Market Opportunities for Biogas Recovery Systems at U.S. Livestock Facilities

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Contents

Biogas is a valuable by-product of decomposing animal waste in livestock operations. It is produced when the organic fraction of manure decomposes anaerobically (i.e., in the absence of oxygen). Biogas typically contains 60 to 70 percent methane, the primary constituent of natural gas. Biogas recovery systems at livestock operations can be a cost-effective source of clean, renewable energy that reduces greenhouse gas emissions.

Table 1. Potential for Biogas Recovery Systems at Swine and Dairy Operations

Animal Sector	Candidate Farms	Energy Generating Potential		
		MW	MWh/year	Thousands of MMBtu/year
Swine	5,596	804	6,341,527	68,710
Dairy	2,645	863	6,802,914	73,709
Total	8,241	1,667	13,144,441	142,419

The greatest potential for implementing a successful biogas capture and use project is when manure is collected as a liquid, slurry, or semi-solid and stored in open pits, ponds, or lagoons. Because the vast majority of large dairy and swine operations in the United States use liquid or slurry manure management systems, biogas production potential at these operations is high, as are the potential greenhouse gas reductions if biogas recovery systems are implemented. Other animal sectors, including poultry farms and beef lots, manage manure primarily in solid form, and efforts to more effectively produce renewable energy from these management systems are also being developed.

Biogas can be collected from manure and burned to supply on-farm energy needs for electricity, heating, cooling, or other energy needs. Surplus electricity or biogas can also be sold to neighboring operations or the utility grid. As of November 2010, AgSTAR estimated that 160 manure anaerobic digester biogas recovery systems were in operation at commercial livestock facilities in the United States. The full potential to provide renewable energy is much greater, however, with an estimated 8,200 U.S. dairy and swine operations (Table 1) that could support biogas recovery systems. Additionally, biogas recovery systems may be feasible at some poultry and beef lot operations as new and improved technologies for these manual types enter the market.

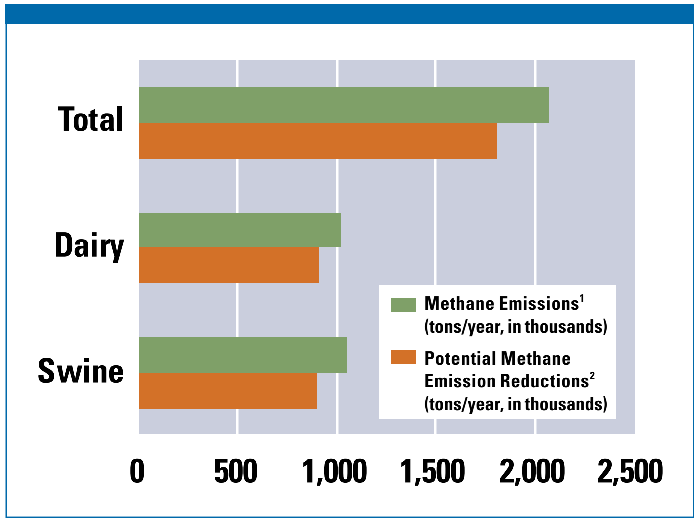
Substantial Environmental Benefits

One of the biggest challenges facing livestock producers is managing the large amount of animal waste (e.g., manure, process water) produced by their operations. Biogas recovery systems offer a number of air and water quality benefits for managing these wastes, including:

Odor control: Odors from anaerobically digested manures are significantly reduced as compared to odors from conventional storage and land application systems. The primary sources of odor from stored livestock manure are volatile organic acids and hydrogen sulfide (i.e., "rotten egg" odor). In an anaerobic digester, volatile organic compounds are reduced to methane and carbon dioxide, which are odorless gases. The volatized fraction of hydrogen sulfide is captured with the collected biogas and is destroyed during combustion.

Water quality protection: Anaerobic digestion provides several water quality benefits. Digesters, particularly heated digesters, can destroy more than 90 percent of disease-causing bacteria that might otherwise enter surface waters and pose a risk to human and animal health. Digesters also reduce biological oxygen demand (BOD). BOD is one measure of the potential for organic wastes to reduce dissolved oxygen in natural waters. Because fish and other aquatic organisms need minimum levels of dissolved oxygen for survival, farm practices that reduce BOD protect the health of aquatic ecosystems.

Figure 1. 2007 Methane Emissions and Potential Reductions with Anaerobic Digesters at Feasible Swine and Dairy Operations



[1] Emissions based on 2007 values from EPA's *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2008*.

[2] Estimates based on installing biogas recovery systems at all feasible operations, as defined in Table 2.

Greenhouse gas reduction: Digesters reduce emissions that contribute to global climate change. Methane currently contributes one-third of all man-made climate forcing and is a potent greenhouse gas with a global warming potential approximately 21 times that of carbon dioxide. In 2007, EPA estimated that livestock and poultry manure emitted almost 8 percent of annual U.S. methane emissions; the majority of those manure emissions came from swine and dairy operations. Biogas recovery systems capture and combust methane, reducing virtually all of the methane that otherwise would be emitted. As shown in Figure 1, installing digesters at dairy and swine operations where it is feasible would reduce methane emissions by another 1.8 million tons per year (representing approximately an 87 percent reduction from these operations).

Biogas can be used as a renewable source of energy. The use of biogas to generate energy can provide the added environmental benefit of offsetting fossil fuel use, which in turn lowers emissions of carbon dioxide (CO_2), another critical greenhouse gas.

Economic Benefits of Biogas Recovery

Biogas recovery systems offer substantial economic benefits, all of which improve the feasibility of a potential project.

Energy use and sale: The principal economic benefit of biogas recovery is for energy use, which can take several different forms. One option is to use biogas as a direct fuel source for heating, boilers, chillers, or drying; or upgraded to a cleaner gas and put into natural gas pipelines for sale. Alternatively, biogas can be combusted in an engine-generator to produce electricity, which can then be used to power on-farm operations or sold to the electric grid. Additionally, waste heat from the engine-generator set can be captured in cogeneration power systems and used for heating the digester, or for water and space heating. All of these options offer financial benefits in the form of reducing energy purchases and, in some cases, direct revenue from the sale of refined biogas or electric power to third parties.

Valuable by-products: Another benefit of anaerobic digestion is the variety of by-products that can be created from the digestate (digester effluent) solids. Examples include fertilizer, livestock bedding, and compost that can be used at the farm or sold. For instance, the nitrogen in manure is converted to a more readily available form for plants after anaerobic digestion. In comparison, manure that is treated or stored under aerobic systems (systems that expose the manure to oxygen) has a higher nitrogen loss as a result of conversion to ammonia and subsequent volatilization.

Renewable energy credits and greenhouse gas markets: Using biogas for energy reduces methane emissions (a greenhouse gas), and reduces demand for fossil fuels for heating or electricity purposes. In more than 30 states, electricity produced from biogas may qualify operations with a digester to receive renewable energy credits or a premium price for their green power. Another emerging source of income is the sale of "carbon credits" in global greenhouse gas markets. Several operations have begun receiving payments for the reduced methane emissions as a result of biogas recovery systems.

Identifying Profitable Systems

Candidate farms for installing biogas recovery systems were identified using the characteristics described in Table 2. These characteristics were selected based on AgSTAR evaluations of the technical and economic performance of successful digester systems operating on commercial scale swine and dairy farms. AgSTAR did not conduct a site specific cost analysis; specific sites conditions, such as energy contracts, environmental permitting requirements, and other variables will impact the economic feasibility of projects.

The methodology for identifying candidate farms and estimating the energy production potential is described in Appendix A. Although there are five operating digesters projects on poultry farms as of November 2010, this report did not assess candidates in this livestock sector. For further discussion of biogas production from poultry manure, please see page 7.

Table 2. Typical Characteristics Where Biogas Recovery Systems May Be Profitability

Animal Type	Dairy	Swine
Manure Management Method[1]	Flushed or scraped freestall barns and open lots	Houses with flush, pit recharge, or pull-plug pit systems[2]
Size of Operation	≥ 500 head	≥ 2,000 head

[1] Total solids content <15% and at least weekly manure collection

[2] Biogas systems are not currently used at swine confinement houses with deep pits. Deep pits under slatted floors are commonly used in cool regions such as the upper Midwest. Deep pit systems would need to be modified to remove manure more frequently before a biogas capture and utilization system could be installed. The feasibility of conversion depends on the value of the biogas produced relative to the capital investment required. Estimates in this report assume that deep pit operations with more than 5,000 head could use biogas systems by converting to at least weekly manure removal.

As shown in Table 1, biogas recovery systems are potentially profitable for more than 8,200 dairy and swine facilities in the United States. These facilities are large operations that use liquid or slurry manure handling systems, and collect manure frequently from animal confinement areas as described in Table 2.

AgSTAR's fact sheet *Anaerobic Digestion Capital Costs for Dairy Farms*, available at **www.epa.gov/agstar**, provides preliminary guidance on estimating capital costs.

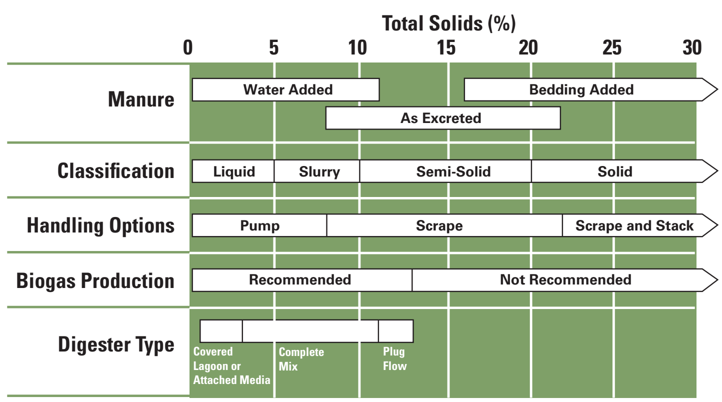
Profitability depends on the ability to recover the capital and operating costs at a reasonable rate of return and generate a long-term income stream. Experience has shown that the profitability of biogas systems depends on the size of the operation, the method of manure management, and local energy costs.

Size of operation: Available data indicate that the unit costs for construction, operation, and maintenance decrease significantly as biogas system size increases. The potential for a positive financial return appears to be most likely at dairy operations with milking herds of at least 500 cows and at swine operations with at least 2,000 total head of confinement capacity. Again, feasibility and profitability at individual operations depends on a number of factors, including but not limited to operation size.

Manure management method: Current digester systems are designed for manure that is handled in a liquid, slurry, or semi-solid state (Figure 2). Collection frequency also influences the feasibility of biogas recovery systems. Manure that is collected at least weekly minimizes the loss of the biodegradable organic matter that is converted into biogas during storage prior to digestion. Confined swine and dairy operations typically remove manure as frequently as every few hours to every few days. In other animal sectors (e.g., poultry and beef operations), manure is typically collected no more than three to four times per year as a result of using dry manure management systems.

Energy costs: The value of biogas depends on the price of the energy it replaces (e.g., electricity, fuel oil, liquefied petroleum gas (LPG)). Typically, biogas is used to generate electricity for on-site use, and any excess electricity is sold to the local electric utility. This strategy provides three possible sources of income:

Figure 2. Manure Handling Practices Affect the Feasibility and Choice of Digester Systems



- **Avoided cost of electricity:** The cost savings from electricity not purchased depends on local electricity rates. Because the total revenue derived from biogas use usually depends heavily on the value of electricity, relatively modest changes in rates can result in a significant change in the size of the operation where biogas capture and utilization will be profitable.
- **Sale of excess electricity to the local utility:** There is significant variation from state to state in the prices that utilities will pay small power producers. Rates can be very attractive in states with net metering, green power markets, or green pricing programs.
- **Waste heat recovery:** Waste heat from engine-generator sets can be recovered and used for space and water heating, thus reducing fuel oil or LPG purchases.

Energy Production Potential

Nationally, swine and dairy operations could generate more than 13 million MWh of electricity each year — equivalent to more than 1,670 MW of electrical grid capacity or more than 44 million MMBtus[1] of displaced fossil fuel use. According to the U.S. Department of Energy, the average price of electricity was about 10 cents per kilowatt-hour (kWh) in 2009. Using this rate, swine and dairy operations could potentially generate $1.3 billion annually in avoided electricity purchases.

Top 10 States for Energy Potential

The number of dairy and swine farms with the potential to recover methane varies significantly from state to state. Figures 3 and 4 depict the number of candidate swine and dairy farms in each state, respectively.

Figure 3: Candidate Swine Farms

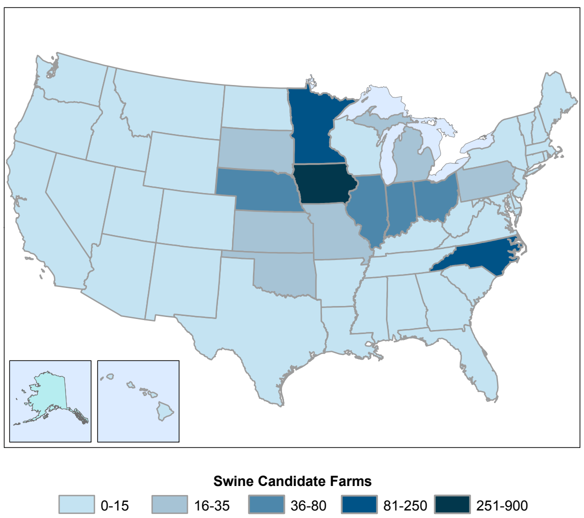


Figure 4: Candidate Dairy Farms

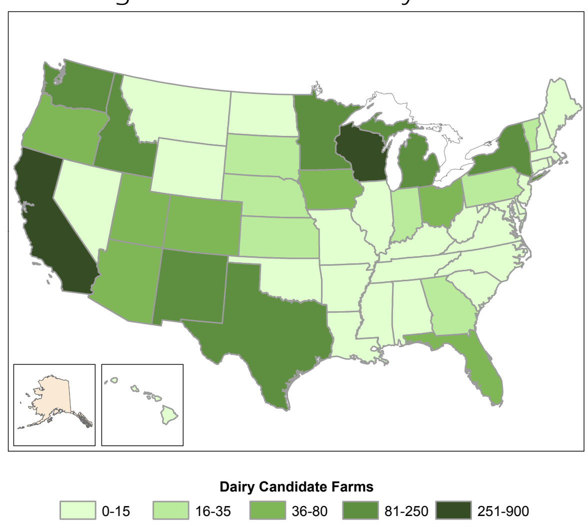


Table 3 identifies the 10 states with the greatest electricity generation potential from swine and dairy operations. For swine, the top 10 states account for approximately 86 percent of the total electricity generation potential. Iowa and North Carolina, the largest pork producing states, account for 29 percent and 18 percent of the total, respectively. For dairies, the top 10 states represent 82 percent of the total potential, with California accounting for 35 percent.

State profiles in Appendix B characterize the market potential in the top ten swine and dairy states with the greatest potential for biogas recovery.

