000, USEPA 1996) Vibrating screens cost between $5,000 and $15,000. Virtually all of the nutrient value of the manure remains in the liquid portion of the separated manure, in the form of which is it land applied as a nutrient source. (Powers, *et al.,* 1995)

Solids may be used for livestock bedding or sold as a soil amendment. Bedding for dairy cattle includes purchased materials like sawdust. On an annual basis, for those dairy farms with digesters that are substituting dry manure solids for saw dust as bedding, cost savings range from \$20 to \$50 per cow per year. (Lusk 1997, Vetter, *et al.*, 1991) Increased incidence of mastitis may be a concern in absence of the composting of the separated solids. (Fulhage and Pfost 1993)

Dried to about 5% water content, manure solids can be bagged and sold as compost. At dairies with digesters that are selling compost commercially, compost from digested manure solids sells for about \$6 to \$8 per cubic yard. (Lusk 1997) Assuming a daily rate of total solids production of 16 lb. per cow and a 25% mechanical recovery of manure solids from digester effluent, this is equivalent to about \$7 per cow per year in terms of saleable compost.

Finally, it is also possible to utilize separated manure solids as cattle feed. Of farms that operate a manure digester, none reports such a use. (Lusk 1997) As a general rule, the recycling of pathogens through farm livestock should be avoided. This may account for some of the absence of 'refeeding' on farms with working manure digesters. In addition, 'refeeding' may not be economical in light of current prices of conventional feeds. (Hobson 1990) In terms of the nutritional value of digested manure solids, the literature is ambiguous. (Hobson and Wheatley 1993, Ward 1993)

Farm Biogas and Energy Potential from Anaerobic Digestion

Potential digester biogas productivity can be approximated from the information given in Table 5 for digester volatile solids destruction in a conventional medium-rate reactor and an estimate of the amount of digester biogas produced per unit of volatile solids destroyed. This is shown in Table 6 in relation to different livestock types and daily manure, manure total solids and manure volatile solids production. A range of estimates found in the scientific literature for biogas productivity per kg of VS destroyed is used. Based on these ranges, the daily production of manure from a mature 635 kg (1,400 lb.) cow, upon digestion in a conventional medium-rate farm reactor, produces 0.4 to 2 cubic meters (m^3) of biogas (14 to 71 cubic feet or ft^3), about 55 to 65% of which is CH_4. Upon digestion, the daily manure production from a 61 kg (135 lb.) market hog results in the production of 0.1 to 0.3 m^3 of biogas (3 to 9 ft^3), or about one-tenth to one-third that of a mature cow, while the daily manure and volatile solids production of a 125 kg (275 lb.) breeding sow results in the daily digester production of 0.1 to 0.4 m^3 of biogas (4 to 14 ft^3), of which 60 to 70% is CH_4. Poultry necessarily produce only a fraction of this, given the size of the animals.

In practice, most medium-rate digesters operating dairy farms are more productive than the estimates given in Table 6 suggest. Published estimates of daily digester biogas production per cow at working farm digesters are shown in Table 7. As can be seen, estimates of daily biogas production vary from 1.1 to 2.5 cubic meters (40 to 90 ft^3) of biogas per day, and Lusk (1996) reports working digesters that are realizing 2.8 cubic meters (100 ft^3) of biogas per cow per day.

No published analysis exists to explain this wide range of observed biogas productivity per cow associated with the digestion of dairy manure in medium-rate farm digesters. It seems possible that variations in HRTs and in feed digestibility may account for a part of this. For dairy manure digestion, hydraulic retention times that are utilized on working farms or in research reactors range from 10 to 25 days. (Campbell, *et al.*, 1997, Coppinger 1978, Hays, *et al.*, 1979, Jewell and Loehr, 1977, Jewell 1984, Jewell, *et al.*, 1981, Lusk 1997, Meyer 1985, Pain 1989, Rorick, *et al.*, 1980, Singh, *et al*., 1984, Weeks, *et al.*, 1989, Wellinger 1988) Over this range, substantial gains in biogas productivity are realized as manure retention time is extended. (Jewell, *et al*., 1984, Pigg, 1977, Singh, *et al.*, 1984, Zeeman, *et al.*, 1983)

With regard to biogas productivity per kg of VS destroyed, Klass (1998) suggests that a well-run medium-rate farm digester should yield 0.8 to 1.1 cubic meters of biogas per kg of VS destroyed (13 to 18 ft^3 per lb. VS destroyed). This suggests that some of the lower values found in the literature (see Table 6) also may reflect biogas performance at poorly operated digesters.

Due to differing animal sizes, it is useful to compare biogas productivity on a per lb. liveweight basis. This is done in Table 8, using the information given in Table 6 and, for dairy, Tables 6 and 7. On a per 453 kg (1,000 lb.) liveweight-generated basis, the digestion of dairy manure and that of swine manure are more similar, about 0.6 to 2 cubic meters of biogas per 453 kg (1,000 lb.) of animal liveweight. Beef tends to be less, due to lower volatile solids generation and drylot losses of volatile solids.

A different way to calculate biogas productivity is on a per unit of volatile solids-added basis. Most of the estimates of biogas productivity that are found in the literature are presented in this form. Estimates of biogas productivity per kilogram of added volatile solids added to the digester are shown in Table 9 for conventional medium-rate farm digesters and different livestock types. The values for dairy manure digestion converge on a value of about 0.3 cubic meters of biogas produced per kilogram of VS fed (4.8 cubic feet per lb. of VS fed) to the typical digester. For beef, the value is about 15% higher than for dairy manure, reflecting a

Table 6. Biogas Productivity per Head of Livestock for Conventional Medium-Rate Farm Anaerobic Digesters

	Dairy Cow (635 kg) [1400 lb.]	**Steer (408 kg) [900 lb.]**	**Market Hog (61 kg) [135 lb.]**	**Breeding Hog (125 kg) [275 lb.]**	**Sow Unit (170 kg) [375 lb.]**	**Layer (1.8 kg) [4 lb.]**
Manure Production (kg/day)	54.4	24.5	3.9	4.1	10.2	1.8
Total Solids Production (kg/day)	7.6	3.5	0.6	1.0	0.9	0.03
Volatile Solids Production (kg/day)	6.4	3.0	0.5	0.8	0.7	0.02
Manure Loss in Handling (%)	10	25	10	10	10	10
Digester Efficiency (%)	20-45	45-55	50-65	50-65	50-65	55-65
Biogas						
m^3/kg VS destroyed/day	0.5-1.1[a]	0.6-0.8	0.5-1.2[b]	0.5-1.2[b]	0.5-1.2[b]	0.75
m^3 biogas/animal/day	0.6-2.8	0.6-1.0	0.1-0.4	0.2-0.5	0.2-0.5	0.008-0.009
% CH_4	55-65	55-65	60-70	60-70	60-70	60-70
m^3 CH_4/animal/day	0.3-1.8	0.3-0.6	0.07-0.25	0.1-0.4	0.1-0.4	0.005-0.006

[a] 8.0-17.6 ft^3 biogas per lb. VS destroyed
[b] 8.0-19.2 ft^3 biogas per lb. VS destroyed

Sources: Manure, total solids, volatile solids production: MWPS (1993).
Digester Efficiency: see Table 5 (% VS destruction).
Biogas productivity per lb. VS destroyed for swine and dairy: Converse, *et al.*, (1975), Fischer, *et al.*, (1977), Fischer, *et al.*, (1987), Fulhage (1993), Hashimoto, *et al.*, (1979), Hawkes, *et al.*, (1984), Hill, *et al.*, (1985), Hill, *et al.*, (1987), Hill and Bolte (1984), Hill and Bolte, (1986), Hill and Bolte (1988), Qasin (1988), Sweeten, *et al.*, (1979), Whittier, (1993).
Biogas productivity for beef and layers and handling losses: Whittier, *et al.*, (1990).

Table 7. Biogas Productivity per Lactating Cow from Anaerobic Digestion of Dairy Manure for Conventional Medium-Rate Farm Reactors

Source	**m^3/cow/d**
Campbell, *et al.*, (1997)	1.63
Fabian (1989)	1.70
Jewell and Loehr (1977)	1.39
Jones, *et al.*, (1982)	1.34
Lusk (1998)	1.27 to 2.75
MWPS (1993)	1.33
Sweeten (1978)	1.08
Weeks, *et al.*, (1989)	2.07 to 2.26
Wellinger (1985)	1.05 to 1.35
West (1985)	1.39
Whittier, *et al.*, (1993)	1.4

[a] medium-rate digesters presently operating at mesophilic temperatures at 13 dairies

higher energy, more digestible diet. For swine and poultry, about 0.375 cubic meters of biogas are produced per kilogram of fed VS (6 cubic feet per lb. VS-fed), or about 25% higher than the value for dairy manure. Substituting in the case of dairy manure digestion the range of values for biogas production per cow given in Table 7, the dairy estimate rises to about 0.21 to 0.43 cubic meters per kilogram of VS-added (3.4 to 7 cubic feet per lb. VS-fed).

It is possible to translate biogas productivity to energy production. This is shown for dairy manure digestion in Table 10. Roughly speaking, the digestion of dairy manure in conventional medium-rate digesters like a CSTR produces about 1.5 to 3 kilowatt-hours of electricity per day per cow. This implies that 8 to 16 cows would be required to provide 1 kW of power. In

Table 8. Anaerobic Digester Productivity per 453 kg (1,000 lb.) of Livestock Liveweight: Conventional Medium-Rate Farm Reactors

	453 kg (1,000 lb.) liveweight of livestock				
	Dairy Cow	**Beef Cattle**	**Market Hog**	**Sow**	**Sow Unit**
Manure Production (kg/day)	39	27	29	15	27
Total Solids Production (kg/day)	5.4	3.9	4.7	3.6	2.5
Volatile Solids Production (kg/day)	4.5	3.3	3.7	2.8	2.0
m^3 Biogas/day	0.41-2.02	0.66-1.08	0.83-2.60	0.63-1.96	0.45-1.39
m^3 CH_4 Biogas/day	0.22-1.31	0.36-0.70	0.50-1.82	0.38-1.37	0.27-0.97

Source: Calculated from Table 6.

Table 9. Digester Biogas Productivity: Literature Point Estimates for Conventional Medium-Rate Reactors

	m^3 biogas/kg volatile solids-added			
	Dairy	**Beef**	**Swine**	**Poultry**
Fulhage (1993)	0.15	0.39	0.37	0.3
Jewell and Loehr (1977)	0.29	0.42	0.46	0.54
Midwest Plan Service (1993)	0.29	0.23	0.32	0.21
NRCS (1996)	0.38	0.31	0.45	0.49
Sweeten (1978)	0.2	0.37	0.38	0.41
Whittier *et al.* (1993)	0.3	0.31	0.25	0.22-0.32
Midpoints from Table 13 below	0.3	0.35	0.375	0.4

Table 10. Potential Energy Production per Lactating Cow from Farm Anaerobic Digestion of Dairy Manure[a]

Source	**m^3/cow/d**	**kWh/cow/day**	**mmbtu-equiv/cow/yr**
Campbell *et al.*, (1997)	1.63	2.13	12.64
Fabian (1989)	1.7	2.22	13.14
Jewell and Loehr (1977)	1.39	1.81[c]	10.73
Jones *et al.*, (1982)	1.34	1.75 [c]	10.36
Lusk (1998)	2.07[b]	2.7	15.99
MWPS (1993)	1.33	1.74	10.29
Sweeten (1978)	1.08	1.4 [c]	8.32
Weeks *et al.*, (1989)	2.07-2.26	2.70-2.95	15.99-17.52
Wellinger (1985)	1.05-1.35	1.37-1.76 [c]	8.12-10.45
West (1985)	1.39	1.81	10.73
Whittier *et al.*, (1993)	1.4	1.82	10.82

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[a] Digestion using conventional medium-rate farm digesters

[b] Mean of mesophilic digesters at 13 dairies; range of 1.27 to 3.58 per cow per day

[c] Calculated at 600 **B**tu/ft^3 and a combined efficiency of the internal combustion engine and the electrical generator of 21%.

terms of energy content, on an annual basis, anaerobic digestion produces about 7 to 15 million Btu (mmbtu) per cow or the equivalent of about 75 to 150 gallons of LPG.

Corresponding values for swine, beef, and poultry are given in Table 11.

Table 11. Potential Energy Production per Head of Livestock from Anaerobic Digestion with Conventional Medium-Rate Reactors

	Dairy	**Beef**	**Swine**	**Poultry**
m^3 biogas/animal/day	1.33-2.75	0.57-1.13	0.08-0.14	0.004-0.013
Biogas energy content (Btu/m^3)[a,b]	15,189	15,189	16,455	16,455
kWh $_{(e)}$ /animal/day[c]	1.5-3.0	0.63-1.26	0.10-0.17	0.005-0.015
Gal LPG-equiv-avail/animal/day	0.21-0.44	0.09-0.18	0.01-0.02	0.001-0.002
kWh $_{(e)}$ /animal/year	540-1,117	232-459	35-62	2-6
Gal LPG-equivalent-available/yr	77-160	33-66	5-9	0.25-0.82
kW$_{(e)}$-equivalent animal numbers	8-16	19-38	142-249	1,531-4,976

[a] 60% CH_4 biogas content for ruminants and 65% CH_4 biogas content for swine and poultry
[b] 600 to 650 Btu/ft^3
[c] calculated at a 25% diesel generator efficiency in converting fuel to electricity

Sources: Biogas Productivity**:** Table 7 above and Aubart (1983), Aubart and Bully (1984), Campbell, *et al.,* (1993), Clark (1988), Fabian (1989), Fulhage (1993), Hayes, *et al.,* (1979), Hill (1984), Jewell (1978), Jewell and Loehr (1977), Jones, *et al..,* *(*1982), Lindsey, *et al.,* (1980), MWPS (1993), Martin and Lichtenberg (1980), Ritchie (1983), Weeks, *et al.,* (1989), Wellinger (1986), West (1988), Whittier, *et al.,* (1993), Zhang, *et al.,* (1990)

Finally, the relationship of biogas productivity to various digester designs and operating parameters is summarized in Table 12. In general, digester biogas productivity increases with increased HRT (to a maximum of 20 to 30 days), reactor temperature (to a maximum of 35 to 40 degree Celsius), manure total solids (to a maximum of 6 to 10%, depending on feed digestibility). As would be expected, it declines with intermittent feeding, acidity in the waste, and the percent of manure lost in collection.

Table 12. Biogas Productivity in Relationship to Waste Type and Collection and Digester Configuration: Conventional Medium-Rate Farm Reactors

Digester Design Parameter	Biogas Productivity
Waste VS biodegradability	Higher with higher VS digestibility
Feed ration	Higher with higher digestibility feeds
Reactor temperature	Optimal at 35-37 C
Waste retention time (HRT)	Higher with increased HRT to 20 to 30 days
Manure total solids	Higher with increased TS content to 6-10%[a]
Waste VS content	Higher with higher VS content
Periodicity of digester loading	Higher with continuous feeding
Toxicity levels	Lower with increased waste toxicity[b]
Percentage of manure lost in collection	Lower with increased manure lost in collection
Manure age	Lower with increased manure age

[a] at appropriate HRTs and reactor temperature
[b] see Table 1

Sources: Cavalletto and Genon (1984), Chen (1985), Fischer and Ianotti (1981), Gunnerson and Stuckey (1986), Hashimoto (1983), Hashimoto, *et al.,* (1979), Hawkes (1979), Hayes, *et al.,* (1979), Hobson (1977), Hobson (1990), Illudo and Awulu (1999), Jewell, *et al.,* (1981), Jewell, *et al.,* (1984), Nielson (1985), Singh, *et al.,* (1984), Summers and Bousfield (1980), Ward (1983), van Velsen and Lettinga (1979), Williams and Hills (1985), Zeeman, *et al*., (1983), Zeeman, *et al*., (1985)

Digester Design Criteria for Conventional Medium-Rate Farm Reactors

As noted above, anaerobic digesters are designed around four basic parameters: reactor temperature, the total solid content of the influent waste, the mean retention of the waste in the reactor (hydraulic retention time), and organic loading rate.

The waste or hydraulic retention time is the mean residence time of waste within the reactor less settled solids in the reactor bottom. The total solids content is the percentage of manure solids by weight. The organic loading rate is simply the mean rate of volatile solids influent feed into the reactor per unit of reactor volume. Digester temperature is the temperature of waste inside the digester vessel.

These parameters are interrelated in fairly predictable ways. Hydraulic retention time (HRT) increases with increased manure total solids content, and decreases with increased reactor temperature or increased organic loading rate. Organic loading rate increasing with increased manure total solids or decreased HRT. Since optimal temperature in the reactor for bacterial activity are 35 to 37 degrees Celsius, any departure from 35 to 37 degrees Celsius results in a reduced rate of digestion, hence in the need to reduce the organic loading rate. Inversely, increased manure solids content results in the need for a longer retention time of the waste in the reactor or a higher reactor temperature.

In reactor design, for economic reasons, these design parameters are chosen to result in maximum biogas production per unit of reactor volume, maximum digester net energy productivity, or more typically, a combination of the two. Digester net energy productivity is a measure of the energy production of the digester, accounting for all digester uses of digester biogas for influent and reactor heating and losses during heat exchange. Biogas productivity per unit of reactor volume is known as volumetric productivity or reactor specific volume.

Volumetric Productivity: Medium-Rate Farm Reactors

Digester biogas productivity varies with hydraulic retention time. Within limits, the longer the waste is retained in the digester, the higher is the level of volatile solids degradation and the larger is the cumulative gas generation per kilogram of VS added to the system. For instance, while 20 to 40% of VS in dairy manure in conventional medium-rate farm reactors is destroyed at HRTs of 20 to 25 days, at 120 days this increases to 60% destruction. This results in a substantial increase in biogas generation per kg of VS fed to the system.

However, the volume of the reactor vessel also increases as the digester retention time is lengthened in a conventional medium-rate reactor. After about 15 to 25 days for dairy manure and 10 to 15 days for swine manure, the rate of gas production increases much more slowly than does the volume of the digester, leading to diminishing biogas returns per unit of volume added to the digester.

This introduces an economic component to digester design—a concern that the digester be sized to maximize gas output per unit of reactor volume. Essentially, to be economically viable, a digester project must yield a return on investment. Biogas production leading to the generation of electricity and the satisfaction of on-farm space and water heating needs is the principal source of revenue for a digester project. Costs arise principally from capital expenditures incurred during digester construction. At declining rates of gas production per unit of digester volume, revenues fall relative to costs, leading to a decline in project profitability. This is a factor due to high project capital costs per unit of digester volume ($400 to 500 per cubic meter of digester volume) in relation to the annual returns per cubic meter of digester volume in terms of operating revenues ($55 to 120 per m^3 of digester volume[1]).
The ratio of gas production to digester volume is called volumetric productivity or the specific

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[1] at 1 to 2 m^3 biogas per m^3 of digester volume-day, 15,189 Btu per m^3, 1 kWh(e) per m^3 of biogas, 25% diesel generator efficiency, efficiency of heat exchange of 70%, a farm electricity rate of $0.07 per kWh and LPG costs of $0.50 per gallon.

volume. Table 13 lists characteristic values for the volumetric productivity of conventional medium-rate farm digesters, along with other measures of digester efficiency discussed above. Values range from 0.15 to 2.5 cubic meters of biogas per cubic meters of digester volume per day (m^3/m^3-d).

As might be expected, volumetric productivity in a medium-rate farm digester decreases rapidly as manure influent is diluted with water. Dilution increases the interior volume of the digester while, particularly at low total solids, depressing biogas productivity. (Cavalletto and Genon, 1984, Hobson, 1979) Roughly speaking, a decrease in the total solids content of digester influent from 8% to 2% results in a 5- to 6-fold increase in reactor volume. (Horton, 1987)

For conventional medium-rate farm digesters, volumetric productivity at 2% manure total solids content is about one-quarter to one-third of volumetric productivity at 6 to 7% manure total solids content. (Cavelletto and Genon 1984, Friman 1986, Singh, *et al.,* 1984) At low manure total solids (1 to 3%), volumetric productivity is characteristically in the range of 0.15 to 0.6 m^3/m^3-d. (Bonazzi, *et al*., 1991, Cavelletto and Genon 1984, Friman 1986, Paris, *et al.,* 1987, Theoleyre and Heduit 1987, Zhang, *et al*., 1990).

By contrast, in the scientific literature, peak volumetric productivity for medium-rate farm digesters occurs near manure total solids content of 5 to 9% or higher, depending on livestock type. (Friman 1986, Pigg 1977, Singh, *et al*., 1984, Wellinger, *et al*., 1991)

Plug flow dairy digester, which utilize high total solids manure (12 to 14%), have characteristically high volumetric productivity (1 to 2 m^3/m^3-d). (Campbell, *et al.,* 1997, Crocker 1985, Erdman 1985, Gunnerson and Stuckey 1986, Jewell 1984, Martin and Lichtenberg 1981)

Volumetric productivity is inversely related to hydraulic retention time. For any one organic loading rate, as the retention time of manure in the digester declines, the digester volume necessary to process the manure also declines, and does so at a faster rate than does biogas productivity. For conventional medium-rate farm reactors, the HRT for optimal volumetric productivity is estimated in the scientific literature to be about 10 days. (Hill 1983, Hashimoto 1983)

Volumetric productivity increases with increasing reactor temperature. As reactor temperature increases, organic waste is degraded more quickly, leading to shorter retention times in the digester and smaller digester volumes. It might be noted, however, that, while volumetric productivity increases with temperature in the digester, net digester energy production, accounting for digester parasitic energy uses, does not, but rather is inversely related to reactor temperature. This is discussed below.

Finally, volumetric productivity can be used in a rough way as an indicator of economic feasibility. Based on estimates given in the scientific literature, for conventional medium-rate farm digesters, a volumetric productivity of 1 m^3/m^3-d is thought to be the absolute minimum level that is required for

Table 13. Digester Productivity: Conventional Medium-Rate Farm Digestion[a,b,c]

	Volumetric Productivity (m^3 biogas/ m^3 digester vol)[d]	Biogas Productivity (m^3biogas/ kg vs added)[d]	Digester Efficiency (% VS destruction)[d]
Dairy	1.5 (0.5-2.5)	0.3 (0.15-0.45)	30% (20-45%)
Swine	1.3 (0.15-2.5)	0.375 (0.15-0.6)	57.5% (50-65%)
Beef	1.5 (0.5-2.5)	0.35 (0.1-0.6)	50% (45-55%)
Poultry	1 (0.5-1.5)	0.4 (0.2-0.6)	60% (55-65%)

[a] Includes results from studies of the performance of specific commercial or pilot-scale CSTRs or plug flow reactors, results from laboratory-scale fermenter experiments, or from more general assessments of medium-rate farm digester performance

[b] For a wide range of total solids content, organic loading rate and HRT

[c] For digestion at mesophilic temperatures

[d] Midpoint of range in literature and the range

Sources: Dairy-AIDR (1984), Bruce (1985), Campbell, *et al.,* (1997), Constant, *et al*., (1989), Converse, *et al.,* (1977), Coppinger, *et al.,* (1978), Crocker (1985), Erdman (1985), Friman (1986), Ghaly and Ben Hassan (1989), Gunnerson and Stuckey (1986), Hashimoto and Chen (1979), Hawkes (1979), Hawkes, *et al.,* (1984), Hayes, *et al.,* (1979), Hill (1983), Hills and Roberts (1980), Hobson and Wheatley (1993), Hobson, *et al.*, (1981), Jewel (1978), Jewel (1984), Jewel and Loehr (1977), Jones and Ogden (1986), Jones, *et al.*, (1982), Kiely and Taluntais (1984), Martin and Dale (1978), Martin and Litchenberg (1981), National Academy of Sciences (1977), Nielson (1985), NRCS (1996), Pain, *et al.,* (1984), Pain (1988), Rorick, *et al.,* (1980), Ruggieri (1986), Sasscer (1984), Singh, *et al*., (1984), Smith (1978), Vetter, *et al*, (1991), Wellinger (1986), Wellinger, *et al*., (1991), West (1988), Whittier, *et al.,* (1993), Zeeman, *et al.,* (1985)

Swine-Aubart (1983), Aubart (1985), Bruce (1985), Cavalletto and Genon (1984), Chen (1985), Constant, *et al.,* (1989), Field (1985), Fischer, *et al.,* (1977), Fischer, *et al.,* (1981), Floyd and Hawkes (1986), Friman (1984), Gunnerson and Stuckey (1986), Hashimoto (1983), Hawkes (1979), Hayes, *et al.,* 1979, Hill (1983), Hill (1984), Hobson, *et al.,* (1979), Hobson, *et al.,* (1981), Horton (1979), Jones, *et al.,* (1982), Mariques and Mariques (1984), Nielson (1985), Nilson and Dahl (1990), NRCS (1996), Ruggieri (1986), Smith (1978), Summers, *et al*., (1980), Summers and Bousfield (1980), Theoloyre and Heduit (1987), Van Velsen and Lettinga (1981), Voermans (1985), Wellinger (1986), West (1988), Wheatley (1988), Whittier, *et al.,* (1993), Zeeman, *et al.,* (1985), Zhang, *et al*., (1990)

Beef-Biljetina (1987), Constant, *et al.,* (1989), Friman (1986), Gunnerson and Stuckey (1987), Hamilton (1985), Hashimoto, *et al.,* (1983), Hashimoto and Chen (1979), Hawkes (1979), Hayes, *et al.,* (1979), Hill (1983), Jones, *et al.,* (1982), NRCS (1996), Sharp (1985), Smith (1978), Varel (1980), Whittier, *et al.,* (1993), Williams and Hills (1981)

Poultry-Aubart (1985), Constant, *et al.,* (1989), Converse, *et al.,* (1980), Converse, *et al.,* (1981), Field, *et al*., (1985), Hawkes (1979), Hayes, *et al.,* (1979), Hill (1983), Hobson, *et al.,* (1981), Jones and Ogden (1986), Morrison, *et al.,* (1980), Nielson (1985), NRCS (1996), Poli, *et al.,* (1985), Safley (1985), Smith (1978), Webb and Hawkes (1985), West (1988), Whittier, *et al.,* (1993)

economic feasibility. (Crocker 1985, Naveau 1984, Perwanger 1981, Rozzi and Passino 1985)

Net Energy Aspects of Digester Feasibility: Conventional Medium-Rate Farm Digesters

In a conventional medium-rate anaerobic digester, the digester vessel is a large consumer of energy. Optimal biogas productivity occurs at about 35 degrees Celsius (95 degrees Fahrenheit). This is quite similar to the temperature of manure as excreted. However, due to losses to the environment, averaged across the year, a more typical temperature of influent manure prior to heating in a northern climate is about 15 degrees Celsius (59 degrees Fahrenheit). (Campbell, *et al.*, 1997) For digestion to proceed, the temperature of livestock manure must be raised about 20 degrees Celsius, and any losses of heat from the digester vessel itself must be compensated.

In a well run medium-rate farm digester operating at optimal manure TS, and recommended reactor temperature, HRT and organic loading rate, about 90 to 95% of digester energy use is for raising the temperature of the influent to the level of the reactor contents and for compensating for wall losses in the digester vessel itself. (Ghosh 1981, Hayes, *et al.,* 1979, MacKie and Bryant 1995, West 1986)

The energy requirements of farm digester and influent heating are largely determined by the total manure solids content. (Horton and Hawkes 1981) This is because the specific heat of manure solids is low in comparison to the specific heat of water. As total manure solids decline, and dilution with water increases, the amount of energy required to raise the influent manure temperature to 35 degrees Celsius increases substantially.

Net digester energy is a measure of the parasitic energy losses to digester and influent heating. It is equal to the gross energy content of the digester biogas less digester energy consumption. At a total manure solids content of 7 to 8%, net digester energy productivity in a conventional medium-rate farm digester is about 70%, implying a parasitic use of about 30% for digester and influent heating. [2] At about 1.5 to 3% total manure solids, net energy productivity in a medium-rate reactor is about zero. (Ghosh 1981, Hawkes 1979, Horton 1979) Net digester energy productivity increases linearly between these two levels. (Stafford, *et al.,* 1983) For conventional estimates of biogas productivity, and digester HRT and temperature, net digester energy productivity at 4% total manure solids would be 50% or less, declining to linearly to its 1.5 to 3% value. (Ghosh 1981, Horton 1979)

At total manure solids above 8%, net energy productivity in conventional medium-rate farm reactors improves to the 80 to 90% range. (Srivistava 1987, Ghosh 1981)

What this means in practice is that at fairly conventional farm reactor design, at 4% total manure solids about one-half of all digester biogas that is produced in medium-rate digesters is utilized for digester and effluent heating; at 1.5 to 2% total manure solids, all of the digester biogas is used to heat the digester (see Table 14).

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[2] Taking fairly conventional for reactor design, e.g., 15 to 20 day HRT, 35 degree Celsius digester temperature, biogas productivity of 0.4 m^3/kg VS added.
The calculation accounts for the efficiency of heat exchange.

It is possible to lower the level of manure total solids by increasing the organic loading rate, and thereby shortening the hydraulic retention time. However, from the above discussion, any substantial shortening of the HRT in a medium-rate reactor will erode the safety factor built into reactor design and thus run afoul of the problem of digester washout. (Ghosh 1981)

Table 14. Digester Net Energy Status in Relation to Influent Manure Total Solids: Conventional Medium-Rate Farm Reactors

Author	**Total Solids**	**Net Energy Condition**[a]
Chen (1985)	<2%[b]	zero net energy
Fannin (1987)	<2%	zero net energy
Ghosh (1981)	3% [c,d]	zero net energy
Hawkes (1979)	2%	zero net energy
Horton (1979)	1.5%	zero net energy
Horton and Hawkes (1981)	3%[e]	zero net energy
Jewell (1979)	1%	negative net energy
Kroeker (1975)	3 to 4%[f]	zero net energy
Nielson (1985)	<4%[g]	zero net energy
Moser (1998)	2%[h]	zero net energy
Pienne (1994)	4%	zero net energy
Srivistava (1987)	1%	negative net energy

[a] digestion at mesophilic temperatures
[b] volatile solids
[c] at biogas productivity of 0.435 m^3 biogas per kg VS-added and 3 kg VS per m^3 digester volume organic loading rate
[d] greater than 3% with typical levels of digester biogas productivity (e.g., 0.3 m^3 biogas per kg VS-added)
[e] CSTR total solids requirement of 4 to 10% for positive net energy
[f] spring and fall values; organic loading rate of 2.1 kg/m^3 and a 15 day HRT
[g] winter
[h] 3% total solids needed for positive net energy

Due to the net energy implication of low TS slurries, particularly swine slurries, reactor design criteria for digestion in conventional medium-rate farm reactors require at least a 4% manure total solids content. More generally, it is recommended that manure total solids content be the maximum level possible consistent with the ability of the digester pumps and piping to handle high total manure solids. (Fischer and Ianotti 1981, Ghosh 1981, Hawkes 1979, Hawkes and Horton 1981, Nielson 1985, Smith 1980) Moser (1998) gives a slightly lower limit of 3% total manure solids.

In practice, this means that the prospects for the digestion of any highly dilute waste with total manure solids at below 3% are limited. This includes wastewater from hydraulic flush systems and pit recharge systems and dilute swine manure stored in below barn deep pits.

Besides total solids and hydraulic retention time, net digester energy is sensitive to reactor temperature, gas productivity and composition, heat exchanger efficiency, the difference between ambient air temperature and digester operating temperature, and the difference between influent temperature before heating and digester operating temperature. (Hawkes, *et al.,* 1981, Horton and Hawkes 1981)

Between 30 and 35 degrees Celsius reactor temperature, the net energy productivity of conventional medium-rate farm reactors like the CSTR, plug flow or slurry-loop declines substantially. (Hawkes, *et al*., 1981, Horton 1981, Horton and Hawkes 1981)

The net energy productivity of conventional medium-rate farm digesters decreases with decreased biogas productivity. As biogas productivity declines from 0.4 to 0.3 m^3/kg VS added to the digester, net digester energy productivity at 4% total manure solids declines from a highly positive to a zero value. (Hawkes 1979) At a value of 0.7 m^3/kg VS added, digester net energy productivity at 2% total influent solids is on the order of 20% rather than zero, all things else held constant. (Ghosh 1981)

Farm digester net energy productivity is sensitive to digester heat exchange efficiency. A range of 50 to 70% is found in the literature for on-farm heat exchange efficiency. (Horton 1979, Hawkes 1979, Hawkes and Horton 1981, Poels, *et al*., 1983, Zhang, *et al*., 1990)[3] At a 50% heat exchange efficiency, digester net energy productivity declines by three-quarters from its value at 70% heat exchange efficiency, all other things being equal.

The net energy productivity of conventional medium-rate farm digesters is also sensitive outdoor ambient temperature, as this influences the temperature of influent manure and the degree of influent heating necessary to raise it to the level of the contents of the reactor vessel. At a 15 degree Celsius (59 degree Fahrenheit) influent temperature, digester net energy productivity is zero or near-zero for 3% total solids manure, again, all other things held constant. (Ghosh 1981) More generally, at conventional farm digester design parameters, winter net energy productivity for a typical Upper Midwest winter is negative for manure with 4% total solids content. (Hawkes 1979, Kroecker 1975)

Using a kinetic model of anaerobic digestion, Ruggieri (1986) calculates that optimal digester net energy productivity for a medium-rate farm reactor is at outdoor ambient air temperatures between 20 and 25 degrees Celsius (68 to 77 degrees Fahrenheit). At 5 degree Celsius outdoor temperatures, net digester energy productivity declines to about one-third of its peak value, and to one-quarter at 0 degrees Celsius.

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[3] 70% heat exchange efficiency is assumed in the calculation by Hawkes and Horton (1981) discussed above.

For a northern tier state, with a 8% total solid manure, typical CSTR net energy performance is generally about 50 to 60%, or lower than the optimal value reported in the literature for a CSTR operating at 8% total manure solids and optimal outdoor temperatures. (Campbell, *et al*., 1997, Jewell 1978, Sobel and Muck 1983) Cold weather operation results in net energy production in the 30 to 50% range. (Hayes, *et al.*, 1979, Sobel and Muck 1983, Wellinger 1988)

Net energy considerations that are relevant to the performance of medium-rate farm digesters are summarized in Table 15. These were taken from the scientific literature. These include a minimum TS content of 2 to 3% for positive digester net energy productivity, and a minimum manure total solids content of 4 to 6% for economic viability.

Table 15. Digester Net Energy Considerations: Conventional Medium-Rate Farm Digester Design

Digester energy needs	10-100% of gas production[a]
Heat exchanger efficiency	40-70%
Winter digester energy needs at 4% total solids	100%
Net Energy at optimal total solids and biogas productivity	70%
Minimum influent total solids for positive net energy	2-3%[b]
Optimum influent total solids for positive net energy	7-9%
Minimum influent total solids for economic biogas yield	4 to 6%

[a] for a range of manure total solids from 10 to 2% total solids, along with a range of reactor temperatures and other factors
[b] see Table 14.

Sources: Chen (1985), Chessire (1986), Fischer and Ianotti (1981), Friman (1986), Gosh (1981), Hawkes (1979), Hawkes, *et al.,* (1981), Hawkes and Horton, (1981), Nielson (1985), Srivistava (1987), Stafford (1978), van Velsen and Lettinga (1981), plus Table 14

Design parameters for optimal CSTR net energy production are shown in Table 16, taken from recommendations in the scientific literature. These include: a 30 degree Celsius reactor temperature, influent total solids content of 7 to 10%, hydraulic retention time of 15 to 25 days, and a 75% heat exchange efficiency.

Operational means to realize optimal net energy production include: rapid movement of manure to the digester after excretion to limit manure heat losses; periodic clean-out of the digester to maintain heat exchanger efficiency; and any means to boost biogas productivity that involve improved influent digestibility. Measures to improve influent digestibility were discussed above, and include co-digestion, the use of higher energy livestock rations, physical pretreatment of influent manure, and the introduction of large amounts of free cellulose to the digester.

Finally, it might be noted that the total solids requirement for optimal digester net energy productivity is consistent with the total solids requirements for optimal reactor volumetric productivity. The shorter recommended HRTs are consistent with the design recommendations for optimal digester volumetric productivity, but not those for optimal biogas productivity, which requires longer HRTs for maximum gross biogas productivity.

Table 16. Design Parameters for Optimal CSTR Net Energy Production

Design Component	Estimate
Reactor Operating Temperature	30 Celsius
Influent Total Solids Content	7-10% [a,b]
Influent Volatile Solids Content	85%
Retention Time	15-25 days
Heat Exchanger Efficiency	75%

[a] For dairy, as high as possible consistent with pumping and 13 to 14% for plug flow digesters

[b] 6 to 7% optimal for swine manure

Sources: Chen (1985), Gosh (1981), Hawkes, *et al.*, (1981), Hawkes, *et al.*, (1984), Hawkes and Horton, (1981), Horton (1979), Horton (1987), Horton and Hawkes, (1981), Van Velsen and Lettinga (1979)

By contrast, the lower reactor temperature that is recommended for optimal digester net energy productivity is inconsistent with the design criteria for optimal volumetric productivity and optimal biogas productivity, which require reactor temperatures of 35 degrees Celsius or more. In digester design, a balancing of these competing demands is necessary.

Recommended Design Criteria for Medium-Rate Farm-Based Digesters

Based on a balancing of the conflicting demands of digester volumetric productivity, net energy productivity, and waste stabilization, reactor designers and researchers have developed a set of digester design recommendations.

A recommended 6 to 8% total manure solids content and a 15- to 20-day hydraulic retention time, along with a 35 degree Celsius reactor temperature and a 3.5 to 5 kg VS per m^3 of digester volume (0.22 to 0.31lb. VS per ft^3) organic loading rate, would comprise a typical CSTR design recommendation. (Bruce 1986, Fischer and Ianotti 1981, Horton and Hawkes 1981, Jewell and Loehr 1977, Nielson 1985, Pigg 1977, Singh, *et al.*, 1984, Smith 1978) For the plug flow design, the recommended HRT would be longer, and the manure total solids content higher.

Table 17 summarizes practice among and recommendations by researchers and practitioners for manure of recommended total solids content for digestion in CSTRs or plug flow digesters. The values at the low end for hydraulic retention time are based on maximum digester volumetric productivity without provision for any safety margin to insure against bacterial wash-out and to guard against reactor instability in the face of irregular farm operation.

Optimizing design to maximize net energy production would result in generally lower reactor temperatures (27 to 30 degrees Celsius) with longer HRTS (20 days), or, at the standard 35 degree Celsius reactor temperatures, generally shorter hydraulic retention times. (Hawkes and Horton 1981, Nielson 1985, van Velsen and Lettinga 1981)

Operational Means to Relax Constraints to Farm Digester Biogas and Energy Productivity

Non-design operational means to substantially improve the productivity of farm-based anaerobic digestion appear to be limited. As discussed above, the biogas productivity per unit of digester manure substrate is fundamentally limited by the lignification of a substantial part of the cellulose and hemicellulose content of livestock manure, particularly dairy manure.

Opportunities include manure pretreatment, co-digestion, the use of cellulose additives, and heightened attention to water management on-farm. Opportunities are listed in Table 18. More efficient operation of the manure collection system may constitute an additional opportunity. As noted above, with more rapid transport of manure from confinement barns to the digester, less heat is lost from excreted manure to the environment, resulting in the need for less digester influent heating, thereby improving digester net energy productivity. This is an important consideration in the operation of medium-rate farm digesters.

Table 17. Digester Design Parameters: Range of Estimates Typically Found in the Literature for Conventional Medium-Rate Farm Reactors

	Total Solids (%)	Reactor Temperature (degrees C)	RetentionTime (days)	Organic Loading Rate (kg $VS/m^3/d$)
Dairy				
CSTR	7-10	35-40	15-20	3-6
Plug Flow	10-13	35-40	20-25	3-7
Swine	4-7	35-40	10-15	3-5[a]
Beef	7-10	35-40	10-15	3-6
CSTR General	6-10	35	15-20	3-5

[a] at a lower manure total solids content, 2 to 3%, the organic loading rate would be less, 2 kg $VS/m^3/d$

Sources: Cattle-Campbell, *et al*., (1997), Chessire (1986), Converse, *et al*., (1977), Fulhage (1993), Gunnerson and Stuckey (1986), Hashimoto (1983), Hill (1983), Hill (1983), Hobson and Wheatley (1993), Jewell and Loerh (1977), Jewell, *et al.*, (1981), Jones, *et al*., (1982), Kiely and Taluntais (1984), Lusk (1997), Nielson (1985), Sax and Lusk (1996), Singh, *et al*., (1984), Smith (1978)
Swine-Chen (1983), Chessire (1986), Fischer, *et al*., (1977), Fischer, *et al*, (1986), Fischer and Ianotti (1981), Hashimoto (1983), Hawkes and Horton (1981), Hill (1983), Hobson and Wheatley (1993), Horton (1987), Jones, *et al*., (1982), Smith (1978), Ruggeri (1986), Schultz, *et al*., (1985), Van Velsen and Lettinga (1981)
CSTR general-Bruce (1985), Fischer, *et al*., (1986), Horton and Hawkes (1981), Stafford (1978), Sweeten, *et al*., (1984), Van Velsen and Lettinga (1979)

Table 18. Operational Means to Raise Digester Biogas and Energy Productivity

Optimize Digester Buffering Capacity
Manure Pretreatment to Increase Rate of Hydrolysis
Addition of Non-lignin-bound Carbohydrate Substrate to Manure Feed
Addition of Lower-fiber, Higher Energy Animal Manure to Existing Manure Feed
Intensified Water Management to Limit Manure Dilution
Rapid Transport of Manure from Barns to Mixing Pit to Minimize Heat Loss

Sources: Fannin (1987), Hawkes (1979), Fannin (1987), Hawkes (1985), Hobson (1988)

Pretreatment alternatives that have been investigated include chemical pretreatment, physical pretreatment to reduce particle size, and pretreatment using high temperatures. (Ashare and Wilson 1979, Tsao 1987) These act by enhancing the hydrolysis of lignin-bound cellulose and hemicellulose. Chemical pretreatment can involve either alkaline treatment of the waste, typically using sodium hydroxide or ammonia, or enzymatic treatment. Biogas productivity has been noted to increase by 10 to 50% with alkaline pretreatment and possible more. (Price and Cheremisinoff 1981, van Velsen 1981, Tsao 1987)

With heat pretreatment, influent waste is heated to temperatures of 80 to 200 degrees Fahrenheit for one-half to several hours. (Hagelberg 1985, Price and Cheremisinoff 1981) Increases in biogas productivity of 40% have been noted. (Hagelberg 1985) Freeze explosion of the cellulose-hemicellulose complex is also discussed in the literature. (Tsao 1987)

Physical pretreatment involves the particle size reduction using mechanical means, including screening, and irradiation. (Tsao 1987, Hawkes, *et al.*, 1984, Pain, *et al.,* 1985)

In the literature, the high cost of chemicals and energy is typically cited as a constraint to the use of pretreatment on-farm for purposes of improving waste biodegradability.
Physical pretreatment for particle size reduction appears to be the only exception. (Hobson and Wheatley 1993)

Pure cellulose additives act to increase biogas yields, but large amounts would be needed to noticeably raise biogas production in a farm digestion, which raises cost concerns. (Hobson 1990) However, substitutes like shredded newsprint might offer a source of more biologically available cellulose.