[1]MMBtu = 1,000,000 Btu

Table 3. Top 10 States for Electricity Generation from Swine and Dairy Manure

State	Number of Candidate Farms	Methane Emissions Reductions (Thousand Tons)	Methane Production Potential (billion ft^3/ year)	Energy Generation Potential (Thousand MMBtu/ year)	Electricity Generation Potential (Thousand MWh/year)
Swine Farms					
Iowa	1,997	301	21.5	19,818	1,829
North Carolina	939	203	13.2	12,145	1,121
Minnesota	707	63	7.3	6,726	621
Illinois	350	39	4.3	3,936	363
Missouri	154	34	3.5	3,265	301
Indiana	296	31	3.5	3,208	296
Oklahoma	56	51	3.4	3,164	292
Nebraska	177	27	3.2	2,942	272
Kansas	80	22	2.3	2,161	199
Texas	10	25	1.6	1,516	140
Remaining 40 States	830	109	10.6	9,828	907
Sub Total	5,596	905	74.4	68,710	6,342
Dairy Farms					
California	889	341	27.9	25,729	2,375
Idaho	203	99	8.9	8,257	762
New Mexico	110	64	5.3	4,930	455
Texas	155	66	5.0	4,644	429
Wisconsin	251	41	4.5	4,178	386
Washington	125	35	3.4	3,183	294
Arizona	54	44	3.1	2,851	263
Michigan	107	26	2.9	2,661	246
New York	111	18	2.1	1,915	177
Colorado	54	22	2.0	1,889	174
Remaining 40 States	588	152	14.6	13,473	1,243
Sub Total	2,645	908	79.9	73,709	6,803
U.S. Total	**8,241**	**1,813**	**154**	**142,419**	**13,144**

Note: Subtotals and totals may not add due to rounding. The procedure for estimating the energy generation potential is explained in Appendix A.

Biogas from Poultry Operations

Poultry operations are classified as either producers of table eggs or birds for meat consumption, the latter including broiler, turkey, duck, and geese production. Most poultry operations reduce manure moisture content by evaporation or the addition of bedding material, or both. Dry manure management systems have lower potential for anaerobic digestion because the microorganisms that degrade the organics require moisture and the manure needs to be in a slurry state. Hence, poultry manure management systems often are not readily adaptable to the use of anaerobic digesters. However, as of November 2010, there are five operational poultry anaerobic digestion systems in the United States, indicating that developers can design systems to overcome the challenges.

The following describes typical poultry management systems:

Broilers and turkeys: The most common type of housing for meat birds is enclosed housing where birds are raised on litter (e.g., wood shavings, rice hulls, chopped straw, peanut hulls). Typically, the top layer of litter and dried manure (termed "cake") that accumulates is removed between flocks (6 to 7 flocks per year are cycled through) with total removal occurring every one to three years. This infrequent removal cycle results in loss of a substantial amount of organic matter that is the source of biogas production under anaerobic conditions. In addition, the litter material that is mixed with the manure has little biogas production potential.

Laying hens: Although many egg producers use systems to reduce manure moisture content in-place, anaerobic digestion can be incorporated into some manure management systems. Typically, layers are raised in cages that are suspended above the floor to separate the layers from the manure.

- High-rise manure management systems utilize two-story houses that provide long-term manure storage under cages located in the upper story of the house. The ventilation system is designed to dry the manure as it accumulates under the caged birds. Therefore, the typical high-rise cage system is not suitable for anaerobic digestion because the manure is too dry and the system is designed for long-term dry storage of manure. In most operations, liquid would have to be added to create a slurry form of manure.
- Scrape, flush, or belt systems are amenable to the inclusion of anaerobic digestion. In the first two systems, cages are suspended over a shallow pit without litter and manure is removed mechanically or hydraulically by flushing. In a belt system, manure is deposited on a continuous belt that is positioned under the cages and moves the manure to the end of the house, where it is placed into a manure spreader for immediate disposal or a storage structure. Because the manure is removed regularly, has a relatively high moisture content, and can be handled as a slurry, these systems are adaptable for anaerobic digester systems.

Dry systems, especially those that incorporate high-rate ventilation, promote volatilization of nitrogen into ammonia, causing a loss of nutrient value. Wet (liquid) manure management systems will retain the nitrogen in the manure until it is applied to the soil, assuming appropriate land application systems are used.

As of November 2010, there were five poultry anaerobic digesters in the United States. However, if current manure management practices are altered, the potential for biogas generation in the industry is high because of the methane generation potential of poultry manure and the large size of typical farms in the industry. Table 4 provides more information about U.S. poultry operations and identifies the states with the largest populations.

Table 4. The Top 10 States with the Largest Number of Layer, Broiler, and Turkey Populations

State	Population (million head)	Total Number of Farms (number)
Layers		
Iowa	53.8	2,966
Ohio	27.1	5,255
Indiana	24.2	3,583
Pennsylvania	22.0	7,604
California	21.1	5,098
Georgia	19.3	2,870
Texas	19.1	14,562
Arkansas	14.0	3,047
North Carolina	12.7	3,736
Florida	11.8	3,361
Remaining 40 States	124.7	93,533
Total Layers	**349.8**	**145,615**
Broilers		
Georgia	235.4	2,170
Arkansas	202.4	2,408
Alabama	178.3	2,263
Mississippi	150.6	1,478
North Carolina	149.9	1,879
Texas	118.6	1,872
Maryland	65.5	783
Delaware	51.1	778
Kentucky	49.8	909
Missouri	46.7	978
Remaining 40 States	354.3	17,150
Total Broilers	**1,602.6**	**32,668**
Turkeys		
Minnesota	18.3	601
North Carolina	17.9	846
Arkansas	9.4	530
Missouri	8.6	868
California	6.7	469
Virginia	6.3	572
Indiana	6.0	498
South Carolina	5.5	337
Iowa	4.0	417
Wisconsin	3.7	780
Remaining 40 States	20.8	11,308
Total Turkeys	**107.2**	**17,226**



Appendix A

Methodology

This section describes the methodology used to estimate the maximum potential for U.S. swine and dairy operations to generate electricity from biogas systems. The general approach was as follows:

1. Characterize swine and dairy animal populations and profiles of farm sizes by state: These data were obtained from U.S. Department of Agriculture (USDA) published reports.
2. Estimate manure management practices: These data were obtained from EPA greenhouse gas inventory reports, which in turn were developed with data from the USDA, expert input, and observations by EPA.
3. Determine the animal populations on farms where biogas systems are feasible: The criteria described in the "Identifying Profitable Systems" section were used to identify candidate farms.
4. Estimate methane emissions and emission reductions from candidate farms: Methane emissions were estimated using EPA's greenhouse gas inventory methodology. It was assumed that when farms convert to a biogas recovery system, the methane emission reduction is essentially 100 percent.
5. Estimate the methane production and electricity generation potential: These estimates were based on literature references and AgSTAR investigations.
6. Estimate the uncertainty associated with the analysis: An uncertainty analysis was performed to determine the uncertainty associated with the data presented in this report.

A more detailed discussion of these steps, including data sources and calculation methodologies, is presented below.

1. Characterizing State Animal Populations and Farm Profiles

The potential of individual states to reduce methane emissions from dairy and swine manures was based, respectively, on estimates of the number of milk cows that have calved, and the number of hogs and pigs in each state as reported in USDA's *2007 Census of Agriculture*.[1]

Census data was used to determine the number of operations in each state with 500 or more cows and the aggregate number of cows on these farms throughout the state. Census data was also used to determine the number of swine operations in each state with a confinement capacity of 2,000 or more head, and the total number of hogs and pigs confined on these operations.

To develop the maps used in Appendix B: State Profiles, county-level population data were obtained from the USDA's 2007 Census of Agriculture. USDA does not publicly disclose all of the data acquired by the census; some county-level population data were non-disclosed and therefore unavailable. To estimate the number of animals in the non-disclosed counties EPA first determined how many non-disclosed counties existed in each state, then subtracted the total number of animals in disclosed counties by the total number of animals in the state, and finally assumed an even distribution of these animals across non-disclosed counties. The resulting estimate of the number of animals in each undisclosed county was then input into the state-level maps.

[1] USDA. 2009. *2007 Census of Agriculture*. National Agriculture Statistics Service, Washington, DC.

2. Estimating Manure Management Practices

This analysis primarily relied upon the manure management system data discussed in EPA's *Inventory for U.S. Greenhouse Gas Emissions and Sinks: 1990-2008*,[2] for which the key data sources were USDA's *2007 Census of Agriculture*, EPA's Office of Water, and other expert sources. More detailed information about the data sources and the development of the manure management system data for dairy and swine populations can be found in the EPA report.

3. Identifying Candidate Farms for Anaerobic Digestion

Candidate farms for feasible anaerobic digestion were assumed to be:

- Dairy farms with anaerobic lagoons or liquid slurry manure management systems and more than 500 cows.
- Swine farms with anaerobic lagoons or liquid slurry manure management systems and more than 2,000 animals, and swine farms with deep pit manure management systems and more than 5,000 animals.

4. Estimating Methane Emissions by State and Animal Group

Methane emissions were estimated based on the methodologies used for EPA's *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2008*.[3] These methodologies were developed by the International Panel on Climate Change (IPCC) and presented in the *2006 IPCC Guidelines for National Greenhouse Gas Inventories*.[4]

Methane emission estimates were developed for each state and animal group using the following equation:

$$\text{Methane} = \text{Population} \times \text{VS} \times \text{TAM} \times \text{MCF} \times B_0 \times 0.041 \times 365$$

where

Methane	=	Total methane emissions from different animal types in different states and manure management systems, pounds (lb) per year
Population	=	Animal population
VS	=	Total volatile solids excretion rate, lb VS per 1,000 lb animal mass per day
TAM	=	Typical animal mass, lb
MCF	=	Methane conversion factor, decimal
B_0	=	Maximum methane producing capacity of manure, cubic feet (ft^3) methane per lb volatile solids
0.041	=	Density of methane at 25° Celsius, lb per ft^3
365	=	Days in a year

[2] U.S. EPA. 2010. *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2008*. Report No. EPA 430-R-10-006. Office of Atmospheric Programs, Washington, DC.

[3] Ibid.

[4] IPCC. 2006. *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. Prepared by the National Greenhouse Gas Inventories Programme, H.S. Eggleston, L. Buendia, K. Miwa, T Ngara, and K. Tanabe (eds.). Japan.

[5] USDA. 1996. *Agricultural Waste Management Field Handbook*. Natural Resources Conservation Service, Washington, DC.

Example data for two types of manure management systems are shown in Table A-1. For swine, total volatile solids (VS) was calculated using a national average VS excretion rate from the *Agricultural Waste Management Field Handbook*,[5] which was multiplied by the typical animal mass (TAM) of the animal and the state-specific animal population. For dairy cattle, regional VS excretion rates that are related to the diet of the animal were used.[6] The maximum methane producing potential of manure (B_0) varies by animal type and is based on values from the literature. The B_0 for dairy cows is 3.84 ft^3 of methane per pound of VS and the B_0 for swine is 7.69 ft^3 of methane per pound of VS.[7,8]

Methane conversion factors (MCFs) were determined for each type of manure management system and are shown in Table A-2. For dry systems, default IPCC factors were used. MCFs for liquid/slurry storage tanks and ponds, anaerobic lagoons, and deep pit systems were calculated based on the forecast performance of biological systems relative to temperature changes as predicted by the van't Hoff-Arrhenius equation. The MCF calculations model the average monthly ambient temperature, a minimum digester system temperature, the carryover of VS in the system from month to month, and a factor to account for management and design practices that result in the loss of VS from lagoon systems.

Example calculations: Page A-4 presents example methane emission reduction calculations from a biogas recovery system. Table A-1 shows the calculation of direct methane emission reductions from a biogas recovery system that replaces a manure storage tank or pond and an anaerobic lagoon on a farm with 500 dairy cows in California. The methane emission reduction from a biogas recovery system is equivalent to the methane emissions from the baseline manure management system that it replaces—not the amount of methane produced by the anaerobic digester. The amount of methane that would be collected and combusted by an anaerobic digester is greater than the amount of methane produced by the baseline manure management systems because digesters are designed to optimize methane production.

[6] Pape, D. and K. Moffroid. 2008. *1990-2007 Volatile Solids and Nitrogen Excretion Rates*. Dataset to EPA from ICF International, Washington DC.

[7] Hashimoto, A.G. 1984. "Methane from Swine Manure: Effect of Temperature and Influent Substrate Composition on Kinetic Parameter (k)." *Agricultural Wastes*, 9:299-308. Elsevier B.V., Amsterdam, Kingdom of the Netherlands.

[8] Morris, G.R. 1976. *Anaerobic Fermentation of Animal Wastes: A Kinetic and Empirical Design Fermentation*. M.S. Thesis. Cornell University, Ithaca, NY.

Table A-1. Methane Emission Reduction Impacts

Factors	Storage Tank or Pond	Anaerobic Lagoon
Number of cows	500	500
Typical animal mass (TAM),[a] lb/cow	1,332	1,332
Total VS excretion rate (VS_E), lb VS/1,000 lb animal mass day	10.1	10.1
B_0, ft^3 CH_4/lb VS	3.84	3.84
MCF in California, decimal	0.346	0.741
CH_4 density, lb CH4/ft^3	0.041	0.041
CH_4 emissions,[b] tons CH_4/yr	67	144
CH_4 emission reduction from biogas capture and utilization,[c] tons CH_4/yr	67	144
Equivalent reduction in CO_2 emissions,[d] tons CO_2/yr	1,407	3,024

[a] The TAM, B_0, and MCF values were obtained from EPA's *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2008*.

[b] CH_4 emissions are calculated for these examples using the equation on page A-2.

$$CH_4 \text{ Emissions} = \text{Number of cows} \times VS_E \times \frac{TAM}{1000} \times MCF \times B_0 \times 0.041 \frac{lbs}{ft^3} \times \frac{365 \text{ days}}{year} \times \frac{1 \text{ ton}}{2000 \text{ lbs}}$$

[c] It is assumed that biogas combustion destroys essentially 100 percent of baseline methane emissions.

[d] CH_4 has approximately 21 times the heat trapping capacity of CO_2.

CO_2 Equivalents = CH_4 Emissions x 21

The use of biogas to generate electricity also reduces CO_2 emissions from conventional power generation sources because fewer fossil fuels are combusted by electric power plants. The following shows an example calculation for estimating reduced CO_2 emissions:

Equation	Values
VS added, lb VS/yr	2,453,065
CH₄ production, ft³ CH₄/yr	10,302,875
Electricity generation potential, kWh/yr	877,676
Reduction in utility carbon dioxide emissions,[a] ton/yr	584

VS added, lb VS/yr — 2,453,065

$$VS = \text{Number of cows} \times VS_E \times \frac{TAM}{1000} \times \frac{365 \text{ days}}{year}$$

CH_4 production, ft^3 CH_4/yr — 10,302,875

$$CH_4 \text{ production} = VS \times \frac{4.2 ft^3 \, CH_4}{\text{lb VS added}}$$

Electricity generation potential, kWh/yr — 877,676

$$\text{Electricity Generation potential} = CH_4 \text{ production} \times \frac{923 \text{ Btu}}{ft^3 CH_4} \times \frac{kWh}{3.413 Btu} \times 0.35 \times 0.9$$

(0.35 is the engine efficiency and 0.9 is the on-line efficiency)

Reduction in utility carbon dioxide emissions,[a] ton/yr — 584

$$\text{Emissions Reduction} = \text{Electricity Generation Potential} \times \frac{1330 \text{ lb}}{MWh} \times \frac{1 \text{ MWh}}{1000 \text{ kWh}} \times \frac{1 \text{ ton}}{2000 \text{ lbs}}$$

[a] Based on 1330 lb of carbon dioxide emitted per MWh generated, which is the national average output emission rate for 2005 from EPA's Emissions & Generation Resource Integrated Database (eGRID). CO_2 emission rates vary across the U.S. depending on local electricity generation sources.

Table A-2. Methane Conversion Factors by State for 2007 (decimal)

State	Dairy		Swine	
	Tank/Pond	Anaerobic Lagoon	Tank/Pond and Deep Pit	Anaerobic Lagoon
Alabama	0.42	0.78	0.42	0.78
Alaska	0.15	0.50	0.15	0.50
Arizona	0.62	0.80	0.39	0.76
Arkansas	0.38	0.76	0.40	0.77
California	0.35	0.74	0.32	0.73
Colorado	0.22	0.66	0.25	0.70
Connecticut	0.25	0.69	0.25	0.69
Delaware	0.32	0.74	0.33	0.74
Florida	0.54	0.79	0.53	0.79
Georgia	0.41	0.77	0.40	0.77
Hawaii	0.59	0.77	0.59	0.77
Idaho	0.25	0.69	0.24	0.68
Illinois	0.32	0.74	0.31	0.74
Indiana	0.29	0.73	0.30	0.73
Iowa	0.27	0.71	0.28	0.71
Kansas	0.33	0.75	0.33	0.75
Kentucky	0.35	0.76	0.35	0.76
Louisiana	0.47	0.79	0.48	0.79
Maine	0.20	0.62	0.20	0.62
Maryland	0.31	0.73	0.31	0.74
Massachusetts	0.24	0.67	0.25	0.68
Michigan	0.25	0.69	0.26	0.70
Minnesota	0.25	0.68	0.26	0.69
Mississippi	0.44	0.78	0.43	0.78
Missouri	0.34	0.75	0.34	0.75
Montana	0.21	0.63	0.22	0.65
Nebraska	0.29	0.72	0.29	0.72
Nevada	0.27	0.71	0.28	0.71
New Hampshire	0.21	0.64	0.22	0.65
New Jersey	0.29	0.72	0.29	0.72
New Mexico	0.30	0.73	0.29	0.72
New York	0.23	0.66	0.23	0.67

(continued on next page)

Table A-2. Methane Conversion Factors by State for 2007 (decimal) (continued)

State	Dairy		Swine	
	Tank/Pond	Anaerobic Lagoon	Tank/Pond and Deep Pit	Anaerobic Lagoon
North Carolina	0.34	0.75	0.39	0.77
North Dakota	0.23	0.66	0.23	0.66
Ohio	0.28	0.71	0.28	0.72
Oklahoma	0.39	0.77	0.36	0.76
Oregon	0.21	0.63	0.21	0.63
Pennsylvania	0.26	0.70	0.28	0.71
Rhode Island	0.26	0.70	0.26	0.70
South Carolina	0.41	0.78	0.42	0.78
South Dakota	0.26	0.70	0.27	0.70
Tennessee	0.35	0.76	0.39	0.77
Texas	0.43	0.78	0.41	0.77
Utah	0.25	0.69	0.24	0.68
Vermont	0.21	0.63	0.21	0.63
Virginia	0.30	0.73	0.33	0.74
Washington	0.21	0.63	0.22	0.65
West Virginia	0.28	0.72	0.28	0.72
Wisconsin	0.24	0.68	0.25	0.69
Wyoming	0.20	0.63	0.23	0.67

5. Estimating Potential Electricity Yield from Methane Production

The estimates of the biogas production potential from dairy cow and swine manure presented in this report are based on the following approach:

- **Methane production:** Based on previously-observed values[9,10,11] and expert judgment, the production of methane from swine manure is estimated to be 6.6 ft^3 of methane per pound of total VS added. For dairy manure, the production of methane is assumed to be 4.2 ft^3 of methane per pound of total VS added to the system.
- **Heating value of methane:** To calculate the energy content of methane produced in swine and dairy anaerobic digesters for this report, EPA used the lower heating value of methane, 923 Btus per ft^3 methane.
- **Engine and on-line efficiency:** Electrical output from a typical generator was estimated at 85 kWh per 1,000 ft^3 of methane. This factor is based on a thermal conversion efficiency of methane to electricity of 35 percent, and an on-line operating rate of 90 percent (to account for down time due to maintenance and repair).

6. Estimating Uncertainty

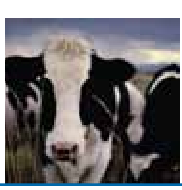
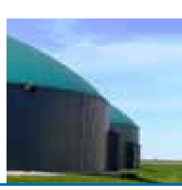
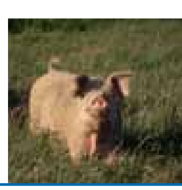
AgSTAR believes the largest sources of uncertainty are associated with the estimated methane emission calculations related to animal population data, the estimates of the number of animals using each type of manure management system, the VS excretion rates, the maximum methane production capacity data, and the methane conversion factors.

The methane emissions calculation was evaluated to determine the amount of uncertainty associated with the calculations. Using a simplified approach similar to the uncertainty analysis developed for EPA's *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2008*, AgSTAR performed a Monte Carlo uncertainty analysis on the methane emission estimates calculated in this report. A model was developed for the uncertainty analysis and uncertainty ranges were assigned to each of the variables in the methane emission calculation. Where available, uncertainty ranges were obtained from the original data source (e.g., USDA publishes uncertainty data for all animal population data). Where not available, uncertainty ranges were estimated based on best professional judgment. For example, AgSTAR assigned an uncertainty range of ± 20 percent for the number of animals using each type of manure management system. Based on the uncertainty analysis, the methane emission calculations were found to have an uncertainty of approximately ± 25 percent.

9 Martin, J.H., Jr. 2002. *A Comparison of the Performance of Three Swine Waste Stabilization Systems*. Final report submitted to the U.S. Environmental Protection Agency AgSTAR Program by Eastern Research Group, Inc., Boston, Massachusetts.

10 Martin, J.H., Jr. 2003. *An Assessment of the Performance of the Colorado Pork, LLC, Anaerobic Digestion and Biogas Utilization System*. Final report submitted to the U.S. Environmental Protection Agency AgSTAR Program by Eastern Research Group, Inc., Boston, Massachusetts.

11 Martin, J.H., Jr. 2004. *A Comparison of Dairy Cattle Manure Management With and Without Anaerobic Digestion and Biogas Utilization*. Final report submitted to the U.S. Environmental Protection Agency AgSTAR Program by Eastern Research Group, Inc., Boston, Massachusetts.

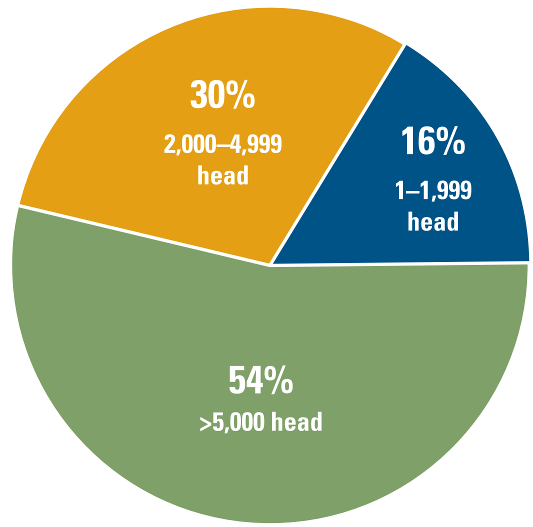
Appendix B

Profiles of Top Ten Swine and Dairy States with Biogas Energy Recovery Potential

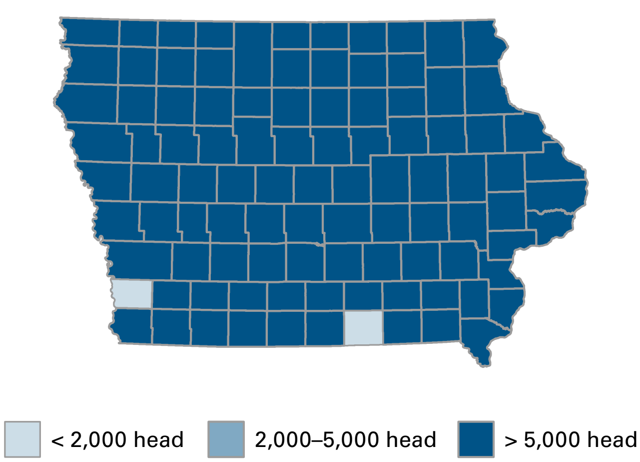
Market Opportunities to Generate Electricity with Anaerobic Digestion (2007)	
Total number of swine operations	8,330
Total number of mature swine (000 head)	19,295
Number of feasible swine operations[1]	1,997
Number of mature swine at feasible operations (000 head)	13,824
Methane emission reduction potential (000 tons/year)	301
Methane production potential (billion ft^3/year)	21.5
Electricity generation potential (000 MWh/yr)	1,829

[1] Anaerobic digestion was considered feasible at all existing operations with flush, pit recharge, or pull-plug pit systems with at least 2,000 swine and at deep pit systems with at least 5,000 swine.

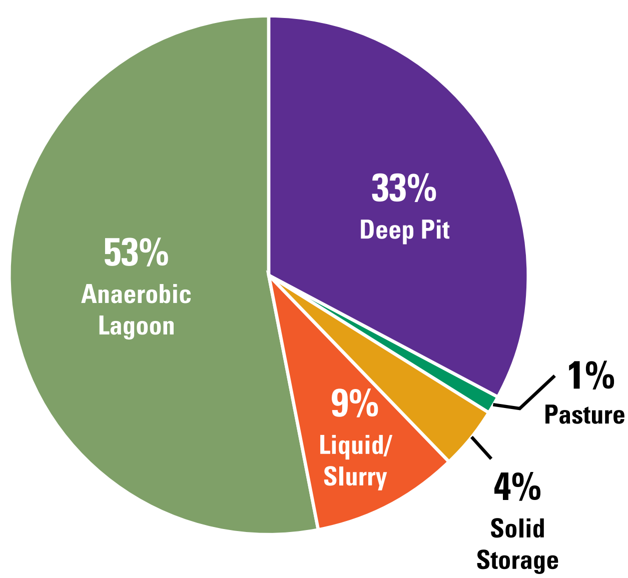
Swine Farm Size



Swine Population by County



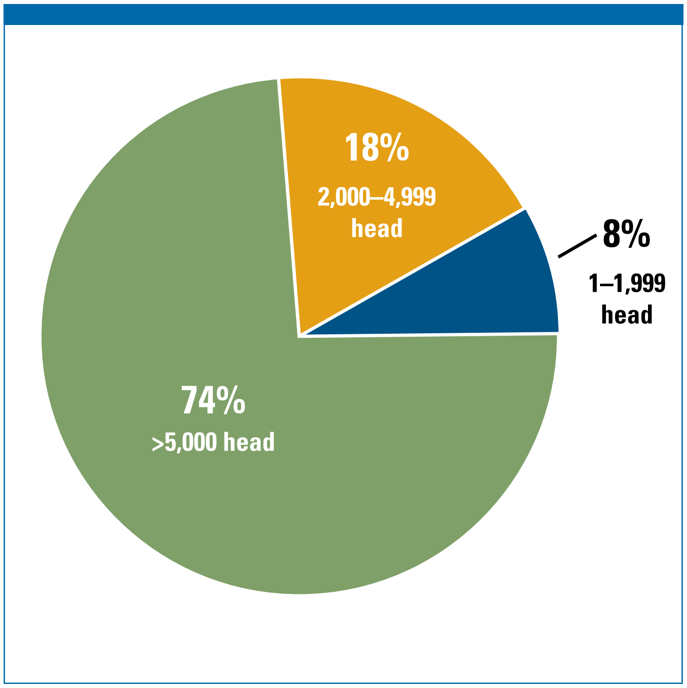
Swine Manure Managed in Each Waste Management System



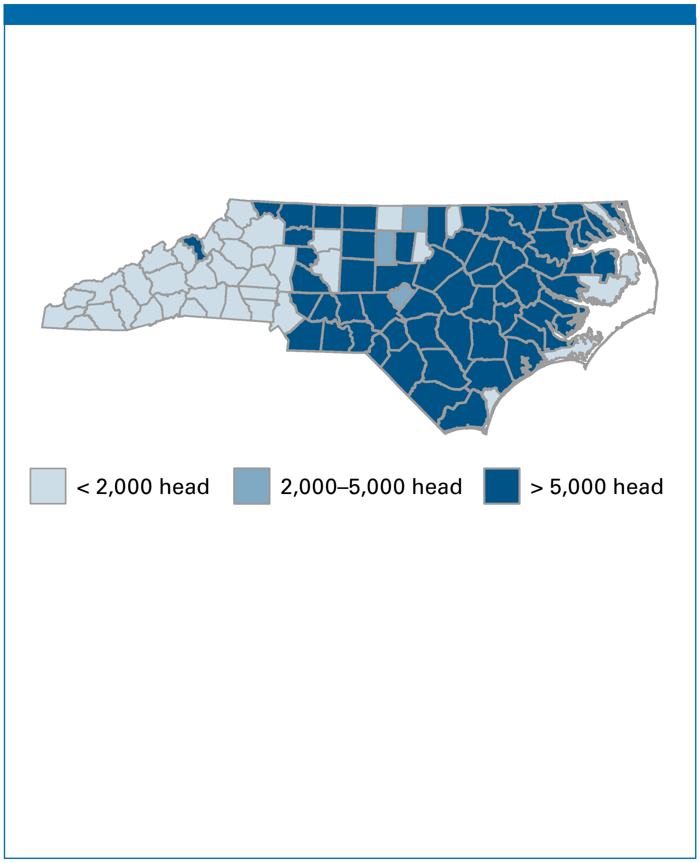
Market Opportunities to Generate Electricity with Anaerobic Digestion (2007)	
Total number of swine operations	2,836
Total number of mature swine (000 head)	10,134
Number of feasible swine operations[1]	939
Number of mature swine at feasible operations (000 head)	8,471
Methane emission reduction potential (000 tons/year)	203
Methane production potential (billion ft^3/year)	13.2
Electricity generation potential (000 MWh/yr)	1,121

[1] Anaerobic digestion was considered feasible at all existing operations with flush, pit recharge, or pull-plug pit systems with at least 2,000 swine and at deep pit systems with at least 5,000 swine.