Co-digestion of low bio-degradability manure with more biodegradable organic wastes is another option to raise digester biogas productivity, but high transportation costs presumably are limiting, particularly with low total solids wastes like whey or dilute swine manure. No co-digestion is reported at working digesters in the US. (Lusk 1997)

The most feasible alternative may involve heightened attention to water management on-farm to prevent excessive manure dilution prior to digestion (e.g., dilution below 12% for the plug flow design and below 4 to 6% for the CSTR design). According to Moser (1996) and Roos and Moser (1997), it should be possible to maintain the total solids content of swine manure stored below barn in pits near 3% with stringent measures to control excess use of water. More efficient operation of the manure collection system may constitute another workable alternative.

This suggests that the design limits for anaerobic digestion are not likely to be easily relaxed, but rather are likely to persist as limiting conditions into at least the immediate future. Table 19 lists limiting factors to the performance of conventional medium-rate farm digesters. These summarized from the prior discussions.

Table 19. Summary of Biological and Design Limits to Farm Anaerobic Digestion, Conventional Medium-Rate Farm Reactors

Limit	**Digester Design Parameter Effected**
Lignin-binding limit to biodegradability	CH_4 productivity per lb. of manure produced
2% total solids (TS) limit for wash-out	manure quality
8-10 day HRT limit for wash-out	reactor size
15-day HRT limit for farm operation	reactor size
4% TS limit for viable volumetric productivity	manure quality
4% TS limit for viable net energy productivity	manure quality
14% TS limit for manure pumpability	manure quality
35 degree Celsius reactor temperature limit	reactor size

Digester Sizing for Conventional Medium-Rate Farm Reactors

The principal component of a conventional medium-rate farm digestion system is the digester vessel or reactor. This is sized in relation to the length of retention of the waste in the reactor. The typical medium-rate farm reactor is sized to handle 15 to 20 times the amount of daily waste generation. About 1 cubic meter (35 cubic feet) of digester volume is necessary per dairy cow in a slow rate reactor like a CSTR or a plug flow digester. (Loll 1986, Smith 1978, Jones, *et al.,* 1982) Swine digesters are sized at about 0.1 cubic meters per market swine and about 0.2 cubic meters per breeding swine. (Aubart 1983, Smith 1987) This assumes a shorter, 10 to 15 day HRT. Anaerobic digestion of beef manure typically requires about 0.5 cubic meters of digester volume per head of beef cattle.

Required digester volumes per ton of daily manure production are shown in Table 20 for rates of manure dilution characteristic of manure handling in dairy and swine operation and equal 20 day HRTs. For dairy, at 10 tons of manure production about 140 cubic meters of plug flow digester volume would be required for digestion at typical hydraulic retention times for dairy manure and 13% total solids content. This would correspond to the manure production of about 125 milking cows. This rises to 1,415 cubic meters for 100 tons per day processing capacity (about 1,250 cows), and 14,300 cubic meters for a processing capacity of 1,000 tons per day.

The corresponding values for swine would be 1,215 cubic meters for the processing of 10 tons of daily swine manure production, rising to about 121,400 cubic meters for 1,000 tons of daily swine manure production. The roughly factor of nine difference in required digester capacity per ton of manure processed is due to the high level of dilution of swine manure. About 2,350

Table 20. Approximate Digester Size in Relation to Waste for Processing: Conventional Medium-Rate Farm Digesters

Manure (Tons/day)	Digester Volume (cubic meters)	Manure (Tons/day)	Digester Volume (cubic meters)
Dairy[a]		Swine[b]	
10	144	10	1,214
100	1,415	100	12,141
1,000	14,300	1,000	121,407

(a) 20-day retention times, free stall barn, CSTR

(b) 20-day retention times, pull plug below barn pit, CSTR digester, FarmWare default values for manure quality for below-barn pit storage

Source: USEPA (1997)

grower hogs would produce 10 ton of swine manure per day, while 1,000 tons of daily manure production would correspond to a grower hog herd of about 23,500 hogs.

Biogas Uses

Digester biogas is comprised of 55 to 70 % CH_4, 30 to 45% CO_2, and 0.2 to 0.6% H2S. (Voermans 1985, Hobson and Wheatley 1993, Moser 1996). The energy content of digester biogas is about 600 Btu per cubic foot of gas.

Storage of digester gas for future use after generation is generally limited on-farm by high costs. Due to its low energy content per cubic foot (25% that of propane gas), digester gas must be compressed prior to storage in steel tanks. The parasitic energy loss associated with gas compression is estimated to be equal to about 20% of the energy content of the initial biogas. (Weeks, *et al.*, 1989) For this reason, storage for future use after gas generation is not thought to be economically feasible for farm digestion. (Martin and Loehr, 1980, West, 1986)

Given the absence of storage as an option, digester biogas must be used or, if there is an excess, flared, as it is generated in the digester. Biogas may be used to generate electricity, to generate hot water and steam in a boiler for space and water heating on-farm, for air conditioning through the use of a gas-fired chiller, and, with substantial clean-up, in place of natural gas as pipeline quality fuel.

The most economically valuable (and widespread) use of the gas is in the generation of electricity for on-site use. (Roos and Moser 1997) Electricity can be generated on-farm with digester biogas using diesel generators ranging in size from 10 to 50 kW. Diesel generators are about 25% efficient in converting the energy in the fuel to electricity. The remaining 75% is waste heat that is either lost to the environment or at least in part is captured and used to heat the digester and used for on-farm space and water heating. As noted above, for a conventional medium-rate digester designed to treat relatively high total solids manure at conventional HRTs (20 days) and reactor temperatures (30 to 35 degrees Celsius), about one-third of digester biogas production is needed for digester heating, or about one-half of the waste heat of the engine.[4] Of the remaining half, about 40% is lost to the environment (based on an overall thermal efficiency of the system, including both engine and waste heat capture, of about 80%). The rest is available for on-site space and water heating uses.

Digester biogas can be combusted in diesel engines without substantial gas clean-up. However, continuous operation of the engines without frequent start-ups and shut-downs is needed to avoid problems associated with acid gas condensation in the engine, including shortened engine and heat exchanger lifetime. (Crocker 1985, Constant, *et al.,* 1989) Diesel engines burning biogas do require more frequent oil changes and possibly incur more wear and tear. (Hobson, 1990)

For purposes of electricity generation, the generator can operate in parallel to the electric distribution utility, matching utility power phasing, frequency and voltage so that farm-produced electricity blends in with power put on the grid by the local utility. (Moser, 1996) This requires an inter-tie panel that, in addition to operating the farm generator in concert with the grid, also automatically disconnects it from the grid in the event of a problem with the generator or a problem in the distribution system. Excess electricity is sold on the grid at rates contractually agreed to. The generator itself runs at a constant rate regardless of farm electrical demand, which results in reduced wear and tear on the engine.

Alternatively, the generator can be set up as an isolated system. However, this requires sophisticated controls and gas storage to match power output to farm loads, as well as over-sized engines and generators.

As a rule of thumb, 10 milking cows would be needed to power a 1 kW generator using a plug flow or slurry-loop digester or a CSTR. (Fischer, *et al*, 1986) Hence, a 500-cow herd would be required to power 50 kW of generation capacity. More recent experience suggests that as few as 8 cows may be necessary to provide 1 kW of installed generation capacity. With regard to market hogs, 1 kW of power would correspond to about 140 140 lb. hogs.

The costs of a diesel engine-generator is about $800 per kilowatt of power installed. (USEPA 1999)

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[4] As discussed in the next section, for dilute manure of 2 to 2.5% total solids, 75% or more of digester biogas production would be needed for digester heating. Assuming an 80% thermal efficiency of the entire system, hence a 20% loss to the environment in the form of uncaptured waste heat, the amount of waste heat available at these manure total solids would be negligible.

Finally, biogas engines meet all California air pollution standards without the need for either gas clean-up or engine modifications. (Moser 1996)

Boiler uses of biogas from digestion do not require substantial gas clean-up. (Constant, *et al.*, 1989, West, 1986) Boilers combusting biogas are about 75% efficient in converting fuel to steam for space and water heating. Boiler uses of biogas are relatively rare in the US in comparison to use involving electricity generation. (Lusk 1997) At least some of this is probably explained by a decade and a half of falling real liquid fuel prices, 1985 to 2000.

Residential and commercial uses of digester gas, whether on-site or through sales to natural gas pipeline companies, require substantial gas clean-up, including the removal of excess CO_2 to raise the heat content of the gas and removal of biogas hydrogen sulfide (H_2S). H_2S can be most economically removed by passing the biogas through 1 or 2 layers of iron oxide to form ferric sulfide, with regeneration by subsequent exposure of the absorbant to oxygen. (Constant, *et al.*, 1989) CO_2 can be removed through water scrubbing. In practice, however, with the exception of research reactors, few US digesters employ gas clean-up. Only one attempt, in the 1980s, has been made to develop pipeline-grade biogas for sale, but it has long since been abandoned.

At present, most farm anaerobic digestion systems utilize the biogas in diesel generators for purposes of electricity generation. It is likely that this condition will continue as excess electric generating capacity becomes increasingly scarce throughout the US and the Midwest, increasing the value of marginal new capacity, and thus providing biogas developers an incentive to produce electricity for the grid.

Future energy conversion technology for digester biogas may include fuel cells and microturbines.

Digester Construction, Materials and Subcomponents

A listing of system components is given in Table 21 for a conventional non-lagoon farm reactor. Sub-components of the digester vessel include the structural components of the reactor and tank insulation. The digester vessel is typically situated below ground to benefit from the insulating qualities and structural support afforded by below ground construction. By situating the digester below ground, it is also possible to exploit the advantages of gravity feed from the barns to the digester. The digester vessel or tank is typically fitted with insulation to a level of R-10 for below ground tank situation and R-20 for above ground tanks. (Jones, *et al.*, 1982) Construction is typically of concrete or, in the case of above ground tanks, enameled or welded-enameled steel. Average vessel lifetimes are 40 years for a concrete tank and 20 years for a steel reactor vessel. (Hobson and Wheatley 1993)

The heating system utilizes large surface area heat exchangers placed in the interior of the digester and internal hot water circulation. Digester heat exchangers are 50 to 80% efficient. (Hawkes 1979) A 70% value comprises good practice for digester heat exchange efficiency. The use of heat exchangers located on the exterior of the digester is limited by the corrosive effects of the digester liquid. With exterior heat exchangers, effluent is removed from the digester vessel to the exterior of the tank for heating. Maximum heat exchanger temperature is

50 to 70 degrees Celsius to prevent the drying of sludge on heat exchanger surfaces and injury to sensitive bacteria populations.

In-tank mixing systems, where utilized, can use either mechanical agitation or biogas injection and recirculation through the digester interior. Gas recirculation requires no interior moving parts. This constitutes its principal advantage. Mechanical mixing using paddle wheels or crew type impellers tends to be shorter-lived and have higher maintenance costs. (Bruce 1985, Hobson and Wheatley 1993) The pre-mix tank is typically sized for two days of manure storage.

The pumping system relies on special solids handling pumps capable of handling high total solids slurries. The piping must be insulated against winter freeze-up, and usually employs corrosion resistant materials. Straight oversized piping is employed to limits problems with blockage. (Fischer, *et al.*, 1986) Reversible pumps are typically employed to clear blockages. (Hobson and Wheatley 1993) Influent feeding is by timer. Sensors are fitted to the digester to deal with overflow in the event of problems with the timers. In the case of a below ground-situated digester and gravity feed into the digester vessel, pumping is limited to effluent pump-out.

The gas use system was described above. Gas is removed from the digester through gas lines. De-watering is effected through a condensate drain. (Moser 1996) Gas lines must be insulated against line freeze. (Constant, *et al.*, 1989)

Finally, a biosolids plant may be added to the system, comprised of a vibrating screen, a screw press or sedimentation basin. Vibrating screens operate best at 6% total manure solids content or less. Clogging is often a problem with mechanical screw presses. As noted above, efficiencies of mechanical liquid-solids separation are low, about 25%, which may suggest the use of a sedimentation basin. Sedimentation basins work more slowly but with a higher yield of solids.

Table 21. Farm Digester Components: CSTR, Plug Flow and Slurry-Loop Designs

Digester Vessel
Insulation
Structural Components

Digester and Influent Heating
Heat exchanger
Hot water piping in the digester

Mixing
Mix tank[a]
In situ mixing[a]

Pumping
Pumps and piping
Timers and sensors

Gas Utilization
Gas cleanup
Diesel engine and electric generator
Gas transport to the engine
Waste heat utilization

Effluent Storage and Utilization
Solids separation
Byproducts processing
Outdoor storage of effluent

[a] optional depending on reactor design

Operating a CSTR, Plug Flow or Slurry-Loop Farm Digester

The operation of a conventional medium-rate farm digester involves the daily feeding of the digester and monitoring of the digester performance and chemistry. In addition, the operation of a farm digester involves routine maintenance of the mechanical part of the system, particularly the engine, and, upon a system upset, intervention to resolve imbalances in the digester. The operation of a farm digester also involves periodic digester clean-out, and digester re-start.

As discussed above, to maintain stable microbial populations, regular feeding of the digester on a daily basis with fresh manure is recommended for medium-rate continuous-feed digesters. While most medium-rate farm digesters can tolerate some degree of irregular feeding, particularly those with long HRTs, digester performance will suffer. For this reason, it is best avoided.

Digester performance is monitored by monitoring biogas productivity, biogas composition, digester pH, digester volatile fatty acid concentration, and effluent volatile solids content. Signs of reactor instability include: a rapid drop-off of digester gas productivity, decreasing pH, increasing volatile fatty acids concentrations in the digester, and declining CH_4 content of the biogas. (Fulhage 1993) Thresholds for inhibition of digester performance were given above in Table 1 for VFA concentration and pH, in Table 5 for characteristic volatile solids destruction in a digester, and in Table 13 for characteristic levels of digester biogas productivity.

As discussed above, too rapid a rate of digester feeding can lead to upset in a conventional medium-rate farm digester. The same is true for irregular digester feeding, a rapid temperature drop in the digester, or accumulation in the digester of substances that, at high levels, are toxic to one or more of the digester bacterial populations. If an imbalance in the digester is detected early enough, intervention could involve as little as slowing the feed rate or adding buffering capacity to the digester in the form of calcium hydroxide or bicarbonate. (Hawkes 1985, Gunnerson and Stuckey, 1986)

If extremely toxic conditions evolve in the digester, complete digester shut-down, followed by clean-out and re-start is often necessary. For a conventional medium-rate farm reactor, start-up time after clean-out is variously estimated at 6 to 9 weeks. (Summers and Bousfield, 1980, Hobson, 1990) During start-up, the digester is fed at a reduced rate, about 20% of normal, increasing about 20% per week until the optimal loading rate is reestablished. (Sweeten, *et al.*, 1984) Innoculum from a healthy digester is added during initial start-up. It is recommended that antibiotics be avoided during start-up or, in this case, re-start. (Fischer and Ianotti, 1981)

The same process is required following periodic clean-out of the digester to remove accumulated solids in the digester bottom. The accumulation of solids in the digester can substantially decrease the efficiency of digester heat exchangers (Campbell, *et al.*, 1997), leading to declining digester net energy productivity. The factors that contribute to net energy productivity in conventional medium-rate digesters were discussed above.

For conventional medium-rate farm digesters, routine monitoring and digester maintenance is estimated to require between 15 and 25 minutes per day of labor. (Campbell, *et al.*, 1997, Hawkes, *et al.*, 1985, Weeks, *et al.*, 1989) Routine maintenance at working digesters is dominated by maintenance of the diesel engine, including frequent oil changes and plug changes. The engine also requires an overhaul on an annual basis.

Historically, most non-design problems encountered during the operation of medium-rate farm digesters have involved failures in the electrical or mechanical parts of the digestion system, especially the pumping components. (Bernardino and Olivera, 1994) Gas-line freezing is another frequently encountered problem, along with the freezing of manure in gravity-fed systems during cold weather. (Constant, *et al.*, 1989, Weeks, *et al.*, 1989) Corrosion is reported to be a problem for some digesters, and not for others. (Constant, *et al.*, 1989, Sievers 1990) Where it has been reported, corrosion has occurred to the digester heat exchangers, engine burner, and engine exhaust piping. (Constant, *et al.*, 1989)

Finally, safety is a concern in the operation of a farm digester like a CSTR. Of the components of biogas, methane is explosive at 5 to 15% oxygen, and hydrogen sulfide (H_2S) can cause respiratory failure or death at levels typically found in biogas (1,000 to 3,000 ppmv). (Moser, 1996) Digester buildings should be equipped with detectors for CH_4 and H_2S, and access to the digester vessel itself should be restricted. Excess biogas should be flared, and all gas lines should be fitted with flame traps. Finally, before cleaning, all gas lines should be purged. (Smith, 1978)

Economics of Anaerobic Digestion for Conventional Medium-Rate Farm Digesters

Minimum design standards are given in the literature for anaerobic digester feasibility using conventional medium-rate farm reactors. These constitute the baseline design conditions for economic feasibility. These are shown in Table 22.

Minimum design standards for economic viability of farm anaerobic digestion include: digester volumetric productivity of at least 1 m^3 biogas/m^3 of digester volume per day; and manure influent total solids of at least 4% and possibly 6%. Also included in Table 22 is an estimated farm electric rate threshold for economic viability of digestion of $0.06 to 0.065 per kWh. This reflects annualized generation costs for anaerobic digestion near this level.

These minimum design standards found in the literature have been developed based on observation of the design conditions that have been attained in economically viable operations, or, conversely, the conditions not attained at operations that clearly do not meet the test of economic feasibility. They are useful in defining conditions under which anaerobic digestion under typical farm conditions is unlikely to be a going concern. Most have been offered as judgments drawn from engineering analyses.

It is possible to develop more thorough analyses of the economic feasibility of anaerobic digestion using cost-benefit analysis. The costs of digestion include capital costs and operating costs. Benefits include monetized and non-monetized benefits to the feedlot owner of digestion in the form of reduced on-farm electricity and space heating bills, reduced bedding costs, reduced labor costs with respect to manure handling, and the benefits of the sale of excess electricity to the grid. Non-monetized benefits to the public take the form of pollution control. In the analysis, the stream of capital costs, including the costs of money, is discounted to account for the time-value of money, and are then annualized to make them directly comparable to annual operating costs and benefits. At any given discount rate, a project is economically viable if project benefits exceed costs.

Table 22. Feasibility Thresholds for Various Physical Digester Parameters: Conventional Medium-Rate Farm Digesters

Condition	**Total Manure Solids**
Minimum influent total solids to avoid CSTR washout	2%
Minimum influent total solids for positive CSTR net energy	2 to 3%
Total solids for minimum required volumetric productivity	4%
Minimum total solids for economic viability	4 to 6%
	Other
Minimum volumetric productivity	1 m^3/m^3 dig. vol.-day
Farm electricity purchase price	$0.06-0.065/kwh
Total capital costs	0,000 per 500 cow-equivalent[a]

[a] $150,000 (1988$)

Sources: Coombs (1990), Moser (1996), Naveau (1986), Perwanger (1986), Rozzi and Passino (1985), Sommers and Bousfield, (1980), and Table 15 above.

Sources of economic benefit from the anaerobic digestion of livestock manure are shown in Table 23. A large number of sources of economic benefit are possible. In practice, however, the economic benefits of anaerobic digestion, regardless of reactor type, are dominated by the benefits to the feedlot owner of the avoided costs of electricity purchases. (Edelman 1984, Hobson and Wheatley 1993) This is due to the relatively low value of waste processing or solid byproducts to the feedlot owner in comparison to the value of the electricity purchases-avoided, as well the difficulties encountered in quantifying the external costs of manure management to the environment and the public.

Second in importance in terms of benefits are the benefits of the avoided costs of LPG purchases for on-farm space and water heating needs. As discussed above, waste heat from the diesel engine can be used for on-farm space and water heating. Next in importance are the avoided costs of bedding.

Table 23. Potential Sources of Public and Private Benefit from Anaerobic Digestion: Monetized and Nonmonetized Benefits

Monetized Avoided Costs to the Feedlot Owner:
Cost of purchased electricity
Cost of LPG for on-farm space and water heating
Farm bedding costs

Nonmonetized Avoided Costs to the Feedlot Owner:
Odor
Reduced nuisance complaints about odors and flies
Reduced manure handling costs

Added Revenue Streams Accruing to the Feedlot Owner:
Off-farm sales of excess electricity production
Off-farm sales of solids as fertilizer or compost
Sales of co-digestion services
Sales of greenhouse gas reduction credits
Public subsidies accruing to renewable energy development

Avoided Public Costs From:
BOD-loading of surface waters
Pathogen-loading of surface waters
Odor and H_2S emissions
Greenhouse gas emissions

Sources: Highham (1998), Lusk (1996), Lusk (1998) and Table 4 above

For anaerobic digestion using conventional medium-rate farm reactors, on a per cow basis, the potential annual benefits from the displacement of purchased electricity, assuming that all farm-generated electricity is used on the farm, are about $35 to 85.[5] As discussed above, the potential annual benefits from avoided bedding purchases are on the order of $35 to50 per cow. (Lusk 1997) The potential benefits from waste heat use are on the order of $15 to 35 per cow per year.

For conventional medium-rate farm digesters, digester operating costs are typically on the order of 3.5% of capital costs, or in the range of $5,000 to 10,000 per year. (Campbell, *et al*.,

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[5] Calculated at 40 to 90 ft^3 biogas/cow/day from Table 7 above, 23% conversion efficiency to electricity, 90% capacity factor, $0.07 per kWh farm electric rate, 75% heat exchanger efficiency, digester parasitic energy use of 33%, and LPG purchase price of $0.5 per gallon

1997, Moser and Mattocks 2000, USEPA 1997)

For medium-rate farm digesters, current capital costs (including the costs of the energy plant and expenses for waste heat and solids utilization) are about $150 to 500 per cubic meter of digester space, depending on reactor size. (Bernardino and Oliviera 1994, Lusk 1998, Moser and Mattocks 2000, USEPA 1997, Zhang, *et al.*, 1990) Small reactors have the highest unit costs, large reactors the least (see Tables 24 and 25). This reflects economies of scale associated with unit digester costs. Economies of scale in digester costs long have been recognized as an essential part of the economics of anaerobic digestion in waste processing. (Hashimoto and Chen 1983, Jewell 1984, Jones and Ogden 1986)

Table 24. Digester Capital Costs: Conventional Medium-Rate Farm Digestion, Dairy Feedlots

Manure (Tons/day)	**Digester Volume (cubic meters)**	**Cost (1995$)**	**Cost $ per m^3**	**Cow-Equivalents (number)**
10	200	$92,500	463	125
100	1,975	$262,700	133	1,225
1,000	19,950	$1,752,800	88	12,250

(a) Estimated for 20-day waste detention times

Source: USEPA (1997)

For conventional medium-rate farm digesters, digester costs per unit volume of reactor space have been declining over time. From a review of 34 studies, Jones and Ogden (1986) determined that the capital costs per m^3 of digester volume for conventional medium-rate farm reactors in the late 1970s and early 1980s were on average $395 at 200 m^3 of digester volume. For $2,000 m^3 of digester volume, they were about $230 per m^3. In 1995 dollars, this is equal to roughly $600 per m^3 at 200 m^3 of digester volume, and $350 per m^3 at 2,000 m^3 of digester volume, which implies that real costs per unit of digester volume have fallen between 20 and 60% since the early 1980s.

The distribution of capital costs for a conventional medium-rate farm anaerobic digestion system, assuming that the costs of effluent storage of digested effluent are not included, would

Table 25. Digester Capital Costs: Conventional Medium-Rate Farm Digestion, Swine Feedlots, Slatted Floors, Below Barn Pit Storage

Manure (Tons/day)	**Digester Volume (cubic meter)[a]**	**Cost (1995$)[b]**	**Finisher-Equivalents (number)**
10	1,695	254,250	2,350
100	16,946	1,525,150	23,500
1,000	169,465	14,445,000	235,000

[a] Estimated for 20-day waste detention times

[b] Calculated at $150 per m^3 for 10 tons per day processing capacity, $90 per m^3 for 100 tons per day processing capacity, and $85 per m^3 for 1,000 tons per day processing capacity, from Table 24 above.

Source: USEPA 1997

be about 45% for the digester, digester equipment and engineering fees, 40% for the energy plant, and 10% for the solids recovery plant. (Hashimoto 1994, Lusk 1998) The energy plant would include the diesel generators, generator building and electric utility inter-tie.

Cost items include: the digester tank, mixers, pumps, the heating system and insulation, pH and nutrient control equipment, the diesel generators, the diesel generator building, the electric utility inter-tie, the mixing tank, the solids recovery plant, excavation fees, and engineering fees. (Biljetina 1987)

Cost effectiveness is calculated using the total present value of the stream of costs over the life of the project, the total present value of the stream of benefits of the project over its lifetime, and some assumed required internal rate of return to investment. The required internal rate of return (IRR) to investment is typically established at the rate of return that could otherwise be earned in a competing investment. A 10 to 14% IRR is typically employed.

It is conventional in the economics literature on anaerobic digestion to define herd threshold levels for economic viability. This is due to the economies of scale evident in the economics of anaerobic digestion. Capital costs per unit volume of digester space rapidly decline as the reactor volume increases. Operating costs also decline with increasing digester size. (Edelman 1984) Gas production per unit of reactor volume is reasonably constant across reactor size, while digester heat losses decline as digester volume increases. (Hawkes 1985, Stafford, *et al.*, 1978) At some point as reactor size increases, the benefits of biogas production per unit of digester volume outstrip the costs, resulting in an economic return to investment. Reactor or digester size is a function of livestock herd size, and, at constant digester design parameters, increases linearly with herd size.

Threshold herd sizes for economically feasible anaerobic digester deployment on dairy and swine feedlots are shown in Table 26. Shown are the results of published analyses for conventional medium-rate farm digesters like the CSTR or plug flow. Estimates of herd sizes that are not viable are shown in Table 27, again for dairy and swine, and again assuming the

Table 26. Estimates of Herd Size Thresholds for Economic Viability of Digester Deployment with Conventional Medium-Rate Farm Reactors

Published Estimate	**Size Threshold For Economic Viability**
Dairy Feedlots	
Ifeadi and Brown (1975)[a]	
Jewell (1984)[b]	1,000
Jones and Ogden (1983)[c]	200
Lusk (1995) (partial manure collection)[d]	1,250 to 1,370
Lusk (1995) (full manure collection)[e]	300
Lusk (1998)[f,g]	<500
Martin and Lichtenberg (1981)[h]	700
Martin and Loehr (1980)	500
Olivier, *et al*., (1986)[i]	400
Scheller (1982)	650
USEPA (1999)	700
Swine Feedlots	
Jones and Ogden (1986)[b]	5,000
Lusk (1995)[j]	2,900 to 3,700

[a] approximate

[b] 12% loan rate

[c] with an assumed 15% per year escalation in price of electricity, approximate value

[d] 50% manure capture

[e] 100% utilization and/or sale of all generated electricity, engine waste heat, and manure co-products

[f] with an assumed farm electric rate of $0.11 per kWh, 20-year project lifetime

[g] positve net present value at a 16% internal rate of return hurdle

[h] with an assumed 10% per year escalation in the price of energy, 20-year project lifetime

[i] with an assumed 6% per year escalation in the price of electricity

[j] with an 8.5% internal rate of return hurdle, 4,000 to 5,000 head of finishing hogs at a 10 to 14% internal rate of return hurdle; with an actual, operating swine feedlot, a value of 10,000 head was also calculated as just viable against an internal rate of return hurdle of 8.8%

use of medium-rate farm digesters. Where it is possible, what now appear to be unrealistically high rates of increase in energy prices, or exceptionally long estimated project lifetimes, are noted.

Most analysis for dairy suggests that digester deployment at herd sizes of 300 cows or less probably is not economical (see Table 27). Early estimates that suggested that anaerobic

Table 27. Estimates of Herd Sizes Not Economically Viability for Digester Deployment with Conventional Medium-Rate Reactors

Published Estimate	Herd Size Not Economically Feasible
Dairy	
Campbell, *et al.*, (1997)	230
Jewell (1978)	100
Lindsey (1986)[a]	120
Lusk (1995) (partial manure collection)[b]	250 to 1,000
Olivier, *et al.*, (1986)[c]	200
Oppenlander, *et al.*, (1979)[d]	200
Sasscer and Morgan (1988)	320
Thornton (1978)	40 to 100
Whittier, *et al.*, (1993)	300
Williams, *et al.*, (1978)	100
Swine	
Aubert (1983)[e,f]	4,000
Castigame, *et al.*, (1979)	100 to 500
Fischer, *et al.*, (1981)	3,200
Fischer, *et al.*, (1986)	3,775
Piccini, *et al.*, (1998)[g]	650
Stafford (1983)	5,000
USEPA (1999)[e,h]	5,100

[a] cost-ineffective at $0.04/kwh, cost-effective at $0.08/kwh ($1985)

b 50% manure capture, partial utilization of project generated electricity

[c] with an assumed 6% per year escalation in the price of electricity

[d] generation costs of $0.09 per kWh

[e] using a low total solids swine manure

[f] with an assumed 13% per year escalation in the price of electricity

[g] feasible at $0.14 to 0.15/kwh farm electric rates

[h] no CH_4 emission reduction potential at 5,100 head that meets a 10% internal rate of return hurdle as a measure of economic viability for project cost and benefits terms that can be monetized

digestion might be economically deployed on small dairy farms assumed that the price of electricity would increase 10 to 15% per year over the life of the project. These estimates probably can be ignored.

For swine, published estimates of herd sizes for which digestion is not economically feasible fall into the 3,000 to 5,000 head range. It might be noted that most of these estimates apply to facilities that manage swine manure predominantly as a 4 to 6% TS slurry. However, Aubart (1983) and USEPA (1999) do provide analyses of the feasibility of digestion using a dilute low total solids swine manure. Again, these estimates assume the use of conventional medium-rate farm digesters.

Less can be deduced from Table 26. Here the calculated threshold herd sizes for economic viability are influenced by high rates of assumed escalation in electricity and energy prices. This makes most of the estimates unreliable. The extreme values at the high-end for dairy derive from one study that utilizes extremely high capital cost estimates ($\$1,050/m^3$ digester volume) and another, more recent, estimate that assumes only partial (50%) manure capture (milk parlor and feed apron only). If, in the latter, Lusk (1995), study, we recalculate the manure production for the 1,250- to 1,370-head threshold in cow-equivalents (assuming 90% manure collection), from Table 26, it seems that a 500- to 800-head threshold or lower might be supportable.

For swine, size thresholds for economic viability depend critically on manure dilution. Analysis using FarmWare, the USEPA evaluative software (USEPA 1997), for high total solids swine manure (5 to 6%) and an assumed 10 to 14% internal rate of return hurdle suggests a threshold for economic viability in the 4,000 to 4,500 head range.[6] This is roughly similar to the results given in Table 26 for non-dilute farm manure with 4 to 6% total solids content (see Table 26).

Dilution to 2% total manure solids necessarily raises this threshold, as is evident from cost and benefits estimates for recently constructed medium-rate CSTRs digesting dilute swine manure. Digester designers report simple payback periods for 5,000 sow farrow-to-wean operations (14,000 finishing hog-equivalent operations) of 15 years, which employing discounted cash flow analysis yields internal rates of return on investment for these projects of less than zero. (Moser and Mattocks 2000, Lorimor 2000) These results are suggestive of the conclusion that only very large swine feedlots managing manure as very dilute slurry are capable of supporting medium rate farm digesters. This is consistent with the discussion above relating manure dilution to digester volume and project capital costs.

Analysis exists for beef feedlots. However, with the exception of one study, in which very high farm electric rates were assumed, none identified a feasible herd size for economical on-farm deployment of anaerobic digestion. This includes assessments of 300 to 3,500 head of steers,

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[6] In terms of nonthreshold calculations, using a simple 3- to 4-year simple payback period as a indicator of economic viability, Moser, *et al.*, (1998) conclude that digester deployments at feedlots sized for 7,500 to 15,000 head of finishing hogs-equivalent (800 to 1,600 sow farrow-to-finish operations) are economically viable. This assumes a minimum 4% total solids manure managed with scrapers.

and one negative assessment for a 45,000-head operation. (Jones and Ogden 1986, Meyer 1985, Miranowski 1976) Again, the analyses assumed the use of conventional medium-rate farm digesters.

For anaerobic lagoons, herd thresholds for economic viability for swine manure, even highly dilute manure, are low, about 2,000 to 3,500 head of market swine. (Sax and Lusk 1995) This is due to the low capital costs involved in covering an existing lagoon, and the lack of required heating and daily management of the lagoon.

A different approach to the assessment of economic feasibility would be to examine failure rates for on-farm anaerobic digestion and its causes. Failure rates for conventional medium-rate farm digesters have fallen dramatically since the middle 1980s. The failure rate for conventional medium rate farm anaerobic digesters from 1970 to the present was about 80%. (Lusk and Moser 1996) Since 1985, the failure rate has dropped to one-fifth. (Lusk 1998) In the literature, this is explained as the result of simpler digester design, enhanced digester reliability, and lower capital costs. (Lusk 1998)

On this basis, it can be concluded that the economic feasibility of anaerobic digestion using conventional medium-rate farm digesters probably has improved since the early to middle 1980s.

In Europe the situation is clouded by extensive governmental subsidization of anaerobic digestion. Typically, capital costs are subsidized at a rate of 23%. (Koberles 1998) Corresponding capital costs per m^3 of digester volume are much higher than those in the US. At the mean European digester cost per m^3 of digester volume, rates of return to investment are an anemic 0.25 per year, even assuming a very long 20-year project life, and equivalent. (Higham 1998) This is roughly equivalent to a 20-year simple payback on investment. The best digestion systems, with capital costs that are similar to US costs, yield a rate of return on investment of 17%, although uncharacteristically long project lifetimes are assumed. Earlier analysis noted that few European farm digesters met the critical 1 m^3/m^3 dig. vol.-day level of volumetric productivity necessary for economic viability. (Naveau 1985)

The economics literature on anaerobic digestion addresses the requirements for anaerobic digestion using conventional medium-rate farm digesters. These preconditions are listed in Table 28.

Total digester capital costs per unit of digester volume must be minimized. A maximum cost of \$200-300 (\$1985) per cubic meter has been suggested. (Oliviera and di Bernardino 1994)

Anaerobic digestion must be well integrated into the existing, or in the case of a new feedlot, proposed farm lay-out and manure management practices. (Lusk 1998) This includes, among other things, rapid movement of manure to the digester with a minimum of heat and manure loss, and facilities to store manure at an appropriate total solids content. Extra costs for major farm redesign to support an anaerobic digestion system cannot be supported by the economics of digestion. This includes supporting components like post-digestion outdoor storage capacity or new animal housing or manure collection equipment.

Table 28. Preconditions for Successful Digester Deployment on Farm

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Efficient manure collection system at low level of manure loss
Pre-existing outdoor manure storage basin, tank or lagoon for digester effluent
Management of manure consistent with a solids content of at least 4%
Large herd size
Large on-farm electricity needs relative to digester electricity production
Farm electricity rates of at least $0.065 per kilowatt-hour
Opportunities for on-farm uses of waste heat and effluent solids
Opportunities for the sale of solids byproducts

Sources: Biljetina (1987), Crocker (1985), Clark (1988)

As noted above, electricity production with associated waste heat capture and on-farm use is the principal source of revenue for a digester project. This benefit is in the form of avoided purchases of high-priced electricity from the grid. The stream of benefits to the digester is maximized by maximizing the rate of this substitution, while also realizing, to the maximum extent possible, the fullest use of waste heat from the diesel engine. Assuming a $0.07 per kWh farm electric rate and a $0.5 per gallon price for LPG, each 1 kWh of electricity that is generated on farm results in a savings of about $0.10, assuming complete on-farm utilization of the waste heat.

Lacking an expensive on-farm electric load to displace, the alternative is sale of electricity to the grid, at rates as low is $0.01 to 0.03 per kWh, the prevailing wholesale rate. This reduces the revenue to the feedlot to $0.04 to 0.06 per kWh and, if space and water heating requirements are minimal on-farm, to $0.01 to 0.03 per kWh, or by 60 to 90%. For this reason, on-farm utilization of electricity should be maximized. (Lusk 1996, Nielson 1985) Digester sizing should be done on the basis of available on-farm electrical loads, rather than on the basis of livestock populations and potentially available manure. (Barth and Hegg 1979, Lusk 1998)

Levelized electrical generation costs for an anaerobic digestion-biogas system, it might be noted, are substantially higher than $0.01 to 0.03 per kWh. This means that, in selling power to the grid as the sole source of project income, a digester owner operating a conventional medium-rate farm digester probably will operate at a loss. This seems to explain the poor performance of digestion on beef feedlots. (Meyer 1985) A $0.06 to 0.065 farm electric rate is sited in the literature as the minimum value necessary for economic viability of on-farm digestion. (Moser 1996)

In general, steam-based uses of digester biogas for space and water heating without electricity generation are rarely pursued. Low warm season demand for space and water heating services results in the sub-optimal levels of biogas utilization, making the economics of digestion problematical.

Full use of all digester waste streams is discussed in the literature as contributing to the viability of on-farm use of anaerobic digestion with conventional medium-rate digesters. (for instance, Lusk 1995) As noted above, if fully utilized, at an LPG price of $0.50 per gallon, for each $0.01 of benefit that is realized through the displacement of purchased electricity, waste heat utilization for space and water heating realizes about $0.004.

The reactor design should be kept simple and be practical for on-farm use. (Stafford, *et al.,* 1983) In the literature, digester failure is associated with excessive reactor complexity and burdensome operating and maintenance demands.

Finally, reactor design should be optimized to the degree possible consistent with the demands of practicality for on-farm use. In the case of medium-rate farm reactors, optimization generally favors shorter waste retention times and lower reactor operating temperatures. (Olivier, *et al.,* 1986)

Rigorous economic analysis of any proposed project resolves farm conditions into a discrete set of economic terms. These are shown in Table 29. Technical optimization of reactor design contributes to capital costs, operating costs, and biogas productivity and availability. Gas use determines how biogas availability is translated to electricity production and the on-farm space and water heating services. The degree to which on-farm pre-conditions involving farm lay-out, management practices and existing facilities are met contributes to digester volumetric productivity and capital costs. It also controls on-farm opportunities to substitute farm-generated electricity for purchased electricity, and determines what extra capital costs are incurred with inappropriate deployments. External constraints like per unit capital costs and farm electric rates contribute to capital costs and internal rate of return.

No rigorous analysis exists regarding the relative contribution of these sets of factors to the economic viability of anaerobic digestion. Analysis of the causes of digester failure rates suggests that all contributed to the observed record of performance. (Barth and Hegg 1979, Bernardini and Oliviera 1994, Coombs 1990, Edelman 1984, Lusk 1998, Naveau 1984, Rozzi and Passino 1985, Rozdilsky 1998)

Factors that encourage the future deployment of anaerobic digestion in farm application are listed in Table 30. These include, among others: rapidly rising feedlot sizes in the livestock industry and concomitant capital deployments, and the need for added electricity generating capacity throughout the Midwest and the US as a whole. The latter should improve electricity buyback rates for farm-generated electricity.