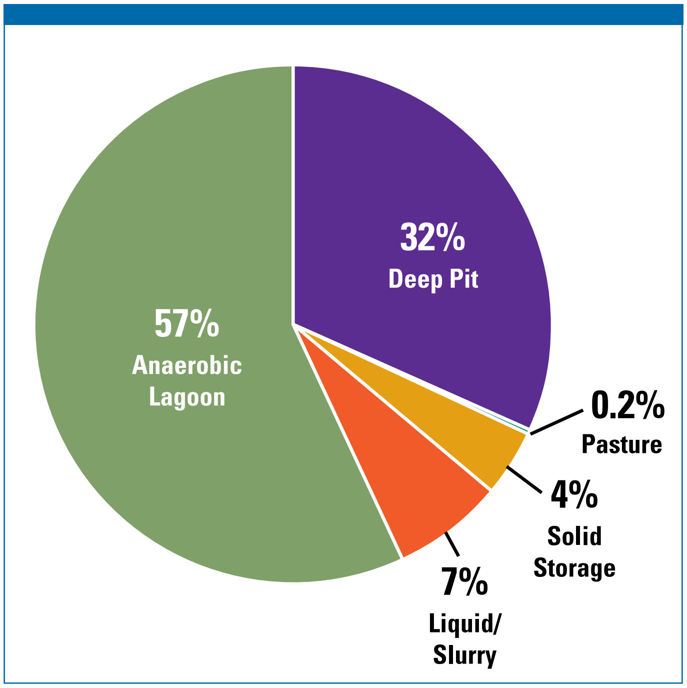
Swine Farm Size



Swine Population by County



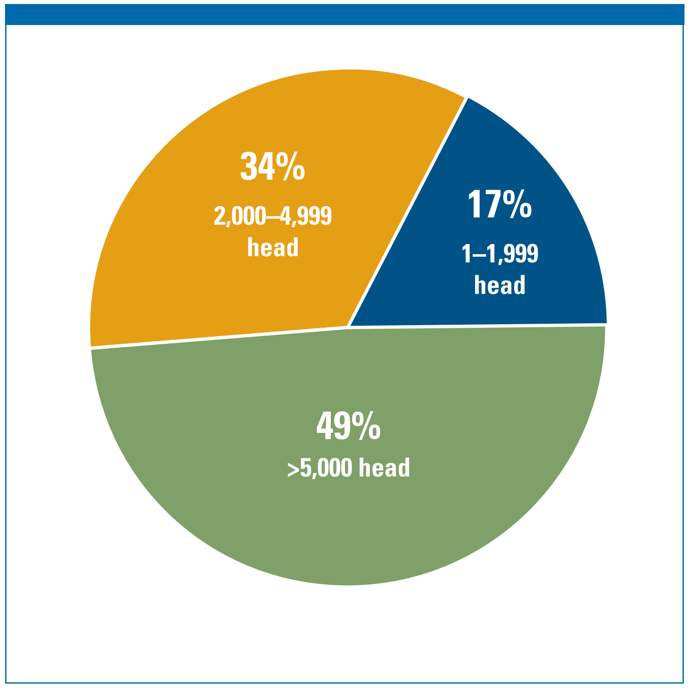
Swine Manure Managed in Each Waste Management System



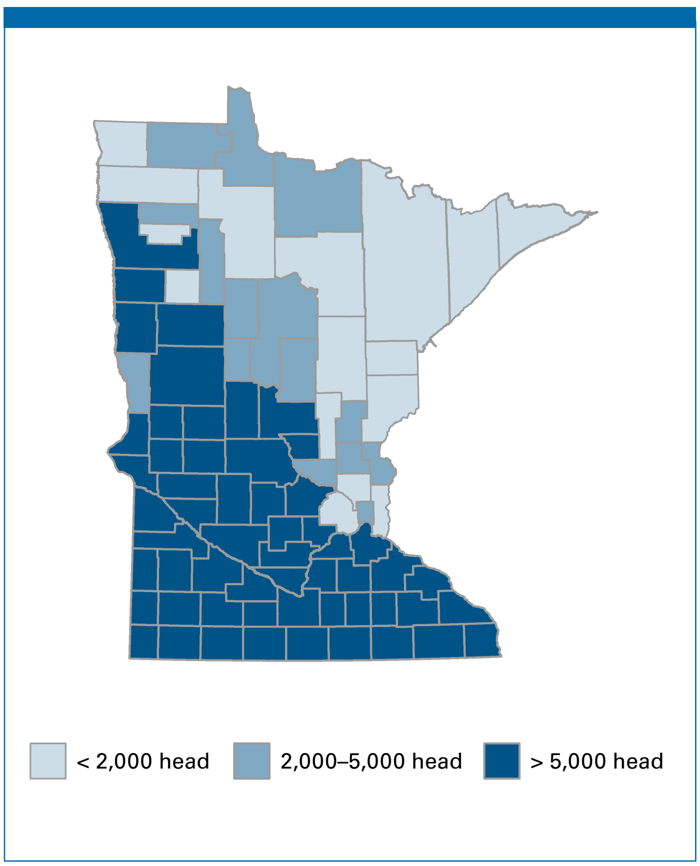
Market Opportunities to Generate Electricity with Anaerobic Digestion (2007)	
Total number of swine operations	4,382
Total number of mature swine (000 head)	7,652
Number of feasible swine operations[1]	707
Number of mature swine at feasible operations (000 head)	4,692
Methane emission reduction potential (000 tons/year)	63
Methane production potential (billion ft^3/year)	7.3
Electricity generation potential (000 MWh/yr)	621

[1] Anaerobic digestion was considered feasible at all existing operations with flush, pit recharge, or pull-plug pit systems with at least 2,000 swine and at deep pit systems with at least 5,000 swine.

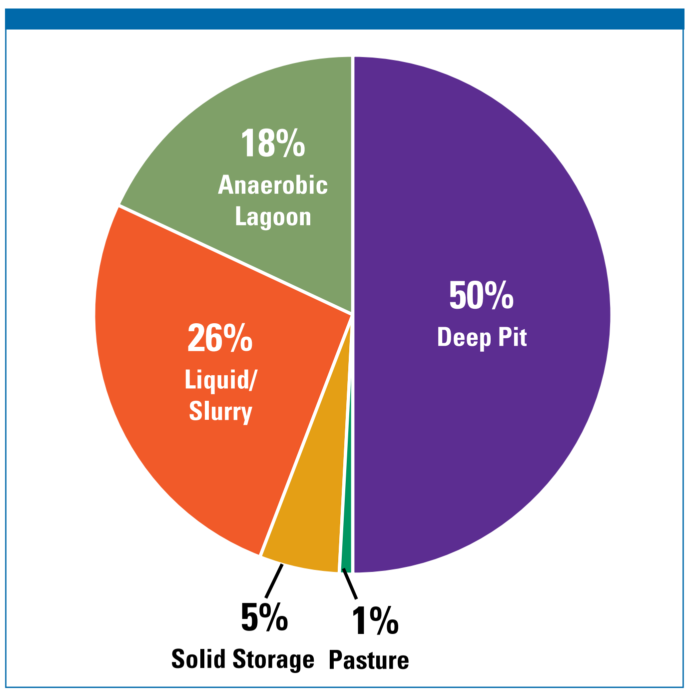
Swine Farm Size



Swine Population by County



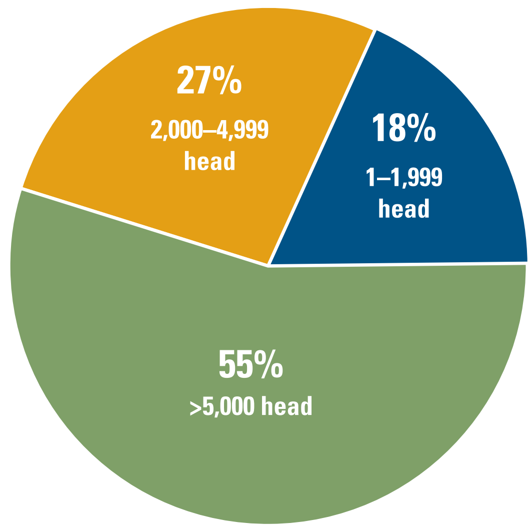
Swine Manure Managed in Each Waste Management System



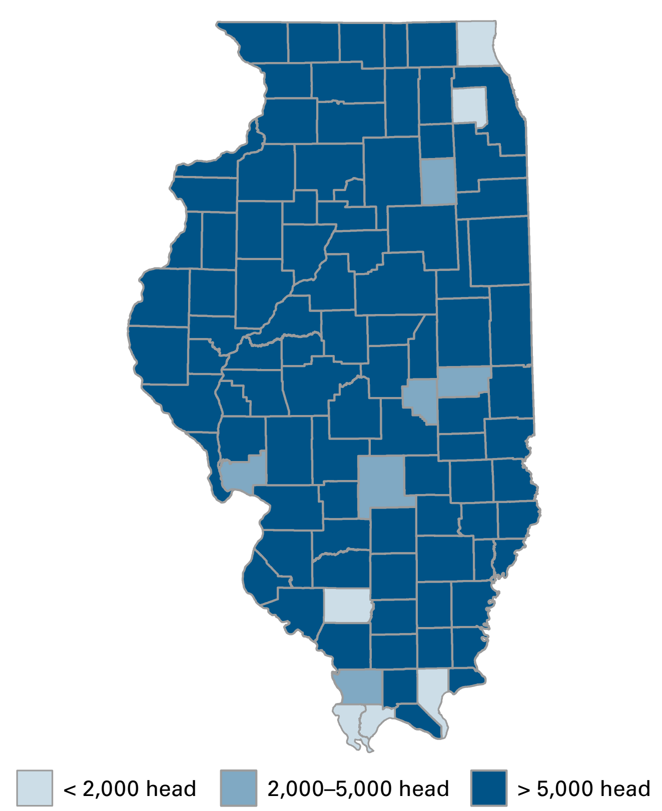
Market Opportunities to Generate Electricity with Anaerobic Digestion (2007)	
Total number of swine operations	2,864
Total number of mature swine (000 head)	4,299
Number of feasible swine operations[1]	350
Number of mature swine at feasible operations (000 head)	2,746
Methane emission reduction potential (000 tons/year)	39
Methane production potential (billion ft^3/year)	4.3
Electricity generation potential (000 MWh/yr)	363

[1] Anaerobic digestion was considered feasible at all existing operations with flush, pit recharge, or pull-plug pit systems with at least 2,000 swine and at deep pit systems with at least 5,000 swine.

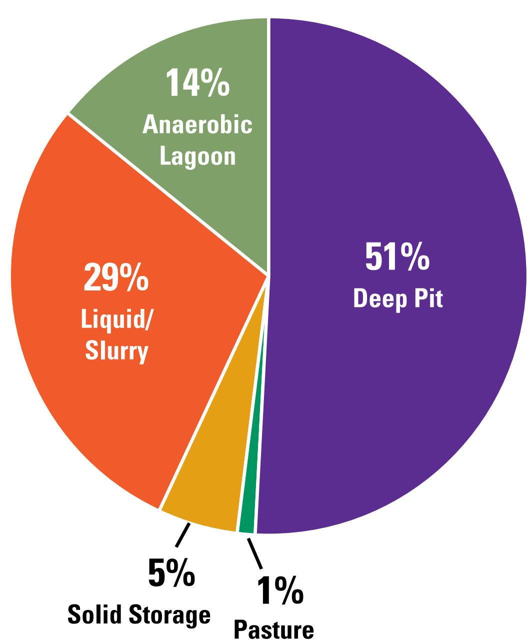
Swine Farm Size



Swine Population by County



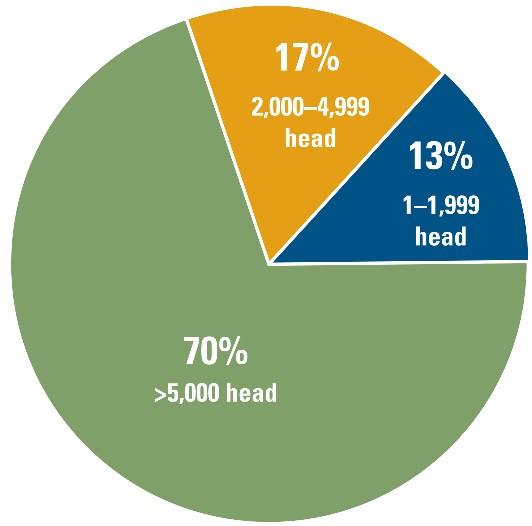
Swine Manure Managed in Each Waste Management System



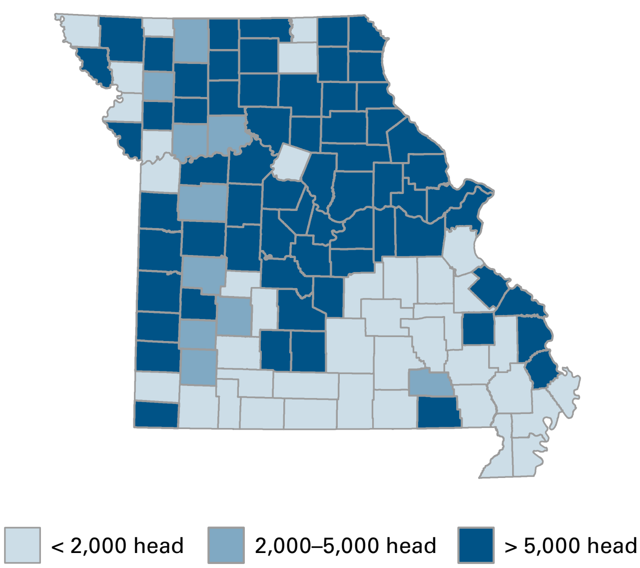
Market Opportunities to Generate Electricity with Anaerobic Digestion (2007)	
Total number of swine operations	2,999
Total number of mature swine (000 head)	3,101
Number of feasible swine operations[1]	154
Number of mature swine at feasible operations (000 head)	2,277
Methane emission reduction potential (000 tons/year)	34
Methane production potential (billion ft^3/year)	3.5
Electricity generation potential (000 MWh/yr)	301

[1] Anaerobic digestion was considered feasible at all existing operations with flush, pit recharge, or pull-plug pit systems with at least 2,000 swine and at deep pit systems with at least 5,000 swine.

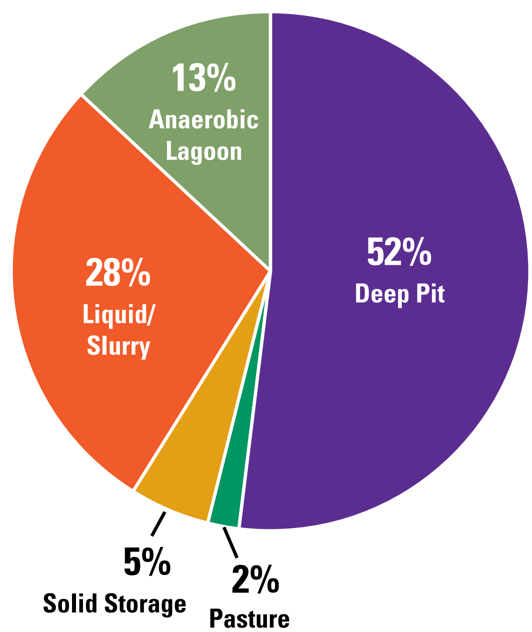
Swine Farm Size



Swine Population by County



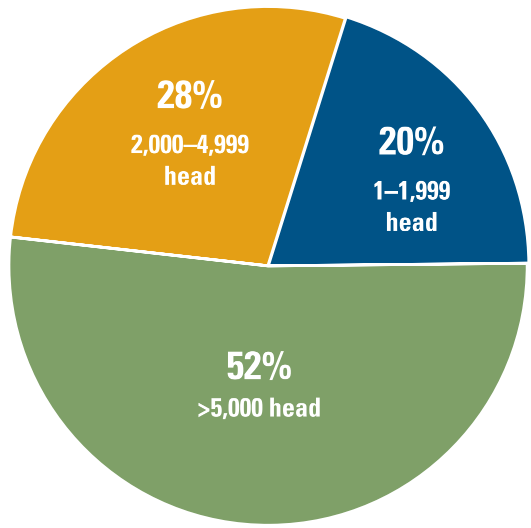
Swine Manure Managed in Each Waste Management System



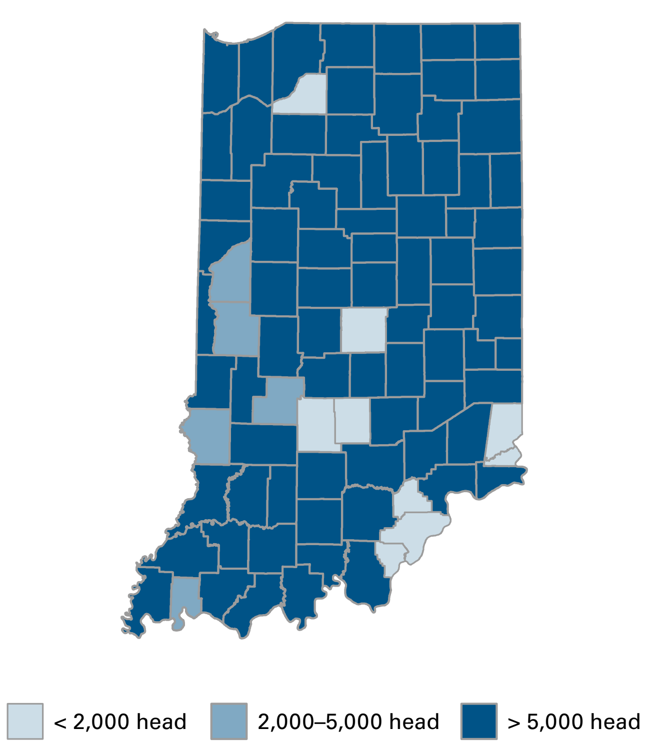
Market Opportunities to Generate Electricity with Anaerobic Digestion (2007)	
Total number of swine operations	3,420
Total number of mature swine (000 head)	3,669
Number of feasible swine operations[1]	296
Number of mature swine at feasible operations (000 head)	2,238
Methane emission reduction potential (000 tons/year)	31
Methane production potential (billion ft^3/year)	3.5
Electricity generation potential (000 MWh/yr)	296

[1] Anaerobic digestion was considered feasible at all existing operations with flush, pit recharge, or pull-plug pit systems with at least 2,000 swine and at deep pit systems with at least 5,000 swine.

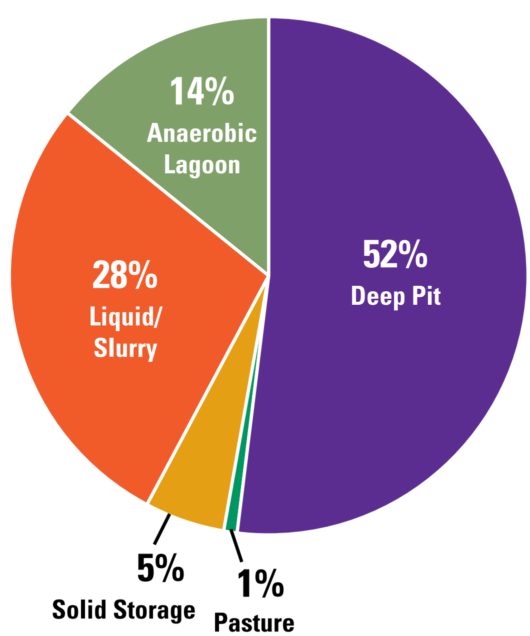
Swine Farm Size



Swine Population by County



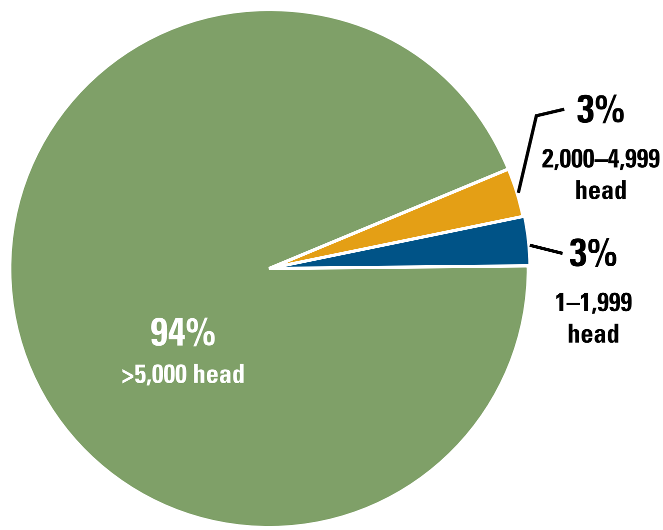
Swine Manure Managed in Each Waste Management System



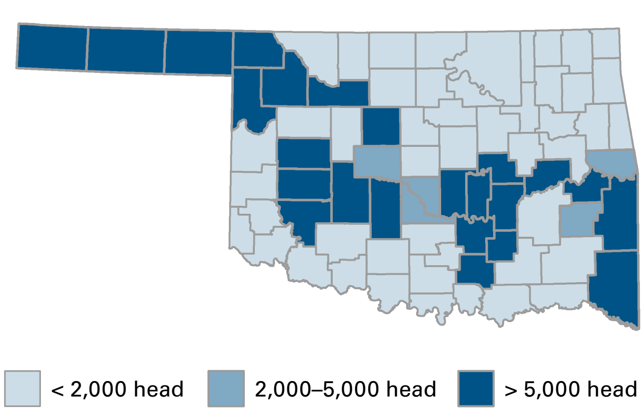
Market Opportunities to Generate Electricity with Anaerobic Digestion (2007)	
Total number of swine operations	2,702
Total number of mature swine (000 head)	2,398
Number of feasible swine operations[1]	56
Number of mature swine at feasible operations (000 head)	2,207
Methane emission reduction potential (000 tons/year)	51
Methane production potential (billion ft^3/year)	3.4
Electricity generation potential (000 MWh/yr)	292

[1] Anaerobic digestion was considered feasible at all existing operations with flush, pit recharge, or pull-plug pit systems with at least 2,000 swine and at deep pit systems with at least 5,000 swine.

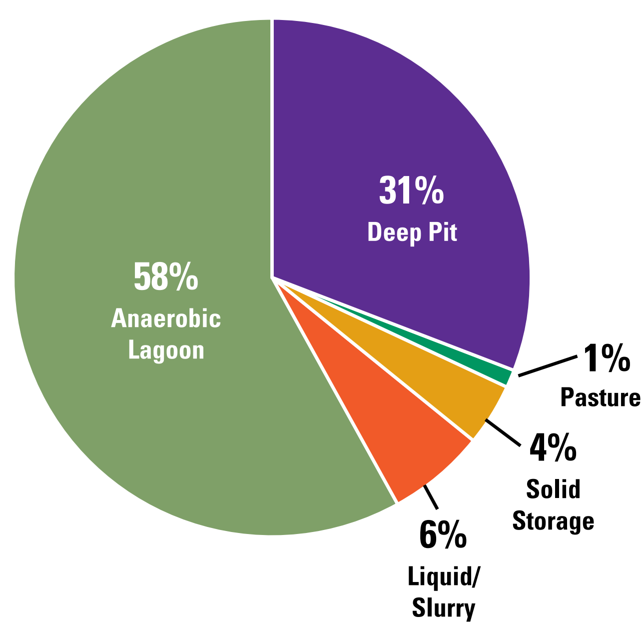
Swine Farm Size



Swine Population by County



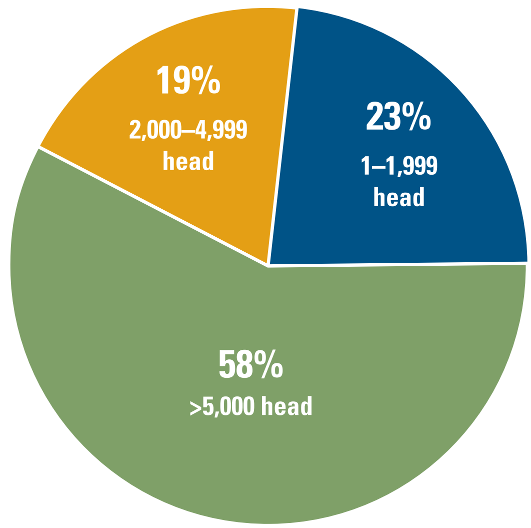
Swine Manure Managed in Each Waste Management System



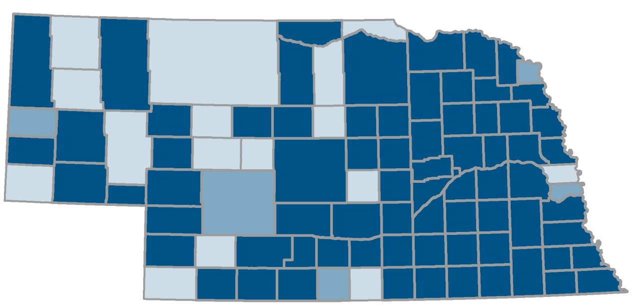
Market Opportunities to Generate Electricity with Anaerobic Digestion (2007)	
Total number of swine operations	2,213
Total number of mature swine (000 head)	3,269
Number of feasible swine operations[1]	177
Number of mature swine at feasible operations (000 head)	2,052
Methane emission reduction potential (000 tons/year)	27
Methane production potential (billion ft^3/year)	3.2
Electricity generation potential (000 MWh/yr)	272

[1] Anaerobic digestion was considered feasible at all existing operations with flush, pit recharge, or pull-plug pit systems with at least 2,000 swine and at deep pit systems with at least 5,000 swine.

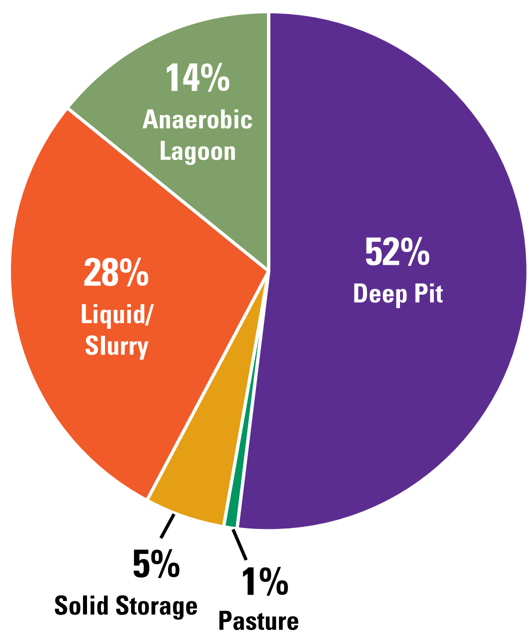
Swine Farm Size



Swine Population by County



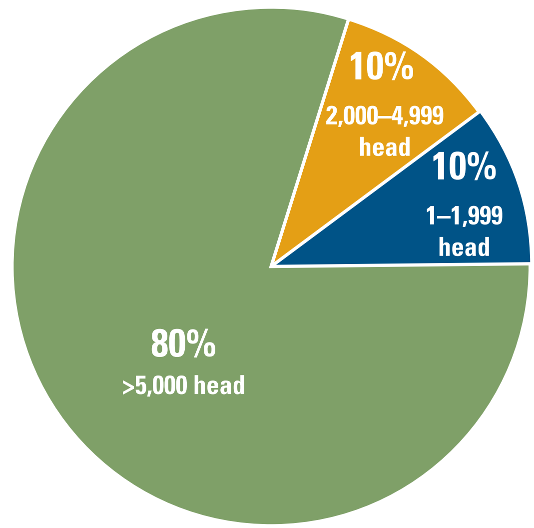
Swine Manure Managed in Each Waste Management System



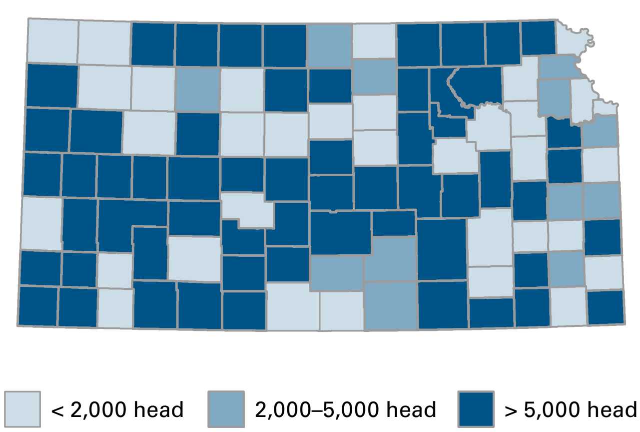
Market Opportunities to Generate Electricity with Anaerobic Digestion (2007)	
Total number of swine operations	1,454
Total number of mature swine (000 head)	1,885
Number of feasible swine operations[1]	80
Number of mature swine at feasible operations (000 head)	1,508
Methane emission reduction potential (000 tons/year)	22
Methane production potential (billion ft^3/year)	2.3
Electricity generation potential (000 MWh/yr)	199

[1] Anaerobic digestion was considered feasible at all existing operations with flush, pit recharge, or pull-plug pit systems with at least 2,000 swine and at deep pit systems with at least 5,000 swine.

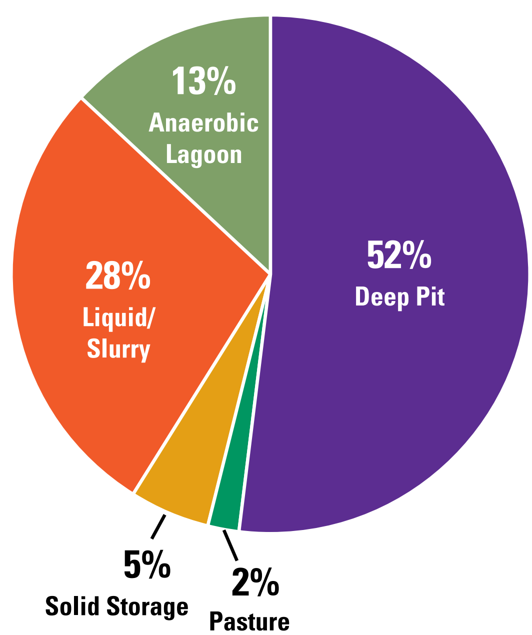
Swine Farm Size



Swine Population by County



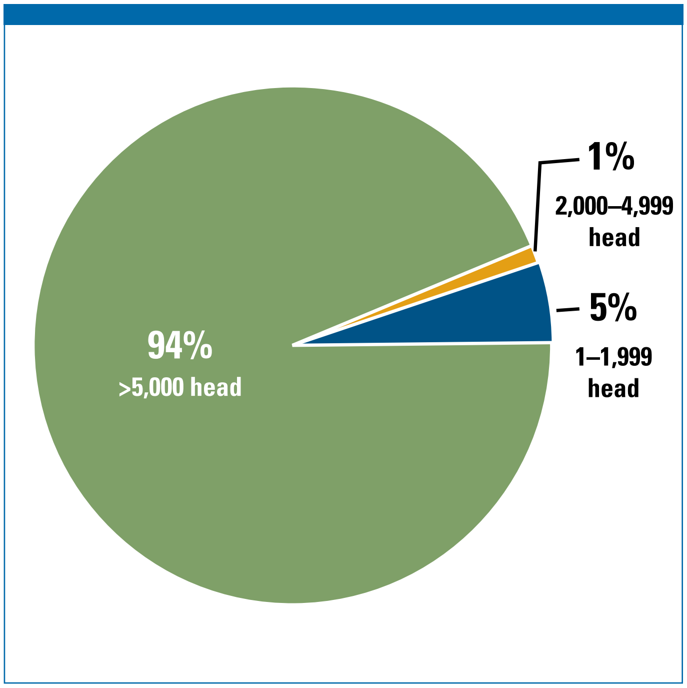
Swine Manure Managed in Each Waste Management System



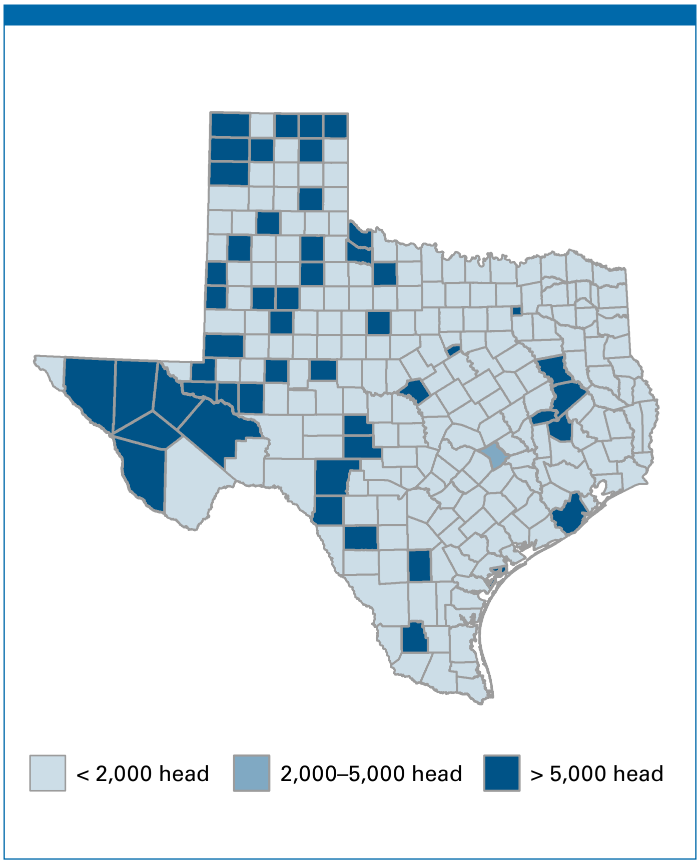
Market Opportunities to Generate Electricity with Anaerobic Digestion (2007)	
Total number of swine operations	4,471
Total number of mature swine (000 head)	1,156
Number of feasible swine operations[1]	10
Number of mature swine at feasible operations (000 head)	1,057
Methane emission reduction potential (000 tons/year)	25
Methane production potential (billion ft^3/year)	1.6
Electricity generation potential (000 MWh/yr)	140

[1] Anaerobic digestion was considered feasible at all existing operations with flush, pit recharge, or pull-plug pit systems with at least 2,000 swine and at deep pit systems with at least 5,000 swine.