The economics literature on anaerobic digestion discusses the economic viability of large centralized anaerobic digesters. The general sense of the literature is that large centralized facilities are not feasible without substantial governmental subsidies. (Parsby *et al.,* 1989) Large centralized facilities are limited economically by transportation costs, plus loading and unloading costs. (Martin 1998, Sorenson 1982)

Table 29. Economic Factors in the Analysis of Anaerobic Digester Feasibility

Capital costs
Financing costs
Annual operating costs
Net biogas, electricity and waste heat production
On-farm electricity and space heating needs
Effluent solids production
Avoided costs of purchased fuels and electricity
Avoided costs of bedding
Sales of electricity and byproducts
Purchase price of sold electricity and byproducts
Depreciation
Tax rate and tax credits
Implicit value of pollution control
Internal rate of return hurdle

The economic feasibility of covered anaerobic lagoons is also discussed in the literature. Although not an option for cool northern tier states, due to low capital and operating costs, covered anaerobic lagoons are generally more cost-effective than medium rate CSTRs, plug flow or slurry-loop reactors. (Badger, *et al.*, 1995, Lusk 1998)

Table 30. Trends Favoring Digester Deployments in the US Livestock Industry

Capital Turnover in Livestock Industry
Increasing Average Dairy and Swine Herd Size
Standardization of Reactor Design

Diminishing Excess Electricity Generation Capacity
Marginal Costs of New Power Generation Sources
Advent of Independent Power Production
Possibility of Marketable Greenhouse Gas Credits for Emission Reductions

Development of the Low-Cost Covered Lagoon
Continued Development of Reactor Designs for Highly Dilute Wastes

Little published work addresses Minnesota-specific conditions. In 1993, the USEPA evaluated the economic potential for farm-based anaerobic digestion on a state-by-state basis, finding little potential to exist in Minnesota. (USEPA 1993) More recent work addressing digester performance at the recently installed Haubenschild digester reports an estimated 5-year simple payback period for this the only working farm digester in Minnesota. (Nelson and Lamb 2000) Additionally, a self-screening assessment method for on-farm anaerobic digestion has been developed for the Agricultural Utilization Research Institute to assist interested livestock producers in assessing the suitability of their operations for on-farm digestion. (Mattocks 1999)

In summary, the following conclusions seem to be supported by the economics literature on anaerobic digestion:

- that the economics of anaerobic digestion are characterized by substantial economies of scale;
- that real capital costs for conventional medium-rate farm anaerobic digesters have declined since the initial deployments of the technology;
- that the failure rate for anaerobic digestion using medium-rate farm digesters has dropped dramatically since the mid-1980s;
- that the economic feasibility of anaerobic digestion using conventional medium-rate farm digesters depends upon, among other things, the total solids content of the manure to be digested, feedlot size, and attainment of a minimum level of volumetric productivity. In addition, full utilization of all waste streams for on-farm energy production and bedding is also necessary;
- that the difference between on-farm electricity costs and farm electric rates constitutes the underlying basis for the economic viability of anaerobic digestion;
- that, to be economically feasible, an anaerobic digester needs to fit easily into existing farm management practices and patterns;
- and, that the anaerobic digestion of any highly dilute manure will be problematical in an economic sense with existing medium-rate farm digestion technology.

Finally, on the basis of the literature published since 1990, it seems that it can be concluded that the size threshold for the economic deployment of anaerobic digestion on dairy feedlots may be in the 500 to 800 cow range.

Alternative Reactor Design

As alluded to above, due to problems that CSTRs encounter in digesting highly dilute wastes like industrial wastewater, much energy has been expended over the last two decades developing high rate reactors. Sometimes called second and third generation anaerobic digestion reactors, these reactors have been developed to digest organic wastes with 2% total solids or less. All are continuous-feed reactor designs. However, as noted above, unlike the conventional CSTR design, these are designed to retain the digester's microbial population even in the face of high rates of digester loading of wastes.

A listing of these reactor types was given above in Table 2, and includes:

- Upflow Anaerobic Sludge Blanket Reactor
- Anaerobic Filter Reactor
- Anaerobic Packed Bed Reactor
- Anaerobic Fluidized Bed Reactor
- Anaerobic Fixed Film Reactor
- Anaerobic Expanded Bed Reactor
- Anaerobic Sequencing Batch Reactor
- Anaerobic Contact Reactor

Using these reactor designs, it is possible, even with a very dilute waste, to increase digester loading rates, thereby shortening the hydraulic retention time of the reactor to a day to a few days and dramatically shrinking the required size of the digester volume.

In second and third generation reactors, microbial biomass is retained in the reactor vessel by filling the digester volume with materials on which the digester flora can attach. In the face of a rapid throughput of waste at digester waste retention times of just a few days, these bacteria adhere to these structures or materials, which limits their removal from the digester. (Colleran, *et al.*, 1982)

Different strategies are employed to retain bacterial biomass in the reactor. In the anaerobic filter design, the reactor vessel is packed with an inert material with a large surface area for microbial attachment. Some media that typically are used include polyethylene net, polyurethane foam and expanded clay film. (Marques and Novais, 1987) The anaerobic fluidized bed (AFB) design utilizes a bed of small particles with a very large surface area for attachment of microbial biomass. (Colleran, *et al.*, 1982, Larson and Maddox, 1987) Anaerobic packed bed (APB) reactors utilize a bed of larger-sized solid materials. (Sanchez, *et al.*, 1995)

Fixed film reactors utilize a submerged static filter for attachment of microbial biomass. (Jewell, 1979) The upflow anaerobic sludge blanket (UASB) reactor design utilizes gravity settling and baffles to prevent solids wash-out to form a sludge blanket to achieve bacterial biomass retention. (Larson and Maddox 1987, Hobson and Wheatley 1993) The UASB design takes advantage of the existence of naturally occurring bacteria of sufficient size and density to settle against the upflow of a liquid.

The anaerobic sequencing batch reactor (ASBR) is a suspended growth reactor treating waste in four distinct phases over a 12-hour cycle, including digester feeding (0.25 hours), digester mixing and gas production (9.5 hours), biomass and solids settling (2 hours), and liquid effluent discharge (0.25 hours). (Zhang and Dugba 1991) During the settling period, particles with the most active attached microbial biomass are allowed to settle to the bottom of the digester and are retained during removal of the liquid effluent. While liquid influent is retained about 2 days in the ASBR, manure solids typically are retained about 14 day in the ASBRs, to allow for maximum stabilization of the waste material. (Zhang, *et al.*, 1997)

The contact reactor design utilizes a similar type of liquid-solid separation in a clarifier, and solids recycle and digestion. (Hobson and Wheatley, 1993)

Second generation reactors include he anaerobic filter, UASB, APB, AFB, and anaerobic contact reactors. The Anaerobic filter design was commercialized in the late 1970s. The upflow anaerobic sludge blanket design was commercialized in the mid- to late-1970s. The ASBR reactor, a recent design, is a third generation reactor.

Typical hydraulic retention times for these second and third generation reactor types are in the range of 1 to 4 days. Nearly all commercial deployments of these reactor types have been for industrial wastewater treatment and treatment of domestic sewage. The UASB is the dominant technology in commercial anaerobic digestion of industrial wastewater produced in, for instance, the paper and pulp industries, distilling, and potato and sugar processing. (Lettinga and van Handel, 1992)

The applicability of second and third generation reactors to the treatment of dilute dairy and swine manure has been investigated by, among others, Bonastre (1987), Chiumenti, *et al.*, (1985), Chiumenti and Welte (1987), Dugba, *et al.*, (1999), Fernandez, *et al.*, (1989), Foresti and Oliviera (1991), Harvey (1985), Lo, *et al.*, (1994), Hill, *et al.*, (1985), Kennedy and van der Berg (1982), Marique (1983), Marique and Novais (1987), Oleszkeiwicz (1983), Powers, *et al.*, (1991), Sanchez, *et al.*, (1995), and Zhang, *et al.*, (1997). While all report success in digesting dilute swine and dairy manure, the general sense of the literature seems to be that the use of the UASB, APB, AFB and anaerobic filter designs for digestion probably requires the prior removal of manure particles. (Harvey, 1985, Hill, *et al.*, 1985, Hobson and Wheatley 1993, Larson and Maddox 1987, Sax and Lusk 1995, Zhang and Dague, 1995) Absent the removal of these particles, these designs tend to clog and plug with wastes with high levels of suspended particles. (Zhang, *et al.*, 1997)

The ASBR design seems to have the best prospects for digestion of dilute swine and dairy manure with greater than 1% total solids. Researchers report adequate rates of digestion at a range of total solids of 0.5 to 2%, with a very good fit reported to swine collection and storage systems that utilize gravity drain below barn pits or hydraulic flush systems. (Zhang, *et al.*, 1997)

At present, no commercial applications have been made using second or third generation reactor designs, in part because of technical problems associated with clogging, in part due to the success of covered lagoons in the more southerly states. Other concerns involve the complexity of the designs. All of the second and third generation reactors types are substantially more complex than the CSTRs, plug flow or slurry-loop digesters currently in use, and thus require more intensive management than current commercially-deployed designs. With its daily cycling, the ASBR design is equally complex. Its viability for on-farm use may depend on whether this extra degree of complexity can be tolerated on working swine feedlots. Two pilot ASBRs were constructed in the late 1990s on swine feedlots to resolve these questions. (Lusk 1998)

Part 2. Study Design

Based upon the technology and economic description of anaerobic digestion, clear technical and size limits exist to the deployment of anaerobic digestion on livestock feedlots. As noted above, conservative design criteria are used to account for most of technical limits to digestion. Size constraints are accounted for by defining minimum levels of feedlot stocking and manure production necessary to support a digester. These minimum required stocking levels reflect the operation of economies of scale in the underlying economics of digestion.

It is possible to evaluate the constraints to digestion arising in digester size using an evaluative model of digester performance. We do this below, solving for herd sizes at which the deployment of anaerobic digestion is viable. A standard digester design is used for each livestock type. Conventional values for livestock manure production, manure quality and digester biogas productivity are used. Technical limits arising from non-size considerations are addressed through the use of conservative design standards, such as are typically used by commercial digester designers. The economic analysis is performed utilizing a wide range of possible values for the relevant economic factors that are involved.

The analysis is conducted using a computer software ‘evaluative’ package developed by the USEPA to support on-farm decisionmaking with respect to anaerobic digestion.

In parallel to the economic analysis, a size-based inventory of dairy and swine feedlots is developed for Minnesota from information taken from state-level feedlot permits and supporting survey information. Given these two pieces of analysis, an estimate of the potential for the economic deployment of anaerobic digestion on Minnesota feedlots is developed.

The approach taken is the same as is taken by USEPA (1998).

The analysis is restricted to swine and dairy feedlots. As noted, the economic viability of digester deployment depends on the presence of large on-farm electrical loads. This condition is not met in the case of beef feedlots. As a result of plans to combust turkey manure to produce electricity, little turkey manure in Minnesota will be available for anaerobic digestion. Manure produced by layers and broilers is available for digestion. However, in comparison to the amount of manure produced at Minnesota swine, dairy, or turkey feedlots, manure production by layers and broilers in Minnesota is small, less than 5% of the total. In addition, software evaluation programs for batch digestion are not readily available for use.

The economic viability of anaerobic digestion is evaluated for two medium-rate digester types: the plug flow reactor type for high total solids manure like dairy manure; and the CSTR for more dilute swine manure. The use of covered anaerobic lagoons is not evaluated due to climatic limitations to their use in Minnesota.

With regard to swine manure, analysis is restricted to swine manure that collects and is stored below barn in deep pits. This reflects, among other thing, limits to the evaluative capacity of the software employed in the analysis. Most swine manure in Minnesota that is not managed below barn is stored in outdoor ponds, basins and tanks. For these systems generally, USEPA projects a manure total solids content of less than 1 percent, largely due to the related use of hydraulic flush systems in moving the manure from confinement buildings to the ponds and tanks. (USEPA 1997) Due to the difficulties encountered in the digestion of so dilute a waste (see Part 1 above), no provision is made in the evaluative software for digestion using conventional medium-rate reactor designs.

However, it also might be noted that, based on the following inventory, below barn pit-stored manure probably accounts for more than two-thirds to three-quarters of the manure produced on swine feedlots in Minnesota, or a substantial fraction.

We evaluate the economic viability of anaerobic digestion of feedlot manure under conditions of various types of governmental aid and conditions where government provides no aid for digester development. Policy instruments for government aid that are considered include: tax incentives for renewable energy; the provision of low- or no-interest financing; grants for capital costs; and sales tax exemptions.

Finally, a framework for policy formulation regarding anaerobic digestion is developed and policy options are formulated.

Part 3. Inventory of Livestock on Minnesota Dairy and Swine Feedlots

Below the livestock inventory is presented for dairy and swine feedlots in Minnesota. In the inventory, estimates are developed for total livestock numbers, total manure production, and total volatile solids production.

Volatile solids production is calculated using the methodology given in USEPA (1995). Also calculated is the maximum methane generation capacity. This is the capacity of livestock manure to produce methane under conditions of complete digestion. Based on maximum methane generation capacity, an estimate is then developed for actual methane generation. All of this is assumed to be emitted to the atmosphere. As discussed above, methane production depends on manure temperature, the realization of anaerobic conditions in stored manure, the duration of manure storage under anaerobic conditions, and other factors.

For any manure type, it is assumed that 18 percent of the maximum methane producing potential of manure is realized with the use of liquid-slurry types of outdoor storage is basins, ponds or tanks. The same is assumed for long-term below barn pit storage of manure. Nine percent of the maximum methane producing potential of manure is assumed to be realized in short-term below barn pit storage systems. Less than 1 percent of the maximum methane producing potential of manure is assumed to be realized for solid forms of manure storage like stockpiling or for daily haul and spread systems.

The inventory was complied during calendar year 1998 using information taken principally form the Minnesota Pollution Control Agency’s Feedlot Registry System. The MPCA Feedlot Permit Registry is a computerized listing of all Federal and state permits issued to feedlots operating in Minnesota. Included in the registry is information on the permitted number of animals at each facility by type and size, level of confinement, and existing manure storage structures and management practices. Feedlots are listed by owner, owner address and feedlot location, down to the county, town, and township level. Entries to the registry are periodic and, according to MPCA staff, some duplication of information can be found in the registry database. (Trapp 1998) Old permit entries are not always deleted upon the issuance of a new permit with a new permit number. Also, no systematic effort is made to determine whether facilities that were permitted in the 1970s and 1980s are still in operation.

To resolve some of the problems associated with the registry, extensive review of the entries was undertaken to eliminate any duplication of information. Fairly detailed information of feedlot location down to the level of township and quarter allowed the identification and removal of duplicate entries.

It might be noted that most feedlots constructed before 1988 were small. Hence the error introduced in the data by the failure to remove permit information for old retired facilities or to remove duplicate information is unlikely to substantially effect inventory totals.

It also might be noted that information on permitted feedlot capacity is not the same as information on actual animals on feedlots. However, where available, permitted capacity probably provides a reasonable sense of the number of total feedlots in Minnesota, the number of animals on them, and the size distribution of Minnesota feedlots. As will be noted later, for the animal type for which we have the most complete coverage in the Feedlot Permit Registry—swine--very good agreement exists between the information extracted from the feedlot permit registry and the annual survey data published by the US Department of Agriculture. The two data sources agree both in terms of total numbers of swine and their distribution by size of facility (see Table 35 below). This gives us confidence in the essential correctness of the information contained in the MPCA feedlot registry system.

To the degree that available information sources allow, livestock populations and VS and CH_4 production are broken down by animal housing type, and manure collection and management system. Size distributions are developed for dairy and swine livestock feedlots. For swine, size distributions were developed for all swine feedlots, regardless of in-place manure management system, and for feedlots employing below barn pit storage. As noted above, in the subsequent economic analysis, the feasibility of anaerobic digestion of swine manure is limited to manure managed in below barn pits. This reflects the limits of the evaluative software that is employed in the analysis, and real-world constraints to digestion using manure flushed to outdoor manure storage structures.

Finally, the registry system makes no distinction between below barn and outdoor stave block pits. According to MPCA feedlot personnel, most stave block pits that are in use on swine feedlots are located below barn. We assume that 100 percent of the listed stave block pits that are permitted on swine feedlots are below ground. This may somewhat inflate the estimates given below for swine manure managed below barn in pits.

Part 3. Inventory of Livestock on Minnesota Dairy and Swine Feedlots

Dairy Inventory

Summary statistics for the dairy inventory are shown in Table 31for 1998. Included are estimates for numbers of cattle, dairy farms, manure production, the production of volatile solids, and the production of methane from manure storage and management.

In 1998, the Minnesota dairy herd was comprised of 551,000 milk cows. 16 million tons of manure is calculated to have been produced by dairy cattle, with an associated 1.9 million tons of volatile solids. Methane production in 1998 from dairy manure storage and management is estimated at about 1,240 mmcf, or 26,315 tons. This is based on an estimated use of liquid-slurry forms of outdoor storage at dairies housing 30 percent of the Minnesota dairy herd, and the use of daily haul and spread practices and stockpiling at dairies housing 40 percent and 30 percent of the dairy herd, respectively. (USEPA 1995)

Table 31. Summary Statistics for Dairy Herd, Dairy Manure and Volatile Solids Production, and Methane Generation: 1998

	units	**value**
Milk cows	number	551,000
Milk replacement heifers	number	295,000
Manure	tons	16,008,000[b]
Volatile solids	tons	1,950,000[b]
Methane	mmcf[a]	1,240[b,s]
Dairy farms	number	9,700
Milk cows per dairy farm	number	57

[a] million cubic feet
[b] calculated from livestock numbers using the methodology given in USEPA (1995)
[c] 26,315 tons of CH_4 or 552,650 CO_2-equivalent tons

Source: MPCA (1999), USDA (1999)

The dairy inventory is shown in Table 32by feedlot size class. The breakdown for feedlots smaller than 200 head is taken from the US Department of Agriculture (USDA), *Minnesota Agricultural Statistics* (1998). These are based on survey information assembled on an annual basis. The detailed breakdown of dairy feedlot size classes for 200-head and above is taken from the Minnesota Pollution Control Agency (MPCA) feedlot permit registry.

Table 32. Dairy Herd Inventory by Herd Size

Dairy Herd Size	Dairy Cows	Dairy Herd Size	Dairy Cows
0 to 49	157,904	**700 to 749**	5,392
50 to 99	227,200	**750 to 799**	11,974
100 to 149	90,880	**800 to 849**	1,500
	(sizes 100-199)	**850 to 899**	3,260
150 to 199	NA	**900 to 949**	1,732
200 to 249	22,661	**950 to 999**	3,680
250 to 299	6,330	**1,000 to 1,049**	0
300 to 349	5,398	**1,050 to 1,099**	3,000
350 to 399	15,220	**1,100 to 1,149**	1,050
400 to 449	9,501	**1,150 to 1,199**	4,425
450 to 499	9,050	**1,200 to 1,249**	0
500 to 549	6,439	**1,250 to 1,299**	2,400
550 to 599	5,574	**1,300 to 1,349**	0
600 to 649	1,166	**1,350 to 1,399**	0
650 to 699	4,845	**1,400 to 1,449**	8,426

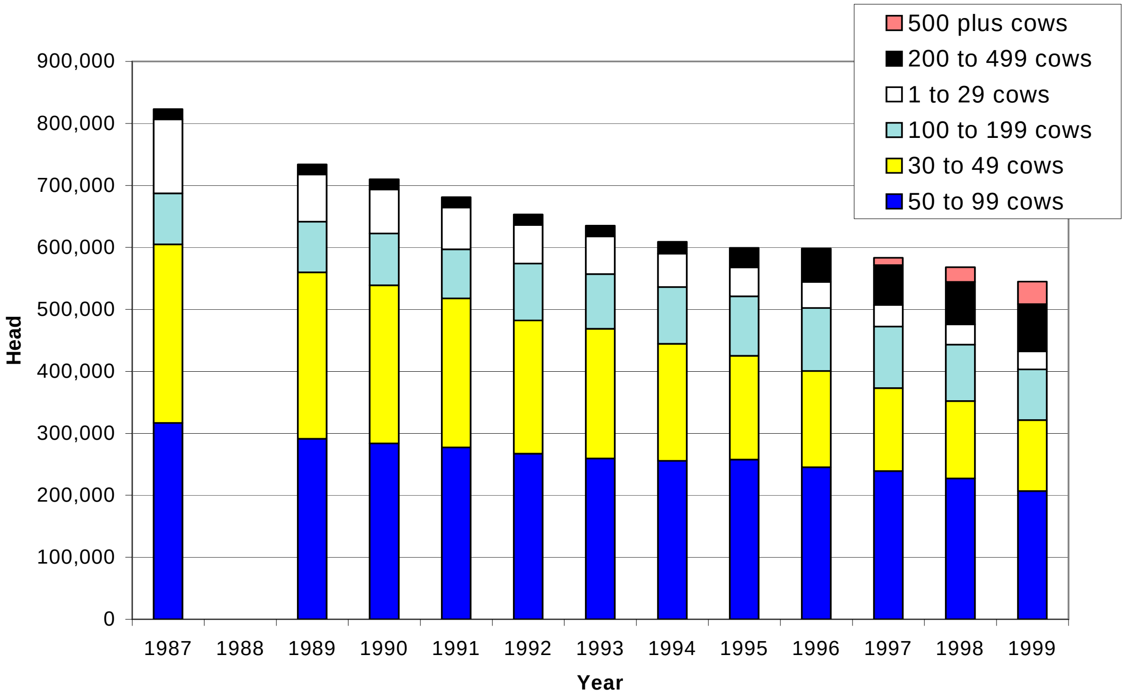
Source: MPCA (1999), USDA (1999)

Historically, the number of cows on Minnesota dairy farms has been small. In 1998, the average number of cows per dairy farm in Minnesota was 57 head. In 1998, about 80% of the herd was found in feedlots with fewer than 200 head of milking cows, and two-thirds was found in herds with fewer than 100 head. However, about 10% of the dairy herd was found in large feedlots with more than 500 milking cows; 3% of the herd inventory was found in feedlots with more than 1,000 head.

In terms of permitted capacity, if the data in the MPCA feedlot permit registry is correct, the pool of permitted dairy farms in Minnesota is limited to the largest 15 percent of dairy farms in the state. However, these account for virtually all of the feedlots found above the 200-head level. The remainder of the herd in 1998 was housed on feedlots holding no MPCA or federal permit.

The historic tend in herd size in the Minnesota dairy sector is shown in Figure 3 for years 1987, and 1989 to the present. The number of dairy cows in feedlot size classes larger than 200-head roughly sextupled between 1994 and 1999.

Figure 1. Milking Cows on Minnesota Dairy Farms (USDA 2000)

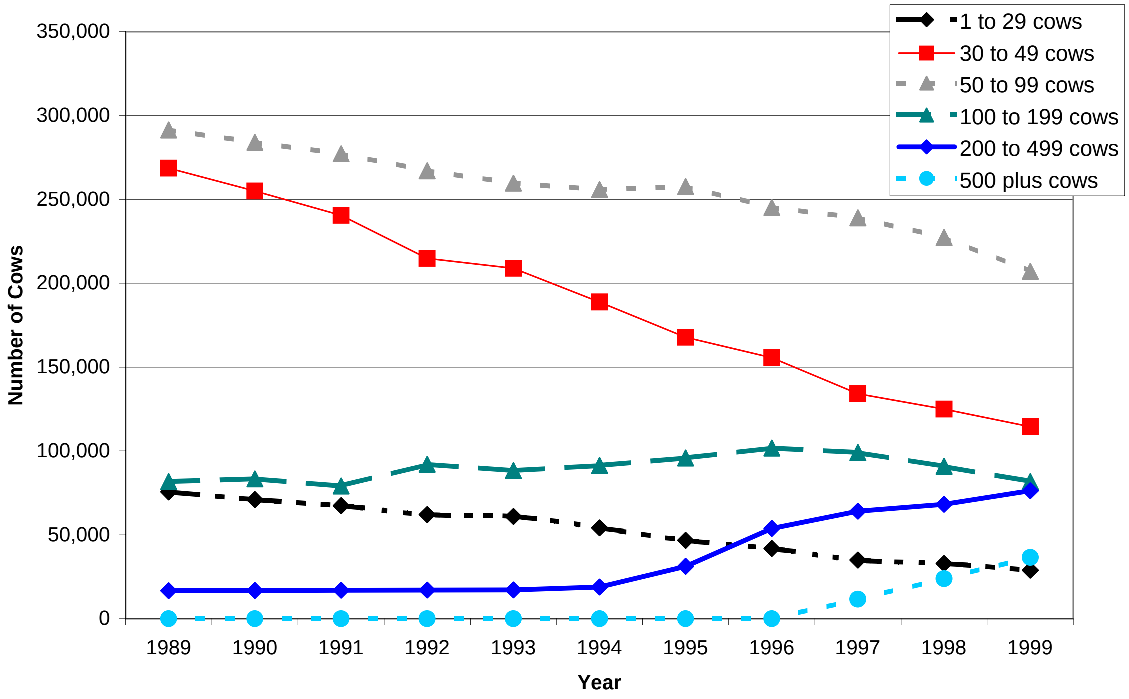


Based on historic trends in the size of the Minnesota dairy herd and trends in herd size, it can be concluded that, by 2008:

- The total size of the herd is likely to decline to about 450,000 head;
- the number of dairy cows in herd sizes 1 to 199 cows is likely to decline by about 200,000 cows;
- the percentage of the dairy inventory that is accounted by cows at feedlots less than 200 milking cows in size will decline from the current 80% to about 40%;
- the number of cows in feedlots of 200-head or greater is likely to increase by 150,000 cows to 250,000 total milking cows;

- the percentage of dairy cows in feedlots of 500-head or greater is likely to exceed 30%;
- the total number of dairy cows in feedlots of 500-head or larger will exceed 150,000 head.

Figure 2. Milking Cows on Minnesota Dairy Farms by Herd Size



In terms of housing arrangements, less is known. Survey data suggest that, in the late 1980s, on the order of two-thirds of the Minnesota dairy herd was housed in tie-stall barns. (Hammond 1989) However, among dairy feedlots larger than 150 cows, free-stall housing arrangements were dominant.

In general, most new dairy feedlots are constructed using free stall barns, particularly the larger dairies. (Stahl 1995) This suggests that of the roughly 400 to 500 new dairies that are likely to be constructed or renovated in the state over the next ten years, the majority will employ free stall housing. Current practices suggest that most manure at these feedlots will be managed as a slurry employing outdoor storage basins, ponds or tanks. (USEPA 1999)

Swine Inventory

The swine sector in Minnesota is comprised of seven production systems. These are show in Table 33 below.

Table 33. Swine Production Systems

System Type	**Animal Combinations**
Finishing Operations	Market finishers (50-240 lb.) and gilts
Nursery Pig-to-Finish	Nursing pigs (10-50 lb.), market finishers and gilts
Nursery Pigs-Only	Nursing pigs
Farrow-to-Wean	Sows, weaners
Farrow-to-Nursery Pig	Sows, weaners, and nursing pigs
Farrow-to-Finish	Sows, boards, weaners, nursing pigs, market finishers
Farrow-and-Finish	Sows and market finishers

Relevant size descriptions and characteristics of each type of swine found in these feedlots are shown in Table 34, below.

As in the case of the dairy inventory, the swine inventory was assembled using the MPCA feedlot permit registry, which for each permitted feedlot includes information on animal type and numbers, type of manure storage system and animal confinement system, ownership, and location. The inventory is current through July 1998. The data have been reviewed to remove any duplicative entries in the registry, and to correct for obvious mistakes made during data entry.

Table 34. Swine Characteristics

	Average Liveweight (lb.)	Annual VS Production (lb./lb. liveweight)	CH_4 Production (ft^3 CH_4/lb VS)
Sows	400	3.1	5.77
Gilts	220	3.1	5.77
Boars	450	3.1	7.53
Finishers	142.5	3.1	7.53
Nursers	30	3.1	7.53
Weaners	13	3.1	7.53

Source: USEPA (1995), USEPA (1997)

The total animal counts in the MPCA feedlot permit registry compare to within 95% to the swine inventory annually assembled by the USDA, *Minnesota Agricultural Statistics* (1999). Table 35 gives the breakdown of the inventory by feedlot size and production type. Also shown are the percentage breakdown of total animals by feedlot size, and the 1998 USDA estimated percentage distribution of swine production by feedlot size. The estimated percentage distribution generated from the MPCA feedlot registry appears to be in good agreement with the annual USDA estimate.

In 1998, 5,593,000 swine were housed on Minnesota feedlots. About 60 percent of these were found in herds large than 2,000 head. About 40 percent of all swine on Minnesota swine feedlots were housed in finishing operations, and another 20 percent were found in nursery pig-to-finish operations.

The swine inventory is presented in Table 36 by production system and in Table 37 by animal type. The Minnesota swine industry is dominated by finishing, nurse-finishing systems, and farrow-to-finish systems which together account for about three-quarters of all generated volatile solids (VS) and methane generating potential. By animal type, volatile solids production of Minnesota swine is dominated by the finishing hog category, which with gilts accounts for about three-quarters of the all generated volatile solids from swine on swine feedlots.

Table 35. Distribution of Swine in Minnesota Feedlots (number of animals)

Type of Operation	**1 to**	**100 to 49**	**500 to 999**	**1,000 to 1,999**	**2,000 to 4,999**	**5,000 plus**	**Total**
Finishing Hog	7,597	194,295	234,630	345,884	1,165,894	114,160	2,062,460
Nursery Pig	675	12,406	10,140	17,825	76,540	193,740	311,326
Nursery Pig- to-Finish	933	104,581	234,478	293,645	427,704	285,046	1,346,387
Farrow- to-Wean	3,126	7,720	7,873	26,998	72,622	19,616	137,955
Farrow- to-Nursery Pig	345	16,911	16,024	23,205	48,975	113,655	219,115
Farrow- to-Finish	89	23,264	119,189	147,061	181,362	206,281	677,241
Farrow-and-Finish	176	7,010	12,496	25,885	31,733	-	77,300
Farrowing Boars	64	450	880	-	-	-	1,394
Swine-Beef	3,256	90,804	145,168	100,678	98,135	24,669	462,710
Swine-Dairy	5,510	38,117	31,039	14,622	23,632	-	112,920
Swine and Other	4,277	45,656	39,787	35,440	43,060	16,020	184,240
Total	**26,048**	**541,214**	**851,699**	**1,031,243**	**2,169,657**	**973,187**	**5,593,048**
% of all Swine, this study	0	0.1	0.15	0.18	0.39	0.17	
USDA, *MN Agric. Stat.* 1998 estimate	0.02	0.11	0.13	0.18	0.56[a]		

Sources: USDA (1999), MPCA (1999)

[a] 2000 to 5000-plus

As noted above, maximum potential methane production is the rate of CH_4 production under conditions of maximum degradation of manure organic matter, subject to the constraints of waste biodegradability. Using the USEPA (1995) methodology, 7.53 cubic feet of CH_4 is assumed to be the maximum potential rate of CH_4 production for market swine, regardless of size. Of this 18 percent is assumed to be realized under actual environmental conditions in outdoor liquid/slurry storage or below barn in long-term storage. For short-term below barn pit storage, a 10 percent value is assumed, after USEPA (1995). A weighted average for all pit stored manure of 15 percent is utilized in the inventory estimates, developed from USEPA estimates of the relative amount of swine manure that is stored below barn pits for periods longer than three months and for periods shorter than three months. For swine manure managed in stockpiles as a solid, a value of less than one percent is assumed.

For breeding swine, the rate of maximum potential CH_4 generation is less, 5.77 ft^3 per lb. of volatile solids excreted. As in the case of market swine, different types of manure storage are assumed to result in different rates of CH_4 production and emission to the atmosphere.

Table 36. Summary Statistics for Swine Producing Feedlots in Minnesota

	Head (number)	Liveweight (lb.)[a]	VS (tons)[a]	CH_4 Emissions Maximum Potential (mmcf)[a]	Actual (mmcf)[a]
Farrow-to-Finish	677,241	104,366,155	161,768	2,113	309
Farrow-to-Wean	137,955	55,328,850	85,760	990	166
Farrow-to-Nurse	219,115	33,009,650	51,165	615	97
Farrow-and-Finish	77,300	17,698,548	27,433	353	56
Farrowing Boars	1,394	627,300	972	11	2
Nursery Pigs	311,326	9,342,720	14,481	218	36
Nursery-to-Finish	1,346,387	136,192,568	211,098	2,997	458
Finishing	2,062,460	300,942,185	466,460	6,891	1,080
Swine-Beef (mixed)	462,710	60,763,821	94,184	1,340	181
Swine-Dairy (mixed)	112,920	15,404,597	23,877	336	45
Swine-Other (mixed)	184,240	25,668,106	58,376	835	79
Total	**5,593,048**	**759,344,499**	**1,195,574**	**16,699**	**2,509**

Source: MPCA (1999) (livestock numbers)

[a] calculated using the methodology given in USEPA (1995)

Table 37. Summary Statistics for Swine Production in Minnesota by Animal Type

				CH_4 Emissions	
	Head (number)	Liveweight (lb.)[a]	VS (tons)[a]	Maximum Potential (mmcf)[a]	Actual (mmcf)[a]
Sows	332,468	132,968,481	206,101	2,379	370
Boars	13,030	5,802,147	8,993	104	17
Gilts	382,590	92,642,886	143,597	1,614	240
Nursing Pigs	1,469,554	44,085,630	86,923	1,310	170
Finishing Hogs	3,395,048	483,845,355	749,960	11,294	1,713
Total	**5,593,048**	**759,344,499**	**1,195,575**	**16,721**	**2,509**

Source: MPCA (1999) (livestock numbers)

[a] calculated using the methodology given in USEPA (1995)

Estimated actual CH_4 generation and emission to the atmosphere are shown in Tables 36 and 37 by production system and by animal type.

The swine inventory is presented in a slightly different fashion in Table 38, by production type and manure management/storage system utilized. Liquid/slurry storage systems include: below barn and outdoor pit storage, lagoon storage, and above ground tank storage. Solid storage systems include: solids stacking slab, manure pack, and stockpiling systems. The unit used in Table 38 is mmcf of potential methane generating capacity of livestock manure.

From Table 38, liquid/slurry systems account for about 90% of all methane generating potential on Minnesota swine feedlots. Solid storage systems account for about 8%, and unidentified about 2%. By production systems, about 95% of the methane generating capacity of manure managed in finishing production systems is associated with liquid or slurry systems of manure storage, while for nursery pig-finishing systems the corresponding value would be about 90%. In terms of production systems, swine finishing operations account for about one-half of the total methane generating capacity of manure produced on swine feedlots in Minnesota, and nursery pig-to-finish operations another one-fifth. Farrow-to-finish operations account for another about one-seventh.

The distribution of volatile solids production and CH_4 emissions between swine production systems and different manure management systems is similar.

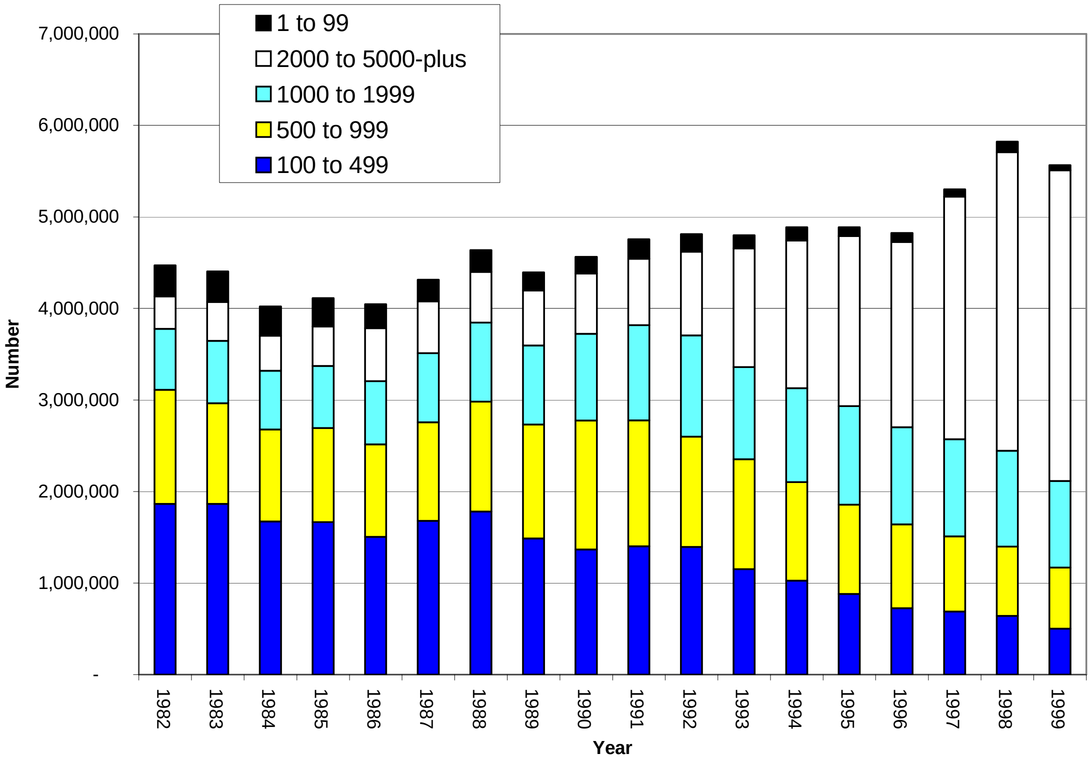
Table 38. Potential Methane Generating Capacity of Minnesota Swine-Only Feedlots by Production Type and Manure Storage and Handling System (mmcf) [a]

	Swine Production Operations							
	Finishing	**Nursery Pig**	**Nursery Pigs-to-Finish**	**Farrow-to-Nursing Pigs**	**Farrow-to-Wean**	**Farrow-to- Finish**	**Farrow-and-Finish**	**Boars**
Below Barn Pit	4805.8	150.7	1999.1	238.5	456.6	1267.7	214.7	3.6
Outdoor Pit	609.8	6.5	67.4	7.6	129.3	26.4	21	0.5
Earthen Basin	869.6	46.2	560	272.6	358.1	487	75.3	7.1
Aerated Lagoon	23.1	0.5	34.5	23.5	0	0.3	0	0
Above Ground Tank	22.6	6.4	65	7.6	0.1	52.3	7.5	0
Solid Stacking Slab	16.6	0	3.8	0.9	0	11.3	0	0
Daily Haul	109.4	0.6	77.3	25.3	9.7	45.5	2.4	0
Stockpiling, No Structure	20.4	0.2	5.9	0	1.4	5.1	0.4	0
Manure Pack in Buildings	220.7	2.4	148.7	22.6	7	192.6	18.8	0
Other	193.3	4.5	36.2	16.4	27.4	25.6	13.8	0
Total	**6891.3**	**218**	**2997.9**	**615**	**989.6**	**2113.8**	**353.9**	**11.2**

Source: MPCA (1999) (livestock numbers by manure storage or management system)

[a] calculated using the methodology given in USEPA (1995)

Figure 5. Swine on Minnesota Swine Farms (USDA 2000)



Finally, the size distribution of the Minnesota swine herd across time is shown graphically in Figure 5. This is based on an annual survey of Minnesota swine feedlot operators. Swine feedlots have been moving toward larger and larger sizes. However, because these data are not broken out by swine production type, they are much less useful than those developed for Minnesota dairy farms. In the economic assessment of anaerobic digestion with regard to swine, it is necessary break out the herd in terms of different production systems. While the available data suggest a continuing trend toward consolidation in the industry, they do not provide a basis for forecasting feedlot sizes for any particular production type, e.g., finishing, nursery pig, farrow-to-finish.

Swine Finishing Inventory

Finishing operations account for about half of the methane generation potential of Minnesota swine operations and half of all emitted methane from that sub-sector. The importance of finishing operations in the Minnesota swine industry is likely to increase. In-shipments of feeder pigs from out-of-state farrowing operations to Minnesota finishing and nursery pig-to-finishing feedlots have been increasing at an annual rate of about 30% per year since the mid-1990s, accounting for about two-thirds of growth in the Minnesota swine herd over this period.

Table 39 gives a breakdown of the finishing sub-sector by manure management system. Liquid systems dominate in finishing production systems, and, of these, below barn pit storage is by far the dominant system of manure management.

Table 39. Summary Statistics for Finishing Swine Systems

	Finishers (number)	Liveweight (lb.)[a]	VS (tons)[a]	Potential Emission (mmcf)[a]	Actual Emissions (mmcf)[a]
Below Barn Pit	1,439,788	209,877,891	325,305	4,806	769
Outdoor Pit	183,271	26,549,188	41,151	610	110
Earthen Basin	258,428	38,067,626	59,013	870	156
Lagoon	6,559	1,061,468	1,644	23	4
Above Ground Tank	6,630	1,014,975	1,574	23	4
Solid Stacking Slab	4,955	722,363	1,120	17	-
Daily Haul	32,370	4,863,761	7,531	109	-
Stockpiling, No Structure	6,063	902,373	1,398	20	-
Manure Pack in Bldgs	65,731	9,916,415	15,349	221	2
Other	58,008	8,476,124	13,134	193	34
Total	2,061,803	301,452,184	467,219	6,891	1,080

Source: MPCA (1999) (livestock numbers by manure storage or management system)

[a] calculated using the methodology given in USEPA (1995)

Tables 40 and 41 give a further breakdown by feedlot size of the finishing sub-sector for all manure management systems and for below barn pit storage systems, respectively. As noted above, due to limits to the evaluative software employed in this study, the economic feasibility of anaerobic digestion of swine manure is evaluated solely with regard to manure managed through below barn pit storage. The below barn pit storage inventory includes both feedlots that use below barn pit storage exclusively and feedlots that utilize below barn pit storage as one of a number of management management-storage systems.

Table 40. Finishing Swine Inventory: All Manure Management Systems

				CH_4 Emissions	
Herd Size (Finishers)	**Finishers (number)**	**Liveweight (lb.)[a]**	**VS (tons)[a]**	**Maximum Potential (mmcf)[a]**	**Actual Emissions (mmcf)[a]**
0-499	201,879	30,716,506	47,591	679.5	96.71
500-999	234,550	34,827,823	53,978	789.4	117.03
1,000-1,499	192,275	27,564,795	42,725	641.0	98.15
1,500-1,999	153,575	22,409,001	34,730	515.1	80.68
2,000-2,499	189,412	27,940,001	43,407	639.0	101.47
2,500-2,999	59,000	8,624,500	13,369	197.9	32.87
3,000-3,499	109,146	16,802,285	26,043	373.5	61.8
3,500-3,999	201,901	28,818,263	44,666	671.9	107.82
4,000-4,499	226,924	32,346,470	50,135	754.9	121.14
4,500-4,999	379,001	54,200,051	84,010	1,262.4	205.41
5,000-5,499	25,360	3,613,800	5,602	84.3	14.11
5,500-5,999	5,700	1,263,000	1,958	22.6	4.07
6,000-6,499	30,961	4,411,943	6,839	103.0	17.30
6,500-6,999	-	-	-	-	-
7,000-7,499	7,246	1,032,840	1,601	24.1	3.86
7,500-7,999	7,868	1,121,190	1,738	26.2	0.05
8,000-8,499	16,300	2,322,750	3,600	54.2	8.68
8,500-8,999	-	-	-	-	-
9,000-9,499	9,300	1,325,250	2,054	30.9	5.3
9,500-9,999	-	-	-	-	-
10,000-10,499	11,403	2,111,860	3,273	21.6	3.46
10,500-10,999	-	-	-	-	-
11,000-11,499	-	-	-	-	-
Total	**2,061,803**	**301,452,287**	**467,219**	**6,891.5**	**1,079.91**

Source: MPCA (1999) (livestock numbers)

[a] calculated using the methodology given in USEPA (1995)

Table 41. Finishing Swine Inventory: Below Barn Pit Storage Systems

				CH_4 Emissions	
Herd Size (Finishers)	Finishers (number)	Liveweight (lb.)[a]	VS (tons)[a]	Maximum Potential (mmcf)[a]	Actual Emissions (mmcf)[a]
0-499	64,000	9,979,509	15,457	218.7	34.68
500-999	116,481	17,324,555	26,852	393.3	61.82
1,000-1,499	118,881	17,087,019	26,483	396.7	61.78
1,500-1,999	104,090	15,187,588	23,537	349.1	55.71
2,000-2,499	145,452	21,376,160	33,132	489.6	78.25
2,500-2,999	45,555	6,708,598	10,398	153.3	24.82
3,000-3,499	75,502	12,008,015	18,612	261.5	41.67
3,500-3,999	165,611	23,600,188	36,581	550.9	88.13
4,000-4,499	209,774	29,901,595	46,347	697.9	111.44
4,500-4,999	326,401	46,512,143	72,093	1,085.6	173.61
5,000-5,499	10,000	1,425,000	2,209	33.3	4.92
5,500-5,999	-	-	-	-	-
6,000-6,499	18,610	2,651,925	4,110	62.0	9.90
6,500-6,999	-	-	-	-	-
7,000-7,499	7,248	1,032,840	1,601	24.1	3.86
7,500-7,999	-	-	-	-	-
8,000-8,499	16,300	2,322,750	3,600	54.2	8.68
8,500-8,999	-	-	-	-	-
9,000-9,499	9,300	1,325,250	2,054	30.9	5.30
9,500-9,999	-	-	-	-	-
10,000-10,499	11,403	2,111,860	3,273	21.6	3.46
10,500-10,999	-	-	-	-	-
11,000-11,499	-	-	-	-	-
Total	**1,444,668**	**210,554,985**	**326,339**	**4,822.7**	**768.01**

Source: MPCA (1999) (livestock numbers)

[a] calculated using the methodology given in USEPA (1995)

As in the case of the dairy industry, new finishing operations are tending toward larger and larger sizes. This trend is expected to continue.

Inventory for Nursery Pig-to-Finish Swine Operations

Nursery pig-to-finish operations account for about 20% of the methane generating potential of Minnesota swine operations. The importance of this type of production system is likely to continue to increase with the continued growth of in-shipments from out-of-state of swine to Minnesota nursery pig-to-finishing operations and finishing operations

The nursery pig-to-finish inventory is shown in Tables 42 by manure management system for animal numbers, liveweight and VS production and emissions. As in the case of finishing operations, the inventory is dominated by below barn pit storage systems.

Table 42. Summary Statistics for Nursery Pig-to-Finishing Swine Systems

	Finishers (number)	Nursery Pigs (number)	Liveweight (lb.)[a]	VS (tons)[a]	Potential Emission (mmcf)[a]	Actual Emissions (mmcf)[a]
Below Barn Pit	497,729	406,252	90,502,308	140,263	1,999	320
Outdoor Pit	15,625	18,825	3,010,988	4,663	67	12
Earthen Basin	141,739	103,530	25,430,473	39,410	560	101
Lagoon	8,169	7,942	1,625,465	2,519	35	6
Above Ground Tank	16,580	10,520	2,963,325	4,593	65	12
Solid Stacking Slab	825	820	168,765	262	4	-
Daily Haul	19,979	14,909	3,698,067	5,727	77	-
Stockpiling, No Structure	1,595	840	271,650	418	6	-
Manure Pack in Bldgs	39,657	23,023	7,314,650	11,344	149	1
Other	9,282	6,758	1,746,049	2,714	36	6
Total	751,180	593,419	136,731,740	211,913	2,998	458

Source: MPCA (1999) (livestock numbers by manure storage or management system)

[a] calculated using the methodology given in USEPA (1995)

Tables 43 and 44 give a breakdown by feedlot size class for the entire population of nurse-to-finish operations, and that part of this swine subsector that utilized below barn pit storage, respectively. As noted above in the discussion of finishing operations, in this study the economic evaluation of anaerobic digestion with regard to swine manure is limited to swine manure managed in below barn pits. This is due to the limits of the evaluative software employed. The below barn pit storage inventory includes both feedlots that use below barn pit storage exclusively and feedlots that utilize below barn pit storage as one of a number of management management-storage systems. Because this is a two-animal system involving no set or rigorously characteristic ratio of finishers to nursing pigs, the inventory shown below is broken both by feedlot size and by varying ratios of finishers to nursing pigs. Feedlot classes are set up in increments of 10%, e.g., 0 to 10% finishers and 90 to 100% nursing pigs, 10 to 20% finishers and 80 to 90% nursing pigs.

Tables 45 through 47 provide additional inventory information for nurse-finish systems for VS generation, emissions, and methane generation potential by feedlot size.

Regarding feedlot consolidation, the same comments made regarding finishing operations also apply to nurse-to-finish operations.

Inventory for Nursing Pig Operations

Nursing pig operations account for about 1.5% of the methane generation potential of Minnesota swine operations and about the same percentage of all emitted methane from that subsector. Table 48 gives a breakdown of animal numbers, liveweight production and emissions from nursing pig operations in Minnesota by manure management system. Liquid systems dominate in finishing production systems, and, of these, below barn pit storage is by far the dominant system of manure management.

Table 43. Nursery Pig-to-Finish Inventory by Number of Finishers

	% finishers of combined nursers and finishers										
Feedlot Size	**0 to 10**	**10 to 20**	**20 to 30**	**30 to 40**	**40 to 50**	**50 to 60**	**60 to 70**	**70 to 80**	**80 to 90**	**90 to 100**	**All**
0-499	1,853	5,038	6,280	12,347	23,667	33,667	29,765	16,780	5,499	660	135,556
500-999	600	2,923	6,626	5,481	12,777	28,723	37,730	46,276	17,813	600	159,549
1,000-1,499	-	-	2,392	10,378	6,936	16,372	30,627	22,709	23,472	2,075	114,961
1,500-1,999	-	-	1,700-	-	7,102	6,530	12,126	16,993	8,782	1500	54,733
2,000-2,499	-	2,295	4,424	4,580	18,289	4,675	35,580	9,038	8,547	7,121	94,549
2,500-2,999	-	-	-	-	5,480	-	2,600	13,268	-	2,520	23,868
3,000-3,499	-	-	-	6,638	3,201	3,280	-	12,806	9,170	3,450	38,545
3,500-3,999	-	-	-	-	7,440	7,588	7,680	7,440	3,605	3,900	37,653
4,000-4,499	-	-	-	-	4,180	-	21,273	8,520	-	4,150	38,123
4,500-4,999	-	-	-	-	-	-	18,600	-	-	-	18,600
5,000-5,499	-	-	-	-	-	-	-	-	-	-	-
5,500-5,999	-	-	-	-	-	-	-	-	-	5,500	5,500
6,000-6,499	-	-	-	-	-	-	-	-	6,273	-	6,273
6,500-6,999	-	-	-	-	-	-	-	6,840	-	-	6,840
7,000-7,499	-	-	-	-	-	-	-	-	-	-	-
7,500-7,999	-	-	-	-	7,680	-	-	-	-	-	7,680
8,000-8,499	-	-	-	-	-	-	-	-	-	-	-
8,500-9,000	-	-	-	-	-	-	-	-	8,700	-	8,700
	2,453	**10,256**	**21,422**	**39,424**	**96,752**	**100,835**	**195,981**	**160,670**	**91,861**	**31,526**	**751,180**

Source: MPCA (1999)

Table 44. Nursery Pig-to-Finish Inventory for Below Barn Pit Storage Systems by Number of Finishers

	% finishers of combined nursing pigs and finishers										
Feedlot Size	**0 to 10**	**10 to 20**	**20 to 30**	**30 to 40**	**40 to 50**	**50 to 60**	**60 to 70**	**70 to 80**	**80 to 90**	**90 to 100**	**All**
0-499	1,361	3,070	4,509	8,481	15,499	24,990	22,350	11,369	3,923	615	96,167
500-999	600	1,480	4,826	2,733	11,257	22,618	30,908	31,108	15,603	-	121,130
1,000-1,499	-	-	2,392	5,378	5,656	11,067	20,305	15,924	16,450	1,075	78,247
1,500-1,999	-	-	-	-	5,312	4,580	6,720	11,923	8,782	1,500	38,817
2,000-2,499	-	2,295	4,424	-	18,289	2,200	28,695	9,038	6,417	7,121	78,479
2,500-2,999	-	-	-	-	5,480	-	2,600	13,268	-	2,520	23,868
3,000-3,499	-	-	-	6,638	3,201	3,280	-	9,774	9,170	-	32,063
3,500-3,999	-	-	-	-	7,440	7,588	3,840	7,440	3,605	-	29,913
4,000-4,499	-	-	-	-	4,180	-	8,505	4,200	-	4,150	21,035
4,500-4,999	-	-	-	-	-	-	18,600	-	-	-	18,600
5,000-5,499	-	-	-	-	-	-	-	-	-	-	-
5,500-5,999	-	-	-	-	-	-	-	-	-	5,500	5,500
6,000-6,499	-	-	-	-	-	-	-	-	6,273	-	6,273
6,500-6,999	-	-	-	-	-	-	-	-	-	-	-
7,000-7,499	-	-	-	-	-	-	-	-	-	-	-
7,500-7,999	-	-	-	-	7,680	-	-	-	-	-	7,680
8,000-8,499	-	-	-	-	-	-	-	-	-	-	-
8,500-9,000	-	-	-	-	-	-	-	-	8,700	-	8,700
	1,961	**6,845**	**16,151**	**23,230**	**83,994**	**76,323**	**142,520**	**114,044**	**78,923**	**22,531**	**566,522**

Source: MPCA (1999)

Table 45. Nursery Pig-to-Finish VS Inventory for Below Barn Pit Storage Systems by Number of Finishers

	% finishers of combined nursing pigs and finishers										
Feedlot Size	**0 to 10**	**10 to 20**	**20 to 30**	**30 to 40**	**40 to 50**	**50 to 60**	**60 to 70**	**70 to 80**	**80 to 90**	**90 to 100**	**All**
0-499	1,313	2,231	2,073	3,100	4,787	7,282	6,061	2,932	865	162	30,806
500-999	384	830	1,994	869	3,593	6,410	8,253	7,974	3,819	-	34,126
1,000-1,499	-	-	1,030	2,150	1,768	3,344	5,387	3,994	3,887	241	21,801
1,500-1,999	-	-	-	-	1,625	1,292	1,641	3,128	2,078	560	10,324
2,000-2,499	-	1,009	1,905	-	4,962	570	7,135	2,241	1,499	1,978	21,299
2,500-2,999	-	-	-	-	2,252	-	630	3,294	-	563	6,739
3,000-3,499	-	-	-	2,613	856	827	-	2,513	2,462	-	9,271
3,500-3,999	-	-	-	-	2,045	1,999	938	1,744	860	-	7,586
4,000-4,499	-	-	-	-	1,538	-	2,086	1,035	-	933	5,592
4,500-4,999	-	-	-	-	-	-	4,578	-	-	-	4,578
5,000-5,499	-	-	-	-	-	-	-	-	-	-	-
5,500-5,999	-	-	-	-	-	-	-	-	-	1,235	1,235
6,000-6,499	-	-	-	-	-	-	-	-	1,661	-	1,661
6,500-6,999	-	-	-	-	-	-	-	-	-	-	-
7,000-7,499	-	-	-	-	-	-	-	-	-	-	-
7,500-7,999	-	-	-	-	2,053	-	-	-	-	-	2,053
8,000-8,499	-	-	-	-	-	-	-	-	-	-	-
8,500-9,000	-	-	-	-	-	-	-	-	1,996	-	1,996
	1,697	**4,070**	**7,002**	**8,732**	**25,479**	**21,724**	**36,709**	**28,855**	**19,127**	**5,672**	**159,067**

Source: Calculated from Table 44 using the methodology given in USEPA (1995)

Table 46. Nursery Pig-to-Finish Maximum Potential Methane Generation Inventory for Below Barn Pit Storage Systems by Number of Finishers (in mmcf)

	% finishers of combined nursing pigs and finishers										
Feedlot Size	**0 to 10**	**10 to 20**	**20 to 30**	**30 to 40**	**40 to 50**	**50 to 60**	**60 to 70**	**70 to 80**	**80 to 90**	**90 to 100**	**All**
0-499	19	25	25	41	66	100	85	45	12	2	421
500-999	6	11	27	13	49	90	117	114	54	-	481
1,000-1,499	-	-	14	28	25	45	77	58	58	4	307
1,500-1,999	-	-	-	-	23	18	25	45	31	7	147
2,000-2,499	-	15	26	-	74	9	107	33	22	27	312
2,500-2,999	-	-	-	-	27	-	10	48	-	9	93
3,000-3,499	-	-	-	33	13	13	-	36	34	-	129
3,500-3,999	-	-	-	-	31	29	14	26	13	-	113
4,000-4,499	-	-	-	-	19	-	31	15	-	14	80
4,500-4,999	-	-	-	-	-	-	69	-	-	-	69
5,000-5,499	-	-	-	-	-	-	-	-	-	-	-
5,500-5,999	-	-	-	-	-	-	-	-	-	19	19
6,000-6,499	-	-	-	-	-	-	-	-	23	-	23
6,500-6,999	-	-	-	-	-	-	-	-	-	-	-
7,000-7,499	-	-	-	-	-	-	-	-	-	-	-
7,500-7,999	-	-	-	-	31	-	-	-	-	-	31
8,000-8,499	-	-	-	-	-	-	-	-	-	-	-
8,500-9,000	-	-	-	-	-	-	-	-	30	-	30
	25	**52**	**92**	**114**	**358**	**303**	**534**	**420**	**277**	**80**	**2,254**

Source: Calculated from Table 45 using the methodology given in USEPA (1995)

Table 47. Nursery Pig-to-Finish Emission Inventory for Below Barn Pit Storage Systems by Number of Finishers (in mmcf of CH_4)

	% finishers of combined nursing pigs and finishers										
Feedlot Size	**0 to 10**	**10 to 20**	**20 to 30**	**30 to 40**	**40 to 50**	**50 to 60**	**60 to 70**	**70 to 80**	**80 to 90**	**90 to 100**	**All**
0-499	3	4	4	6	9	13	13	6	2	-	60
500-999	1	2	4	2	8	14	18	17	7	-	73
1,000-1,499	-	-	2	4	4	7	12	9	9	1	48
1,500-1,999	-	-	-	-	4	2	4	7	5	1	23
2,000-2,499	-	2	4	-	12	1	17	5	4	4	50
2,500-2,999	-	-	-	-	4	-	2	8	-	1	15
3,000-3,499	-	-	-	5	2	2	-	6	4	-	19
3,500-3,999	-	-	-	-	5	5	3	4	2	-	18
4,000-4,499	-	-	-	-	3	-	5	2	-	2	13
4,500-4,999	-	-	-	-	-	-	11	-	-	-	11
5,000-5,499	-	-	-	-	-	-	-	-	-	-	-
5,500-5,999	-	-	-	-	-	-	-	-	-	3	3
6,000-6,499	-	-	-	-	-	-	-	-	4	-	4
6,500-6,999	-	-	-	-	-	-	-	-	-	-	-
7,000-7,499	-	-	-	-	-	-	-	-	-	-	-
7,500-7,999	-	-	-	-	6	-	-	-	-	-	6
8,000-8,499	-	-	-	-	-	-	-	-	-	-	-
8,500-9,000	-	-	-	-	-	-	-	-	5	-	5
Total	**4**	**8**	**15**	**17**	**57**	**45**	**84**	**64**	**41**	**13**	**348**

Source: Calculated from Table 46 using the methodology given in USEPA (1995)

Table 48. Summary Statistics for Nursery Pig Swine Systems

	Nursery Pigs (number)	Liveweight (lb.)[a]	VS (tons)[a]	Potential Emission (mmcf)[a]	Actual Emissions (mmcf)[a]
Below Barn Pit	215,241	6,457,230	10,009	151	24
Outdoor Pit	9,325	279,750	434	7	1
Earthen Basin	65,980	1,979,400	3,068	46	8
Lagoon	700	21,000	33	1	-
Above Ground Tank	9,200	276,000	428	6	1
Solid Stacking Slab	-	-	-	-	-
Daily Haul	838	25,140	39	1	-
Stockpiling, No Structure	250	7,500	12	-	-
Manure Pack in Bldgs	3,330	107,604	166	2	-
Other	6,455	193,650	300	5	1
Total	**311,319**	**9,347,274**	**14,487**	**218**	**36**

Source: MPCA (1999) (livestock numbers by manure storage or management system)

[a] calculated using the methodology given in USEPA (1995)

Tables 49 and 50 give a further breakdown by feedlot size of the nursery pig production type for all manure management systems and for below barn pit storage systems, respectively. As above, the below barn pit storage inventory includes both feedlots that use below barn pit storage exclusively and feedlots that utilize below barn pit storage as one of a number of management management-storage systems.

Table 49. Nursery Pig-Only System Inventory: All Manure Management Systems

				CH_4 Emissions	
Herd Size (Nursery Pigs)	**Nursery Pigs (number)**	**Liveweight (lb.)[a]**	**VS (tons)[a]**	**Maximum Potential (mmcf)[a]**	**Actual Emissions (mmcf)[a]**
0-499	13,074	399,924	619	9.3	1.43
500-999	10,140	304,200	472	7.2	1
1,000-1,499	9,425	282,750	438	6.6	0.94
1,500-1,999	8,400	252,000	391	6	0.96
2,000-2,499	20,100	603,000	935	14.1	2.32
2,500-2,999	5,340	160,200	249	3.74	0.64
3,000-3,499	9,600	288,000	446	6.7	1.08
3,500-3,999	3,900	117,000	181	2.7	0.44
4,000-4,499	28,000	840,000	1,302	19.6	3.14
4,500-4,999	9,600	288,000	446	6.7	1.08
5,000-5,499	-	-	-	-	-
5,500-5,999	16,900	507,000	786	11.9	1.98
6,000-6,499	54,000	1,620,000	2,511	37.8	6.05
6,500-6,999	-	-	-	-	-
7,000-7,499	28,760	862,800	1,338	20.1	3.53
7,500-7,999	-	-	-	-	-
8,000-8,499	48,000	144,000	2,232	33.6	5.71
8,500-8,999	-	-	-	-	-
9,000-9,499	-	-	-	-	-
9,500-9,999	-	-	-	-	-
10,000-10,499	-	-	-	-	-
10,500-10,999	-	-	-	-	-
11,000-11,499	-	-	-	-	-
11,500-11,999	-	-	-	-	-
12,000-12,499	-	-	-	-	-
12,500-12999	-	-	-	-	-
13,000-13,499	-	-	-	-	-
14,000-14,499	-	-	-	-	-
14,500-14,999	-	-	-	-	-
15,000-15,499	46,080	1,328,400	2,143	32.3	5.38
15,500-15999	-	-	-	-	
Total	**311,319**	**9,347,274**	**14,487**	**218.1**	**35.69**

Source: MPCA (1999) (livestock numbers)

[a] calculated using the methodology given in USEPA (1995)

Table 50. Nursery Pig-Only System Inventory: Below Barn Pit Storage

Herd Size (Nursery Pigs)	Nursery Pigs (number)	Liveweight (lb.)[a]	VS (tons)[a]	CH_4 Emissions Maximum Potential (mmcf)[a]	 Actual Emissions (mmcf)[a]
0-499	2,456	73,680	116	1.8	0.27
500-999	3,200	96,000	149	2.3	0.36
1,000-1,499	7,025	210,750	327	4.9	0.79
1,500-1,999	6,700	201,000	312	4.8	0.75
2,000-2,499	15,300	459,000	712	10.7	1.72
2,500-2,999	2,640	79,200	123	1.9	0.3
3,000-3,499	9,600	288,000	446	6.7	1.08
3,500-3,999	3,900	117,000	181	2.7	0.44
4,000-4,499	28,000	840,000	1,302	19.6	3.14
4,500-4,999	9,600	288,000	446	6.7	1.08
5,000-5,499	-	-	-	-	-
5,500-5,999	11,100	333,000	516	7.8	1.25
6,000-6,499	54,000	1,620,000	2,511	37.8	6.05
6,500-6,999	-	-	-	-	-
7,000-7,499	7,000	210,000	326	4.9	0.78
7,500-7,999	-	-	-	-	-
8,000-8,499	24,000	720,000	1,116	16.8	2.69
8,500-8,999	-	-	-	-	-
9,000-9,499	-	-	-	-	-
9,500-9,999	-	-	-	-	-
10,000-10,499	-	-	-	-	-
10,500-1,9999	-	-	-	-	-
11,000-11,499	-	-	-	-	-
11,500-11,999	-	-	-	-	-
12,000-12,499	-	-	-	-	-
12,500-12,999	-	-	-	-	-
13,000-13,499	-	-	-	-	-
13,500-13,999	-	-	-	-	-
14,000-14,499	-	-	-	-	-
15,000-15,499	30,720	921,600	1428	21.5	3.44
15,500-15,999	-	-	-	-	-
Total	**215,241**	**6,457,230**	**10,009**	**150.1**	**24.12**

Source: MPCA (1999) (livestock numbers)

[a] calculated using the methodology given in USEPA (1995)

Inventory for Farrow-to-Wean Operations

Farrow-to-wean operations account for about 5% of the methane generating potential of Minnesota swine operations. The farrow-to-wean inventory is shown in Table 51 by manure management system. The inventory is dominated by liquid/slurry manure management systems, particularly below barn pit storage and outdoor earthen basin storage.

Table 51. Summary Statistics for Farrow-to-Wean Swine Systems

	Sows (number)	**Liveweight (lb.)[a]**	**VS (tons)[a]**	**Potential Emission (mmcf)[a]**	**Actual Emissions (mmcf)[a]**
Below Barn Pit	63,234	25,525,950	39,565	457	73
Outdoor Pit	18,078	7,233,184	11,212	129	23
Earthen Basin	47,127	20,018,850	31,029	358	64
Lagoon	-	-	-	-	-
Above Ground Tank	308	8,000	12	-	-
Solid Stacking Slab	-	-	-	-	-
Daily Haul	1,360	544,000	843	10	-
Stockpiling, No Structure	189	75,600	117	1	-
Manure Pack in Bldgs	891	421,225	646	7	-
Other	3,831	1,532,400	2,375	27	5
Total	**135,018**	**55,359,209**	**85,800**	**990**	**166**

Source: MPCA (1999) (livestock numbers by manure storage or management system)

[a] calculated using the methodology given in USEPA (1995)

Tables 52 and 53 give a further breakdown by feedlot size of the farrow-to-wean subsector for all manure management systems and for below barn pit storage systems, respectively. As above, the inventory for feedlots using below barn pit storage includes both feedlots that use below barn pit storage exclusively and feedlots that utilize below barn pit storage as one of a number of management management-storage systems.

Table 52. Farrow-to-Wean System Inventory: All Manure Management Systems

Herd Size (Sows)	Sows (number)	Liveweight (lb.)[a]	VS (tons)[a]	CH_4 Emissions Maximum Potential (mmcf)[a]	CH_4 Emissions Actual Emissions (mmcf)[a]
0-499	10,774	4,372,359	6,772	77.7	11.98
500-999	7,788	3,153,450	4,888	56.4	9.37
1,000-1,499	17,977	7,436,950	11,526	133.1	21.12
1,500-1,999	8,410	3,392,800	5,259	60.8	9.94
2,000-2,499	26,299	10,743,700	16,653	192.2	32.42
2,500-2,999	26,030	10,812,950	16,759	193.4	32..93
3,000-3,499	9,164	3,710,600	5,752	66.4	11.08
3,500-3,999	-	-	-	-	-
4,000-4,499	-	-	-	-	-
4,500-4,999	9,200	3,878,000	6,010	69.4	11.66
5,000-5,499	5,376	2,258,400	3,501	40.4	7.27
5,500-5,999	-	-	-	-	-
6,000-6,499	-	-	-	-	-
6,500-6,999	-	-	-	-	-
7,000-7,499	-	-	-	-	-
7,500-7,999	-	-	-	-	-
8,000-8,499	-	-	-	-	-
8,500-8,999	-	-	-	-	-
9,000-9,499	-	-	-	-	-
9,500-9,999	-	-	-	-	-
10,000-10,499	-	-	-	-	-
10,500-10,999	-	-	-	-	-
11,000-11,499	-	-	-	-	-
11,500-11,999	-	-	-	-	-
12,000-12,499	-	-	-	-	-
12,500-12,999	-	-	-	-	-
13,000-13,499	-	-	-	-	-
13,500-13,999	-	-	-	-	-
14,000-14,499	14,000	5,600,000	8,680	100.2	18.03
15,000-15,499	-	-	-	-	-
15,500-15,999	-	-	-		-
Total	**135,018**	**55,359,209**	**85,800**	**989.7**	**165.8**

Source: MPCA (1999) (livestock numbers)

[a] calculated using the methodology given in USEPA (1995)

Table 53. Farrow-to-Wean Systems Inventory: Below Barn Pit Storage Systems

Herd Size (Sows)	Sows (number)	Liveweight (lb.)[a]	VS (tons)[a]	CH_4 Emissions Maximum Potential (mmcf)[a]	CH_4 Emissions Actual Emissions (mmcf)[a]
0-499	1,436	588,800	912	10.5	1.69
500-999	5,162	2,076,050	3,218	37.1	5.94
1,000-1,499	10,777	4,481,350	6,945	80.3	12.88
1,500-1,999	6,852	2,769,600	4,293	49.6	7.93
2,000-2,499	14,564	5,932,700	9,196	106.7	16.97
2,500-2,999	12,966	5,312,850	8,235	95	15.21
3,000-3,499	6,064	2,425,600	3,760	43.4	6.94
3,500-3,999	-	-	-	-	-
4,000-4,499	-	-	-	-	-
4,500-4,999	4,600	1,939,000	3,005	34.7	5.55
5,000-5,499	-	-	-	-	-
5,500-,9999	-	-	-	-	-
6,000-6,499	-	-	-	-	-
6,500-6,999	-	-	-	-	-
7,000-7,499	-	-	-	-	-
7,500-7,999	-	-	-	-	-
8,000-8,499	-	-	-	-	-
8,500-8,999	-	-	-	-	-
9,000-9,499	-	-	-	-	-
9,500-9,999	-	-	-	-	-
10,000-10,499	-	-	-	-	-
10,500-1,999	-	-	-	-	-
11,000-11,499	-	-	-	-	-
11,500-11,999	-	-	-	-	-
12,000-12,499	-	-	-	-	-
12,500-12,999	-	-	-	-	-
13,000-13,499	-	-	-	-	-
13,500-13,999	-	-	-	-	-
14,000-14,499	-	-	-	-	-
15,000-15,499	-	-	-	-	-
15,500-15,999	-	-	-	-	-
Total	**62,421**	**25,525,950**	**39,565**	**456.6**	**73.1**

Source: MPCA (1999) (livestock numbers)

[a] calculated using the methodology given in USEPA (1995)

Inventory for Farrow-to-Finish Operations

Farrow-to-finish operations account for about 12.5% of the methane generation potential of Minnesota swine operations and about the same percentage of all emitted methane from that subsector. Table 54 gives a breakdown of animal numbers, liveweight production and emissions for farrow-to-finish operations in Minnesota by manure management system. Liquid /slurry systems dominate in farrow-finish production systems, and, of these, below barn pit storage and earthen basin storage are the most important types of manure storage.

Table 54. Summary Statistics for Farrow-to-Finish Swine Systems

	Sows (number)	Finishers (number)	Liveweight (lb.)[a]	VS (tons)[a]	Potential Emission (mmcf)[a]	Actual Emissions (mmcf)[a]
Below Barn Pit	40,392	248,076	63,536,858	98,461	1,268	201
Outdoor Pit	1,406	3,242	1,285,865	2,004	26	5
Earthen Basin	24,958	79,531	23,274,438	36,110	487	88
Lagoon	40	0	1,600	25	-	-
Above Ground Tank	2,627	8,205	2,547,250	3,948	52	9
Solid Stacking Slab	494	2,080	534,225	829	11	-
Daily Haul	3,323	5,225	2,273,983	3,526	46	-
Stockpiling, No Structure	391	434	295,073	480	5	-
Manure Pack in Bldgs	9,955	32,922	9,493,753	14,709	193	2
Other	1,540	3,802	1,534,125	2,255	26	4
Total	**85,126**	**383,517**	**104,777,170**	**162,327**	**2,114**	**309**

Source: MPCA (1999) (livestock numbers by manure storage or management system)

[a] calculated using the methodology given in USEPA (1995)

Tables 55 and 56 give a breakdown by feedlot size class for the entire population of farrow-to-finish operations, and that part of this swine subsector that utilized below barn pit storage, respectively. As noted above, in Part 4 of this study, the economic analysis of anaerobic digestion of swine manure is limited to manure that is managed below barn in deep pits. The below barn pit storage inventory includes both feedlots that use below barn pit storage exclusively and feedlots that utilize below barn pit storage as one of a number of management management-storage systems.

Table 55. Farrow-to-Finish Inventory by Number of Sows

	% sows of combined sows and finishers										
Feedlot Size	**0 to 10**	**10 to 20**	**20 to 30**	**30 to 40**	**40 to 50**	**50 to 60**	**60 to 70**	**70 to 80**	**80 to 90**	**90 to 100**	**All**
0-499	4,284	19,102	12,075	3,401	1,441	1,313	1,210	295	774	280	44,175
500-999	-	1,838	3,696	3,261	1,474	1,730	500	525	-	-	13,024
1,000-1,499	-	1,104	1,200	-	2,772	-	-	3,450	-	2,260	10,786
1,500-1,999	-	-	-	-	-	1,510	1,780	-	-	-	3,290
2,000-2,499	-	-	-	2,480	-	-	-	-	-	-	4,880
2,500-2,999	-	-	-	-	-	-	-	-	2,600	-	2,600
3,000-3,499	-	-	-	-	-	3,265	-	-	-	3,106	6,371
3,500-3,999	-	-	-	-	-	-	-	-	-	-	-
4,000-4,499	-	-	-	-	-	-	-	-	-	-	-
4,500-4,999	-	-	-	-	-	-	-	-	-	-	-
5,000-5,499	-	-	-	-	-	-	-	-	-	-	-
5,500-5,999	-	-	-	-	-	-	-	-	-	-	-
6,000-6,499	-	-	-	-	-	-	-	-	-	-	-
6,500-6,999	-	-	-	-	-	-	-	-	-	-	-
7,000-7,499	-	-	-	-	-	-	-	-	-	-	-
7,500-7,999	-	-	-	-	-	-	-	-	-	-	-
8,000-8,499	-	-	-	-	-	-	-	-	-	-	-
8,500-9,000	-	-	-	-	-	-	-	-	-	-	-
Total	**6,684**	**22,044**	**16,971**	**9,142**	**5,687**	**7,818**	**3,490**	**4,270**	**3,374**	**5,646**	**85,126**

Source: MPCA (1999)

Table 56. Farrow-to-Finish Inventory for Below Barn Pit Storage Systems by Number of Sows

	% sows of combined sows and finishers										
Feedlot Size	**0 to 10**	**10 to 20**	**20 to 30**	**30 to 40**	**40 to 50**	**50 to 60**	**60 to 70**	**70 to 80**	**80 to 90**	**90 to 100**	**All**
0-499	3,177	14,280	7,628	2,817	1,121	775	782	292	614	280	31,769
500-999	-	1,308	1,590	1,945	1,474	1,730	500	525	-	-	9,072
1,000-1,499	-	-	-	-	1,400	-	-	2,210	-	2,260	5,870
1,500-1,999	-	-	-	-	-	1,510	-	-	-	-	1,510
2,000-2,499	2,400	-	-	-	-	-	-	-	-	-	2,400
2,500-2,999	-	-	-	-	-	-	-	-	2,600	-	2,600
3,000-3,499	-	-	-	-	-	-	-	-	-	3,106	3,106
3,500-3,999	-	-	-	-	-	-	-	-	-	-	-
4,000-4,499	-	-	-	-	-	-	-	-	-	-	-
4,500-4,999	-	-	-	-	-	-	-	-	-	-	-
5,000-5,499	-	-	-	-	-	-	-	-	-	-	-
5,500-5,999	-	-	-	-	-	-	-	-	-	-	-
6,000-6,499	-	-	-	-	-	-	-	-	-	-	-
6,500-6,999	-	-	-	-	-	-	-	-	-	-	-
7,000-7,499	-	-	-	-	-	-	-	-	-	-	-
7,500-7,999	-	-	-	-	-	-	-	-	-	-	-
8,000-8,499	-	-	-	-	-	-	-	-	-	-	-
8,500-9,000	-	-	-	-	-	-	-	-	-	-	-
Total	**5,577**	**15,588**	**9,218**	**4,762**	**3,995**	**4,015**	**1,282**	**3,030**	**3,214**	**5,646**	**56,327**

Source: MPCA (1999)

Table 57. Farrow-to-Finish VS Inventory for Below Barn Pit Storage Systems by Number of Sows

	% sows of combined sows and finishers										
Feedlot Size	**0 to 10**	**10 to 20**	**20 to 30**	**30 to 40**	**40 to 50**	**50 to 60**	**60 to 70**	**70 to 80**	**80 to 90**	**90 to 100**	**All**
0-499	16,482	29,779	10,582	3,410	1,195	751	664	259	529	244	63,895
500-999	-	2,590	2,332	2,464	1,385	1,471	506	454	-	-	11,202
1,000-1,499	-	-	-	-	1,396	-	-	1,602	-	1,848	4,846
1,500-1,999	-	-	-	-	-	1,389	-	-	-	-	1,389
2,000-2,499	35,707	-	-	-	-	-	-	-	-	-	35,707
2,500-2,999	-	-	-	-	-	-	-	-	1,860	-	1,860
3,000-3,499	-	-	-	-	-	-	-	-	-	2,023	2,023
3,500-3,999	-	-	-	-	-	-	-	-	-	-	-
4,000-4,499	-	-	-	-	-	-	-	-	-	-	-
4,500-4,999	-	-	-	-	-	-	-	-	-	-	-
5,000-5,499	-	-	-	-	-	-	-	-	-	-	-
5,500-5,999	-	-	-	-	-	-	-	-	-	-	-
6,000-6,499	-	-	-	-	-	-	-	-	-	-	-
6,500-6,999	-	-	-	-	-	-	-	-	-	-	-
7,000-7,499	-	-	-	-	-	-	-	-	-	-	-
7,500-7,999	-	-	-	-	-	-	-	-	-	-	-
8,000-8,499	-	-	-	-	-	-	-	-	-	-	-
8,500-9,000	-	-	-	-	-	-	-	-	-	-	-
Total	**52,189**	**32,369**	**12,914**	**5,874**	**3,976**	**3,611**	**1,170**	**2,315**	**2,389**	**4,115**	**120,922**

Source: Calculated from Table 56 using the methodology given in USEPA (1995)

Table 58. Farrow-to-Finish Maximum Potential Methane Generation Inventory for Below Barn Pit Storage Systems by Number of Sows (in mmcf)

	% sows of combined sows and finishers										
Feedlot Size	**0 to 10**	**10 to 20**	**20 to 30**	**30 to 40**	**40 to 50**	**50 to 60**	**60 to 70**	**70 to 80**	**80 to 90**	**90 to 100**	**All**
0-499	232	414	150	45	15	10	8	3	7	3	886
500-999	-	36	32	31	18	18	6	6	-	-	146
1,000-1,499	-	-	-	-	18	-	-	19	-	23	59
1,500-1,999	-	-	-	-	-	18	-	-	-	-	18
2,000-2,499	412	-	-	-	-	-	-	-	-	-	412
2,500-2,999	-	-	-	-	-	-	-	-	22	-	22
3,000-3,499	-	-	-	-	-	-	-	-	-	24	24
3,500-3,999	-	-	-	-	-	-	-	-	-	-	-
4,000-4,499	-	-	-	-	-	-	-	-	-	-	-
4,500-4,999	-	-	-	-	-	-	-	-	-	-	-
5,000-5,499	-	-	-	-	-	-	-	-	-	-	-
5,500-5,999	-	-	-	-	-	-	-	-	-	-	-
6,000-6,499	-	-	-	-	-	-	-	-	-	-	-
6,500-6,999	-	-	-	-	-	-	-	-	-	-	-
7,000-7,499	-	-	-	-	-	-	-	-	-	-	-
7,500-7,999	-	-	-	-	-	-	-	-	-	-	-
8,000-8,499	-	-	-	-	-	-	-	-	-	-	-
8,500-9,000	-	-	-	-	-	-	-	-	-	-	-
Total	**644**	**450**	**181**	**76**	**50**	**45**	**14**	**28**	**28**	**49**	**1,566**

Source: Calculated from Table 57 using the methodology given in USEPA (1995)

Table 59. Farrow-to-Finish Emission Inventory for Below Barn Pit Storage Systems by Number of Sows (in mmcf of CH_4)

	% sows of combined sows and finishers										
Feedlot Size	**0 to 10**	**10 to 20**	**20 to 30**	**30 to 40**	**40 to 50**	**50 to 60**	**60 to 70**	**70 to 80**	**80 to 90**	**90 to 100**	**All**
0-499	32	57	19	6	2	1	1	-	1	-	119
500-999	-	6	5	5	3	3	1	1	-	-	23
1,000-1,499	-	-	-	-	3	-	-	3	-	4	10
1,500-1,999	-	-	-	-	-	3	-	-	-	-	3
2,000-2,499	66	-	-	-	-	-	-	-	-	-	66
2,500-2,999	-	-	-	-	-	-	-	-	4	-	4
3,000-3,499	-	-	-	-	-	-	-	-	-	4	4
3,500-3,999	-	-	-	-	-	-	-	-	-	-	-
4,000-4,499	-	-	-	-	-	-	-	-	-	-	-
4,500-4,999	-	-	-	-	-	-	-	-	-	-	-
5,000-5,499	-	-	-	-	-	-	-	-	-	-	-
5,500-5,999	-	-	-	-	-	-	-	-	-	-	-
6,000-6,499	-	-	-	-	-	-	-	-	-	-	-
6,500-6,999	-	-	-	-	-	-	-	-	-	-	-
7,000-7,499	-	-	-	-	-	-	-	-	-	-	-
7,500-7,999	-	-	-	-	-	-	-	-	-	-	-
8,000-8,499	-	-	-	-	-	-	-	-	-	-	-
8,500-9,000	-	-	-	-	-	-	-	-	-	-	-
Total	**98**	**63**	**24**	**11**	**8**	**7**	**2**	**4**	**5**	**8**	**228**

Source: Calculated from Table 58 using the methodology given in USEPA (1995)

Because this is a multi-animal combined system involving no set or rigorously characteristic ratio of sows to finishing hogs, the inventory shown below is broken both by feedlot size and by varying ratios of sows to finishing hogs. Feedlot classes are set up in increments of 10%, e.g., 0 to 10% sows and 90 to 100% finishing hogs, 10 to 20% sows and 80 to 90% finishing hogs. The chain of animal types intermediate between sows and finishing hogs in the production chain produce account for only a small part of total VS generated and of the methane production potential of farrow-to-finish systems. In the economic calculation of feasibility that appears later in this report, numbers of these intermediate animal types, e.g., boars, nursing pigs, are assumed to be proportional to the number of sows in ratios of 2.3 to 1 nursing pigs to sows and 0.05 to 1 boars to sows, which correspond to the typical ratios found in farrow-to-finish operations. (USEPA 1997)

Tables 56 through 59 above provide additional inventory information for nurse-finish systems for VS generation, emissions, and methane generation potential by feedlot size.

Inventory for Farrow-to-Nursery Pig Operations

Farrow-to-nursery swine operations account for about 3.5% of the methane generation potential of Minnesota swine operations and about 4% of all emitted methane from manure from swine production. Table 60 gives a breakdown of the farrow-to-nursery pig subsector by manure management system. Liquid/slurry systems dominate in finishing production systems, and, of these, earthen basins and below barn pit storage are the most important systems for manure storage. As above for other production systems, the below barn pit storage inventory includes both feedlots that use below barn pit storage exclusively and feedlots that utilize below barn pit storage as one of a number of management management-storage systems.

Tables 61 and 62 give a breakdown by feedlot size class for the entire population of farrow-to-nursery pig operations, and that part of this swine subsector that utilized below barn pit storage, respectively. The same conditions as above for other production systems describe the below barn pit storage inventory. Because this is a multi-animal combined system involving no set or rigorously characteristic ratio of sows to finishing hogs, the inventory shown below is broken both by feedlot size and by varying ratios of sows to finishing hogs. Feedlot classes are set up in increments of 10%, e.g., 0 to 10% sows and 90 to 100% nursery pigs, 10 to 20% sows and 80 to 90% nursery pigs.