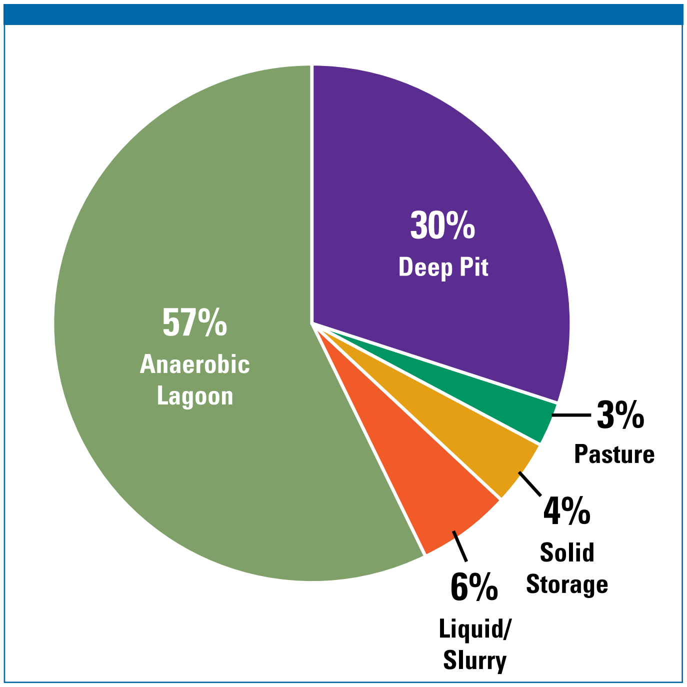
Swine Farm Size



Swine Population by County



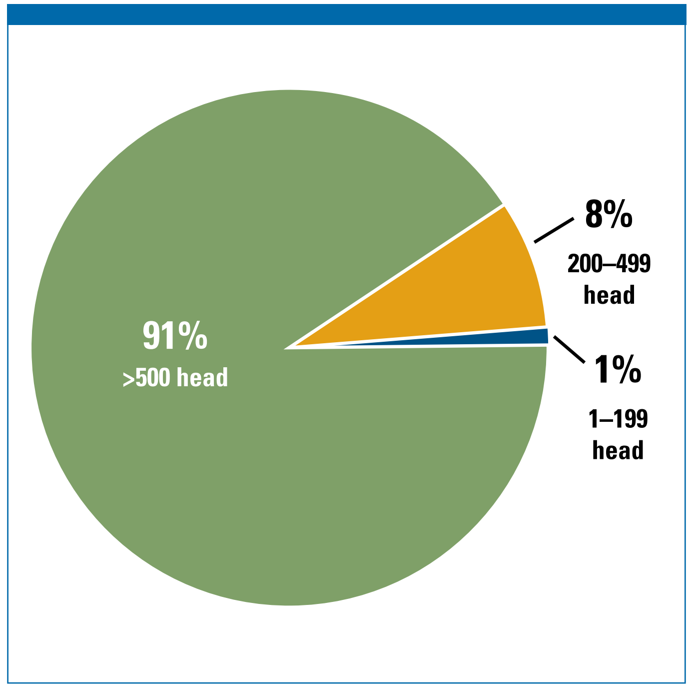
Swine Manure Managed in Each Waste Management System



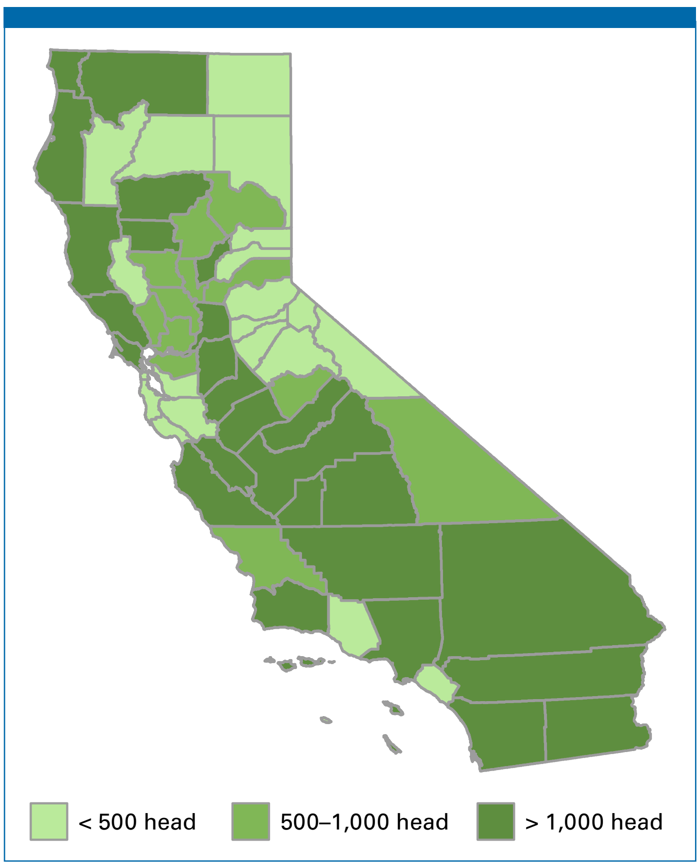
Market Opportunities to Generate Electricity with Anaerobic Digestion (2007)	
Total number of dairy operations	2,165
Total number of mature dairy cows (000 head)	1,841
Number of feasible dairy cow operations[1]	889
Number of mature dairy cows at feasible operations (000 head)	1,352
Methane emission reduction potential (000 tons/year)	341
Methane production potential (billion ft^3/year)	27.9
Electricity generation potential (000 MWh/yr)	2,375

[1] Anaerobic digestion was considered feasible at all existing operations with flushed or scraped freestall barns and drylots with at least 500 dairy cows.

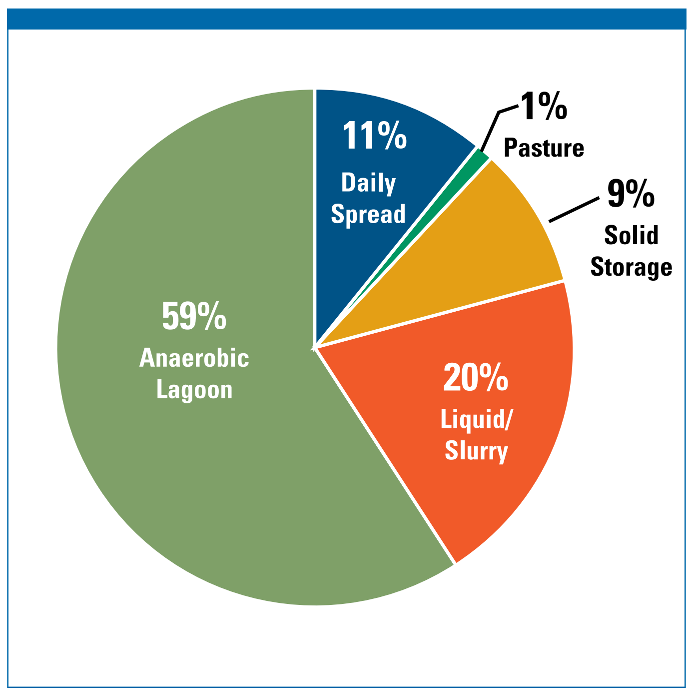
Dairy Farm Size



Dairy Population by County



Dairy Manure Managed in Each Waste Management System

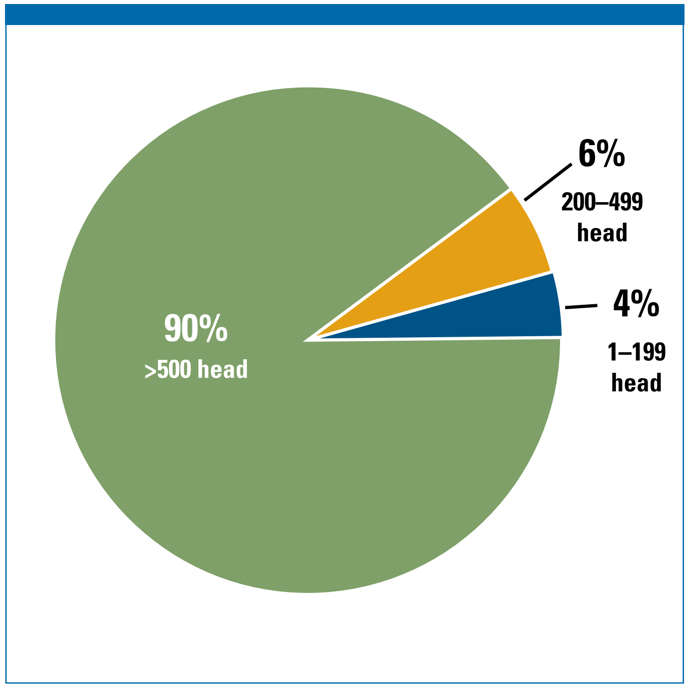


Market Opportunities to Generate Electricity with Anaerobic Digestion (2007)

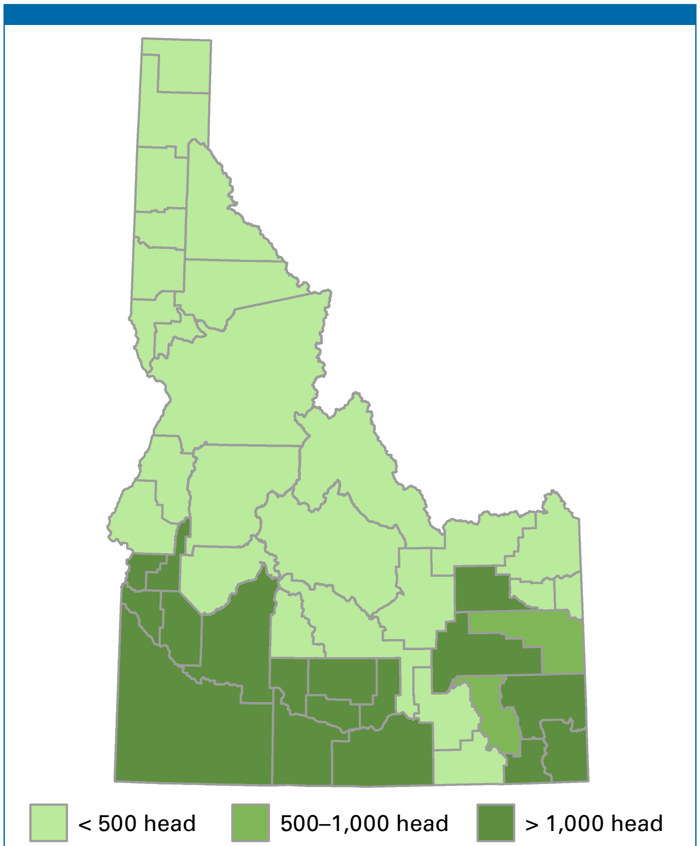
Total number of dairy operations	811
Total number of mature dairy cows (000 head)	536
Number of feasible dairy cow operations[1]	203
Number of mature dairy cows at feasible operations (000 head)	430
Methane emission reduction potential (000 tons/year)	99
Methane production potential (billion ft^3/year)	8.9
Electricity generation potential (000 MWh/yr)	762

[1] Anaerobic digestion was considered feasible at all existing operations with flushed or scraped freestall barns and drylots with at least 500 dairy cows.

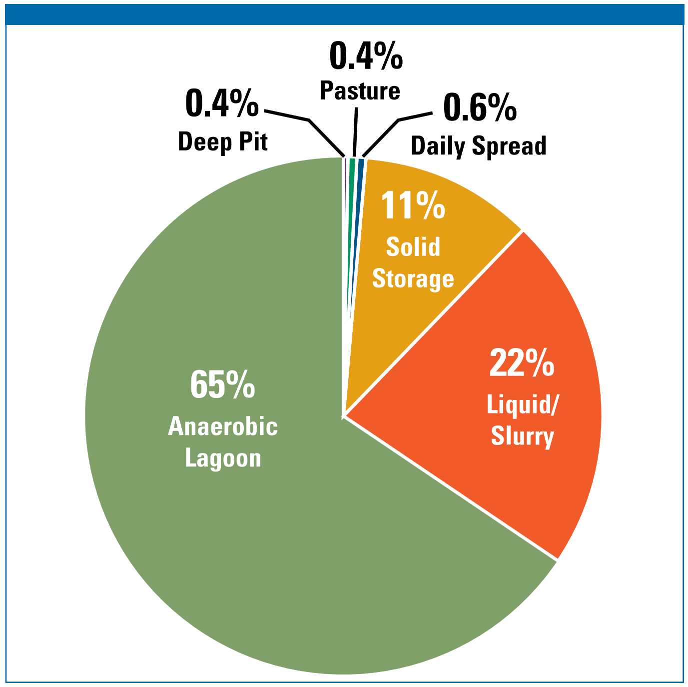
Dairy Farm Size



Dairy Population by County



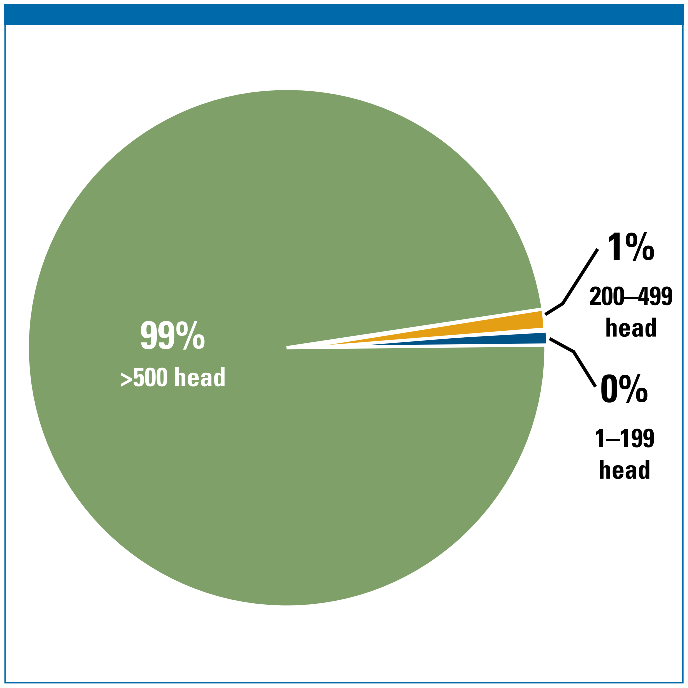
Dairy Manure Managed in Each Waste Management System



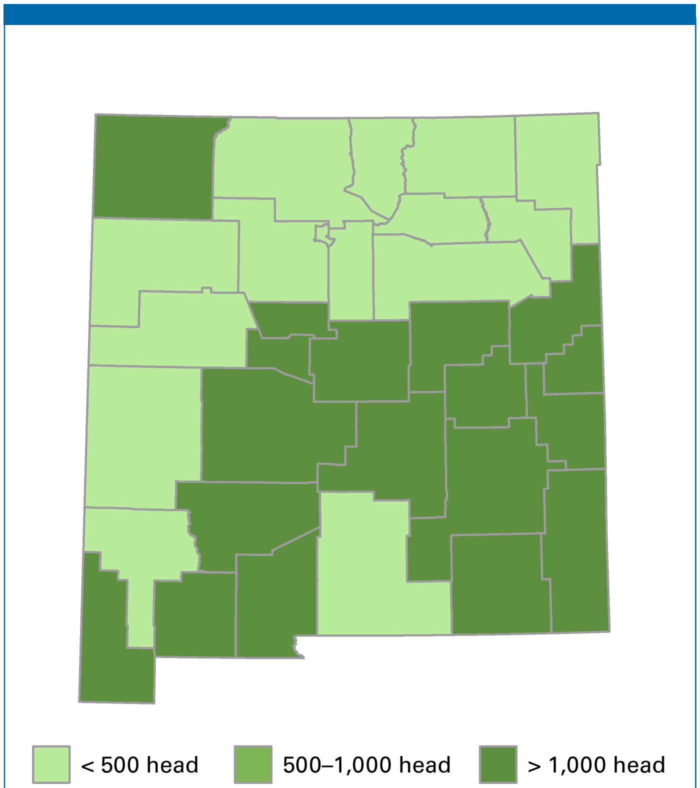
Market Opportunities to Generate Electricity with Anaerobic Digestion (2007)	
Total number of dairy operations	272
Total number of mature dairy cows (000 head)	326
Number of feasible dairy cow operations[1]	110
Number of mature dairy cows at feasible operations (000 head)	261
Methane emission reduction potential (000 tons/year)	64
Methane production potential (billion ft^3/year)	5.3
Electricity generation potential (000 MWh/yr)	455

[1] Anaerobic digestion was considered feasible at all existing operations with flushed or scraped freestall barns and drylots with at least 500 dairy cows.