Table 60. Summary Statistics for Farrow-to-Nursery Pig Swine Systems

	Sows (number)	Nursery Pigs (number)	Liveweight (lb.)[a]	VS (tons)[a]	Potential Emission (mmcf)[a]	Actual Emissions (mmcf)[a]
Below Barn Pit	28,354	45,430	12,908,250	20,011	239	38
Outdoor Pit	776	2,935	398,450	618	8	1
Earthen Basin	28,873	78,468	14,523,340	22,513	273	49
Lagoon	2,596	5,760	1,269,700	1,969	24	4
Above Ground Tank	850	2,200	406,000	629	8	1
Solid Stacking Slab	100	200	49,000	76	1	-
Daily Haul	2,672	7,625	1,336,800	2071	25	-
Stockpiling, No Structure	-	-	-	-	-	-
Manure Pack in Bldgs	2,773	2,760	1,288,025	1987	23	-
Other	1,984	2,782	897,107	1,386	16	3
Total	68,978	147,960	33,076,672	51,260	615	97

Source: MPCA (1999) (livestock numbers by manure storage or management system)

[a] calculated using the methodology given in USEPA (1995)

Tables 63 through 65 provide additional inventory information for nurse-finish systems for VS generation, emissions, and methane generation potential by feedlot size.

Table 61. Farrow-to-Nursery Pig System Inventory by Number of Sows

	% sows of combined sows and finishers										
Feedlot Size	**0 to 10**	**10 to 20**	**20 to 30**	**30 to 40**	**40 to 50**	**50 to 60**	**60 to 70**	**70 to 80**	**80 to 90**	**90 to 100**	**All**
0-499	187	1,601	5,092	3,272	1,797	500	-	316	-	-	12,765
500-999	-	-	6,173	2,226	600	567	-	-	-	-	9,566
1,000-1,499	-	-	6,460	1,260	1,240	1,200	2,457	-	1,230	-	13,847
1,500-1,999	-	-	1,500	-	-	-	-	-	-	-	1,500
2,000-2,499	-	-	-	-	2,400	-	-	-	-	-	2,400
2,500-2,999	-	-	10,192	5,192	2,566	-	-	-	-	-	17,950
3,000-3,499	-	-	-	-	-	-	-	-	-	-	-
3,500-3,999	-	-	-	-	-	-	-	-	-	-	-
4,000-4,499	-	-	-	-	-	-	-	-	-	-	-
4,500-4,999	-	-	-	-	-	-	-	-	-	-	-
5,000-5,499	-	-	-	-	-	-	-	-	-	-	-
5,500-5,999	-	-	-	-	-	-	-	-	-	-	-
6,000-6,499	-	-	-	-	-	-	-	-	-	-	-
6,500-6,999	-	-	-	-	-	-	-	-	-	-	-
7,000-7,499	-	-	-	-	-	-	-	-	-	-	-
7,500-7,999	-	-	-	-	-	-	-	-	-	-	-
8,000-8,499	-	-	-	-	-	-	-	-	-	-	-
8,500-9,000	-	-	-	-	-	-	-	-	-	-	-
9,000-9,500	-	-	-	-	-	-	-	-	-	-	-
9,500-10,000	-	-	-	-	-	-	-	-	-	-	-
10,000-10,500	-	-	-	-	-	-	-	-	-	-	-
10,500-11,000	-	-	-	-	-	10,950	-	-	-	-	10,950
Total	**187**	**1,601**	**29,417**	**11,950**	**8,603**	**13,217**	**2,457**	**316**	**1,230**	**-**	**68,978**

Source: MPCA (1999)

Table 62. Farrow-to-Nursery Pig System Inventory for Below Barn Pit Storage Systems by Number of Sows

	% sows of combined sows and finishers										
Feedlot Size	**0 to 10**	**10 to 20**	**20 to 30**	**30 to 40**	**40 to 50**	**50 to 60**	**60 to 70**	**70 to 80**	**80 to 90**	**90 to 100**	**All**
0-499	138	743	3,275	1,809	1,303	300	-	-	-	-	7,568
500-999	-	-	1,530	-	-	567	-	-	-	-	2,097
1,000-1,499	-	-	1,212	-	1,240	1,200	1,085	-	1,230	-	5,967
1,500-1,999	-	-	-	-	-	-	-	-	-	-	-
2,000-2,499	-	-	-	-	2,400	-	-	-	-	-	2,400
2,500-2,999	-	-	-	-	2,566	-	-	-	-	-	2,566
3,000-3,499	-	-	-	-	-	-	-	-	-	-	-
3,500-3,999	-	-	-	-	-	-	-	-	-	-	-
4,000-4,499	-	-	-	-	-	-	-	-	-	-	-
4,500-4,999	-	-	-	-	-	-	-	-	-	-	-
5,000-5,499	-	-	-	-	-	-	-	-	-	-	-
5,500-5,999	-	-	-	-	-	-	-	-	-	-	-
6,000-6,499	-	-	-	-	-	-	-	-	-	-	-
6,500-6,999	-	-	-	-	-	-	-	-	-	-	-
7,000-7,499	-	-	-	-	-	-	-	-	-	-	-
7,500-7,999	-	-	-	-	-	-	-	-	-	-	-
8,000-8,499	-	-	-	-	-	-	-	-	-	-	-
8,500-9,000	-	-	-	-	-	-	-	-	-	-	-
9,000-9,500	-	-	-	-	-	-	-	-	-	-	-
9,500-10,000	-	-	-	-	-	-	-	-	-	-	-
10,000-10,500	-	-	-	-	-	-	-	-	-	-	-
10,500-11,000	-	-	-	-	-	10,950	-	-	-	-	10,950
Total	**138**	**743**	**6,017**	**1,809**	**7,509**	**13,017**	**1,085**	**-**	**1,230**	**-**	**31,548**

Source: MPCA (1999)

Table 63. Farrow-to-Nursery Pig System VS Inventory for Below Barn Pit Storage Systems by Number of Sows

	% sows of combined sows and finishers										
Feedlot Size	**0 to 10**	**10 to 20**	**20 to 30**	**30 to 40**	**40 to 50**	**50 to 60**	**60 to 70**	**70 to 80**	**80 to 90**	**90 to 100**	**All**
0-499	208	692	2,550	1,325	926	206	-	-	-	-	5,907
500-999	-	-	1,160	-	-	381	-	-	-	-	1,541
1,000-1,499	-	-	912	-	880	797	717	-	766	-	4,072
1,500-1,999	-	-	-	-	-	-	-	-	-	-	-
2,000-2,499	-	-	-	-	1,628	-	-	-	-	-	1,628
2,500-2,999	-	-	-	-	1,793	-	-	-	-	-	1,793
3,000-3,499	-	-	-	-	-	-	-	-	-	-	-
3,500-3,999	-	-	-	-	-	-	-	-	-	-	-
4,000-4,499	-	-	-	-	-	-	-	-	-	-	-
4,500-4,999	-	-	-	-	-	-	-	-	-	-	-
5,000-5,499	-	-	-	-	-	-	-	-	-	-	-
5,500-5,999	-	-	-	-	-	-	-	-	-	-	-
6,000-6,499	-	-	-	-	-	-	-	-	-	-	-
6,500-6,999	-	-	-	-	-	-	-	-	-	-	-
7,000-7,499	-	-	-	-	-	-	-	-	-	-	-
7,500-7,999	-	-	-	-	-	-	-	-	-	-	-
8,000-8,499	-	-	-	-	-	-	-	-	-	-	-
8,500-9,000	-	-	-	-	-	-	-	-	-	-	-
9,000-9,500	-	-	-	-	-	-	-	-	-	-	-
9,500-10,000	-	-	-	-	-	-	-	-	-	-	-
10,000-10,500	-	-	-	-	-	-	-	-	-	-	-
10,500-11,000	-	-	-	-	-	7,289	-	-	-	-	7,289
Total	**208**	**692**	**4,622**	**1,325**	**5,227**	**8,674**	**717**	**-**	**766**	**-**	**22,230**

Source: Calculated from Table 62 using the methodology given in USEPA (1995)

Table 64. Farrow-to-Nursery Pig System Maximum Potential Methane Generation Inventory for Below Barn Pit Storage Systems by Number of Sows (in mmcf)

	% sows of combined sows and finishers										
Feedlot Size	**0 to 10**	**10 to 20**	**20 to 30**	**30 to 40**	**40 to 50**	**50 to 60**	**60 to 70**	**70 to 80**	**80 to 90**	**90 to 100**	**All**
0-499	3	8	31	16	11	2	-	-	-	-	71
500-999	-	-	14	-	-	5	-	-	-	-	19
1,000-1,499	-	-	11	-	11	9	8	-	9	-	48
1,500-1,999	-	-	-	-	-	-	-	-	-	-	-
2,000-2,499	-	-	-	-	19	-	-	-	-	-	19
2,500-2,999	-	-	-	-	21	-	-	-	-	-	21
3,000-3,499	-	-	-	-	-	-	-	-	-	-	-
3,500-3,999	-	-	-	-	-	-	-	-	-	-	-
4,000-4,499	-	-	-	-	-	-	-	-	-	-	-
4,500-4,999	-	-	-	-	-	-	-	-	-	-	-
5,000-5,499	-	-	-	-	-	-	-	-	-	-	-
5,500-5,999	-	-	-	-	-	-	-	-	-	-	-
6,000-6,499	-	-	-	-	-	-	-	-	-	-	-
6,500-6,999	-	-	-	-	-	-	-	-	-	-	-
7,000-7,499	-	-	-	-	-	-	-	-	-	-	-
7,500-7,999	-	-	-	-	-	-	-	-	-	-	-
8,000-8,499	-	-	-	-	-	-	-	-	-	-	-
8,500-9,000	-	-	-	-	-	-	-	-	-	-	-
9,000-9,500	-	-	-	-	-	-	-	-	-	-	-
9,500-10,000	-	-	-	-	-	-	-	-	-	-	-
10,000-10,500	-	-	-	-	-	-	-	-	-	-	-
10,500-11,000	-	-	-	-	-	86	-	-	-	-	86
Total	**3**	**8**	**56**	**16**	**62**	**102**	**8**	**-**	**9**	**-**	**264**

Source: Calculated from Table 63 using the methodology given in USEPA (1995)

Table 65. Farrow-to-Nursery Pig System Emission Inventory for Below Barn Pit Storage Systems by Number of Sows (in mmcf of CH_4)

	% sows of combined sows and finishers										
Feedlot Size	**0 to 10**	**10 to 20**	**20 to 30**	**30 to 40**	**40 to 50**	**50 to 60**	**60 to 70**	**70 to 80**	**80 to 90**	**90 to 100**	**All**
0-499	1	1	4	2	2	-	-	-	-	-	10
500-999	-	-	2	-	-	1	-	-	-	-	3
1,000-1,499	-	-	2	-	2	2	1	-	1	-	8
1,500-1,999	-	-	-	-	-	-	-	-	-	-	-
2,000-2,499	-	-	-	-	3	-	-	-	-	-	3
2,500-2,999	-	-	-	-	3	-	-	-	-	-	3
3,000-3,499	-	-	-	-	-	-	-	-	-	-	-
3,500-3,999	-	-	-	-	-	-	-	-	-	-	-
4,000-4,499	-	-	-	-	-	-	-	-	-	-	-
4,500-4,999	-	-	-	-	-	-	-	-	-	-	-
5,000-5,499	-	-	-	-	-	-	-	-	-	-	-
5,500-5,999	-	-	-	-	-	-	-	-	-	-	-
6,000-6,499	-	-	-	-	-	-	-	-	-	-	-
6,500-6,999	-	-	-	-	-	-	-	-	-	-	-
7,000-7,499	-	-	-	-	-	-	-	-	-	-	-
7,500-7,999	-	-	-	-	-	-	-	-	-	-	-
8,000-8,499	-	-	-	-	-	-	-	-	-	-	-
8,500-9,000	-	-	-	-	-	-	-	-	-	-	-
9,000-9,500	-	-	-	-	-	-	-	-	-	-	-
9,500-10,000	-	-	-	-	-	-	-	-	-	-	-
10,000-10,500	-	-	-	-	-	-	-	-	-	-	-
10,500-11,000	-	-	-	-	-	14	-	-	-	-	14
Total	**1**	**1**	**8**	**2**	**10**	**17**	**1**	**-**	**1**	**-**	**41**

Source: Calculated from Table 64 using the methodology given in USEPA (1995)

Inventory for Farrow-and-Finish Operations

Farrow-and-finish operations account for about 2% of the methane generation potential of Minnesota swine operations and about the same percentage of all emitted methane from that subsector. Table 66 gives a breakdown of animal numbers, liveweight production and emissions for farrow-and-finish operations in Minnesota by manure management system. Liquid /slurry systems dominate in farrow-finish production systems, and, of these, below barn pit storage is the single most important type of manure storage for this production system.

Table 66. Summary Statistics for Farrow-and-Finish Swine Systems

	Sows (number)	Finishers (number)	Liveweight (lb.)[a]	VS (tons)	Potential Emission (mmcf)[a]	Actual Emissions (mmcf)[a]
Below Barn Pit	15,229	30,036	10,838,318	16,762	215	34
Outdoor Pit	470	5,276	946,430	1,505	21	4
Earthen Basin	6,768	7,556	4,000,905	6,170	75	14
Lagoon	-	-	-	-	-	-
Above Ground Tank	300	1,600	348,000	539	8	1
Solid Stacking Slab	1	-	400	1	-	-
Daily Haul	102	475	118,238	181	2	-
Stockpiling, No Structure	-	-	22,000	34	-	-
Manure Pack in Bldgs	1,095	3,195	1,121,877	1,687	19	-
Other	662	2,700	543,939	1,015	14	2
Total	**26,627**	**50,838**	**18,051,107**	**27,894**	**354**	**56**

Source: MPCA (1999) (livestock numbers by manure storage or management system)

[a] calculated using the methodology given in USEPA (1995)

Tables 67 and 68 give a breakdown by feedlot size class for the entire population of farrow-and-finish operations, and that part of this swine subsector that utilized below barn pit storage, respectively. As above for other systems, the below barn pit storage inventory includes both

Table 67. Farrow-and-Finish Inventory by Number of Sows

	% sows of combined sows and finishers										
Feedlot Size	**0 to 10**	**10 to 20**	**20 to 30**	**30 to 40**	**40 to 50**	**50 to 60**	**60 to 70**	**70 to 80**	**80 to 90**	**90 to 100**	**All**
0-499	981	2,978	792	428	1,133	148	120	295	40	40	6,955
500-999	-	-	-	-	-	500	858	525	-	-	1,883
1,000-1,499	-	-	-	-	-	1,199	-	3,450	1,208	-	5,857
1,500-1,999	-	-	-	-	-	-	-	-	1,500	1,620	3,120
2,000-2,499	-	-	-	-	-	-	-	-	-	2,312	2,312
2,500-2,999	-	-	-	-	-	-	-	-	2,800	2,864	5,664
3,000-3,499	-	-	-	-	-	-	-	-	-	3,106	3,106
3,500-3,999	-	-	-	-	-	-	-	-	-	-	-
4,000-4,499	-	-	-	-	-	-	-	-	-	-	-
4,500-4,999	-	-	-	-	-	-	-	-	-	-	-
5,000-5,499	-	-	-	-	-	-	-	-	-	-	-
5,500-5,999	-	-	-	-	-	-	-	-	-	-	-
6,000-6,499	-	-	-	-	-	-	-	-	-	-	-
6,500-6,999	-	-	-	-	-	-	-	-	-	-	-
7,000-7,499	-	-	-	-	-	-	-	-	-	-	-
7,500-7,999	-	-	-	-	-	-	-	-	-	-	-
8,000-8,499	-	-	-	-	-	-	-	-	-	-	-
8,500-9,000	-	-	-	-	-	-	-	-	-	-	-
Total	**981**	**2,978**	**792**	**428**	**1,133**	**1,849**	**978**	**4,270**	**5,548**	**9,942**	**28,897**

Source: MPCA (1999)

Table 68. Farrow-and-Finish Inventory for Below Barn Pit Storage Systems by Number of Sows

	% sows of combined sows and finishers										
Feedlot Size	**0 to 10**	**10 to 20**	**20 to 30**	**30 to 40**	**40 to 50**	**50 to 60**	**60 to 70**	**70 to 80**	**80 to 90**	**90 to 100**	**All**
0-499	645	1,781	270	262	1,135	148	-	-	-	-	4,241
500-999	-	-	-	-	-	-	-	-	-	-	-
1,000-1,499	-	-	-	-	-	1,199	-	-	-	-	1,199
1,500-1,999	-	-	-	-	-	-	-	-	1,500	1,620	3,120
2,000-2,499	-	-	-	-	-	-	-	-	-	2,312	2,312
2,500-2,999	-	-	-	-	-	-	-	-	-	2,864	2,864
3,000-3,499	-	-	-	-	-	-	-	-	-	3,106	3,106
3,500-3,999	-	-	-	-	-	-	-	-	-	-	-
4,000-4,499	-	-	-	-	-	-	-	-	-	-	-
4,500-4,999	-	-	-	-	-	-	-	-	-	-	-
5,000-5,499	-	-	-	-	-	-	-	-	-	-	-
5,500-5,999	-	-	-	-	-	-	-	-	-	-	-
6,000-6,499	-	-	-	-	-	-	-	-	-	-	-
6,500-6,999	-	-	-	-	-	-	-	-	-	-	-
7,000-7,499	-	-	-	-	-	-	-	-	-	-	-
7,500-7,999	-	-	-	-	-	-	-	-	-	-	-
8,000-8,499	-	-	-	-	-	-	-	-	-	-	-
8,500-9,000	-	-	-	-	-	-	-	-	-	-	-
Total	**645**	**1,781**	**270**	**262**	**1,135**	**1,347**	**-**	**-**	**1,500**	**9,902**	**16,842**

Source: MPCA (1999)

Table 69. Farrow-and-Finish VS Inventory for Below Barn Pit Storage Systems by Number of Sows

	% sows of combined sows and finishers										
Feedlot Size	**0 to 10**	**10 to 20**	**20 to 30**	**30 to 40**	**40 to 50**	**50 to 60**	**60 to 70**	**70 to 80**	**80 to 90**	**90 to 100**	**All**
0-499	3,861	4,312	399	296	1,077	118	-	-	-	-	10,063
500-999	-	-	-	-	-	-	-	-	-	-	-
1,000-1,499	-	-	-	-	-	964	-	-	-	-	964
1,500-1,999	-	-	-	-	-	-	-	-	983	1,048	2,031
2,000-2,499	-	-	-	-	-	-	-	-	-	1,451	1,451
2,500-2,999	-	-	-	-	-	-	-	-	-	1,837	1,837
3,000-3,499	-	-	-	-	-	-	-	-	-	1,987	1,987
3,500-3,999	-	-	-	-	-	-	-	-	-	-	-
4,000-4,499	-	-	-	-	-	-	-	-	-	-	-
4,500-4,999	-	-	-	-	-	-	-	-	-	-	-
5,000-5,499	-	-	-	-	-	-	-	-	-	-	-
5,500-5,999	-	-	-	-	-	-	-	-	-	-	-
6,000-6,499	-	-	-	-	-	-	-	-	-	-	-
6,500-6,999	-	-	-	-	-	-	-	-	-	-	-
7,000-7,499	-	-	-	-	-	-	-	-	-	-	-
7,500-7,999	-	-	-	-	-	-	-	-	-	-	-
8,000-8,499	-	-	-	-	-	-	-	-	-	-	-
8,500-9,000	-	-	-	-	-	-	-	-	-	-	-
Total	**3,861**	**4,312**	**399**	**296**	**1,077**	**1,082**	**-**	**-**	**983**	**6,322**	**18,333**

Source: Calculated from Table 67 using the methodology given in USEPA (1995)

Table 70. Farrow-and-Finish Maximum Potential Methane Generation Inventory for Below Barn Pit Storage Systems by Number of Sows (in mmcf)

	% sows of combined sows and finishers										
Feedlot Size	**0 to 10**	**10 to 20**	**20 to 30**	**30 to 40**	**40 to 50**	**50 to 60**	**60 to 70**	**70 to 80**	**80 to 90**	**90 to 100**	**All**
0-499	54	56	5	4	12	2	-	-	-	-	133
500-999	-	-	-	-	-	-	-	-	-	-	-
1,000-1,499	-	-	-	-	-	12	-	-	-	-	12
1,500-1,999	-	-	-	-	-	-	-	-	12	12	24
2,000-2,499	-	-	-	-	-	-	-	-	-	17	17
2,500-2,999	-	-	-	-	-	-	-	-	-	21	21
3,000-3,499	-	-	-	-	-	-	-	-	-	23	23
3,500-3,999	-	-	-	-	-	-	-	-	-	-	-
4,000-4,499	-	-	-	-	-	-	-	-	-	-	-
4,500-4,999	-	-	-	-	-	-	-	-	-	-	-
5,000-5,499	-	-	-	-	-	-	-	-	-	-	-
5,500-5,999	-	-	-	-	-	-	-	-	-	-	-
6,000-6,499	-	-	-	-	-	-	-	-	-	-	-
6,500-6,999	-	-	-	-	-	-	-	-	-	-	-
7,000-7,499	-	-	-	-	-	-	-	-	-	-	-
7,500-7,999	-	-	-	-	-	-	-	-	-	-	-
8,000-8,499	-	-	-	-	-	-	-	-	-	-	-
8,500-9,000	-	-	-	-	-	-	-	-	-	-	-
Total	**54**	**56**	**5**	**4**	**12**	**14**	**-**	**-**	**12**	**73**	**230**

Source: Calculated from Table 69 using the methodology given in USEPA (1995)

Table 71. Farrow-and-Finish Emission Inventory for Below Barn Pit Storage Systems by Number of Sows (in mmcf of CH$_4$)

	% sows of combined sows and finishers										
Feedlot Size	**0 to 10**	**10 to 20**	**20 to 30**	**30 to 40**	**40 to 50**	**50 to 60**	**60 to 70**	**70 to 80**	**80 to 90**	**90 to 100**	**All**
0-499	8	8	1	1	2	-	-	-	-	-	20
500-999	-	-	-	-	-	-	-	-	-	-	-
1,000-1,499	-	-	-	-	-	2	-	-	-	-	2
1,500-1,999	-	-	-	-	-	-	-	-	2	2	4
2,000-2,499	-	-	-	-	-	-	-	-	-	3	3
2,500-2,999	-	-	-	-	-	-	-	-	-	3	3
3,000-3,499	-	-	-	-	-	-	-	-	-	4	4
3,500-3,999	-	-	-	-	-	-	-	-	-	-	-
4,000-4,499	-	-	-	-	-	-	-	-	-	-	-
4,500-4,999	-	-	-	-	-	-	-	-	-	-	-
5,000-5,499	-	-	-	-	-	-	-	-	-	-	-
5,500-5,999	-	-	-	-	-	-	-	-	-	-	-
6,000-6,499	-	-	-	-	-	-	-	-	-	-	-
6,500-6,999	-	-	-	-	-	-	-	-	-	-	-
7,000-7,499	-	-	-	-	-	-	-	-	-	-	-
7,500-7,999	-	-	-	-	-	-	-	-	-	-	-
8,000-8,499	-	-	-	-	-	-	-	-	-	-	-
8,500-9,000	-	-	-	-	-	-	-	-	-	-	-
Total	**8**	**8**	**1**	**1**	**2**	**2**	**-**	**-**	**2**	**12**	**36**

Source: Calculated from Table 70 using the methodology given in USEPA (1995)

feedlots that use below barn pit storage exclusively and feedlots that utilize below barn pit storage as one of a number of management management-storage systems.

The inventory is developed consistent with the approach taken above for other two-animal systems. The inventory shown below is broken both by feedlot size and by varying ratios of sows to finishing hogs. Feedlot classes are set up in increments of 10%, e.g., 0 to 10% sows and 90 to 100% finishing hogs, 10 to 20% sows and 80 to 90% finishing hogs.

Tables 69 through 71 present additional information on volatile solids produced, methane emissions and methane generation capacity of Minnesota farrow-and finish feedlots by herd size.

Part 4. Economic Assessment of Digester Feasibility on Minnesota Feedlots

Approach to the Economic Analysis of Digester Feasibility

The economic viability of digester deployment is size-limited. Digesters become economical only above a certain size threshold that allows for economies of scale in methane production and large on-farm electricity and space heating loads. The approach taken here is, for each livestock production system, to identify the threshold of feedlot size at which viability conditions are met. This is done utilizing fairly conventional Internal Rate of Return (IRR) criteria.

For analysis, the US Environmental Protection Agency FarmWare software analysis program was utilized. This follows the use of FarmWare for a similar evaluation of digester feasibility by USEPA (1999).

FarmWare is comprised of two distinct subcomponents: an engineering optimization subprogram and an economic optimization subprogram. Based on feedlot type and size, daily manure production, and available manure collection and storage facilities, FarmWare generates optimized design and operating characteristics for the digester component of the system, and optimized design parameters and operating characteristics for the pumping, mixing, mixing tank and gas utilization components of the system. Outputs include optimized digester size and digester dimensions (e.g., total volume, working volume, and wall, floor, ceiling and freeboard dimensions); heat exchange requirements; piping and insulation associated with the digester heating system; piping and pumping requirements for moving influent from barns to the mixing tank and the digester and for removing effluent to storage; and digester mixing requirements. The size of the power generation component of the system is calculated from total gas availability and on-farm electrical needs. Required construction materials and services are calculated from optimized digester size. Total capital and operating costs are calculated within the engineering subcomponent, based on system design parameters.

Digester heating requirements are based on the observed performance of working digesters under optimized conditions. This will be discussed further below. Available waste heat for farm heating needs is calculated in the model based on digester heating needs and heat exchange efficiency. Digester biogas production, electrical generation and use, and labor requirements are calculated based on the observed performance of working digesters and the efficiency of power generation using hundred KW-scale diesel generators.

The total volume of waste exiting the digester is calculated based on the volume of diluted manure entering the digester and total solids destruction in the digester. The total volume of waste entering the digester is calculated from total excreted waste, the total solids content of excreted waste, and dilution during collection or in storage. Available manure and manure VS available for digestion is based on observed yearly amounts of manure production per animal by livestock type and livestock size.

The economic component of FarmWare is an economic optimization program that, for a specified internal rate of return hurdle, will evaluate costs and benefits of digester projects for economic viability. An Internal Rate of Return is the project discount rate at which the net present value of a stream of costs and benefits of a project is zero. Normally, it is at the rate of return on investment that could otherwise be earned from alternative investments of capital. A common yardstick is the average annual rate of return historically associated with investments in the stock market. Given a stream of benefits and costs from a digester project, including interest costs, for any given IRR, FarmWare calculates the net present value of that investment.

Some important financial parameters in the evaluation of profitability include: project capital costs, loan rate, operating costs, background rate of inflation of operating costs, project lifetime, annual benefits, and internal rate of return or discount rate. The FarmWare decision support software takes the cost components necessary for the economic analysis from the results of the engineering optimization.

FarmWare develops the stream of project benefits from the estimates of the physical outputs of the digester project in question, again, as developed from the engineering analysis. The economic benefits of digestion derive principally from the displacement of high-cost electricity purchases from the grid. The sale of excess of electricity back to the grid constitutes a lesser source of benefit. The same is true of heating fuel-avoided as a result of the use of the waste heat from the power generation system and any sales of bedding or compost. FarmWare develops the stream of project benefits from the avoided purchase of electricity and LPG, as drawn from the engineering optimization, and some inflation or deflation rate with regard to the costs of energy. No benefit is assumed from the sale of excess of electricity back to the grid or from the sale of effluent byproducts. These benefits must be evaluated outside the model and introduced into the model as an exogenous input.

Credits for early greenhouse gas reduction are evaluated externally and are used as inputs to the model on the benefits side. Early credit amounts were calculated using three levels of credit valuation: $0/ton of CO_2-equivalent emissions, $1/ ton, and $5/ton. For purposes of calculating early credits, it is assumed that 90% of all methane produced in and emitted from liquid manure storage ponds, tanks and pits is avoided with digestion with biogas combustion. As discussed above, it is possible that the US will have a voluntary early credits program up and running within five years. At present, early credits are being offered in Canada under the GERT program at about $3/ton.

Economic feasibility is evaluated under market conditions. However, in addition to feasibility under prevailing market conditions, the feasibility of digester deployment was also evaluated under a series of policy initiatives designed to variously reduce project costs or to raise project benefits levels. These were delineated below in Table 72.

Table 72: Policy Initiatives Investigated

Policy Cases
$0.015/kwh renewable energy subsidy
2% interest rate buydown
4% interest rate buydown
8% interest rate buydown
$25,000 grant for capital expenditures
$15,000 grant for capital expenditures
Sales tax exemption for capital expenditures

A 2.5% sales tax is in effect on purchases of manure management systems. The diesel generator component of the gas utilization system may or may not qualify for this low rate of sales tax. It is possible that purchase of the diesel generator may involve a sale tax at the 8.5% rate. We utilize a 2.75% sales tax on equipment and materials purchases to account for the possibility that the generator may be taxed at the higher rate. No sales tax is charged against services like engineering-design services.

For dairy feedlots, it is possible using FarmWare to evaluate the cost effectiveness of covered anaerobic lagoons, Continuously-Stirred Tank Reactors (CSTRs) and plug flow reactors. Since climate largely restricts the use of anaerobic lagoons to areas well to the south of Minnesota, the covered lagoon option was not evaluated for economic feasibility. Of the plug flow and CSTR reactor designs, the Continuously-Stirred Tank Reactor design tends to involve higher capital and operating costs and is associated with larger threshold herd sizes. For this reason, we restrict our analysis to the plug flow design, the most economically promising design that can be evaluated using FarmWare. The slurry loop design, it might be noted, cannot be evaluated using the FarmWare model without substantial modifications.

We evaluate the feasibility of digestion at dairy feedlots with free stall housing, flush manure collection systems for the milking parlor and feed apron (or simply the milking parlor) and mechanical scraping for the remainder of the feedlot. Complete flush systems generally are not used in Minnesota due to cold winters. Digestion is also evaluated for dairies with tie stall housing, flush systems of manure collection for the milking parlor, and mechanical scraping of manure for the remainder of the feedlot.

For swine, it is possible with FarmWare to evaluate viability of digester deployments at different herd sizes using either the CSTR reactor design and covered anaerobic lagoon design. It is not possible to evaluate, for instance, any of the second and third reactors types discussed above. For reasons noted above with regard to anaerobic lagoons, we evaluate feasibility of swine manure digestion using the CSTR reactor design.

With regard to prevailing manure management and storage practices, for reasons discussed above, we restrict the analysis of the economic feasibility of swine manure digestion to feedlots that manage manure using slotted floors and storage below barn in deep pits.

Regarding the approach taken in this study, economic feasibility is evaluated as a size-dependent condition. For each feedlot type, the minimum feedlot size necessary for economically viable deployments of anaerobic digestion is determined. This is done by sequentially testing different feedlot sizes for economic viability at internal rate of return hurdles of 10 and 14%. This follows the approach taken in USEPA (1999) Due to the large number of candidate feedlot configurations, an initial screening of viability was done using FarmWare default values and related values. Minimum feedlot size for economic viability is compared to maximum feedlot sizes found in Minnesota. For those feedlot types for which there appeared to be a basis for economic viability in the initial screening, a second more refined evaluation was conducted. This involved more realistic treatment of farm electric rates, electric buyback rates, and net energy considerations.

Extensive sensitivity analysis is done for digester applications at dairy feedlots to determine the lower limit of herd size for economic viability. The evaluation was done across a range of housing types and manure management practices. For swine, an extensive evaluation is conducted of the economic prospects of swine finishing operations across a range of different assumptions. This is in addition to the screening evaluation. This is performed to determine whether in fact the screening evaluation was an adequate tool for use in evaluating the economic feasibility of different classes of swine operations.

For those feedlot types for which minimum feedlot sizes for viability were found in the screening analysis to exceed the largest feedlot sizes found in Minnesota, the evaluation is terminated with the screening evaluation.

The sources of the most significant parameter estimates that were used as inputs in the initial screening are shown in Table 73.

Numerical estimates of alternative parameter estimates, along with the default estimates, again for the more important model inputs for the economic analysis, are shown in Table 74. Of particular important are: the discount rate, loan rate, manure total solids, current agricultural electric rate, utility electricity buyback rate, digester biogas productivity, and assumptions made about early credits salability and value.

Table 73. Sources for Parameter Estimates Used in Default Screening in This Study

Parameter	Source for Default Screening Value	Description
Animal Train-Dairy	FarmWare Generated Default	Idealized Train
Animal Train-Swine	All Ranges Evaluated	
Animal Size	FarmWare Generated Default	Various
Production VS per lb. animal liveweight	FarmWare Generated Default	
Level of Confinement	FarmWare Generated Default	Total
Manure Total Solids in Storage	FarmWare Generated Default	14% dairy, 2% swine
Digester Type-Dairy	Specified	Plug Flow
Digester Type-Swine	FarmWare Generated Default	CSTR
Digester Size and Design	FarmWare Generated Default	
Digester Capital Cost	FarmWare Generated Default	
Digester Operating Cost	FarmWare Generated Default	
Biogas Productivity	FarmWare Generated Default	6 ft^3/lb VS
Digester Parasitic Energy Use	FarmWare Generated Default	26.7% of biogas
On-Farm Electrical Load	FarmWare Generated Default	
Farm Electricity Rates	FarmWare Generated Default	$0.06/kwh
Method for Depreciating Capital	FarmWare Generated Default	Straight Line
Government Financial Assistance	Specified	Various
Loan and Inflation Rate	Specified	8% (loan) 3% (inflation)
Internal Rate of Return Hurdle	Specified	10-14%

Source: USEPA 1997

Of the default parameter estimates listed in Table 74 and used in the screening evaluation, in the choice of these parameters we depart from the FarmWare default values solely in the case of agricultural loan rate, the background rate of inflation, and the choice of discount rate. Loan and interest rate values were chosen to reflect mid-1990s conditions. With regard to the project discount rate, we employ a range of 10 to 14%, which reflects the average rate of return for the larger stock market from the early 1980s to the present and the early 1990s to the present, respectively.

Of parameter estimates used in the post-screening evaluation of feasibility, of particular interest are digester net energy/parasitic digester energy use, digester biogas productivity, and agricultural electric rates and buyback rates for electric utility purchases of farm-produced electricity. Also important are assumptions made about the value and salability of credits for early greenhouse gas reductions and the value of co-products produced from the digester effluent.

Table 74. Significant Parameter Estimates Used in this Study

Parameter	**Default Value**	**Alternative Values**
Animal liveweight, dairy (lb./head)	1,400	1,100-1,500
Animal liveweight, finishing swine (lb./head)	180	120-150
Animal liveweight, sows (lb./head)	400	
Biogas Productivity (ft^3/lb VS)	6	4-7
Manure Total Solids in Storage -Dairy (%)	14	8-14
Manure Total Solids in Storage -Swine (%)	2	1-6
Digester Parasitic Energy Use (% of digester biogas)	26.7	25 to >100
Inflation Rate (%)	3	1-5
Loan Rate (%)	8	7-10
Farm Electric Rate ($/kWh)	0.06	0.04-0.08
Internal Rate of Return Hurdle	10-14%	10-17
Offsets Assumptions		
Odor Control Benefits ($/head)	None	$0.25
Buy-back Price of Electricity ($/kWh)	$0.015	$0.015-0.04
Type of Power Sales	Baseload	partial peak load
Bedding and Other Co-products Benefits	None	$5,000 per year per dairy operation
GWP for CH4	21	15-25

Sources: USEPA 1997 and Part 1 above of this report

In the technical description of digestion above in Part 1, it was noted that digester net energy and digester parasitic energy use is closely related to the total solids content of the influent manure. At total solids contents of 8% or more, digester parasitic energy use is typically about 25%, and digester net energy production is strongly positive. At a total solids manure content of 1.5 to 3%, digester net energy production is negative or almost negative. The FarmWare evaluative software calculates parasitic digester energy use for heating based on a constant 26.7% rate of consumption of digester biogas, irrespective of influent total solids. To account for the effects of varying total solids of influent manure in the post-screening evaluation, it was necessary to adjust downward the amount of waste available at low manure total solids to satisfy farm space heating needs.

Dairy manure managed in a slurry form tends to have total solids in the 8 to 14% range, swine manure managed in below barn pits, total solids in the 1.5-3% range.

Agricultural electric rates across Minnesota vary from $0.04 to $0.08/kwh. Mean agricultural rates in Minnesota weighted to account for the distribution of livestock populations across different electrical cooperatives are $0.07/kwh for both dairy and swine. This is the value that we use in the post-screening evaluation of feasibility. However, it is important to note that the use of a single weighted average for the state for purposes of evaluation probably acts to understate the economic feasibility of digester applications at small feedlot sizes in high electricity-cost counties of Minnesota, and to overstate feasibility at large feedlot sizes in low-cost counties. As noted in the technical description of digestion, a retail agricultural electric rate of $0.06/kwh is often used as a minimum requirement for digester economic feasibility.

No energy demand charge was factored into the calculation, similar to the approach taken in USEPA (1999). For purposes of simplicity, the economic issue is envisioned as one of benefits derived from and in relation to **new** costs. The focus of the decision at hand is whether to incur **new** costs. The decision rule is that **new** expenses are incurred if, through new expenditures, a satisfactory return on those new expenditures is earned in the form of return to investment.

Default biogas productivity in the FarmWare decision support model is 6 ft^3 per lb. volatile solids. This is a reasonable approximation for digester productivity with plug flow reactors utilizing dairy manure and fresh swine manure in CSTRs. With aged manure, which might be found in those below barn pits used simultaneously to collect fresh manure and to store digested manure effluent, this value is likely to be somewhat lower.

The FarmWare default value for the sale price per kWh of on-farm generated electricity is $0.015/kwh. Since most utility purchases of electricity generated using renewable sources of energy are at rates that are substantially higher than this, in the screening evaluation we utilize sale prices of $0.015 to $0.04/kwh to evaluate economic feasibility.

No value was ascribed in the evaluation of economic feasibility to co-product sales or the use of digester solids for bedding, or for odor control, after USEPA (1999). Likewise, no value was ascribed to the distributed generation benefits to the electrical grid of farm-based anaerobic digestion. Some analysis suggests that these benefits annually could total $500 to 800 per kW of generation capacity installed. (Lusk 1998)

Lastly, due to changes in the nondigester parts of the manure management system that have to be made to accommodate digestion, the economic evaluation of the deployment of anaerobic digesters is limited to new feedlots or expansions at existing feedlots. This is due to the economics of anaerobic digestion, which will not easily accommodate extra costs of retrofits to the long-term manure storage pits, ponds and tanks and animal housing facilities.[7] This requires that future trends in herd sizes be forecasted to determine economic feasibility against the likely expected population of feedlots in Minnesota 5 to 10 years in the future.

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[7] If budgeted as part of an expansion that will take place anyway, regardless of the deployment of anaerobic digestion, these costs need not be included in the costs of digestion.

Dairy Assessment

Size thresholds for economic feasibility in the dairy sector are shown in Tables 75 to 100 for two different housing configurations and two different manure handling systems. The results of the evaluation of free stall dairies using flush systems for milking parlors and feed aprons and scraping for the remainder of the feedlot are shown in Tables 75 to 83. Tables 84 to 91 have results for of free stall dairies employing flush systems for the milking parlor only (with the remainder scraped). The results for dairies that utilize tie stall housing are presented in Tables 92 to 99. Included in the initial two tables of each set are the results for the initial screening evaluation at 10 and 14% project discount rates. Following these are results using farm electric rates that are more representative of the average Minnesota condition than the FarmWare default values, a range of prices for electricity sold for resale to electricity retailers of $0.015 to $0.04/kwh, and two different discount rates (10 and 14%). As of December 1998, the largest dairy feedlot in Minnesota had a permitted capacity of 1,500 head of milk cows.

Table 75. Threshold Herd Size for Dairy Operations for Economically Viable Deployment of Anaerobic Digesters: Free Stall, Flush Parlor and Feed Apron and Scrape Rest, $0.06/kwh Farm Electric Rates, $0.015 Electricity Sale Price to the Grid, 14% Internal Rate of Return Hurdle

	Credits for Early Reductions in $ per CO_2-Equivalent Tons		
	$0/ton	**$1/ton**	**$5/ton**
Base Case	1150	1050	800
Policy Cases			
Energy Production Subsidy			
$0.015/kwh subsidy	450	450	400
Interest Rate Buydowns			
2% interest buydown	950	850	650
4% interest buydown	800	750	550
8% interest buydown	550	550	450
Grants for Capital Costs			
$25,000 capital cost subsidy	850	700	550
$15,000 capital cost subsidy	850	850	600
Sales Tax Exemption	1050	1000	750

Table 76. Threshold Herd Size for Dairy Operations for Economically Viable Deployment of Anaerobic Digesters: Free Stall, Flush Parlor and Feed Apron and Scrape Rest, $0.06/kwh Farm Electric Rates, $0.015 Electricity Sale Price to the Grid, 10% Internal Rate of Return Hurdle

	Credits for Early Reductions in \$ per CO_2-Equivalent Tons		
	\$0/ton	**\$1/ton**	**\$5/ton**
Base Case	1050	950	700
Policy Cases			
Energy Production Subsidy			
$0.015/kwh subsidy	450	400	350
Interest Rate Buydowns			
2% interest buydown	850	800	600
4% interest buydown	700	650	500
8% interest buydown	500	500	400
Grants for Capital Costs			
$25,000 capital cost subsidy	700	650	500
$15,000 capital cost subsidy	850	800	600
Sales Tax Exemption	1000	950	700

The results from the screening evaluation for of free stall dairies using flush systems for milking parlors and feed aprons and scraping for the remainder of the feedlot are shown below in Tables 75 and 76. Under market conditions, according to the assessment, deployment of anaerobic digestion at dairies of 1,050 to 1,150 cows or greater would be economically feasible. With policy intervention, and without any credit for early greenhouse gas reductions, the threshold for economically feasible deployment of anaerobic digestion is estimated to be between 450 and 1,050 dairy cows. With early credits and various policy interventions, the threshold is estimated at between 350 and 1,000 dairy cows.

Tables 77 to 83 contain results for post-screening secondary evaluation of free stall dairies using flush systems for milking parlors and feed aprons and scraping for the remainder of the feedlot. Under this realistic evaluation, under market conditions, assuming no credit for greenhouse gas reductions, the minimum herd size for economic feasibility is estimated to be 650 to 700 milking cows. With policy intervention, the minimum herd size that is required for the economically viable digester deployment is estimated to be some 350 to 650 milking cows. With both credits for early greenhouse gas reductions and policy intervention, the minimum herd size is also estimated to be 350 to 650 lactating cows.

Table 77. Threshold Herd Size for Dairy Operations for Economically Viable Deployment of Anaerobic Digesters: Free Stall, Flush Parlor and Feed Apron and Scrape Rest, $0.07/kwh Farm Electric Rates, $0.015 Electricity Sale Price to the Grid, 14% Internal Rate of Return Hurdle

	Credits for Early Reductions in $ per CO_2-Equivalent Tons		
	$0/ton	**$1/ton**	**$5/ton**
Base Case	700	650	550
Policy Cases			
Energy Production Subsidy			
$0.015/kwh subsidy	350	350	300
Interest Rate Buydowns			
2% interest buydown	600	550	450
4% interest buydown	500	450	400
8% interest buydown	400	400	350
Grants for Capital Costs			
$25,000 capital cost subsidy	500	450	400
$15,000 capital cost subsidy	600	500	450
Sales Tax Exemption	650	650	500

Table 78. Threshold Herd Size for Dairy Operations for Economically Viable Deployment of Anaerobic Digesters: Free Stall, Flush Parlor and Feed Apron and Scrape Rest, $0.07/kwh Farm Electric Rates, $0.0275 Electricity Sale Price to the Grid, 14% Internal Rate of Return Hurdle

	Credits for Early Reductions in $ per CO_2-Equivalent Tons		
	$0/ton	**$1/ton**	**$5/ton**
Base Case	700	650	550
Policy Cases			
Energy Production Subsidy			
$0.015/kwh subsidy	350	350	300
Interest Rate Buydowns			
2% interest buydown	600	500	450
4% interest buydown	500	450	400
8% interest buydown	400	400	350
Grants for Capital Costs			
$25,000 capital cost subsidy	500	450	400
$15,000 capital cost subsidy	600	500	450
Sales Tax Exemption	650	650	500

Table 79. Threshold Herd Size for Dairy Operations for Economically Viable Deployment of Anaerobic Digesters: Free Stall, Flush Parlor and Feed Apron and Scrape Rest, $0.07/kwh Farm Electric Rates, $0.04 Electricity Sale Price to the Grid, 14% Internal Rate of Return Hurdle

	Credits for Early Reductions in $ per CO_2-Equivalent Tons			
	$0/ton	**$1/ton**	**$5/ton**	**$10/ton**
Base Case	700	650	550	450
Policy Cases				
Energy Production Subsidy				
$0.015/kwh subsidy	350	350	300	300
Interest Rate Buydowns				
2% interest buydown	600	550	450	400
4% interest buydown	500	450	400	350
8% interest buydown	400	400	350	300
Grants for Capital Costs				
$25,000 capital cost subsidy	450	450	400	350
$15,000 capital cost subsidy	600	500	450	350
Sales Tax Exemption	650	650	500	450

Table 82 contains results for post-screening secondary evaluation of free stall dairies using flush systems for milking parlors and feed aprons and scraping for the remainder of the feedlot for a 10% project discount rate and $0.07/kwh farm electric rates and a wider range of credit for the early reduction of greenhouse gas emissions. At $5 to $10 per CO_2-equivalent ton of emissions avoided ($18 to $36 per ton of carbon-equivalent), the threshold for economic feasibility is estimated at between 400 and 500 milking cows. With policy intervention, this declines to 300 to 400 lactating cows.

Table 83 shows the results of additional sensitivity analyses for free stall dairies using flush systems for milking parlors and feed aprons and scraping for the remainder of the feedlot. These results assume market conditions with no governmental intervention to improve digester feasibility. With no credit for early reductions of greenhouse gas emissions, the minimum herd size for economic feasibility is estimated to be between 400 and 500 milking cows. With credits for early reductions, this threshold is near 300 to 400 cows.

Table 80. Threshold Herd Size for Dairy Operations for Economically Viable Deployment of Anaerobic Digesters: Free Stall, Flush Parlor and Feed Apron and Scrape Rest, $0.07/kwh Farm Electric Rates, $0.015 Electricity Sale Price to the Grid, 10% Internal Rate of Return Hurdle

	Credits for Early Reductions in $ per CO_2-Equivalent Tons		
	$0/ton	**$1/ton**	**$5/ton**
Base Case	650	600	500
Policy Cases			
Energy Production Subsidy			
$0.015/kwh subsidy	350	350	300
Interest Rate Buydowns			
2% interest buydown	550	500	450
4% interest buydown	500	450	400
8% interest buydown	350	350	300
Grants for Capital Costs			
$25,000 capital cost subsidy	450	400	350
$15,000 capital cost subsidy	550	500	400
Sales Tax Exemption	600	550	450

Table 81. Threshold Herd Size for Dairy Operations for Economically Viable Deployment of Anaerobic Digesters: Free Stall, Flush Parlor and Feed Apron and Scrape Rest, $0.07/kwh Farm Electric Rates, $0.0275 Electricity Sale Price to the Grid, 10% Internal Rate of Return Hurdle

	Credits for Early Reductions in $ per CO_2-Equivalent Tons		
	$0/ton	**$1/ton**	**$5/ton**
Base Case	650	600	500
Policy Cases			
Energy Production Subsidy			
$0.015/kwh subsidy	350	350	300
Interest Rate Buydowns			
2% interest buydown	550	500	450
4% interest buydown	500	450	400
8% interest buydown	350	350	300
Grants for Capital Costs			
$25,000 capital cost subsidy	450	400	350
$15,000 capital cost subsidy	550	500	400
Sales Tax Exemption	600	550	450

Table 82. Threshold Herd Size for Dairy Operations for Economically Viable Deployment of Anaerobic Digesters: Free Stall, Flush Parlor and Feed Apron and Scrape Rest, $0.07/kwh Farm Electric Rates, $0.04 Electricity Sale Price to the Grid, 10% Internal Rate of Return Hurdle

	Credits for Early Reductions in \$ per CO_2-Equivalent Tons			
	$0/ton	**$1/ton**	**$5/ton**	**$10/ton**
Base Case	650	600	500	400
Policy Cases				
Energy Production Subsidy				
$0.015/kwh subsidy	350	350	300	300
Interest Rate Buydowns				
2% interest buydown	550	500	450	350
4% interest buydown	450	450	400	300
8% interest buydown	350	350	300	250
Grants for Capital Costs				
$25,000 capital cost subsidy	450	400	350	300
$15,000 capital cost subsidy	500	500	400	350
Sales Tax Exemption	600	550	450	400

Table 83. Sensitivity Analysis for Dairy Digesters: Threshold Herd Size, Free Stall, Flush Parlor and Feed Apron and Scrape Rest, Base Case, $0.07/kwh Farm Electric Rates, $0.04 Electricity Sale Price to the Grid, 10% Internal Rate of Return Hurdle

	Credits for Early Reductions in \$ per CO_2-Equivalent Tons			
	$0/ton	**$1/ton**	**$5/ton**	**$10/ton**
Project Life (12 years)	400	400	350	350
Reduced capital cost (-$25,000)	450	400	350	300
Buyback rate ($0.055/kwh)	400	350	300	250
Agricultural electric rates ($0.08/kwh)	400	350	300	250
Higher biogas production rate (B_0=7)	450	450	350	300
Discount rate (8%)	500	450	400	350

Tables 84 to 91 include parallel results for free stall feedlots using flush systems for the milking parlor and with scraping for the remainder of the feedlot. For all cases except tax credits for renewable energy productions, herd thresholds for this housing and manure management combination are above 1,500 cows. With subsidies, however, herd thresholds for economic viability are estimated to be about 500 milking cows.

Table 84. Threshold Herd Size for Dairy Operations for Economically Viable Deployment of Anaerobic Digesters: Free Stall, Flush Parlor and Scrape Rest, $0.06/kwh Farm Electric Rates, $0.015 Electricity Sale Price to the Grid, 14% Internal Rate of Return Hurdle

	Credits for Early Reductions in $ per CO_2-Equivalent Tons		
	$0/ton	**$1/ton**	**$5/ton**
Base Case	>1500	>1500	>1500
Policy Cases			
Energy Production Subsidy			
$0.015/kwh subsidy	500	450	400
Interest Rate Buydowns			
2% interest buydown	>1500	>1500	>1500
4% interest buydown	>1500	>1500	1500
8% interest buydown	>1500	1500	750
Grants for Capital Costs			
$25,000 capital cost subsidy	>1500	>1500	>1500
$15,000 capital cost subsidy	>1500	>1500	>1500
Sales Tax Exemption	>1500	>1500	>1500

Table 85. Threshold Herd Size for Dairy Operations for Economically Viable Deployment of Anaerobic Digesters: Free Stall, Flush Parlor and Scrape Rest, $0.06/kwh Farm Electric Rates, $0.015 Electricity Sale Price to the Grid, 10% Internal Rate of Return Hurdle

	Credits for Early Reductions in $ per CO_2-Equivalent Tons		
	$0/ton	**$1/ton**	**$5/ton**
Base Case	>1500	>1500	>1500
Policy Cases			
Energy Production Subsidy			
$0.015/kwh subsidy	500	450	350
Interest Rate Buydowns			
2% interest buydown	>1500	>1500	>1500
4% interest buydown	>1500	>1500	1250
8% interest buydown	>1500	1500	600
Grants for Capital Costs			
$25,000 capital cost subsidy	>1500	>1500	>1500
$15,000 capital cost subsidy	>1500	>1500	>1500
Sales Tax Exemption	>1500	>1500	>1500

Tables 86 to 91 include results for the screening evaluation for free stall feedlots using flush systems for the milking parlor and scraping for the remainder of the feedlot. Under market conditions, and assuming no credit for early reductions of greenhouse gas emissions, the threshold herd size for economic viability of digestion is estimated to be from 900 to greater than 1,500 milking cows. With policy interventions, this range declines to 300 to greater than 1,500 milking cows. At the most realistic prices for the utility purchase of farm-generated electricity--$0.0275 to $0.04 per kWh—and the most aggressive policy interventions, herd size thresholds fall into the 300 to 1000 milking cow range. At high levels of credit for early greenhouse gas reductions, threshold herd sizes are estimated at 200 to 400 lactating cows.

Table 86. Threshold Herd Size for Dairy Operations for Economically Viable Deployment of Anaerobic Digesters: Free Stall, Flush Parlor and Scrape Rest, $0.07/kwh Farm Electric Rates, $0.015 Electricity Sale Price to the Grid, 14% Internal Rate of Return Hurdle

	Credits for Early Reductions in $ per CO_2-Equivalent Tons		
	$0/ton	**$1/ton**	**$5/ton**
Base Case	>1500	>1500	1500
Policy Cases			
<u>Energy Production Subsidy</u>			
$0.015/kwh subsidy	400	400	300
<u>Interest Rate Buydowns</u>			
2% interest buydown	>1500	>1500	1050
4% interest buydown	>1500	>1500	600
8% interest buydown	1050	850	400
<u>Grants for Capital Costs</u>			
$25,000 capital cost subsidy	>1500	>1500	1000
$15,000 capital cost subsidy	>1500	>1500	1200
<u>Sales Tax Exemption</u>	>1500	>1500	1300

Table 87. Threshold Herd Size for Dairy Operations for Economically Viable Deployment of Anaerobic Digesters: Free Stall, Flush Parlor and Scrape Rest, $0.07/kwh Farm Electric Rates, $0.0275 Electricity Sale Price to the Grid, 14% Internal Rate of Return Hurdle

	Credits for Early Reductions in $ per CO_2-Equivalent Tons		
	$0/ton	**$1/ton**	**$5/ton**
Base Case	>1500	1500	800
Policy Cases			
<u>Energy Production Subsidy</u>			
$0.015/kwh subsidy	400	1100	600
<u>Interest Rate Buydowns</u>			
2% interest buydown	1300	1100	600
4% interest buydown	900	800	500
8% interest buydown	550	450	300
<u>Grants for Capital Costs</u>			
$25,000 capital cost subsidy	1450	1100	500
$15,000 capital cost subsidy	>1500	1300	650
<u>Sales Tax Exemption</u>	>1500	1350	700

Table 88. Threshold Herd Size for Dairy Operations for Economically Viable Deployment of Anaerobic Digesters: Free Stall, Flush Parlor and Scrape Rest, $0.07/kwh Farm Electric Rates, $0.04 Electricity Sale Price to the Grid, 14% Internal Rate of Return Hurdle

	Credits for Early Reductions in $ per CO_2-Equivalent Tons			
	$0/ton	**$1/ton**	**$5/ton**	**$10/ton**
Base Case	950	900	550	400
Policy Cases				
Energy Production Subsidy				
$0.015/kwh subsidy	300	300	250	200
Interest Rate Buydown				
2% interest buydown	750	650	450	350
4% interest buydown	550	500	350	300
8% interest buydown	400	350	250	200
Grants for Capital Costs				
$25,000 capital cost subsidy	650	550	350	250
$15,000 capital cost subsidy	800	650	450	300
Sales Tax Exemption	850	750	500	350

Table 89. Threshold Herd Size for Dairy Operations for Economically Viable Deployment of Anaerobic Digesters: Free Stall, Flush Parlor and Scrape Rest, $0.07/kwh Farm Electric Rates, $0.015 Electricity Sale Price to the Grid, 10% Internal Rate of Return Hurdle

	Credits for Early Reductions in $ per CO_2-Equivalent Tons		
	$0/ton	**$1/ton**	**$5/ton**
Base Case	>1500	>1500	1300
Policy Cases			
Energy Production Subsidy			
$0.015/kwh subsidy	350	350	250
Interest Rate Buydowns			
2% interest buydown	>1500	>1500	850
4% interest buydown	>1500	>1500	600
8% interest buydown	750	600	350
Grants for Capital Costs			
$25,000 capital cost subsidy	>1500	>1500	800
$15,000 capital cost subsidy	>1500	>1500	1050
Sales Tax Exemption	>1500	>1500	1050

Table 90. Threshold Herd Size for Dairy Operations for Economically Viable Deployment of Anaerobic Digesters: Free Stall, Flush Parlor and Scrape Rest, $0.07/kwh Farm Electric Rates, $0.0275 Electricity Sale Price to the Grid, 10% Internal Rate of Return Hurdle

	Credits for Early Reductions in $ per CO_2-Equivalent Tons		
	$0/ton	**$1/ton**	**$5/ton**
Base Case	>1500	1300	700
Policy Cases			
Energy Production Subsidy			
$0.015/kwh subsidy	300	300	250
Interest Rate Buydowns			
2% interest buydown	1100	900	550
4% interest buydown	750	650	400
8% interest buydown	450	400	300
Grants for Capital Costs			
$25,000 capital cost subsidy	1100	850	450
$15,000 capital cost subsidy	>1500	1050	550
Sales Tax Exemption	>1500	1100	600

Table 91. Threshold Herd Size for Dairy Operations for Economically Viable Deployment of Anaerobic Digesters: Free Stall, Flush Parlor and Scrape Rest, $0.07/kwh Farm Electric Rates, $0.04 Electricity Sale Price to the Grid, 10% Internal Rate of Return Hurdle

	Credits for Early Reductions in $ per CO_2-Equivalent Tons			
	$0/ton	**$1/ton**	**$5/ton**	**$10/ton**
Base Case	800	750	500	350
Policy Cases				
Energy Production Subsidy				
$0.015/kwh subsidy	250	250	200	200
Interest Rate Buydown				
2% interest buydown	650	550	400	300
4% interest buydown	500	450	350	250
8% interest buydown	350	300	250	200
Grants for Capital Costs				
$25,000 capital cost subsidy	550	500	300	250
$15,000 capital cost subsidy	650	600	400	300
Sales Tax Exemption	750	700	450	350

Tables 92 to 93 include parallel results for tie stall feedlots using flush systems for the milking parlor and with scraping for the remainder of the feedlot. For all cases except tax credits for renewable energy productions, herd thresholds for this housing and manure management combination are above 1,500 cows. With subsidies, however, herd thresholds for economic viability are estimated to be about 500 milking cows.

Table 92. Threshold Herd Size for Dairy Operations for Economically Viable Deployment of Anaerobic Digesters: Tie Stall, Flush Parlor and Scrape Rest, $0.06/kwh Farm Electric Rates, $0.015 Electricity Sale Price to the Grid, 14% Internal Rate of Return Hurdle

	Credits for Early Reductions in $ per CO_2-Equivalent Tons		
	$0/ton	**$1/ton**	**$5/ton**
Base Case	>1500	>1500	>1500
Policy Cases			
Energy Production Subsidy			
$0.015/kwh subsidy	550	500	350
Interest Rate Buydowns			
2% interest buydown	>1500	>1500	>1500
4% interest buydown	>1500	>1500	>1500
8% interest buydown	>1500	>1500	650
Grants for Capital Costs			
$25,000 capital cost subsidy	>1500	>1500	>1500
$15,000 capital cost subsidy	>1500	>1500	>1500
Sales Tax Exemption	>1500	>1500	>1500

Table 93. Threshold Herd Size for Dairy Operations for Economically Viable Deployment of Anaerobic Digesters: Tie Stall, Flush Parlor and Scrape Rest, \$0.06/kwh Farm Electric Rates, \$0.015 Electricity Sale Price to the Grid, 10% Internal Rate of Return Hurdle

	Credits for Early Reductions in \$ per CO_2-Equivalent Tons		
	\$0/ton	**\$1/ton**	**\$5/ton**
Base Case	>1500	>1500	>1500
Policy Cases			
Energy Production Subsidy			
\$0.015/kwh subsidy	500	450	350
Interest Rate Buydowns			
2% interest buydown	>1500	>1500	>1500
4% interest buydown	>1500	>1500	1200
8% interest buydown	>1500	1500	600
Grants for Capital Costs			
\$25,000 capital cost subsidy	>1500	>1500	>1500
\$15,000 capital cost subsidy	>1500	>1500	>1500
Sales Tax Exemption	>1500	>1500	>1500

Tables 94 to 99 include results for the post-screening evaluation for tie stall feedlots using flush systems for the milking parlor and scraping for the remainder of the feedlot. Under market conditions, and assuming no credit for early reductions of greenhouse gas emissions, the threshold herd size for economic viability of digestion is estimated to be from 900 to greater than 1,500 milking cows. With policy interventions, this range declines to 250 to greater than 1,500 milking cows. At the most realistic prices for the utility purchase of farm-generated electricity--\$0.0275 to \$0.04 per kWh—and the most aggressive policy interventions, herd size thresholds fall into the 300 to 1,300 milking cow range. At high levels of credit for early greenhouse gas reductions, threshold herd sizes are estimated at 150 to 350 lactating cows.

Table 94. Threshold Herd Size for Dairy Operations for Economically Viable Deployment of Anaerobic Digesters: Tie Stall, Flush Parlor and Scrape Rest, \$0.07/kwh Farm Electric Rates, \$0.015 Electricity Sale Price to the Grid, 14% Internal Rate of Return Hurdle

	Credits for Early Reductions in \$ per CO_2-Equivalent Tons		
	\$0/ton	**\$1/ton**	**\$5/ton**
Base Case	>1500	>1500	1450
Policy Cases			
Energy Production Subsidy			
\$0.015/kwh subsidy	400	350	300
Interest Rate Buydowns			
2% interest buydown	>1500	>1500	1000
4% interest buydown	>1500	>1500	700
8% interest buydown	1000	800	400
Grants for Capital Costs			
\$25,000 capital cost subsidy	>1500	>1500	1000
\$15,000 capital cost subsidy	>1500	>1500	1200
Sales tax Exemption	>1500	>1500	1300

Table 95. Threshold Herd Size for Dairy Operations for Economically Viable Deployment of Anaerobic Digesters: Tie Stall, Flush Parlor and Scrape Rest, \$0.07/kwh Farm Electric Rates, \$0.0275 Electricity Sale Price to the Grid, 14% Internal Rate of Return Hurdle

	Credits for Early Reductions in \$ per CO_2-Equivalent Tons		
	\$0/ton	**\$1/ton**	**\$5/ton**
Base Case	>1500	>1500	800
Policy Cases			
Energy Production Subsidy			
\$0.015/kwh subsidy	350	300	250
Interest Rate Buydowns			
2% interest buydown	1300	1050	650
4% interest buydown	900	800	500
8% interest buydown	550	450	300
Grants for Capital Costs			
\$25,000 capital cost subsidy	1350	1050	500
\$15,000 capital cost subsidy	>1500	1250	600
Sales tax Exemption	>1500	1350	700

Table 96. Threshold Herd Size for Dairy Operations for Economically Viable Deployment of Anaerobic Digesters: Tie Stall, Flush Parlor and Scrape Rest, $0.07/kwh Farm Electric Rates, $0.04 Electricity Sale Price to the Grid, 14% Internal Rate of Return Hurdle

	Credits for Early Reductions in $ per CO_2-Equivalent Tons			
	$0/ton	**$1/ton**	**$5/ton**	**$10/ton**
Base Case	900	800	500	350
Policy Cases				
Energy Production Subsidy				
$0.015/kwh subsidy	250	250	250	150
Interest Rate Buydown				
2% interest buydown	800	650	450	300
4% interest buydown	550	500	350	300
8% interest buydown	400	350	250	200
Grants for Capital Costs				
$25,000 capital cost subsidy	650	550	350	250
$15,000 capital cost subsidy	800	650	450	300
Sales Tax Exemption	850	750	500	350

Table 97. Threshold Herd Size for Dairy Operations for Economically Viable Deployment of Anaerobic Digesters: Tie Stall, Flush Parlor and Scrape Rest, $0.07/kwh Farm Electric Rates, $0.015 Electricity Sale Price to the Grid, 10% Internal Rate of Return Hurdle

	Credits for Early Reductions in $ per CO_2-Equivalent Tons		
	$0/ton	**$1/ton**	**$5/ton**
Base Case	>1500	>1500	1200
Policy Cases			
Energy Production Subsidy			
$0.015/kwh subsidy	350	350	250
Interest Rate Buydowns			
2% interest buydown	>1500	>1500	850
4% interest buydown	>1500	1300	600
8% interest buydown	700	600	350
Grants for Capital Costs			
$25,000 capital cost subsidy	>1500	>1500	750
$15,000 capital cost subsidy	>1500	>1500	950
Sales tax Exemption	>1500	>1500	1050

Table 98. Threshold Herd Size for Dairy Operations for Economically Viable Deployment of Anaerobic Digesters: Tie Stall, Flush Parlor and Scrape Rest, $0.07/kwh Farm Electric Rates, $0.0275 Electricity Sale Price to the Grid, 10% Internal Rate of Return Hurdle

	Credits for Early Reductions in $ per CO_2-Equivalent Tons		
	$0/ton	**$1/ton**	**$5/ton**
Base Case	>1500	1300	700
Policy Cases			
Energy Production Subsidy			
$0.015/kwh subsidy	300	300	250
Interest Rate Buydowns			
2% interest buydown	1050	900	550
4% interest buydown	750	650	400
8% interest buydown	450	400	300
Grants for Capital Costs			
$25,000 capital cost subsidy	1100	850	450
$15,000 capital cost subsidy	1300	1050	550
Sales tax Exemption	1350	1100	600

Table 99. Threshold Herd Size for Dairy Operations for Economically Viable Deployment of Anaerobic Digesters: Tie Stall, Flush Parlor and Scrape Rest, $0.06/kwh Farm Electric Rates, $0.04 Electricity Sale Price to the Grid, 10% Internal Rate of Return Hurdle

	Credits for Early Reductions in $ per CO_2-Equivalent Tons			
	$0/ton	**$1/ton**	**$5/ton**	**$10/ton**
Base Case	800	750	450	350
Policy Cases				
Energy Production Subsidy				
$0.015/kwh subsidy	250	250	200	200
Interest Rate Buydown				
2% interest buydown	650	550	400	300
4% interest buydown	500	450	350	250
8% interest buydown	350	300	250	200
Grants for Capital Costs				
$25,000 capital cost subsidy	550	500	300	250
$15,000 capital cost subsidy	650	600	400	300
Sales Tax Exemption	750	700	450	350

Conclusion

The economic feasibility of anaerobic digestion can be characterized in terms of minimum required feedlot herd size. For dairy feedlots, the minimum required herd size is estimated to range from 600 head of dairy cattle to greater than 1,500 head for purely market conditions. With policy intervention, depending on the particular measures chosen, the range broadens to 250 to greater than 1,500 head of milking cows. The calculation is sensitive to what is assumed about the discount rate, the purchase price of farm-based electricity by the electric utilities, and associated housing and manure collection systems.

Most newly constructed dairies employ free-stall housing. The marginal costs of electricity generated with new plants fall into the $0.04 to 0.055 per kWh range. Under current market conditions, the value of carbon credits is about $1 per ton CO_2-equivalent ($3 to 4 per metric ton of carbon-equivalent). Table 100 provides summary estimates for herd threshold size for these conditions. Without policy interventions, threshold herd size for economically viable deployment of anaerobic digestion is in the 600 to 900 cow range. With policy intervention, this declines up to about 250 to 350 cows. As noted above, between one-sixth and one-fifth of all dairy cows in Minnesota are presently in dairies with 250 head or more. At present trends, by 2008, this is likely to exceed one-half.

For the 600 to 900 cow threshold (no policy intervention), about 5 percent of all Minnesota cows are in dairies of or greater than this size limit. A reasonable guess is that this will triple by 2008.

It is also possible that, with a slightly more optimistic appraisal of project lifetime (13 years), project discount rate, or sale price of farm-generated electricity to the grid, minimum herd size thresholds for feasibility even under market conditions could be as low as 350 to 450 head.

The potential for near-term (5 to 10 years) deployment of anaerobic digestion is best approximated by the amount of new construction at Minnesota dairies at herd sizes exceeding the size limits discussed just above. Much of the herd expansion likely in the 250 to 900 head class of dairy feedlots is likely to involve new construction.

Given this, and given the range of parameters tested, we can reasonably conclude that between 10 and 50 percent of the dairy inventory is or, within little more than half a decade, will be in feedlots large enough to economically support anaerobic digestion as a manure management practice. Values in the middle or at the higher end of this range presuppose public intervention in the market to lower capital costs or boost operating revenue. Lacking public intervention, and given the rate of consolidation in the industry, over the short-term, out to 2008, anaerobic digestion may be feasible at feedlots accounting for roughly 10 percent of the Minnesota dairy cow inventory. This would be accompanied by a parallel 10 percent reduction in the emission to the atmosphere of CH_4.

Table 100. Summary of Threshold Herd Size for New Dairies with Free Stall Housing and $0.04/kwh Electricity Buyback Rate

	Threshold Herd Size
Base Case[a]	
Flush Parlor and Feed Apron	650 to 700
Flush Parlor	800 to 950
Base Case with Early Credits[b]	
Flush Parlor and Feed Apron	600 to 650[c]
Flush Parlor	750 to 900[c]
Policy Intervention[d]	
Flush Parlor and Feed Apron	350
Flush Parlor	250 to 300

[a] $0.04/kwh electric utility buyback rate and no early credit value
[b] $0.04/kwh buyback rate and $1 per CO_2-equivalent per ton credit for early action
[c] 500 to 550 cow threshold at $5 per ton credit for early action
[d] $0.015 per kwh tax incentive (most aggressive action evaluated)

Swine Assessment

Size thresholds for economic feasibility in the swine sector are shown in Tables 101 to 118 for seven different production systems. Analysis was performed for: finishing, nursing pig-finishing, nursing pig, farrow-to-nursing pig, farrow-to-wean, farrow-to-finish, and farrow-and-finish systems. For each production system, below barn pit storage is assumed for manure management.

An extensive evaluation is conducted of the economic prospects of swine finishing operations across a range of different assumptions. This is in addition to the screening evaluation. This is performed to determine whether in fact the screening evaluation was an adequate tool for use in evaluating the economic feasibility of different classes of swine operations.

For the remaining system, assessment was limited to an initial screening analysis. None of these systems evinced evidence of economic feasibility over the range of feedlot size typically found in Minnesota for these production types.

Finishing Swine Assessment

Size thresholds for economic feasibility for finishing hog operations are shown in Tables 101 to 108. As noted above, the analysis is limited to finishing operations that utilize below barn pit storage of manure. The animal train for finishing operations assumes 47% to 53% split in hog populations at each finishing feedlot between growers (50 to 100 lb.) and finishing hogs (100 to 250 lb.). Specific information on hog sizes for hogs larger than 50 lb. is lacking in the Minnesota feedlot permit registry system. The analysis assumes the deployment of continuously mixed tank reactors (CSTRs). The largest finishing hog feedlot in Minnesota in the inventory is permitted for 9,000 head of finishing hogs.

The sequence of analysis that is pursued is similar to that for dairy: an initial screening analysis followed by assessment using more realistic estimates for farm electric rates and selling price for farm-generated electricity to the grid. However, in addition, due to the large heating requirements of dilute manure, digestion on finishing feedlots is also evaluated using a more realistic treatment of digester net energy production. Lastly, feasibility is also evaluated at elevated levels of manure total solids.

The results of screening analysis for finishing hog operations are shown in Tables 101 and 102 for market conditions and seven policy cases, three different dollar values for early reduction credits, and two different discount rates. In almost every instance evaluated, the required herd or feedlot size was found to far exceed the largest feedlot size for finishing operations found in Minnesota. The sole exception was in the case of the very highest credit value for early greenhouse gas reductions ($5 per CO_2-equivalent ton or $18 per ton of carbon-equivalent) and the most aggressive policy interventions.

Table 101. Herd Size Thresholds for Swine Finishing Operations (Growing Pig Train Included) for Economically Viable Deployment of Anaerobic Digestion: $0.06/kwh Farm Electric Rates, $0.015 Electricity Sale Price to the Grid, Default Total Solids, 14% Internal Rate of Return Hurdle

	CO_2-Equivalent Emissions Reductions Early Credits		
	$0/ton	**$1/ton**	**$5/ton**
Base Case	>11,000	>11,000	>11,000
$0.015/kwh Subsidy	>11,000	>11,000	8,850
2% Interest Rate Buydown	>11,000	>11,000	>11,000
4% Interest Rate Buydown	>11,000	>11,000	>11,000
8% Interest Rate Buydown	>11,000	>11,000	8,150
$25,000 Grant for Capital Expenditures	>11,000	>11,000	>11,000
$15,000 Grant for Capital Expenditures	>11,000	>11,000	>11,000
Sales Tax Exemption	>11,000	>11,000	>11,000

Table 102. Herd Size Thresholds for Swine Finishing Operations (Growing Pig Train Included) for Economically Viable Deployment of Anaerobic Digestion: $0.06/kwh Farm Electric Rates, $0.015 Electricity Sale Price to the Grid, Default Total Solids, 10% Internal Rate of Return Hurdle

	CO_2-Equivalent Emissions Reductions Early Credits		
	$0/ton	**$1/ton**	**$5/ton**
Base Case	>11,000	>11,000	>11,000
$0.015/kwh Subsidy	>11,000	>11,000	7,650
2% Interest Rate Buydown	>11,000	>11,000	>11,000
4% Interest Rate Buydown	>11,000	>11,000	10,800
8% Interest Rate Buydown	>11,000	>11,000	6,550
$25,000 Grant for Capital Expenditures	>11,000	>11,000	>11,000
$15,000 Grant for Capital Expenditures	>11,000	>11,000	>11,000
Sales Tax Exemption	>11,000	>11,000	>11,000

As discussed above, a more realistic assessment would treat, in addition, the net energy implications of the digestion of very dilute manure. Tables 103 to 105 give the results of an assessment that considers these net energy implications. Three different cases are considered. Tables 103 and 104 treat feasibility for different discount rates and a $0.04 per kWh sale price of farm-generated electricity on to the grid. FarmWare default values are used for manure total solids and farm electric rates. Table 105 gives the results for analysis under the most optimistic combination of assessment parameters: 10% discount rate, $0.07 per kWh farm electric rates, and $0.04 per kWh sale price of farm-generated electricity.

In the case of every combination of parameters tested, a minimum feedlot size for economic feasibility was calculated that exceeded the maximum size of finishing swine operations in Minnesota.

In the calculations underlying the results given in Tables 103 to 105, net digester energy production is treated in an approximate way by assuming for a very dilute manure that all digester waste heat is necessary for digester heating.[8] Thus no space heating or water heating benefits are assumed in the calculation of economic feasibility. Based on the literature, for

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[8] In a more realistic treatment, digester net energy consumption and production would be explicitly modeled based on manure total solids content, waste retention time, reactor temperature, and waste volatile solids content. Also included would be the assumed digester biogas productivity and CH_4 content, any predigestion in the below barn pit, assumed heat exchanger efficiency, and pit manure and influent temperature. A seasonality component also should be included.

very dilute manure, one might expect digester heating needs that are equal to perhaps two-thirds to more than 100% of the biogas output of the digester (see the net energy productivity discussion in Part 1). This would leave between zero and one-third of the biogas for purposes other than digester heating. About one-quarter of the energy content of the biogas exits the system in the form of electricity. Inefficiencies in heat exchange at the barns and in water heating applications act to further erode whatever surplus, if any, is left.

Table 103. Herd Size Thresholds for Swine Finishing Operations (Growing Pig Train Included) for Economically Viable Deployment of Anaerobic Digestion: $0.06/kwh Farm Electric Rates, $0.04/kwh Electricity Sale Price to the Grid, Default Total Solids, Net Energy Accounted for, 14% Internal Rate of Return Hurdle

	CO_2-Equivalent Emissions Reductions Early Credits		
	$0/ton	**$1/ton**	**$5/ton**
Base Case	>11,000	>11,000	>11,000
$0.015/kwh Subsidy	>11,000	>11,000	>11,000
2% Interest Rate Buydown	>11,000	>11,000	>11,000
4% Interest Rate Buydown	>11,000	>11,000	>11,000
8% Interest Rate Buydown	>11,000	>11,000	>11,000
$25,000 Grant for Capital Expenditures	>11,000	>11,000	>11,000
$15,000 Grant for Capital Expenditures	>11,000	>11,000	>11,000
Sales Tax Exemption	>11,000	>11,000	>11,000

Table 104. Herd Size Thresholds for Swine Finishing Operations (Growing Pig Train Included) for Economically Viable Deployment of Anaerobic Digestion: $0.06/kwh Farm Electric Rates, $0.04/kwh Electricity Sale Price to the Grid, Default Total Solids, Net Energy Accounted for, 10% Internal Rate of Return Hurdle

	CO_2-Equivalent Emissions Reductions Early Credits		
	$0/ton	**$1/ton**	**$5/ton**
Base Case	>11,000	>11,000	>11,000
$0.015/kwh Subsidy	>11,000	>11,000	>11,000
2% Interest Rate Buydown	>11,000	>11,000	>11,000
4% Interest Rate Buydown	>11,000	>11,000	>11,000
8% Interest Rate Buydown	>11,000	>11,000	>11,000
$25,000 Grant for Capital Expenditures	>11,000	>11,000	>11,000
$15,000 Grant for Capital Expenditures	>11,000	>11,000	>11,000
Sales Tax Exemption	>11,000	>11,000	>11,000

Table 105. Herd Size Thresholds for Swine Finishing Operations (Growing Pig Train Included) for Economically Viable Deployment of Anaerobic Digestion: $0.07/kwh Farm Electric Rates, $0.04/kwh Electricity Sale Price to the Grid, Default Total Solids, Net Energy Accounted for, 10% Internal Rate of Return Hurdle

	CO_2-Equivalent Emissions Reductions Early Credits		
	$0/ton	**$1/ton**	**$5/ton**
Base Case	>11,000	>11,000	>11,000
$0.015/kwh Subsidy	>11,000	>11,000	>11,000
2% Interest Rate Buydown	>11,000	>11,000	>11,000
4% Interest Rate Buydown	>11,000	>11,000	>11,000
8% Interest Rate Buydown	>11,000	>11,000	>11,000
$25,000 Grant for Capital Expenditures	>11,000	>11,000	>11,000
$15,000 Grant for Capital Expenditures	>11,000	>11,000	>11,000
Sales Tax Exemption	>11,000	>11,000	>11,000

It is possible that, with intensified water management on the feedlot, a conscientious feedlot owner might be able to raise the total solids content of the influent manure. Tables 106 and 107 give the results of the evaluation using a 3 percent manure total solids content for pit-stored manure and two different project discount rates. For digester net energy production, we use the percentage estimates of Ghosh (1981), incorporating them using the approach outlined above. In the analysis for Table 106, we assume a $0.06/kwh farm electric rate, a $0.015/kwh electricity sale price to the electric grid, and a 14% internal rate of return hurdle. In the assessment that underlies the results given in Table 107, we raise the farm electric rate to $0.07 per kWh and the selling price for farm-generated electricity to $0.04 per kWh. A 10% discount rate is also assumed in this analysis.

As in the other results for finishing swine operations, there is little evidence in the results given in Tables 106 and 107 of economic feasibility. The sole exception was in the case of the very highest credit value for early greenhouse gas reductions ($5 per CO_2-equivalent ton or $18 per ton of carbon-equivalent) and the most aggressive policy interventions.

Table 106. Herd Size Thresholds for Swine Finishing Operations (Growing Pig Train Included) for Economically Viable Deployment of Anaerobic Digestion: $0.06/kwh Farm Electric Rates, $0.015/kwh Electricity Sale Price to the Grid, 3% Total Solids, Net Energy Accounted for, 14% Internal Rate of Return Hurdle

	CO_2-Equivalent Emissions Reductions Early Credits		
	$0/ton	**$1/ton**	**$5/ton**
Base Case	>11,000	>11,000	>11,000
$0.015/kwh Subsidy	>11,000	>11,000	>11,000
2% Interest Rate Buydown	>11,000	>11,000	>11,000
4% Interest Rate Buydown	>11,000	>11,000	>11,000
8% Interest Rate Buydown	>11,000	>11,000	>11,000
$25,000 Grant for Capital Expenditures	>11,000	>11,000	>11,000
$15,000 Grant for Capital Expenditures	>11,000	>11,000	>11,000
Sales Tax Exemption	>11,000	>11,000	>11,000

Table 107. Herd Size Thresholds for Swine Finishing Operations (Growing Pig Train Included) for Economically Viable Deployment of Anaerobic Digestion: $0.07/kwh Farm Electric Rates, $0.04/kwh Electricity Sale Price to the Grid, 3% Total Solids, Net Energy Accounted for, 10% Internal Rate of Return Hurdle

	CO_2-Equivalent Emissions Reductions Early Credits		
	$0/ton	**$1/ton**	**$5/ton**
Base Case	>11,000	>11,000	>11,000
$0.015/kwh Subsidy	>11,000	>11,000	9,850
2% Interest Rate Buydown	>11,000	>11,000	>11,000
4% Interest Rate Buydown	>11,000	>11,000	>11,000
8% Interest Rate Buydown	>11,000	>11,000	10,500
$25,000 Grant for Capital Expenditures	>11,000	>11,000	>11,000
$15,000 Grant for Capital Expenditures	>11,000	>11,000	>11,000
Sales Tax Exemption	>11,000	>11,000	>11,000

Table 108 completes the analysis given in Table 107 by incorporating higher feedlot operating costs. It is not known how much operating costs might rise as a result of heightened water management. Heightened water management might result in higher labor costs and added costs to reduce leakage from piping or below barn pit walls. For the purposes of calculation, we assume that heightened water management might double digester operating costs up to an extra $7,000 per year. In most instances, an additional $4,000 to 5,000 in operating costs was assumed. With the exception of high operating costs, the remainder of the analysis is identical to that underlying the analysis given in Table 107.

The results given in Table 108 are qualitatively similar to those given in Tables 101 through 107; calculated minimum herd size for finishing swine operations for economic feasibility exceed in every case tested the largest feedlot size currently found in the state of Minnesota.

Finally, also considered were 3% TS content and an alternative value for digester net energy productivity (25%). The results were similar to those shown in Table 108. Adding on to the capital cost total the costs associated with a second storage structure in addition to the below barn pit for the storage of digester effluent—a factor heretofore ignored--only renders the result more negative. [9]

Table 108. Herd Size Thresholds for Swine Finishing Operations (Growing Pig Train Included) for Economically Viable Deployment of Anaerobic Digestion: $0.07/kwh Farm Electric Rates, $0.04/kwh Electricity Sale Price to the Grid, 3% Total Solids, Increased Operating Costs for Intensified Water Management, Net Energy Accounted for, 10% Internal Rate of Return Hurdle

	CO_2-Equivalent Emissions Reductions Early Credits		
	$0/ton	**$1/ton**	**$5/ton**
Base Case	>11,000	>11,000	>11,000
$0.015/kwh Subsidy	>11,000	>11,000	>11,000
2% Interest Rate Buydown	>11,000	>11,000	>11,000
4% Interest Rate Buydown	>11,000	>11,000	>11,000
8% Interest Rate Buydown	>11,000	>11,000	>11,000
$25,000 Grant for Capital Expenditures	>11,000	>11,000	>11,000
$15,000 Grant for Capital Expenditures	>11,000	>11,000	>11,000
Sales Tax Exemption	>11,000	>11,000	>11,000

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[9] For feedlots that utilize below barn pit storage, a second storage structure in addition to the storage capacity of the below barn pit would be necessary to allow for six-month storage of digester effluent. Some swine farms that utilize below barn pits for manure storage are equipped with a second, preexisting outdoor storage structure. Many are not. Since construction of a second storage structure would involve extra costs above and beyond those incurred in meeting the minimum level of feedlot manure storage capacity for the purposes of environmental protection, they probably should be factored into the cost of the digester. None of the results given in Tables 101 to 108 account for the extra costs of a second on-farm pit or tank to store existing digester effluent.