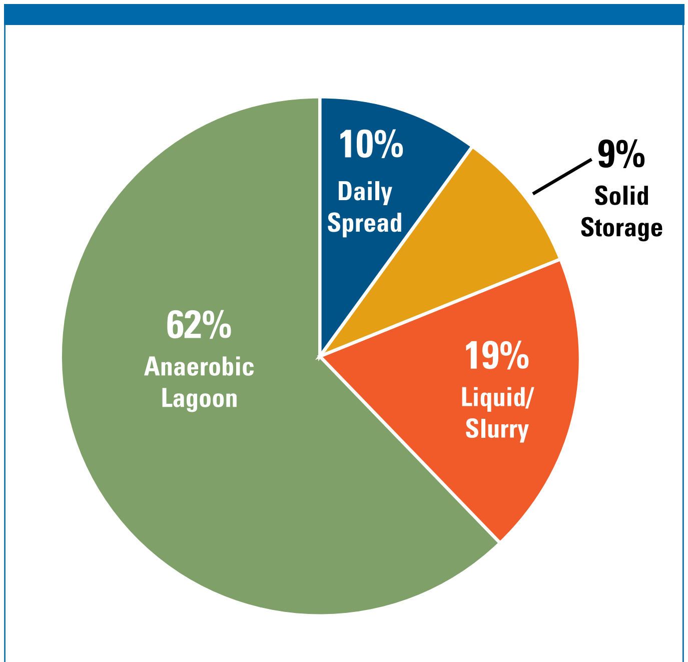
Dairy Farm Size



Dairy Population by County



Dairy Manure Managed in Each Waste Management System

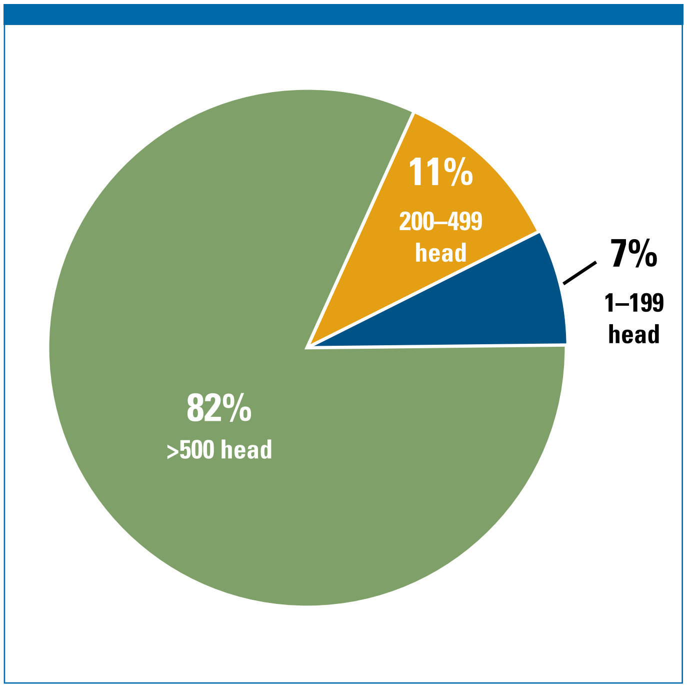


Market Opportunities to Generate Electricity with Anaerobic Digestion (2007)

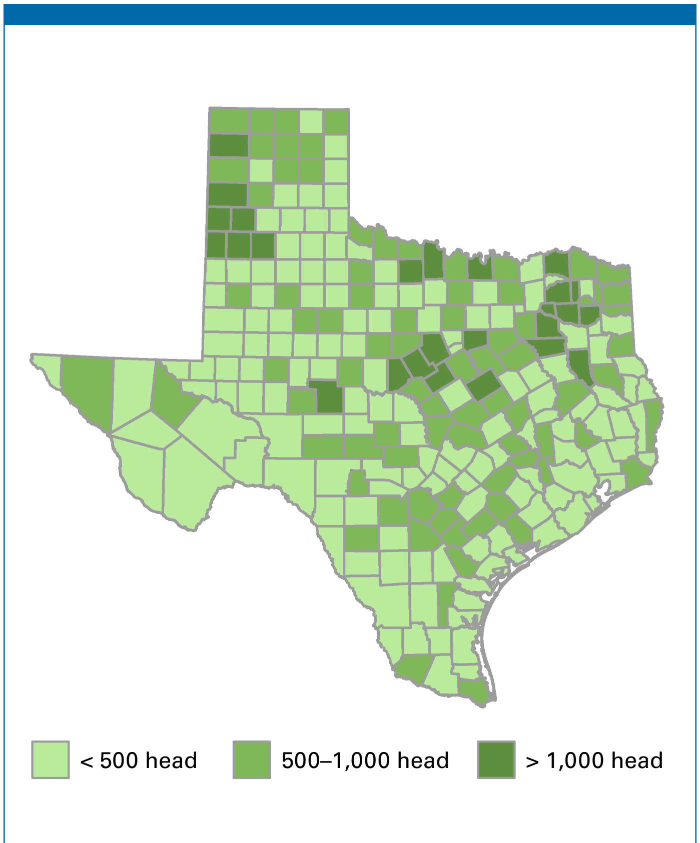
Total number of dairy operations	1,293
Total number of mature dairy cows (000 head)	404
Number of feasible dairy cow operations[1]	155
Number of mature dairy cows at feasible operations (000 head)	266
Methane emission reduction potential (000 tons/year)	66
Methane production potential (billion ft^3/year)	5.0
Electricity generation potential (000 MWh/yr)	429

[1] Anaerobic digestion was considered feasible at all existing operations with flushed or scraped freestall barns and drylots with at least 500 dairy cows.

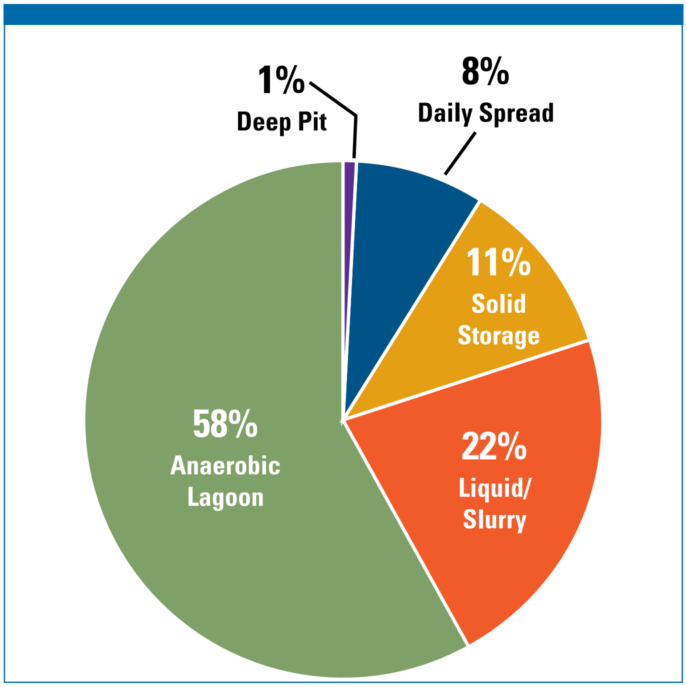
Dairy Farm Size



Dairy Population by County



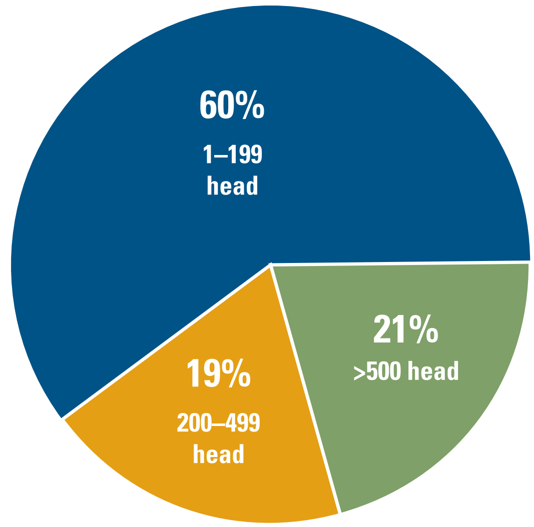
Dairy Manure Managed in Each Waste Management System



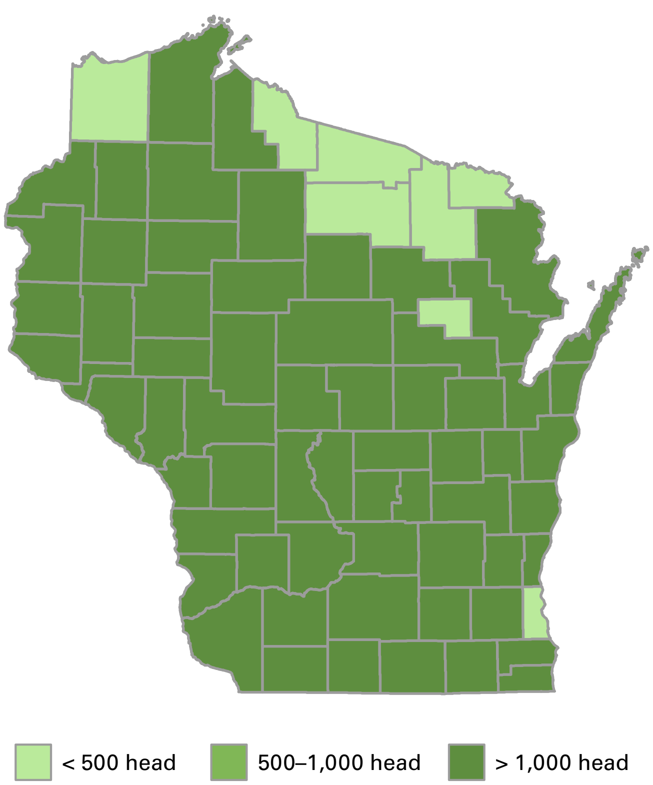
Market Opportunities to Generate Electricity with Anaerobic Digestion (2007)	
Total number of dairy operations	14,158
Total number of mature dairy cows (000 head)	1,249
Number of feasible dairy cow operations[1]	251
Number of mature dairy cows at feasible operations (000 head)	238
Methane emission reduction potential (000 tons/year)	41
Methane production potential (billion ft^3/year)	4.5
Electricity generation potential (000 MWh/yr)	386

[1] Anaerobic digestion was considered feasible at all existing operations with flushed or scraped freestall barns and drylots with at least 500 dairy cows.

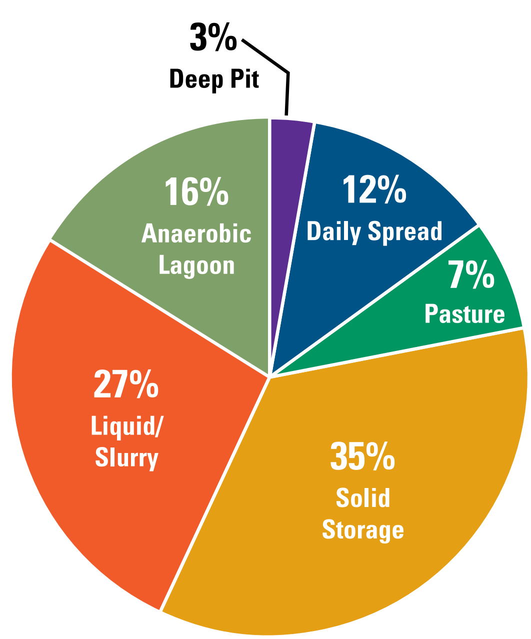
Dairy Farm Size



Dairy Population by County



Dairy Manure Managed in Each Waste Management System

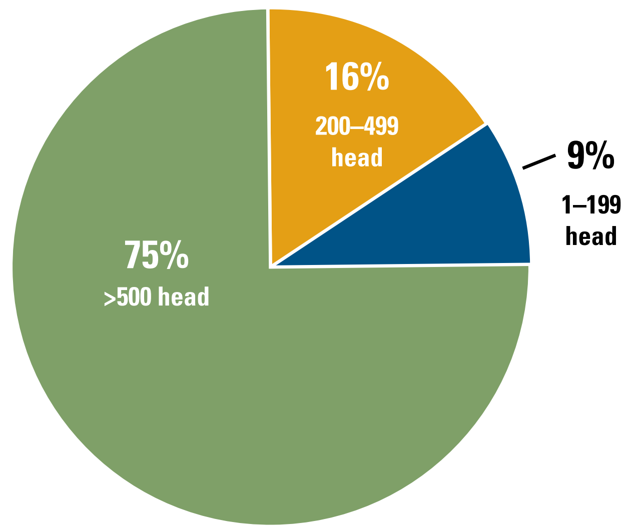


Market Opportunities to Generate Electricity with Anaerobic Digestion (2007)

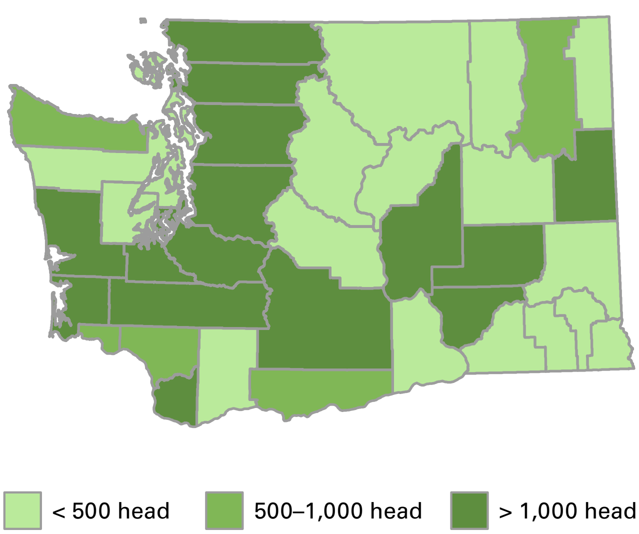
Total number of dairy operations	817
Total number of mature dairy cows (000 head)	243
Number of feasible dairy cow operations[1]	125
Number of mature dairy cows at feasible operations (000 head)	163
Methane emission reduction potential (000 tons/year)	35
Methane production potential (billion ft³/year)	3.4
Electricity generation potential (000 MWh/yr)	294

[1] Anaerobic digestion was considered feasible at all existing operations with flushed or scraped freestall barns and drylots with at least 500 dairy cows.