The results of feasibility analysis for finishing operations comprised solely of finishing hogs with out growers are given in Appendix A1, tables a through f. In general, the deployment of anaerobic digestion at finishing feedlots of this type appears to possess better economics that grower-finisher finishing operations. However, as above, when an effort is made to account for the net energy implications of the digestion of dilute manure, little economic case can be made for digestion at swine finishing operations (see Appendix A1, Tables A1-b through A1-d and A1-f).

As discussed above, roughly half of all swine on Minnesota swine feedlots by liveweight are housed in finishing operations. This percentage is likely to continue to increase. Again, as noted above, in-shipments of feeder swine from other states to Minnesota finishing operations and nursery pig-to-finishing operations are increasing at an annual rate of about 30% per year, doubling every few years. These in-shipments of feeder pigs now constitute the single largest source of growth in the swine herd in Minnesota.

Economic Assessment of Nursery Pig-to-Finish Swine Operations

Size thresholds for nurse-finishing operations are shown in Table 109 for an initial screening evaluation. Parallel estimates for the seven policy cases are shown in Table 110. The results in Tables 109 and 110 assume a 14% discount rate. Additional screening results for a 10% discount rate are given in Appendix A2.

The analysis was conducted for different percentage distributions of finishing hogs to all feedlot animals (e.g., finishing hogs plus nursing pigs). 47% of all finishing hogs are assumed to be growing pigs, and 53% are assumed to be fully-grown finishing hogs. Due to constraints on the numbers of animals that can be evaluated using FarmWare, it was not possible to evaluate the 0 to 10% finisher and 90 to 100% nursery pig combination of animals. Feasibility was evaluated over the range of feedlot sizes for this type of operation found in Minnesota. The largest nursing pig/finishing hog operation in the feedlot inventory has a permitted capacity of 9,000 finishing hogs and growing pigs.

Based on Tables 109 and 110 and Appendix A-2, size thresholds for digester deployment at nursery pig-to-finish hog feedlots exceed 9,000 head of finishing hogs for the initial screening analysis under nearly all conditions. These exceed 9,000 head under market conditions, conditions of extensive governmental intervention either to lower the costs of digestion or to provide the feedlot additional revenue from the sale of products, or conditions where credits for early reductions of greenhouse gas emission are provided.

Table 109. Herd Size Threshold for Economically Viable Deployment of Anaerobic Digesters: Swine, Nursery Pig-to-Finish Systems (with Grower Train), Below Barn Pit Storage, Initial Screening Assessment, 14% Internal Rate of Return Hurdle

	Credits for Early Reductions in \$ per CO_2-Equivalent Tons		
	\$0/ton	**\$1/ton**	**\$5/ton**
% finishers of animals			
0 to 10	NA	NA	NA
10 to 20	>9,000	>9,000	>9,000
20 to 30	>9,000	>9,000	>9,000
30 to 40	>9,000	>9,000	>9,000
40 to 50	>9,000	>9,000	>9,000
50 to 60	>9,000	>9,000	>9,000
60 to 70	>9,000	>9,000	>9,000
70 to 80	>9,000	>9,000	>9,000
80 to 90	>9,000	>9,000	>9,000
90 to 100	>9,000	>9,000	>9,000

NA=not available due to calculative limits of FarmWare

Based on the extended treatment of digester deployment at finishing operations, it is unlikely that further refinement of the analysis will change this conclusion. On this basis, no further evaluation is performed.

Roughly one-fifth of all swine on Minnesota swine feedlots by liveweight are housed in nursery pig-to-finish swine operations. As noted above, given trends in total numbers of in-shipments of feeder pigs from out-of-state farrowing systems to Minnesota nursery pig-to-finishing operations and finishing operations, this percentage share will likely rise with time.

Table 110. Herd Size Threshold for Economically Viable Deployment of Anaerobic Digesters: Swine, Nursery Pig-to-Finish Systems (With Grower Train), Below Barn Pit Storage, Initial Screening Assessment, 14% Internal Rate of Return Hurdle, Policy Cases

Policy Case 1: $0.015/kwh subsidy

	Credits for Early Reductions in $ per CO_2-Equivalent Tons		
	$0/ton	**$1/ton**	**$5/ton**
% finishers of animals			
0 to 10	NA	NA	NA
10 to 20	>9,000	>9,000	>9,000
20 to 30	>9,000	>9,000	>9,000
30 to 40	>9,000	>9,000	>9,000
40 to 50	>9,000	>9,000	>9,000
50 to 60	>9,000	>9,000	>9,000
60 to 70	>9,000	>9,000	>9,000
70 to 80	>9,000	>9,000	8,450
80 to 90	>9,000	>9,000	8,250
90 to 100	>9,000	>9,000	8,000

Policy Case 2: 2% Interest Rate Buy-down

0 to 10	NA	NA	NA
10 to 20	>9,000	>9,000	>9,000
20 to 30	>9,000	>9,000	>9,000
30 to 40	>9,000	>9,000	>9,000
40 to 50	>9,000	>9,000	>9,000
50 to 60	>9,000	>9,000	>9,000
60 to 70	>9,000	>9,000	>9,000
70 to 80	>9,000	>9,000	>9,000
80 to 90	>9,000	>9,000	>9,000
90 to 100	>9,000	>9,000	>9,000

Table 110. Herd Size Threshold for Economically Viable Deployment of Anaerobic Digesters: Swine, Nursery Pig-to-Finish Systems, Policy Cases (cont.)

Policy Case 3: 4% Interest Rate Buy-down

0 to 10	NA	NA	NA
10 to 20	>9,000	>9000	>9,000
20 to 30	>9,000	>9000	>9,000
30 to 40	>9,000	>9000	>9,000
40 to 50	>9,000	>9000	>9,000
50 to 60	>9,000	>9000	>9,000
60 to 70	>9,000	>9000	>9,000
70 to 80	>9,000	>9000	>9,000
80 to 90	>9,000	>9000	>9,000
90 to 100	>9,000	>9000	>9,000

Policy Case 4: 8% Interest Rate Buy-down

0 to 10	NA	NA	NA
10 to 20	>9,000	>9,000	>9,000
20 to 30	>9,000	>9,000	>9,000
30 to 40	>9,000	>9,000	>9,000
40 to 50	>9,000	>9,000	>9,000
50 to 60	>9,000	>9,000	>9,000
60 to 70	>9,000	>9,000	>9,000
70 to 80	>9,000	>9,000	7,950
80 to 90	>9,000	>9,000	7,650
90 to 100	>9,000	>9,000	7,350

Policy Case 5: $25,000 grant for Capital Expenditures

0 to 10	NA	NA	NA
10 to 20	>9,000	>9,000	>9,000
20 to 30	>9,000	>9,000	>9,000
30 to 40	>9,000	>9,000	>9,000
40 to 50	>9,000	>9,000	>9,000
50 to 60	>9,000	>9,000	>9,000
60 to 70	>9,000	>9,000	>9,000
70 to 80	>9,000	>9,000	>9,000
80 to 90	>9,000	>9,000	>9,000
90 to 100	>9,000	>9,000	>9,000

NA=not available due to calculative limits of FarmWare

Table 110. Herd Size Threshold for Economically Viable Deployment of Anaerobic Digesters: Swine, Nursery Pig-to-Finish Systems, Policy Cases (cont.)

Policy Case 6: $15,000 grant for Capital Expenditures

0 to 10	NA	NA	NA
10 to 20	>9,000	>9,000	>9,000
20 to 30	>9,000	>9,000	>9,000
30 to 40	>9,000	>9,000	>9,000
40 to 50	>9,000	>9,000	>9,000
50 to 60	>9,000	>9,000	>9,000
60 to 70	>9,000	>9,000	>9,000
70 to 80	>9,000	>9,000	>9,000
80 to 90	>9,000	>9,000	>9,000
90 to 100	>9,000	>9,000	>9,000

Policy Case 7: Sales Tax Exemption for Capital Expenditures

0 to 10	NA	NA	NA
10 to 20	>9,000	>9,000	>9,000
20 to 30	>9,000	>9,000	>9,000
30 to 40	>9,000	>9,000	>9,000
40 to 50	>9,000	>9,000	>9,000
50 to 60	>9,000	>9,000	>9,000
60 to 70	>9,000	>9,000	>9,000
70 to 80	>9,000	>9,000	>9,000
80 to 90	>9,000	>9,000	>9,000
90 to 100	>9,000	>9,000	>9,000

NA=not available due to calculative limits of FarmWare

Economic Assessment of Nursing Pig Operations

Size thresholds for nursing pig-only operations are shown in Table 111 for an initial screening evaluation. The results given in Table 111 assume a 14% discount rate. Additional screening results for a 10% discount rate are given in Appendix A3. Feasibility was evaluated over the range of feedlot sizes for this type of operation found in Minnesota. The largest nursing pig/finishing hog operation in the feedlot inventory has a permitted capacity of 15,500 nursing pigs.

Based on Table 111 and Appendix A-3, size thresholds for digester deployment at nursery pig-only feedlots exceed 15,500 head of nursing pigs for the initial screening analysis under nearly all conditions. These exceed 15,500 head under market conditions, and conditions of extensive governmental intervention either to lower the costs of digestion or to provide the feedlot additional revenue from the sale of products. The only indication of economic feasibility is in the case where credits for early greenhouse gas reductions are provided, and at levels that are roughly 5-times present market levels.

Given the evident lack of economic potential for digester deployment in the initial screening analysis, no further evaluation is performed.

Roughly 2 percent of all swine on Minnesota swine feedlots by liveweight are housed in nursery pigs-only operations.

Table 111. Thresholds for Economically Viable Deployment of Anaerobic Digesters: Swine, Nursery Pig-Only Operations, Below Barn Pit Storage, Initial Screening Assessment, 14% Internal Rate of Return Hurdle

	CO_2-Equivalent Emissions Reductions Early Credits		
	$0/ton	**$1/ton**	**$5/ton**
Base Case	>15,500	>15,500	>15,500
$0.015/kwh Subsidy	>15,500	>15,500	12,750
2% Interest Rate Buydown	>15,500	>15,500	>15,500
4% Interest Rate Buydown	>15,500	>15,500	14,850
8% Interest Rate Buydown	>15,500	>15,500	10,300
$25,000 Grant for Capital Expenditures	>15,500	>15,500	>15,500
$15,000 Grant for Capital Expenditures	>15,500	>15,500	>15,500
Sales Tax Exemption	>15,500	>15,500	>15,500

Economic Assessment of Farrow-to-Finish Operations

Results for the screening assessment for feasibility for farrow-to-finish swine operations are shown in Tables 112 and 113. The results given in Table 112 assume a 14% discount rate. Additional screening results for a 10% discount rate are given in Appendix A5. The analysis was conducted for different percentage distributions of farrowing sows to sows plus finishing hogs. To reduce the amount of time required for each test computation, feedlot totals for nursing pigs and boars were left at FarmWare defaults for the number of sows evaluated. As in the other assessments presented above, the population of finishing swine was divided between finishing hogs and growing pigs at a 53% to 47% ratio.

The largest farrow-to-finish operation in the feedlot inventory has a permitted capacity of 3,500 farrowing sows. Based on Table 112 and Appendix A-5, size thresholds for digester deployment at farrow-to-finish feedlots exceed 3,500 head of sows for the initial screening analysis under nearly all conditions. For the few instances where feasibility might be indicated ($0.015 per kWh tax credits for electricity generation or the provision of interest free 10-year loans **and** credit for early action salable at $5/CO$_2$-equivalent ton), but a few percent of the farrow-to-finish inventory might be affected.

The screening analysis that is used for the initial assessment of feasibility appears to provide a reasonable indication of the feasibility or unfeasibility of anaerobic digester applications (see Finishing Swine Assessment, above). Since it appears, on the basis of the initial screening analysis, that anaerobic digestion at Farrow-to-finish operations of the size characteristic of Minnesota feedlots is unfeasible across a wide range of conditions, no further, more detailed assessment is performed.

Roughly 15 percent of all swine on Minnesota swine feedlots by liveweight are housed in farrow-to-finish operations.

Table 112. Herd Size Threshold for Economically Viable Deployment of Anaerobic Digesters: Swine, Farrow-to-Finish Operations, Below Barn Pit Storage, Initial Screening Assessment, 14% Internal Rate of Return Hurdle

	Credits for Early Reductions in \$ per CO$_2$-Equivalent Tons		
	\$0/ton	**\$1/ton**	**\$5/ton**
% sows to sows plus finishers			
0 to 10	NA	NA	NA
10 to 20	>3,500	>3,500	>3,500
20 to 30	>3,500	>3,500	>3,500
30 to 40	>3,500	>3,500	>3,500
40 to 50	>3,500	>3,500	>3,500
50 to 60	>3,500	>3,500	>3,500
60 to 70	>3,500	>3,500	>3,500
70 to 80	>3,500	>3,500	>3,500
80 to 90	>3,500	>3,500	>3,500
90 to 100	>3,500	>3,500	>3,500

NA=not available due to calculative limits of FarmWare

Table 113. Herd Size Threshold for Economically Viable Deployment of Anaerobic Digesters: Digesters: Swine, Farrow-to-Finish Operations, Below Barn Pit Storage, Initial Screening Assessment, 14% Internal Rate of return Hurdle, Policy Cases

Policy Case 1: \$0.015/kwh subsidy

	Credits for Early Reductions in \$ per CO_2-Equivalent Tons		
	\$0/ton	**\$1/ton**	**\$5/ton**
% sows to sows plus finishers			
0 to 10	NA	NA	NA
10 to 20	>3,500	>3,500	>3,500
20 to 30	>3,500	>3,500	>3,500
30 to 40	>3,500	>3,500	2,900
40 to 50	>3,500	>3,500	2,850
50 to 60	>3,500	>3,500	2,800
60 to 70	>3,500	>3,500	2,900
70 to 80	>3,500	>3,500	2,900
80 to 90	>3,500	>3,500	3,000
90 to 100	>3,500	>3,500	3,100
Policy Case 2: 2% Interest Rate Buy-down			
0 to 10	NA	NA	NA
10 to 20	>3,500	>3,500	>3,500
20 to 30	>3,500	>3,500	>3,500
30 to 40	>3,500	>3,500	>3,500
40 to 50	>3,500	>3,500	>3,500
50 to 60	>3,500	>3,500	>3,500
60 to 70	>3,500	>3,500	>3,500
70 to 80	>3,500	>3,500	>3,500
80 to 90	>3,500	>3,500	>3,500
90 to 100	>3,500	>3,500	>3,500
Policy Case 3: 4% Interest Rate Buy-down			
0 to 10	NA	NA	NA
10 to 20	>3,500	>3,500	>3,500
20 to 30	>3,500	>3,500	>3,500
30 to 40	>3,500	>3,500	>3,500
40 to 50	>3,500	>3,500	>3,500
50 to 60	>3,500	>3,500	>3,500
60 to 70	>3,500	>3,500	>3,500
70 to 80	>3,500	>3,500	>3,500
80 to 90	>3,500	>3,500	>3,500
90 to 100	>3,500	>3,500	3,450

Table 113. Herd Size Threshold for Economically Viable Deployment of Anaerobic Digesters: Digesters: Swine, Farrow-to-Finish Operations, Policy Cases (cont.)

Policy Case 4: 8% Interest Rate Buy-down

0 to 10	NA	NA	NA
10 to 20	>3,500	>3,500	>3,500
20 to 30	>3,500	>3,500	>3,500
30 to 40	>3,500	>3,500	>3,500
40 to 50	>3,500	>3,500	2,950
50 to 60	>3,500	>3,500	2,800
60 to 70	>3,500	>3,500	2,900
70 to 80	>3,500	>3,500	2,900
80 to 90	>3,500	>3,500	2,950
90 to 100	>3,500	>3,500	3,000

Policy Case 5: $25,000 grant for Capital Expenditures

0 to 10	NA	NA	NA
10 to 20	>3,500	>3,500	>3,500
20 to 30	>3,500	>3,500	>3,500
30 to 40	>3,500	>3,500	>3,500
40 to 50	>3,500	>3,500	>3,500
50 to 60	>3,500	>3,500	>3,500
60 to 70	>3,500	>3,500	>3,500
70 to 80	>3,500	>3,500	>3,500
80 to 90	>3,500	>3,500	>3,500
90 to 100	>3,500	>3,500	>3,500

Policy Case 6: $15,000 grant for Capital Expenditures

0 to 10	NA	NA	NA
10 to 20	>3,500	>3,500	>3,500
20 to 30	>3,500	>3,500	>3,500
30 to 40	>3,500	>3,500	>3,500
40 to 50	>3,500	>3,500	>3,500
50 to 60	>3,500	>3,500	>3,500
60 to 70	>3,500	>3,500	>3,500
70 to 80	>3,500	>3,500	>3,500
80 to 90	>3,500	>3,500	>3,500
90 to 100	>3,500	>3,500	>3,500

Table 113. Herd Size Threshold for Economically Viable Deployment of Anaerobic Digesters: Digesters: Swine, Farrow-to-Finish Operations, Policy Cases (cont.)

Policy Case 7: Sales Tax Exemption for Capital Expenditures

0 to 10	NA	NA	NA
10 to 20	>3,500	>3,500	>3,500
20 to 30	>3,500	>3,500	>3,500
30 to 40	>3,500	>3,500	>3,500
40 to 50	>3,500	>3,500	>3,500
50 to 60	>3,500	>3,500	>3,500
60 to 70	>3,500	>3,500	>3,500
70 to 80	>3,500	>3,500	>3,500
80 to 90	>3,500	>3,500	>3,500
90 to 100	>3,500	>3,500	>3,500

NA=not available due to calculative limits of FarmWare

Economic Assessment of Farrow-to-Nursery Pig Operations

Size thresholds for the economic feasibility of anaerobic digester are shown in Table 114 and 115 for farrow-to-nurse feedlots in Minnesota for the initial screening analysis. As in the case of other swine production systems, feasibility is evaluated solely for feedlots with below barn pit storage. The analysis was conducted for different percentage distributions of farrowing sows to sows plus nursery pigs. The analysis was conducted using a 14% internal rate of return hurdle.

Parallel screening analysis employing a 10% rate of return hurdle is presented in Appendix A-6.

Maximum feedlot size for farrow-to-nurse operations is 3,000 head of sows for all percentage combinations of sows to nursery pigs except the 50 to 60% sows and 40 to 50% nursery pig increment. For this percentage combination, maximum feedlot size in Minnesota is 11,000 head of farrowing sows.

Based on Tables 114 and 115 and Appendix A-6, size thresholds for digester deployment at farrow-to-nursery feedlots exceed maximum feedlot size for the initial screening analysis under nearly all conditions. The sole exception is for the 50 to 60% sows and 40 to 50% nursery pig increment under conditions of a $0.015 per kWh tax incentive. Given the apparent lack of feasibility across a very wide-range of conditions, the analysis is concluded with the initial screening analysis, and the conclusion of little feasibility at characteristic Minnesota herd sizes. This mirrors conditions for other swine production systems.

Roughly 4% of the swine inventory in Minnesota by liveweight is found in farrow-to-nursery-pig systems.

Table 114. Herd Size Threshold for Economically Viable Deployment of Anaerobic Digesters: Swine, Farrow-to-Nursery Pig Operations, Below Barn Pit Storage, Initial Screening Assessment, 14% Internal Rate of Return Hurdle

	Credits for Early Reductions in $ per CO_2-Equivalent Tons		
	$0/ton	**$1/ton**	**$5/ton**
% sows to sows plus nursery pigs			
0 to 10	NA	NA	NA
10 to 20	>3,000	>3,000	>3,000
20 to 30	>3,000	>3,000	>3,000
30 to 40	>3,000	>3,000	>3,000
40 to 50	>3,000	>3,000	>3,000
50 to 60	>11,000	>11,000	>11,000
60 to 70	>3,000	>3,000	>3,000
70 to 80	>3,000	>3,000	>3,000
80 to 90	>3,000	>3,000	>3,000
90 to 100	>3,000	>3,000	>3,000

NA=not available due to calculative limits of FarmWare

Table 115. Herd Size Threshold for Economically Viable Deployment of Anaerobic Digesters: Digesters: Swine, Farrow-to-Nursery Operations, Below Barn Pit Storage, Initial Screening Assessment, 14% Internal Rate of Return Hurdle, Policy Cases

Policy Case 1: $0.015/kwh subsidy

	Credits for Early Reductions in $ per CO_2-Equivalent Tons		
	$0/ton	**$1/ton**	**$5/ton**
% sows of animals			
0 to 10	NA	NA	NA
10 to 20	>3,000	>3,000	>3,500
20 to 30	>3,000	>3,000	>3,000
30 to 40	>3,000	>3,000	>3,000
40 to 50	>3,000	>3,000	>3,000
50 to 60	8,300	6,450	3,250
60 to 70	>3,000	>3,000	>3,000
70 to 80	>3,000	>3,000	>3,000
80 to 90	>3,000	>3,000	>3,000
90 to 100	>3,000	>3,000	>3,000

Policy Case 2: 2% Interest Rate Buy-down

0 to 10	NA	NA	NA
10 to 20	>3,000	>3,000	>3,000
20 to 30	>3,000	>3,000	>3,000
30 to 40	>3,000	>3,000	>3,000
40 to 50	>3,000	>3,000	>3,000
50 to 60	>11,000	>11,000	9,250
60 to 70	>3,000	>3,000	>3,000
70 to 80	>3,000	>3,000	>3,000
80 to 90	>3,000	>3,000	>3,000
90 to 100	>3,000	>3,000	>3,000

Policy Case 3: 4% Interest Rate Buy-down

0 to 10	NA	NA	NA
10 to 20	>3,000	>3,000	>3,000
20 to 30	>3,000	>3,000	>3,000
30 to 40	>3,000	>3,000	>3,000
40 to 50	>3,000	>3,000	>3,000
50 to 60	>11,000	>11,000	5,900
60 to 70	>3,000	>3,000	>3,000
70 to 80	>3,000	>3,000	>3,000
80 to 90	>3,000	>3,000	>3,000
90 to 100	>3,000	>3,000	>3,000

Table 115. Herd Size Threshold for Economically Viable Deployment of Anaerobic Digesters: Digesters: Swine, Farrow-to-Nursery Operations, Policy Cases (cont.)

Policy Case 4: 8% Interest Rate Buy-down

0 to 10	NA	NA	NA
10 to 20	>3,000	>3,000	>3,000
20 to 30	>3,000	>3,000	>3,000
30 to 40	>3,000	>3,000	>3,000
40 to 50	>3,000	>3,000	>3,000
50 to 60	>11,000	7,950	3,100
60 to 70	>3,000	>3,000	>3,000
70 to 80	>3,000	>3,000	>3,000
80 to 90	>3,000	>3,000	>3,000
90 to 100	>3,000	>3,000	>3,000

Policy Case 5: $25,000 grant for Capital Expenditures

0 to 10	NA	NA	NA
10 to 20	>3,000	>3,000	>3,000
20 to 30	>3,000	>3,000	>3,000
30 to 40	>3,000	>3,000	>3,000
40 to 50	>3,000	>3,000	>3,000
50 to 60	>11,000	>11,000	>11,000
60 to 70	>3,000	>3,000	>3,000
70 to 80	>3,000	>3,000	>3,000
80 to 90	>3,000	>3,000	>3,000
90 to 100	>3,000	>3,000	>3,000

Policy Case 6: $15,000 Grant for Capital Expenditures

0 to 10	NA	NA	NA
10 to 20	>3,000	>3,000	>3,000
20 to 30	>3,000	>3,000	>3,000
30 to 40	>3,000	>3,000	>3,000
40 to 50	>3,000	>3,000	>3,000
50 to 60	>11,000	>11,000	>11,000
60 to 70	>3,000	>3,000	>3,000
70 to 80	>3,000	>3,000	>3,000
80 to 90	>3,000	>3,000	>3,000
90 to 100	>3,000	>3,000	>3,000

Table 115. Herd Size Threshold for Economically Viable Deployment of Anaerobic Digesters: Digesters: Swine, Farrow-to-Nursery Operations, Policy Cases (cont.)

Policy Case 7: Sales Tax Exemption for Capital Expenditures

0 to 10	NA	NA	NA
10 to 20	>3,000	>3,000	>3,000
20 to 30	>3,000	>3,000	>3,000
30 to 40	>3,000	>3,000	>3,000
40 to 50	>3,000	>3,000	>3,000
50 to 60	>11,000	>11,000	>11,000
60 to 70	>3,000	>3,000	>3,000
70 to 80	>3,000	>3,000	>3,000
80 to 90	>3,000	>3,000	>3,000
90 to 100	>3,000	>3,000	>3,000

NA=not available due to calculative limits of FarmWare

Economic Assessment of Farrow and Finish Operations

Results for the initial screening analysis for farrow-and-finish swine feedlots are shown in Tables 116 and 117. The results in Tables 116 and 117 assume a 14% internal rate of return hurdle. Additional screening results for a 10% discount rate are given in Appendix A-7. Size thresholds in every instance investigated in the initial screening analysis exceed maximum herd sizes for farrow-and-finish swine feedlots in Minnesota.

Roughly 3% of the swine inventory in Minnesota by liveweight is found in farrow-and-finish operations.

Table 116. Herd Size Threshold for Economically Viable Deployment of Anaerobic Digesters: Swine, Farrow-and Finish Operations, Below Barn Pit Storage, Initial Screening Assessment, 14% Internal Rate of Return Hurdle

	Credits for Early Reductions in $ per CO_2-Equivalent Tons		
	$0/ton	**$1/ton**	**$5/ton**
% sows to sows plus finishers			
0 to 10	NA	NA	NA
10 to 20	>3,500	>3,500	>3,500
20 to 30	>3,500	>3,500	>3,500
30 to 40	>3,500	>3,500	>3,500
40 to 50	>3,500	>3,500	>3,500
50 to 60	>3,500	>3,500	>3,500
60 to 70	>3,500	>3,500	>3,500
70 to 80	>3,500	>3,500	>3,500
80 to 90	>3,500	>3,500	>3,500
90 to 100	>3,500	>3,500	>3,500

NA=not available due to calculative limits of FarmWare

Table 117. Herd Size Threshold for Economically Viable Deployment of Anaerobic Digesters: Digesters: Swine, Farrow-and-Finish Operations, Below Barn Pit Storage, Initial Screening Assessment, 14% Internal Rate of Return Hurdle, Policy Cases

Policy Case 1: $0.015/kwh subsidy

	Credits for Early Reductions in $ per CO_2-Equivalent Tons		
	$0/ton	**$1/ton**	**$5/ton**
% sows to sows plus finishers			
0 to 10	NA	NA	NA
10 to 20	>3,500	>3,500	>3,500
20 to 30	>3,500	>3,500	2,750
30 to 40	>3,500	>3,500	>3,500
40 to 50	>3,500	>3,500	>3,500
50 to 60	>3,500	>3,500	>3,500
60 to 70	>3,500	>3,500	>3,500
70 to 80	>3,500	>3,500	>3,500
80 to 90	>3,500	>3,500	>3,500
90 to 100	>3,500	>3,500	>3,500

Policy Case 2: 2% Interest Rate Buy-down

0 to 10	NA	NA	NA
10 to 20	>3,500	>3,500	>3,500
20 to 30	>3,500	>3,500	>3,500
30 to 40	>3,500	>3,500	>3,500
40 to 50	>3,500	>3,500	>3,500
50 to 60	>3,500	>3,500	>3,500
60 to 70	>3,500	>3,500	>3,500
70 to 80	>3,500	>3,500	>3,500
80 to 90	>3,500	>3,500	>3,500
90 to 100	>3,500	>3,500	>3,500

Policy Case 3: 4% Interest Rate Buy-down

0 to 10	NA	NA	NA
10 to 20	>3,500	>3,500	>3,500
20 to 30	>3,500	>3,500	>3,500
30 to 40	>3,500	>3,500	>3,500
40 to 50	>3,500	>3,500	>3,500
50 to 60	>3,500	>3,500	>3,500
60 to 70	>3,500	>3,500	>3,500
70 to 80	>3,500	>3,500	>3,500
80 to 90	>3,500	>3,500	>3,500
90 to 100	>3,500	>3,500	>3,500

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Table 117. Herd Size Threshold for Economically Viable Deployment of Anaerobic Digesters: Digesters: Swine, Farrow-and-Finish Operations, Policy Cases (cont.)

Policy Case 4: 8% Interest Rate Buy-down

0 to 10	NA	NA	NA
10 to 20	>3,500	>3,500	>3,500
20 to 30	>3,500	>3,500	2,850
30 to 40	>3,500	>3,500	3,050
40 to 50	>3,500	>3,500	3,350
50 to 60	>3,500	>3,500	>3,500
60 to 70	>3,500	>3,500	>3,500
70 to 80	>3,500	>3,500	>3,500
80 to 90	>3,500	>3,500	>3,500
90 to 100	>3,500	>3,500	>3,500

Policy Case 5: $25,000 grant for Capital Expenditures

0 to 10	NA	NA	NA
10 to 20	>3,500	>3,500	>3,500
20 to 30	>3,500	>3,500	>3,500
30 to 40	>3,500	>3,500	>3,500
40 to 50	>3,500	>3,500	>3,500
50 to 60	>3,500	>3,500	>3,500
60 to 70	>3,500	>3,500	>3,500
70 to 80	>3,500	>3,500	>3,500
80 to 90	>3,500	>3,500	>3,500
90 to 100	>3,500	>3,500	>3,500

Policy Case 6: $15,000 grant for Capital Expenditures

0 to 10	NA	NA	NA
10 to 20	>3,500	>3,500	>3,500
20 to 30	>3,500	>3,500	>3,500
30 to 40	>3,500	>3,500	>3,500
40 to 50	>3,500	>3,500	>3,500
50 to 60	>3,500	>3,500	>3,500
60 to 70	>3,500	>3,500	>3,500
70 to 80	>3,500	>3,500	>3,500
80 to 90	>3,500	>3,500	>3,500
90 to 100	>3,500	>3,500	>3,500

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Table 117. Herd Size Threshold for Economically Viable Deployment of Anaerobic Digesters: Digesters: Swine, Farrow-and-Finish Operations, Policy Cases (cont.)

Policy Case 7: Sales Tax Exemption for Capital Expenditures

0 to 10	NA	NA	NA
10 to 20	>3,500	>3,500	>3,500
20 to 30	>3,500	>3,500	>3,500
30 to 40	>3,500	>3,500	>3,500
40 to 50	>3,500	>3,500	>3,500
50 to 60	>3,500	>3,500	>3,500
60 to 70	>3,500	>3,500	>3,500
70 to 80	>3,500	>3,500	>3,500
80 to 90	>3,500	>3,500	>3,500
90 to 100	>3,500	>3,500	>3,500

NA=not available due to calculative limits of FarmWare

Economic Assessment of Farrow-to-Wean Operations

Size thresholds for the initial screening evaluation of feasibility for farrow-to-wean swine operations are shown in Table 118. Under existing market conditions, the minimum feedlot size required in the initial screening for economically feasible deployment of digester technology exceeds 15,500 head of sows. Under the most aggressive forms of governmental intervention, minimum required herd size is near 6,600 to 8,600 head of sows, depending on the availability of credits for early reductions of CH_4 emissions.

As of 1998, no farrow-to-wean operation in Minnesota had more than 15,500 head of sows. About 90% of all swine in the inventory that were in farrow-to-wean feedlots in Minnesota, by liveweight, were housed in feedlots with 5,500 head of sows or fewer, well below the size threshold for feasible digester deployment identified in the initial screening analysis.

Roughly 7% of the swine inventory in Minnesota by liveweight is found in farrow-to-wean operations.

Parallel screening analysis using a 10% discount rate can be found in Appendix A-4.

Table 118. Herd Size Threshold for Economically Viable Deployment of Anaerobic Digesters: Swine, Farrow-to-Wean Operations, Below Barn Pit Storage, Initial Screening Assessment, 14% Internal Rate of Return Hurdle

	CO_2-Equivalent Emissions Reductions Early Credits		
	\$0/ton	**\$1/ton**	**\$5/ton**
Base Case	>15,000	>15,000	>15,000
\$0.015/kwh Subsidy	8,500	6,600	3,300
2% Interest Rate Buydown	>15,000	>15,000	9,850
4% Interest Rate Buydown	>15,000	>15,000	6,150
8% Interest Rate Buydown	12,550	8,250	3,150
\$25,000 Grant for Capital Expenditures	>15,000	>15,000	>15,000
\$15,000 Grant for Capital Expenditures	>15,000	>15,000	>15,000
Sales Tax Exemption	>15,000	>15,000	>15,000

Summary of the Economic Assessment for Swine Production

Different problems are encountered in the economic analysis of swine production systems than are encountered in the analysis of dairy deployments. Analysis must be done on the basis of different swine production systems. Eight distinct systems must be evaluated, each with many possible percentage combinations of animals by type.

We have a point estimate for 1998 for the distribution of swine by feedlot size within each distinct swine production system, but little knowledge of historical trends in herd size for each production system on which to base a forecast of herd size across swine production systems.

Finally, unlike the situation in dairy deployments of digestion, with swine manure we have the confounding influence of low total manure solids on digester net energy output. The effect of manure dilution on digester physical and economic performance can be only approximated.

Given this situation, we restrict the test of feasibility of swine applications of digestion to the prevailing distribution of swine feedlots in Minnesota by size and type. In addition, we have developed a two-stage process for analysis, comprised of an initial screening analysis for all feedlot configurations, and a second, more physically and economically realistic treatment for feedlot configurations that pass the initial screening test for feasibility.

The results for swine finishing systems are unambiguous across all tested conditions, both initial screening tests and more detailed, more physically and economically realistic tests. For finishing swine operations in Minnesota, the deployment of anaerobic digestion does not appear to be commercially feasible. Threshold herd sizes for economical deployment far exceed both the size of finishing operations characteristics of Minnesota swine production and maximum herd size for Minnesota finishing operations—under all conditions tested.

For nursery pig-to-finish, nursery pig-only, farrow-to-finish, and farrow-and-finish systems, the tests are limited to the initial screening analyses. For these systems, under the conditions of the initial screening, anaerobic digestion is not economically feasible at either current average or current maximum feedlot size.

For most swine by liveweight in the remainder of swine production in Minnesota, the same is true. Thus for all swine by liveweight on Minnesota swine feedlots, excepting about 1 to 2% of swine on those feedlots (see Table 119), the conditions do not appear to favor economically feasible deployment of digestion.

These conclusions rest on two assumptions. First, as noted above, these results assume current feedlot sizes. At present, we have no basis for the development of forecasts of future feedlot size across swine production systems. Second, these conclusions rest on the assumption that results taken from the initial screening analysis are generally indicative of results produced using more physically and economically realistic digester representations. Based on the complete complement of tests for finishing operations, this appears to be true; such representations do not appear to produce analytical results that differ from those of the screening analysis. A better-developed analysis might extend the test of feasibility using the most physically and economically realistic descriptions of digestion beyond just finishing systems. Also, a better-developed assessment also might test feasibility in relation to likely future herd sizes.

Within these limits, it appears that economically feasible deployment of anaerobic digestion at swine feedlot is limited to a few percent of the swine inventory.

Several other caveats are in order. First, the above results do not apply to swine feedlots that manage their manure in a more solid form. Although very little of swine manure in Minnesota is managed as a solid, it is possible that a small amount of newly constructed feedlot capacity could be designed for the management of manure as excreted with 6 to 8% total solids. In such a form, swine manure probably could be economically digested at herd sizes that are comparable to those for dairy farms, e.g., 500 to 800 head of cows-equivalent or 4,000 to 5,000 head of finishing swine. It is also possible that intensive water management in below barn pits to a degree not evaluated above (e.g., resulting in a 4% TS manure) could have the same effect, though the economics of such intensive management are not well understood.

Second, the above results also do not necessarily apply to third generation digester types. As noted above in Part I, it is possible that, due to reduced required reactor size, the use of third generation reactors could improve the economics of digestion using highly dilute manure. This will not be known until we have actual deployments on a commercial scale at operating feedlots.

Table 119. Summary of Feasibility Analysis for Anaerobic Digestion for Swine Production Systems in Minnesota

Swine Production System	% of Swine (by liveweight)	% of swine by Liveweight in systems meeting threshold herd size	
		Initial Screening	Complete Analysis
Finishing	49	0	0
Nursery-pig-to-finish	21	0	NA
Nursery pig-only	3	0	NA
Farrow-to-finish	15	0	NA
Farrow-and-finish	3	0	NA
Farrow-to-nursery-pig	4	30	NA
Farrow-to-wean	7	10	NA

Part 5. Renewable Energy and Methane Control Potential

Renewable Energy Analysis

For dairy farms, the renewable energy potential of anaerobic digestion can be calculated from an average rate of electric power generation of 2.5 kWh per day per cow. At an expected dairy herd of 482,000 in 2010, and feasibility estimated for 10 to 50% of the herd, roughly 45 to 220 million kWh per year of electricity generation could be expected from digester biogas produced on Minnesota dairy farms. Current annual electricity consumption in Minnesota is some 58,200 million kWh, which suggests a renewable energy potential from anaerobic digestion of between 0.06 and 0.3 percent of existing statewide consumption.

As noted above, the potential for digestion on swine farms is probably small. If anaerobic digestion is economically feasible on feedlots with 1% of all swine on swine feedlot by liveweight, 2 million kWh could be generated on Minnesota swine feedlots.

Methane Control Potential

By 2010, the emission of methane from manure storage and management on dairy farms is forecast to total roughly 727,000 CO_2-equivalent tons. This assumes that manure on new dairy feedlots or dairy expansions is managed as a slurry in ponds or tanks. From the above analysis, anaerobic digestion might be economically feasible on dairy feedlots with 10 to 50% of the dairy inventory. This suggests that between 73,000 and 364,000 CO_2-equivalent tons per year of methane emissions potentially can be avoided through the economically feasible deployment of anaerobic digestion. To this, another 10,000 to 15,000 CO_2-equivalent tons could be added from the digestion of swine manure. This assumes that anaerobic digestion is feasible on swine feedlots comprising 1% of all swine by liveweight in Minnesota.

Statewide emissions of greenhouse gases from all emission sources in 1997 are estimated to have totaled 140 million CO_2-equivalent tons. At a rate of growth of 1% per year, by 2010 emissions will approach 155 million tons. In relation to aggregate statewide emissions, the contribution of anaerobic digestion at economically feasible rates of deployment to emissions control always will be small, on the order of a few tenths of a percent of weighted emissions.

In terms of emissions reductions needed to realize a cap on statewide greenhouse gas emissions at 1990 levels, at best anaerobic digestion, at the rates of deployment discussed above, could contribute but a few percent to the overall effort. Thus as a mitigation strategy, digestion could be useful only as a part of a larger set of emissions reductions.

Part 6. Policy Options

Based on the above analysis, we can conclude the following:

- the largest opportunities for digestion using commercially demonstrated reactor designs are to be found in the dairy industry;
- the digestion of swine manure could result in substantially larger amounts of biogas production, but, in terms of net energy production and economic feasibility, the potential for digestion on swine feedlots is limited by the low total solids content of swine manure managed in below barn pits. The best hope for digestion of highly dilute swine manure may lie with experimental third generation reactor designs or in regimes of intensive water management in swine facilities and below barn;
- digester deployment is now cost-effective under market conditions on feedlots with 600 to 900 head of dairy cows:
- the market potential for digester deployment on dairy feedlots is probably on the order of 10 percent of the dairy herd. With slightly more optimistic appraisals of factors like project lifetime or discount rate, this conceivably could be tripled to on the order of one-quarter of the herd by 2010;
- the almost total absence of anaerobic digestion on Minnesota dairy feedlots cannot be explained by objective economic assessment of digester feasibility;

- governmental intervention to raise operating revenues from or to lower the capital costs associated with digester deployment could substantially improve the economics of digestion on Minnesota dairy farms;
- and, at present market prices, the sale of credits for the early reduction of greenhouse gas emissions can do little to improve the economics of digestion.

From these conclusions, some of the elements of policy are evident: a focus on the dairy industry, a focus principally on large feedlots, attention to the apparent short-fall in digester deployments from what is calculated to be economically feasible under current conditions, and, in the case of swine, focus on long-term research and development activities.

However, broader questions are also involved in the design of strategic directions in policy—questions that transcend concerns for mere project cost-effectiveness. What is the proper role of government in the economy? Is market failure real, and if so, how can it best be addressed? What is the place of socioeconomic considerations in the development of policy? Also, there are questions as to how government ought to act to most efficiently realize its ends.

The development of strategic directions in policy necessarily involves the fusion of these two sets of concerns, the economic and the philosophical.

A discrete number of possible bases for action on anaerobic digestion is evident, based on these two sets of concerns.

<u>Free Market Approach Correcting for Market Failure.</u> The analysis contained in the preceding sections of this study suggests that market conditions will support digester deployments covering roughly 3 to 10 percent of the current Minnesota dairy herd (25,000 to 75,000 cows). In fact, deployments of anaerobic digestion on Minnesota dairy farms have been limited to but one farm and only about 600 head of dairy cattle. This appears to represent a substantial under-utilization of anaerobic digestion from an economic perspective.

This is an instance of what is known in the economics literature as market failure—an instance where, due to imperfections, markets sub-optimally allocate resources to various production activities.

As discussed earlier, good up-to-date information regarding the technical and economic performance of anaerobic digesters is often unavailable to livestock and dairy producers. This may explain much of the discrepancy between actual levels of digester deployment and what the analysis suggests is economically feasible.

Such an instance of market failure might be rectified through on-the-ground demonstration of the technical and economic performance of digestion on working feedlots. On-the-ground demonstrations at working farms can make real to producers the performance characteristics and demands of anaerobic digestion in a way that is probably not possible through more traditional programs for the dissemination of information in the agricultural sector. The question is one of observational evidence of successful deployment, and access to an actual producer regarding questions of digester installation, operation, economic performance, and integration into farm operations. The fact of effective local demonstration is also important.

Essentially, anaerobic digestion may work in a Georgia or Illinois, but will it work in Blue Earth or Otter Tail County, Minnesota?

To broadly demonstrate the technical and economic performance characteristics of anaerobic digestion, it may be necessary for the state to fund a part or whole of a series of demonstration digester projects in rural Minnesota. Acting on its own, the market does not seem capable of getting the necessary initial deployments in-place.

Financial incentives for the deployment of anaerobic include: low or no-interest loans, grants for capital expenditures, income and sales tax incentives based on capital expenditures, tax incentives per kWh of electricity generated or sold onto the electrical grid, and government mandates requiring the purchase of farm-generated electricity by electric utilities. Investigation above has shown the tax incentives per kWh of electricity generated appear to have the most beneficial effect on project finances.

Any demonstration program is probably best restricted to the application of plug flow digesters on dairy feedlots, and at large enough feedlots to insure commercial success of each digester deployment. For a 800 cow dairy, a $0.015 per kWh tax incentive annually would amount to about $8,500.

In addition to demonstration projects, other interventions to correct market failure include: the continued supply of information to livestock and dairy producers on anaerobic digestion through agricultural extension; and use of green pricing in electricity markets. Through green pricing of electricity generated through digestion, consumers can signal their willingness to support farm-based renewable energy production. This may help to ameliorate some of the inefficiencies associated with the existence of monopolistic conditions in electricity markets. Useful information that might be provided producers would relate to: capital and operating costs, size limits for economic feasibility, and operating benefits in terms of electricity generation, reduced BOD and pathogen potential of digested manure, and avoided purchases of electricity and heating fuel.

This approach requires direct governmental intervention. It rests finally on the assumption that the principal role of government in a free market economy is limited to the correction of market distortions arising from monopoly power in markets and constraints on information flow.

<u>Pure Free Market Approach.</u> Alternatively, in classical economics, it is implicitly assumed that markets efficiently allocate resources to maximize social welfare. No market imperfections are assumed to inhibit the efficient operation of markets. Demand, supply, and production cost determine how resources are allocated amongst competing needs.

Under a free market approach to digester policy, these conditions are assumed to prevail. Markets are assumed to efficiently allocate resources to their most productive uses without the need for governmental intervention. It is assumed that markets are not limited in their operation by imperfections arising from monopoly power in markets, constraints to the flow of information, or bounded consumer or producer rationality. Flows of capital and labor are assumed to be fluid. It is further assumed that social welfare, understood in an economic sense, is optimized through the efficient operation of markets, again without the need for governmental intervention.

Under these assumptions, the market acting on its own is the sole agent of action in society in developing anaerobic digestion as a resource. No role is evident for government.

Long-term R&D. Third generation digesters remain experimental. While developed specifically for the digestion of dilute swine manure, they have yet to be deployed on a working swine feedlot. Little has been published with regard to the capital and operating costs of third generation reactors. In particular, little information is available regarding either level of expertise required of the feedlot owner in operating a third generation reactor like a anaerobic sequencing batch reactor (ASBR), or the amount of time daily committed to the operation and maintenance of an ASBR. It is impossible to establish either the practicality of third generation reactor applications at working swine feedlots, or the economic feasibility of such applications without this type of information.

A longer-term research and development program is needed to evaluate the practicality of third (and second) generation reactor concepts for the digestion of swine manure at working feedlots. What reactor design types have the greatest potential for use on swine feedlots? What are the practical limits to the use of such reactor designs on swine feedlots? What changes to existing designs could render digestion more suitable for use at actual swine production facilities?

A longer-term research and development strategy would allow us to answer these questions. This would materially help in the long-term development of digestion in the state.

A long-term research and development strategy is relatively low-cost. This is its principal appeal. The principal disadvantage of such a response is the slow rate at which new knowledge can be developed, and only slowly diffused into the economy in terms of new advanced technology.

A government-led long-term research and development strategy implicitly assumes that the normal operation of markets does not result in optimal levels of investment in research and development.

Renewable Energy Development. While the potential contribution of anaerobic digestion to electricity generation is small as a percentage of total state generation, it is possible to treat anaerobic digestion as a part of a larger governmental program of subsidies to encourage renewable energy development. Subsidies of $0.015 per kWh currently are provided by the state of Minnesota to wind power developers to encourage the development of wind energy resources. Based on the above analysis, the provision of a similarly sized tax incentive to the developers of anaerobic digestion would act to increase the size of the resources that is cost-effective to develop up to 5-fold.

The estimated renewable energy potential of anaerobic digestion is about 10 to 40% of total electricity production in 1999 from wind power.

The principal rationale for this type of policy is the diversification of energy supply. It is implicitly assumed that the market, acting on its own, is incapable of realizing substantial market diversification, and that governmental intervention will be required.

Agricultural Development. It is possible to design a strategic approach to anaerobic digester development as part of a larger governmental program to aid the Minnesota livestock industry. Such an approach assumes that there is an inherent good in efforts on the part of the government to support rural communities through aid to rural industry.

Measures that might be taken to promote digestion include: grants for capital expenditures, sales tax rebates, tax subsidies for energy production, mandates governing the purchase and purchase price of farm-based electricity sold onto the grid, and the provision of low interest loan monies for capital expenditures.

Such an approach fits nicely to existing programs of support to rural communities. This is its principal appeal. The principal drawback to this approach is the absence of evident guideposts for the development of funding levels or levels of governmental involvement. Essentially, what level of governmental activity and expenditure is too little, what too much?

Full Environmental Costing. The operation of large animal feedlots can result in the release of nutrients and pathogens to surface and ground water. Air emissions of ammonia, hydrogen sulfide, and methane are also an issue, as is odor. The costs to the physical, biological and social environmental of feedlot discharges and emissions at best are only partially reflected in the market prices of the dairy and pork products from Minnesota feedlots. Were market prices to fully reflect all production costs, meat and dairy products would be priced higher than they are now, consumption would be less, and, by definition, the impacts of the feedlot production of meat and dairy products would be at or near economically efficient levels. Mitigation measures that would enable a higher level of production would be highly valued, improving the economics of waste treatment technologies and systems like anaerobic digestion.

Environmental costs can be internalized in the market prices charged for goods and services through emission and effluent fees, taxation, and the rationing effects on price of effluent and emission caps set at ‘safe’ or acceptable levels.

The principal advantage of externalities’ pricing is that the proper pricing of environmental impacts leads to the most efficient allocation of resources in society.

In practice the use of full environmental costing is limited by the absence of detailed economic analyses of the costs to the physical and biological environmental of confined animal operations. Other limits arise from the evident unwillingness of state and local governments to impose increased costs on small livestock producers during a time of feedlot consolidation into larger operations. In addition, a decision to impose heightened fee levels or increased levels of taxation on livestock producers in Minnesota may act to place domestic livestock producers at a competitive disadvantage vis-a-vis producers from other states. Taken together, in practice these considerations have tended to limit the appeal of externalities’ pricing of feedlot environmental effects.

As a substitute for full externalities pricing, it is possible that a low nominal charge could be instituted, with the proceeds directed toward the long-term development of mitigation measures.

Given the different purposes and philosophical assumptions underlying each strategic direction discussed above, few objective standards exist to help society in choosing between broad directions strategic directions for policy. In addition, for standards for which there is broad acceptance, policy implications are not always clear. For instance, while cost-effectiveness may be widely accepted as a criterion useful in the development and evaluation of policy, it is not obvious whether the conditions of cost-effectiveness are better met with respect to digester policy through a long-term R & D program or through efforts to correct market imperfections through the funding of pilot demonstration projects. The analysis of cost-effectiveness at this level has yet to be done.

Given this condition, the best approach open to society in the development of digester policy may be a ‘second best’ approach, one that utilizes those approaches to resource policy that now command the greatest assent in society, as opposed to those that are determined to be optimal.

Of all the approaches discussed above, in general, efforts on the part of government to intervene in markets to correct market failure probably command the greatest assent.

In addition, the principal of complementarity might play a role. A number of the strategic directions for policy that are enumerated above are complementary. Energy diversification is a complement to a strategy of farm income support. Either of these is a complement to a program of government intervention to correct market failure. The basis for this is in a shared set of potential policy options built around governmental financial assistance to anaerobic digester development (see Table 120). This provides a second basis for a ‘second best’ policy.

Table 120. Potential Governmental Actions to Promote Anaerobic Digestion

Rationale	**Policy Actions**
Correction of Market Failure	Tax incentives, low interest loans, and grants for demonstration digesters Green pricing of electricity Mandates on the purchase of farm-generated electricity Information provision
Market Development	Development of early credits system for reductions of emissions of greenhouse gases
Long-term R&D	Development and demonstration of third- generation reactors
Economic Efficiency	Ecological taxation and emission and effluent fees
Energy Diversification	Energy production tax credit
Farm Income Support	Tax incentives, low interest loans, grants, and mandates

Conclusion

Anaerobic digestion is a technically feasible approach to the treatment of livestock waste. The environmental benefits of anaerobic digestion include reduced manure BOD, pathogen and weed destruction, elimination of feedlot odor, and hydrogen sulfide and methane emission control.. In addition, anaerobic digestion produces substantial amounts of biogas that can be used to generate electricity for on-farm use or sale to the grid, as well as heat for on-farm space and water heating. Waste treatment using anaerobic digestion produces a chemically stabilized product that is less environmentally harmful than untreated manure, and that retains most of its nutrient value.

A number of different digester designs are commercially available. For Minnesota, due to its cold winters, these are limited to digesters with an external source of heating. Due to these heating needs, these tend to be capital intensive. To minimize capital expenses, these are designed for short manure retention times in the digester. Three digester designs are available to Minnesota livestock producers: plug flow and slurry-loop digesters for high total solids manure like dairy manure, and continuously stirred tank reactors (CSTRs), which can handle manure with lower total solids content.

Based on the analysis found in the available scientific and engineering literature, anaerobic digestion using currently commercially available digester designs is probably most feasibly instituted on dairy feedlots. Highly dilute manure like the swine manure that one finds in below barn pit storage, requires large energy inputs to digest. This acts to limit the economic prospects of digestion on swine feedlots in cold climates. The digestion of dairy manure is not plagued by the problems associated with low total solids manure. For this reason, in the US, nearly all commercial deployments of the digester types available for use in Minnesota have been at dairy feedlots, rather than swine feedlots.

Due to economies of scale, the economics of anaerobic digestion deployment tends to favor large rather than small feedlots.

Analysis of the economics of digestion of manure on Minnesota dairy feedlots suggests that digester deployment is now cost-effective under market conditions on feedlots with 600 to 900 head of dairy cows. Based on the economic analysis, the market potential for digester deployment on dairy feedlots is probably on the order of 10 percent of the dairy herd. With slightly more optimistic appraisals of factors like project lifetime or discount rate, this conceivably could be tripled to on the order of one-quarter of the herd by 2010.

For reasons noted above, at this time little economic potential adheres to the digestion of swine manure at feedlots of the size characteristic of existing Minnesota swine feedlots. The best approach to the digestion of swine manure may involve the use of third generation reactor types like Anaerobic Sequencing Batch Reactors. None has been commercially deployed at a working feedlot. The intensive management of water use in swine facilities and below barn may also be a possibility, though the economic aspects of this, including the potential for adoption by producers, remain quite uncertain.

A range of governmental interventions to facilitate the introduction of anaerobic digestion on Minnesota feedlots was investigated. It was concluded that governmental actions that lower capital costs of digestion or raise the operating revenues from digestion through the provision of financial incentives can substantially improve the economics of anaerobic digestion on animal feedlots. In the case of dairy feedlots, without policy interventions, threshold herd size for economically viable deployment of anaerobic digestion is in the 600 to 900 cow range. With policy intervention, this declines up to about 250 to 350 cows. Between one-sixth and one-fifth of all dairy cows in Minnesota are presently in dairies with 250 head or more. Based on an extension of current trends, this figure is likely to rise to 50% by 2008.

While there appears to be substantial economic potential for the deployment of anaerobic digestion on Minnesota dairy feedlots, in fact, only one digester is currently in operation. Governmental intervention to correct market failures may be necessary to encourage much more widespread use of this technology. Possible policy measures to promote the use of anaerobic digestion on Minnesota feedlots include: tax incentives for renewable energy production, grants for capital expenditures, low- and no-interest loans, sales tax rebates on capital expenses, and government mandates governing the purchase and purchase price of farm-generated electricity sold onto the grid.

Appendix A.

Table A1-a. Herd Size Thresholds for Swine Finishing Operations (Without Grower Train) for Economically Viable Deployment of Anaerobic Digestion: $0.06/kwh Farm Electric Rates, $0.015 Electricity Sale Price to Utilities, Default Total Solids, 14% Internal Rate of Return Hurdle

	CO_2-Equivalent Emissions Reductions Early Credits		
	$0/ton	**$1/ton**	**$5/ton**
Base Case	>11,000	>11,000	>11,000
$0.015/kwh Subsidy	8,950	7,300	2,850
2% Interest Rate Buydown	>11,000	>11,000	>11,000
4% Interest Rate Buydown	>11,000	>11,000	>11,000
8% Interest Rate Buydown	9,600	7,300	3,900
$25,000 Grant for Capital Expenditures	>11,000	>11,000	>11,000
$15,000 Grant for Capital Expenditures	>11,000	>11,000	>11,000
Sales Tax Exemption	>11,000	>11,000	>11,000

Table A1-b. Herd Size Thresholds for Swine Finishing Operations (Without Grower Train) for Economically Viable Deployment of Anaerobic Digestion: $0.06/kwh Farm Electric Rates, $0.015 to $0.04/kwh Electricity Sale Price to Utilities, Default Total Solids, Net Energy Accounted for, 10%Internal Rate of Return Hurdle

	CO_2-Equivalent Emissions Reductions Early Credits		
	$0/ton	**$1/ton**	**$5/ton**
Base Case	>11,000	>11,000	>11,000
$0.015/kwh Subsidy	>11,000	>11,000	>11,000
2% Interest Rate Buydown	>11,000	>11,000	>11,000
4% Interest Rate Buydown	>11,000	>11,000	>11,000
8% Interest Rate Buydown	>11,000	>11,000	>11,000
$25,000 Grant for Capital Expenditures	>11,000	>11,000	>11,000
$15,000 Grant for Capital Expenditures	>11,000	>11,000	>11,000
Sales Tax Exemption	>11,000	>11,000	>11,000

Table A1-c. Herd Size Thresholds for Swine Finishing Operations (Without Grower Train) for Economically Viable Deployment of Anaerobic Digestion: $0.06/kwh Farm Electric Rates, $0.04/kwh Electricity Sale Price to Utilities, Default Total Solids, Net Energy Accounted for, 10% Internal Rate of Return Hurdle

	CO_2-Equivalent Emissions Reductions Early Credits		
	$0/ton	**$1/ton**	**$5/ton**
Base Case	>11,000	>11,000	>11,000
$0.015/kwh Subsidy	>11,000	>11,000	>11,000
2% Interest Rate Buydown	>11,000	>11,000	>11,000
4% Interest Rate Buydown	>11,000	>11,000	>11,000
8% Interest Rate Buydown	>11,000	>11,000	>11,000
$25,000 Grant for Capital Expenditures	>11,000	>11,000	>11,000
$15,000 Grant for Capital Expenditures	>11,000	>11,000	>11,000
Sales Tax Exemption	>11,000	>11,000	>11,000

Table A1-d. Herd Size Thresholds for Swine Finishing Operations (Without Grower Train) for Economically Viable Deployment of Anaerobic Digestion: $0.06/kwh Farm Electric Rates, $0.04/kwh Electricity Sale Price to Utilities, 3% Total Solids, Net Energy Accounted for, 14% Internal Rate of Return Hurdle

	CO_2-Equivalent Emissions Reductions Early Credits		
	$0/ton	**$1/ton**	**$5/ton**
Base Case	>11,000	>11,000	>11,000
$0.015/kwh Subsidy	>11,000	>11,000	6,900
2% Interest Rate Buydown	>11,000	>11,000	>11,000
4% Interest Rate Buydown	>11,000	>11,000	>11,000
8% Interest Rate Buydown	>11,000	>11,000	8,250
$25,000 Grant for Capital Expenditures	>11,000	>11,000	>11,000
$15,000 Grant for Capital Expenditures	>11,000	>11,000	>11,000
Sales Tax Exemption	>11,000	>11,000	>11,000

Table A1-e. Herd Size Thresholds for Swine Finishing Operations (Without Grower Train) for Economically Viable Deployment of Anaerobic Digestion: $0.07/kwh Farm Electric Rates, $0.04/kwh Electricity Sale Price to Utilities, 3% Total Solids, Net Energy Accounted for, 10% Internal Rate of Return Hurdle

	CO_2-Equivalent Emissions Reductions Early Credits		
	$0/ton	**$1/ton**	**$5/ton**
Base Case	>11,000	>11,000	>11,000
$0.015/kwh Subsidy	>11,000	8,100	4,500
2% Interest Rate Buydown	>11,000	>11,000	8,900
4% Interest Rate Buydown	>11,000	>11,000	6,750
8% Interest Rate Buydown	>11,000	10,400	4,450
$25,000 Grant for Capital Expenditures	>11,000	>11,000	8,900
$15,000 Grant for Capital Expenditures	>11,000	>11,000	10,250
Sales Tax Exemption	>11,000	>11,000	10,550

Table A1-f. Herd Size Thresholds for Swine Finishing Operations (Without Grower Train) for Economically Viable Deployment of Anaerobic Digestion: $0.07/kwh Farm Electric Rates, $0.04/kwh Electricity Sale Price to Utilities, 3% Total Solids, Net Energy Accounted for, Higher Operating Costs, 10% Internal Rate of Return Hurdle

	CO_2-Equivalent Emissions Reductions Early Credits		
	$0/ton	**$1/ton**	**$5/ton**
Base Case	>11,000	>11,000	>11,000
$0.015/kwh Subsidy	>11,000	>11,000	6,900-8,400
2% Interest Rate Buydown	>11,000	>11,000	>11,000
4% Interest Rate Buydown	>11,000	>11,000	>11,000
8% Interest Rate Buydown	>11,000	>11,000	7,450-8,600
$25,000 Grant for Capital Expenditures	>11,000	>11,000	>11,000
$15,000 Grant for Capital Expenditures	>11,000	>11,000	>11,000
Sales Tax Exemption	>11,000	>11,000	>11,000

Table A2. Herd Size Thresholds for Economically Viable Deployment of Anaerobic Digesters: Swine, Nursery Pig-Finisher Systems (with Grower Train), Below Barn Pit Storage, Initial Screening Assessment, 10% Internal Rate of Return Hurdle

	Credits for Early Reductions in $ per CO_2-Equivalent Tons		
	$0/ton	**$1/ton**	**$5/ton**
% finishers of animals			
Base Case			
0 to 10	NA	NA	NA
10 to 20	>9,000	>9,000	>9000
20 to 30	>9,000	>9,000	>9000
30 to 40	>9,000	>9,000	>9000
40 to 50	>9,000	>9,000	>9000
50 to 60	>9,000	>9,000	>9000
60 to 70	>9,000	>9,000	>9000
70 to 80	>9,000	>9,000	>9000
80 to 90	>9,000	>9,000	>9000
90 to 100	>9,000	>9,000	>9000
Policy Case 1: $0.015/kwh subsidy			
0 to 10	NA	NA	NA
10 to 20	>9,000	>9,000	>9,000
20 to 30	>9,000	>9,000	>9,000
30 to 40	>9,000	>9,000	>9,000
40 to 50	>9,000	>9,000	>9,000
50 to 60	>9,000	>9,000	8,700
60 to 70	>9,000	>9,000	7,550
70 to 80	>9,000	>9,000	7,300
80 to 90	>9,000	>9,000	7,200
90 to 100	>9,000	>9,000	7,050
Policy Case 2: 2% Interest Rate Buy-down			
0 to 10	NA	NA	NA
10 to 20	>9,000	>9,000	>9,000
20 to 30	>9,000	>9,000	>9,000
30 to 40	>9,000	>9,000	>9,000
40 to 50	>9,000	>9,000	>9,000
50 to 60	>9,000	>9,000	>9,000
60 to 70	>9,000	>9,000	>9,000
70 to 80	>9,000	>9,000	>9,000
80 to 90	>9,000	>9,000	>9,000
90 to 100	>9,000	>9,000	>9,000

Table A2 (cont). Herd Size Thresholds for Economically Viable Deployment of Anaerobic Digesters: Swine, Nursery Pig-Finisher Systems (With Grower Train), Below Barn Pit Storage, Initial Screening Assessment, 10% Internal Rate of Return Hurdle, Policy Cases

Policy Case 3: 4% Interest Rate Buy-down

	Credits for Early Reductions in $ per CO_2-Equivalent Tons		
	$0/ton	**$1/ton**	**$5/ton**
% finishers of animals			
0 to 10	NA	NA	NA
10 to 20	>9,000	>9000	>9,000
20 to 30	>9,000	>9000	>9,000
30 to 40	>9,000	>9000	>9,000
40 to 50	>9,000	>9000	>9,000
50 to 60	>9,000	>9000	>9,000
60 to 70	>9,000	>9000	>9,000
70 to 80	>9,000	>9000	>9,000
80 to 90	>9,000	>9000	>9,000
90 to 100	>9,000	>9000	>9,000

Policy Case 4: 8% Interest Rate Buy-down

0 to 10	NA	NA	NA
10 to 20	>9,000	>9,000	>9,000
20 to 30	>9,000	>9,000	>9,000
30 to 40	>9,000	>9,000	>9,000
40 to 50	>9,000	>9,000	>9,000
50 to 60	>9,000	>9,000	8,400
60 to 70	>9,000	>9,000	6,850
70 to 80	>9,000	>9,000	6,500
80 to 90	>9,000	>9,000	6,300
90 to 100	>9,000	>9,000	6,050

Policy Case 5: $25,000 grant for Capital Expenditures

0 to 10	NA	NA	NA
10 to 20	>9,000	>9,000	>9,000
20 to 30	>9,000	>9,000	>9,000
30 to 40	>9,000	>9,000	>9,000
40 to 50	>9,000	>9,000	>9,000
50 to 60	>9,000	>9,000	>9,000
60 to 70	>9,000	>9,000	>9,000
70 to 80	>9,000	>9,000	>9,000
80 to 90	>9,000	>9,000	>9,000
90 to 100	>9,000	>9,000	>9,000

Table A2 (cont). Herd Size Thresholds for Economically Viable Deployment of Anaerobic Di Swine, Nursery Pig-Finisher Systems (With Grower Train), Below Barn Pit Storage, Initial Assessment, 10% Internal Rate of Return Hurdle, Policy Cases

Policy Case 6: $15,000 grant for Capital Expenditures

0 to 10	NA	NA	NA
10 to 20	>9,000	>9,000	>9,000
20 to 30	>9,000	>9,000	>9,000
30 to 40	>9,000	>9,000	>9,000
40 to 50	>9,000	>9,000	>9,000
50 to 60	>9,000	>9,000	>9,000
60 to 70	>9,000	>9,000	>9,000
70 to 80	>9,000	>9,000	>9,000
80 to 90	>9,000	>9,000	>9,000
90 to 100	>9,000	>9,000	>9,000

Policy Case 7: Sales Tax Exemption for Capital Expenditures

0 to 10	NA	NA	NA
10 to 20	>9,000	>9,000	>9,000
20 to 30	>9,000	>9,000	>9,000
30 to 40	>9,000	>9,000	>9,000
40 to 50	>9,000	>9,000	>9,000
50 to 60	>9,000	>9,000	>9,000
60 to 70	>9,000	>9,000	>9,000
70 to 80	>9,000	>9,000	>9,000
80 to 90	>9,000	>9,000	>9,000
90 to 100	>9,000	>9,000	>9,000

Table A3. Herd Size Thresholds for Economically Viable Deployment of Anaerobic Digesters: Swine, Nursery Pig-Only Operations, Below Barn Pit Storage, Initial Screening Assessment, 10% Internal Rate of Return Hurdle

	CO_2-Equivalent Emissions Reductions Early Credits		
	$0/ton	**$1/ton**	**$5/ton**
Base Case	>15,500	>15,500	>15,500
$0.015/kwh Subsidy	>15,500	>15,500	11,600
2% Interest Rate Buydown	>15,500	>15,500	>15,500
4% Interest Rate Buydown	>15,500	>15,500	13,100
8% Interest Rate Buydown	>15,500	>15,500	9,050
$25,000 Grant for Capital Expenditures	>15,500	>15,500	15,000
$15,000 Grant for Capital Expenditures	>15,500	>15,500	>15,500
Sales Tax Exemption	>15,500	>15,500	>15,500

Table A4. Herd Size Threshold for Economically Viable Deployment of Anaerobic Digesters: Swine, Farrow-to-Wean Operations, Below Barn Pit Storage, Initial Screening Assessment, 10% Internal Rate of Return Hurdle

	CO_2-Equivalent Emissions Reductions Early Credits		
	$0/ton	**$1/ton**	**$5/ton**
Base Case	>15,000	>15,000	13,100
$0.015/kwh Subsidy	6,700	5,400	2,850
2% Interest Rate Buydown	>15,000	>15,000	7,450
4% Interest Rate Buydown	>15,000	>15,000	4,850
8% Interest Rate Buydown	8,150	5,850	2,600
$25,000 Grant for Capital Expenditures	>15,000	>15,000	10,800
$15,000 Grant for Capital Expenditures	>15,000	>15,000	11,750
Sales Tax Exemption	>15,000	>15,000	11,000

Table A5. Herd Size Thresholds for Economically Viable Deployment of Anaerobic Digesters: Swine, Farrow-to-Finish Operations, Below Barn Pit Storage, Initial Screening Assessment, 10% Internal Rate of Return Hurdle

	Credits for Early Reductions in \$ per CO_2-Equivalent Tons		
	\$0/ton	**\$1/ton**	**\$5/ton**
% finishers of animals			
Base Case			
0 to 10	NA	NA	NA
10 to 20	>3,500	>3,500	>3,500
20 to 30	>3,500	>3,500	>3,500
30 to 40	>3,500	>3,500	>3,500
40 to 50	>3,500	>3,500	>3,500
50 to 60	>3,500	>3,500	>3,500
60 to 70	>3,500	>3,500	>3,500
70 to 80	>3,500	>3,500	>3,500
80 to 90	>3,500	>3,500	>3,500
90 to 100	>3,500	>3,500	>3,500
Policy Case 1: \$0.015/kwh subsidy			
0 to 10	NA	NA	NA
10 to 20	>3,500	>3,500	>3,500
20 to 30	>3,500	>3,500	3,050
30 to 40	>3,500	>3,500	2,450
40 to 50	>3,500	>3,500	2,400
50 to 60	>3,500	>3,500	2,400
60 to 70	>3,500	>3,500	2,500
70 to 80	>3,500	>3,500	2,550
80 to 90	>3,500	>3,500	2,600
90 to 100	>3,500	>3,500	2,650

Table A5 (cont). Herd Size Thresholds for Economically Viable Deployment of Anaerobic Digesters: Digesters: Swine, Farrow-to-Finish Operations, Below Barn Pit Storage, Initial Screening Assessment, 10% Internal Rate of return Hurdle, Policy Cases

Policy Case 2: 2% Interest Rate Buy-down

	Credits for Early Reductions in $ per CO_2-Equivalent Tons		
	$0/ton	**$1/ton**	**$5/ton**
% finishers of animals			
0 to 10	NA	NA	NA
10 to 20	>3,500	>3,500	>3,500
20 to 30	>3,500	>3,500	>3,500
30 to 40	>3,500	>3,500	>3,500
40 to 50	>3,500	>3,500	>3,500
50 to 60	>3,500	>3,500	>3,500
60 to 70	>3,500	>3,500	>3,500
70 to 80	>3,500	>3,500	>3,500
80 to 90	>3,500	>3,500	>3,500
90 to 100	>3,500	>3,500	>3,500

Policy Case 3: 4% Interest Rate Buy-down

0 to 10	NA	NA	NA
10 to 20	>3,500	>3,500	>3,500
20 to 30	>3,500	>3,500	>3,500
30 to 40	>3,500	>3,500	>3,500
40 to 50	>3,500	>3,500	>3,500
50 to 60	>3,500	>3,500	>3,500
60 to 70	>3,500	>3,500	>3,500
70 to 80	>3,500	>3,500	>3,500
80 to 90	>3,500	>3,500	>3,500
90 to 100	>3,500	>3,500	>3,500

Policy Case 4: 8% Interest Rate Buy-down

0 to 10	NA	NA	NA
10 to 20	>3,500	>3,500	>3,500
20 to 30	>3,500	>3,500	>3,500
30 to 40	>3,500	>3,500	2,450
40 to 50	>3,500	>3,500	2,300
50 to 60	>3,500	>3,500	2,250
60 to 70	>3,500	>3,500	2,300
70 to 80	>3,500	>3,500	2,350
80 to 90	>3,500	>3,500	2,350
90 to 100	>3,500	>3,500	2,400

Table A5 (cont). Herd Size Thresholds for Economically Viable Deployment of Anaerobic Digesters: Digesters: Swine, Farrow-to-Finish Operations, Below Barn Pit Storage, Initial Screening Assessment, 10% Internal Rate of return Hurdle, Policy Cases

Policy Case 5: $25,000 grant for Capital Expenditures

0 to 10	NA	NA	NA
10 to 20	>3,500	>3,500	>3,500
20 to 30	>3,500	>3,500	>3,500
30 to 40	>3,500	>3,500	>3,500
40 to 50	>3,500	>3,500	>3,500
50 to 60	>3,500	>3,500	>3,500
60 to 70	>3,500	>3,500	>3,500
70 to 80	>3,500	>3,500	>3,500
80 to 90	>3,500	>3,500	>3,500
90 to 100	>3,500	>3,500	>3,500

Policy Case 6: $15,000 grant for Capital Expenditures

0 to 10	NA	NA	NA
10 to 20	>3,500	>3,500	>3,500
20 to 30	>3,500	>3,500	>3,500
30 to 40	>3,500	>3,500	>3,500
40 to 50	>3,500	>3,500	>3,500
50 to 60	>3,500	>3,500	>3,500
60 to 70	>3,500	>3,500	>3,500
70 to 80	>3,500	>3,500	>3,500
80 to 90	>3,500	>3,500	>3,500
90 to 100	>3,500	>3,500	>3,500

Policy Case 7: Sales Tax Exemption for Capital Expenditures

0 to 10	NA	NA	NA
10 to 20	>3,500	>3,500	>3,500
20 to 30	>3,500	>3,500	>3,500
30 to 40	>3,500	>3,500	>3,500
40 to 50	>3,500	>3,500	>3,500
50 to 60	>3,500	>3,500	>3,500
60 to 70	>3,500	>3,500	>3,500
70 to 80	>3,500	>3,500	>3,500
80 to 90	>3,500	>3,500	>3,500
90 to 100	>3,500	>3,500	>3,500

Table A6. Herd Size Thresholds for Economically Viable Deployment of Anaerobic Digesters: Digesters: Swine, Farrow-to-Nursery Operations, Below Barn Pit Storage, Initial Screening Assessment, 10% Internal Rate of Return Hurdle

	Credits for Early Reductions in $ per CO_2-Equivalent Tons		
	$0/ton	**$1/ton**	**$5/ton**
% finishers of animals			
Base Case			
0 to 10	NA	NA	NA
10 to 20	>3,000	>3,000	>3,000
20 to 30	>3,000	>3,000	>3,000
30 to 40	>3,000	>3,000	>3,000
40 to 50	>3,000	>3,000	>3,000
50 to 60	>11,000	>11,000	>11,000
60 to 70	>3,000	>3,000	>3,000
70 to 80	>3,000	>3,000	>3,000
80 to 90	>3,000	>3,000	>3,000
90 to 100	>3,000	>3,000	>3,000
Policy Case 1: $0.015/kwh subsidy			
0 to 10	NA	NA	NA
10 to 20	>3,000	>3,000	2,800
20 to 30	>3,000	>3,000	2,600
30 to 40	>3,000	>3,000	2,750
40 to 50	>3,000	>3,000	2,850
50 to 60	6,600	5,300	2,850
60 to 70	>3,000	>3,000	2,850
70 to 80	>3,000	>3,000	2,900
80 to 90	>3,000	>3,000	2,900
90 to 100	>3,000	>3,000	2,900
Policy Case 2: 2% Interest Rate Buy-down			
0 to 10	NA	NA	NA
10 to 20	>3,000	>3,000	>3,000
20 to 30	>3,000	>3,000	>3,000
30 to 40	>3,000	>3,000	>3,000
40 to 50	>3,000	>3,000	>3,000
50 to 60	>11,000	>11,000	7,050
60 to 70	>3,000	>3,000	>3,000
70 to 80	>3,000	>3,000	>3,000
80 to 90	>3,000	>3,000	>3,000
90 to 100	>3,000	>3,000	>3,000

Table A6 (cont). Herd Size Thresholds for Economically Viable Deployment of Anaerobic Digesters: Digesters: Swine, Farrow-to-Nursery Operations, Below Barn Pit Storage, Initial Screening Assessment, 14% Internal Rate of Return Hurdle, Policy Cases

Policy Case 3: 4% Interest Rate Buy-down

	Credits for Early Reductions in \$ per CO_2-Equivalent Tons		
	\$0/ton	**\$1/ton**	**\$5/ton**
% finishers of animals			
0 to 10	NA	NA	NA
10 to 20	>3,000	>3,000	>3,000
20 to 30	>3,000	>3,000	>3,000
30 to 40	>3,000	>3,000	>3,000
40 to 50	>3,000	>3,000	>3,000
50 to 60	>11,000	>11,000	4,700
60 to 70	>3,000	>3,000	>3,000
70 to 80	>3,000	>3,000	>3,000
80 to 90	>3,000	>3,000	>3,000
90 to 100	>3,000	>3,000	>3,000

Policy Case 4: 8% Interest Rate Buy-down

0 to 10	NA	NA	NA
10 to 20	>3,000	>3,000	2,700
20 to 30	>3,000	>3,000	2,500
30 to 40	>3,000	>3,000	2,500
40 to 50	>3,000	>3,000	2,550
50 to 60	7,900	5,700	2,550
60 to 70	>3,000	>3,000	2,550
70 to 80	>3,000	>3,000	2,550
80 to 90	>3,000	>3,000	2,550
90 to 100	>3,000	>3,000	2,550

Policy Case 5: \$25,000 grant for Capital Expenditures

0 to 10	NA	NA	NA
10 to 20	>3,000	>3,000	>3,000
20 to 30	>3,000	>3,000	>3,000
30 to 40	>3,000	>3,000	>3,000
40 to 50	>3,000	>3,000	>3,000
50 to 60	>11,000	>11,000	9,900
60 to 70	>3,000	>3,000	>3,000
70 to 80	>3,000	>3,000	>3,000
80 to 90	>3,000	>3,000	>3,000
90 to 100	>3,000	>3,000	>3,000

Table A6 (cont). Herd Size Thresholds for Economically Viable Deployment of Anaerobic Digesters: Swine, Farrow-to-Nursery Operations, Below Barn Pit Storage, Initial Screening Assessment, 14% Internal Rate of Return Hurdle, Policy Cases

Policy Case 6: $15,000 grant for Capital Expenditures

0 to 10	NA	NA	NA
10 to 20	>3,000	>3,000	>3,000
20 to 30	>3,000	>3,000	>3,000
30 to 40	>3,000	>3,000	>3,000
40 to 50	>3,000	>3,000	>3,000
50 to 60	>11,000	>11,000	10,800
60 to 70	>3,000	>3,000	>3,000
70 to 80	>3,000	>3,000	>3,000
80 to 90	>3,000	>3,000	>3,000
90 to 100	>3,000	>3,000	>3,000

Policy Case 7: Sales Tax Exemption for Capital Expenditures

0 to 10	NA	NA	NA
10 to 20	>3,000	>3,000	>3,000
20 to 30	>3,000	>3,000	>3,000
30 to 40	>3,000	>3,000	>3,000
40 to 50	>3,000	>3,000	>3,000
50 to 60	>11,000	>11,000	>11,000
60 to 70	>3,000	>3,000	>3,000
70 to 80	>3,000	>3,000	>3,000
80 to 90	>3,000	>3,000	>3,000
90 to 100	>3,000	>3,000	>3,000

Table A7. Herd Size Thresholds for Economically Viable Deployment of Anaerobic Digesters: Swine, Farrow-and Finish Operations, Below Barn Pit Storage, Initial Screening Assessment, 10% Internal Rate of Return Hurdle

	Credits for Early Reductions in $ per CO_2-Equivalent Tons		
	$0/ton	**$1/ton**	**$5/ton**
% finishers of animals			
Base Case			
0 to 10	NA	NA	NA
10 to 20	>3,500	>3,500	>3,500
20 to 30	>3,500	>3,500	>3,500
30 to 40	>3,500	>3,500	>3,500
40 to 50	>3,500	>3,500	>3,500
50 to 60	>3,500	>3,500	>3,500
60 to 70	>3,500	>3,500	>3,500
70 to 80	>3,500	>3,500	>3,500
80 to 90	>3,500	>3,500	>3,500
90 to 100	>3,500	>3,500	>3,500
Policy Case 1: $0.015/kwh subsidy			
0 to 10	NA	NA	NA
10 to 20	>3,500	>3,500	3,100
20 to 30	>3,500	>3,500	2,300
30 to 40	>3,500	>3,500	2,600
40 to 50	>3,500	>3,500	3,000
50 to 60	>3,500	>3,500	3,400
60 to 70	>3,500	>3,500	>3,500
70 to 80	>3,500	>3,500	>3,500
80 to 90	>3,500	>3,500	>3,500
90 to 100	>3,500	>3,500	>3,500
Policy Case 2: 2% Interest Rate Buy-down			
0 to 10	NA	NA	NA
10 to 20	>3,500	>3,500	>3,500
20 to 30	>3,500	>3,500	>3,500
30 to 40	>3,500	>3,500	>3,500
40 to 50	>3,500	>3,500	>3,500
50 to 60	>3,500	>3,500	>3,500
60 to 70	>3,500	>3,500	>3,500
70 to 80	>3,500	>3,500	>3,500
80 to 90	>3,500	>3,500	>3,500

Table A7 (cont). Herd Size Thresholds for Economically Viable Deployment of Anaerobic Digesters: Digesters: Swine, Farrow-and-Finish Operations, Below Barn Pit Storage, Initial Screening Assessment, 10% Internal Rate of Return Hurdle, Policy Cases

Policy Case 3: 4% Interest Rate Buy-down

	Credits for Early Reductions in $ per CO_2-Equivalent Tons		
	$0/ton	$1/ton	$5/ton
% finishers of animals			
0 to 10	NA	NA	NA
10 to 20	>3,500	>3,500	>3,500
20 to 30	>3,500	>3,500	>3,500
30 to 40	>3,500	>3,500	>3,500
40 to 50	>3,500	>3,500	>3,500
50 to 60	>3,500	>3,500	>3,500
60 to 70	>3,500	>3,500	>3,500
70 to 80	>3,500	>3,500	>3,500
80 to 90	>3,500	>3,500	>3,500
90 to 100	>3,500	>3,500	>3,500

Policy Case 4: 8% Interest Rate Buy-down

0 to 10	NA	NA	NA
10 to 20	>3,500	>3,500	>3,500
20 to 30	>3,500	>3,500	2,150
30 to 40	>3,500	>3,500	2,350
40 to 50	>3,500	>3,500	2,700
50 to 60	>3,500	>3,500	3,000
60 to 70	>3,500	>3,500	3.150
70 to 80	>3,500	>3,500	3,300
80 to 90	>3,500	>3,500	3,450
90 to 100	>3,500	>3,500	>3,500

Policy Case 5: $25,000 grant for Capital Expenditures

0 to 10	NA	NA	NA
10 to 20	>3,500	>3,500	>3,500
20 to 30	>3,500	>3,500	>3,500
30 to 40	>3,500	>3,500	>3,500
40 to 50	>3,500	>3,500	>3,500
50 to 60	>3,500	>3,500	>3,500
60 to 70	>3,500	>3,500	>3,500
70 to 80	>3,500	>3,500	>3,500
80 to 90	>3,500	>3,500	>3,500
90 to 100	>3,500	>3,500	>3,500

Table A7 (cont). Herd Size Thresholds for Economically Viable Deployment of Anaerobic Digesters: Digesters: Swine, Farrow-and-Finish Operations, Below Barn Pit Storage, Initial Screening Assessment, 10% Internal Rate of Return Hurdle, Policy Cases

Policy Case 6: $15,000 grant for Capital Expenditures

0 to 10			
10 to 20	NA	NA	NA
20 to 30	>3,500	>3,500	>3,500
30 to 40	>3,500	>3,500	>3,500
40 to 50	>3,500	>3,500	>3,500
50 to 60	>3,500	>3,500	>3,500
60 to 70	>3,500	>3,500	>3,500
70 to 80	>3,500	>3,500	>3,500
80 to 90	>3,500	>3,500	>3,500
90 to 100	>3,500	>3,500	>3,500
	>3,500	>3,500	>3,500

Policy Case 7: Sales Tax Exemption for Capital Expenditures

0 to 10			
10 to 20	NA	NA	NA
20 to 30	>3,500	>3,500	>3,500
30 to 40	>3,500	>3,500	>3,500
40 to 50	>3,500	>3,500	>3,500
50 to 60	>3,500	>3,500	>3,500
60 to 70	>3,500	>3,500	>3,500
70 to 80	>3,500	>3,500	>3,500
80 to 90	>3,500	>3,500	>3,500
90 to 100	>3,500	>3,500	>3,500
	>3,500	>3,500	>3,500

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