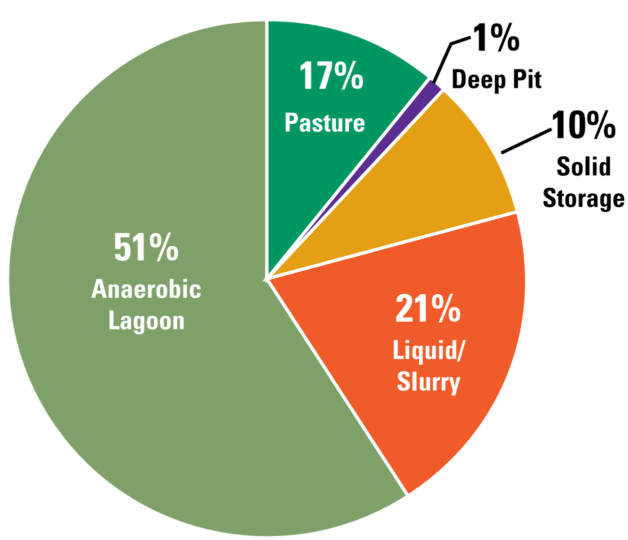
Dairy Farm Size



Dairy Population by County



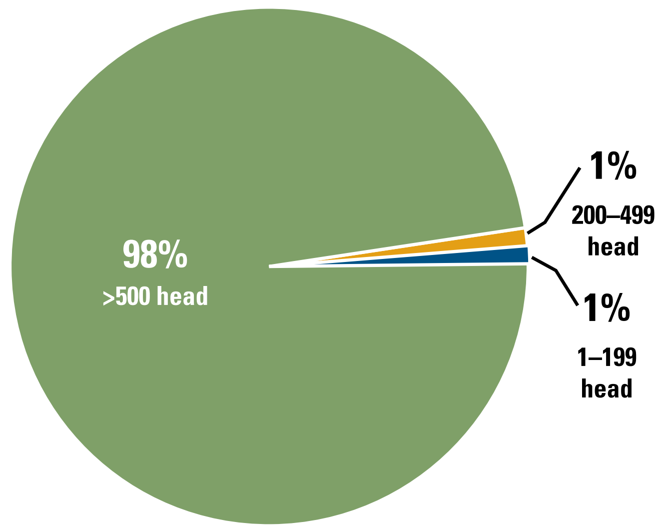
Dairy Manure Managed in Each Waste Management System



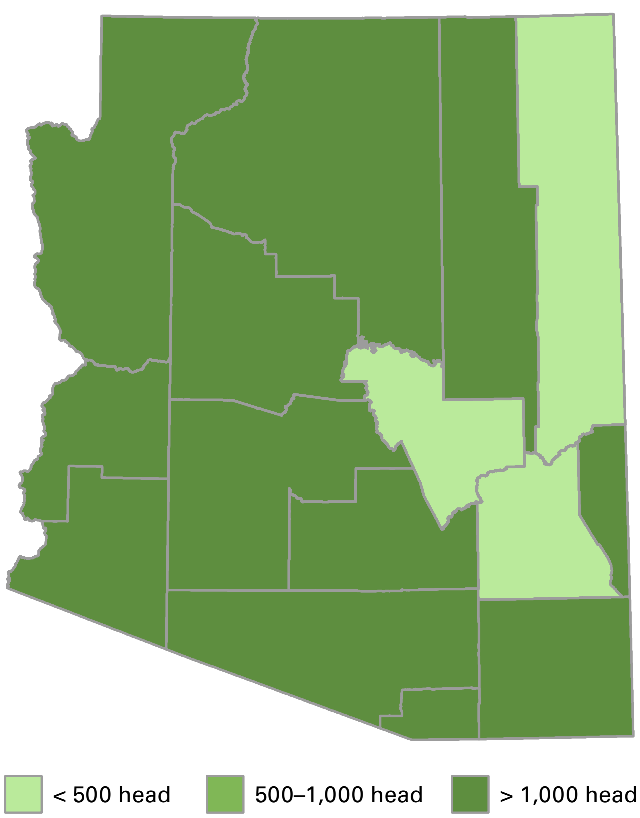
Market Opportunities to Generate Electricity with Anaerobic Digestion (2007)	
Total number of dairy operations	182
Total number of mature dairy cows (000 head)	184
Number of feasible dairy cow operations[1]	54
Number of mature dairy cows at feasible operations (000 head)	146
Methane emission reduction potential (000 tons/year)	44
Methane production potential (billion ft^3/year)	3.1
Electricity generation potential (000 MWh/yr)	263

[1] Anaerobic digestion was considered feasible at all existing operations with flushed or scraped freestall barns and drylots with at least 500 dairy cows.

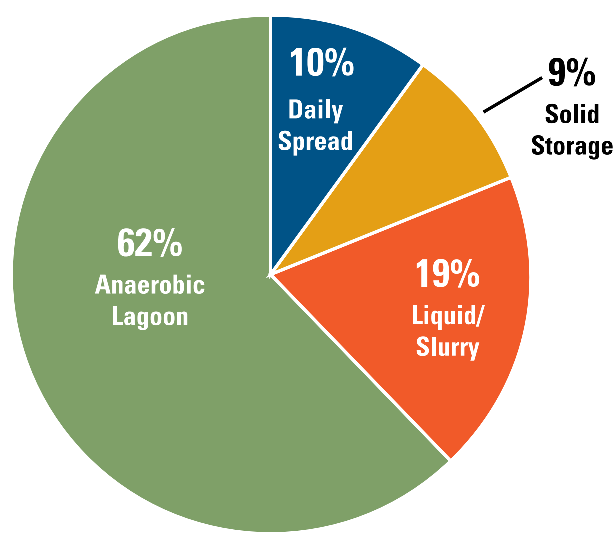
Dairy Farm Size



Dairy Population by County



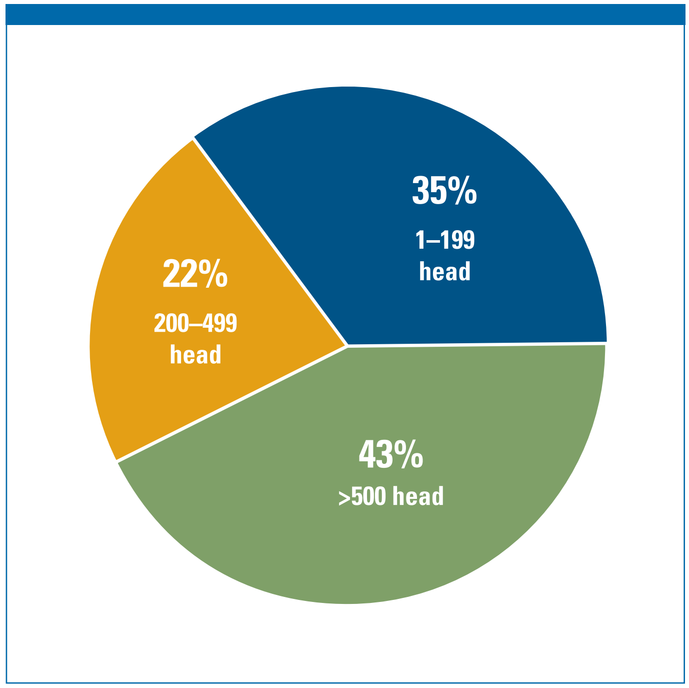
Dairy Manure Managed in Each Waste Management System



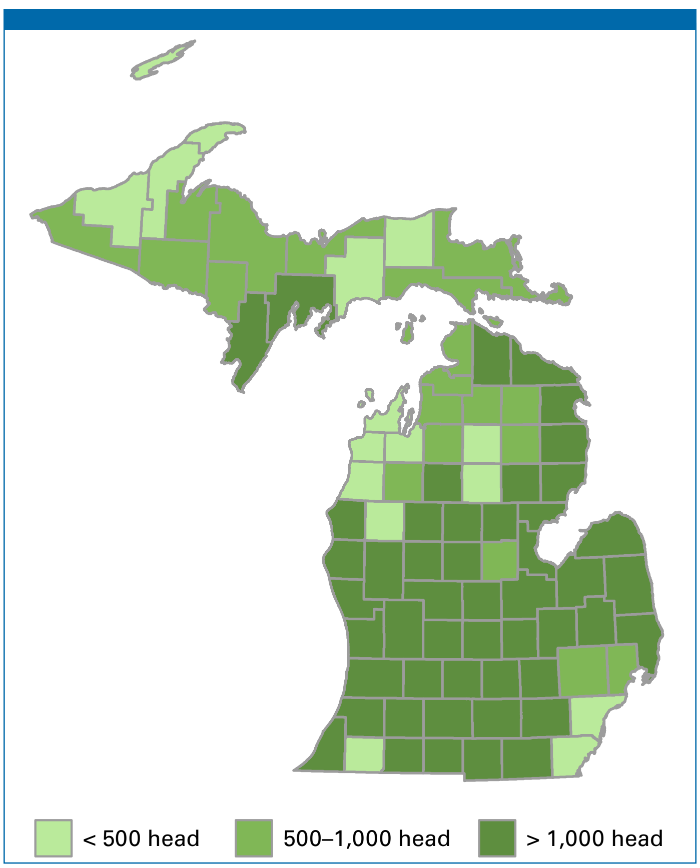
Market Opportunities to Generate Electricity with Anaerobic Digestion (2007)	
Total number of dairy operations	2,647
Total number of mature dairy cows (000 head)	344
Number of feasible dairy cow operations[1]	107
Number of mature dairy cows at feasible operations (000 head)	138
Methane emission reduction potential (000 tons/year)	26
Methane production potential (billion ft^3/year)	2.9
Electricity generation potential (000 MWh/yr)	246

[1] Anaerobic digestion was considered feasible at all existing operations with flushed or scraped freestall barns and drylots with at least 500 dairy cows.

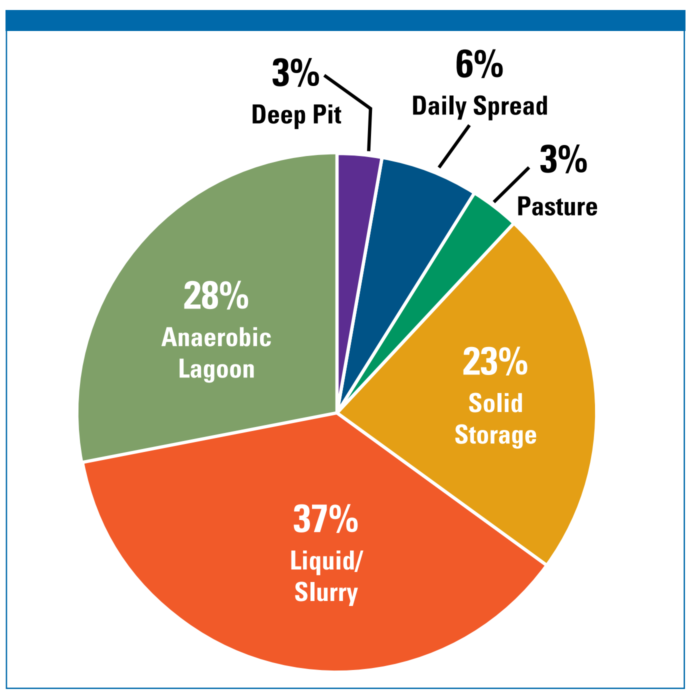
Dairy Farm Size



Dairy Population by County



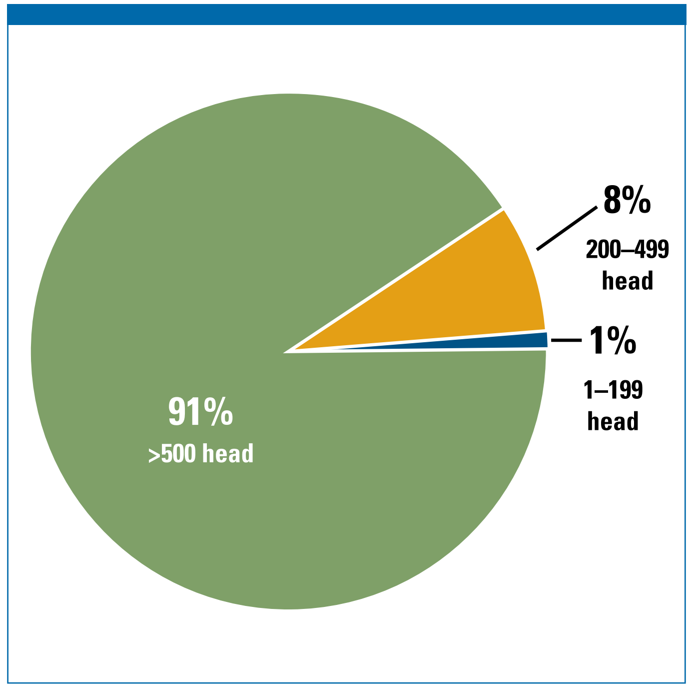
Dairy Manure Managed in Each Waste Management System



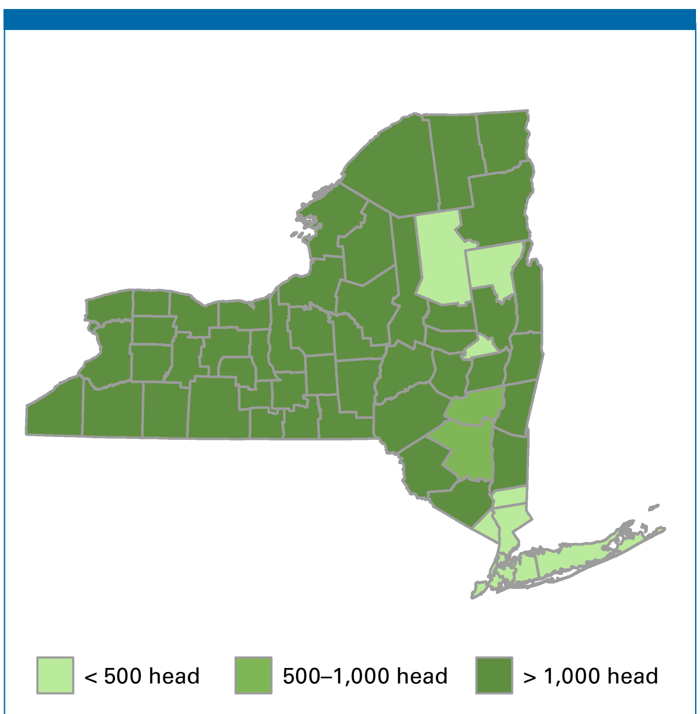
Market Opportunities to Generate Electricity with Anaerobic Digestion (2007)	
Total number of dairy operations	5,683
Total number of mature dairy cows (000 head)	626
Number of feasible dairy cow operations[1]	111
Number of mature dairy cows at feasible operations (000 head)	109
Methane emission reduction potential (000 tons/year)	18
Methane production potential (billion ft^3/year)	2.1
Electricity generation potential (000 MWh/yr)	177

[1] Anaerobic digestion was considered feasible at all existing operations with flushed or scraped freestall barns and drylots with at least 500 dairy cows.

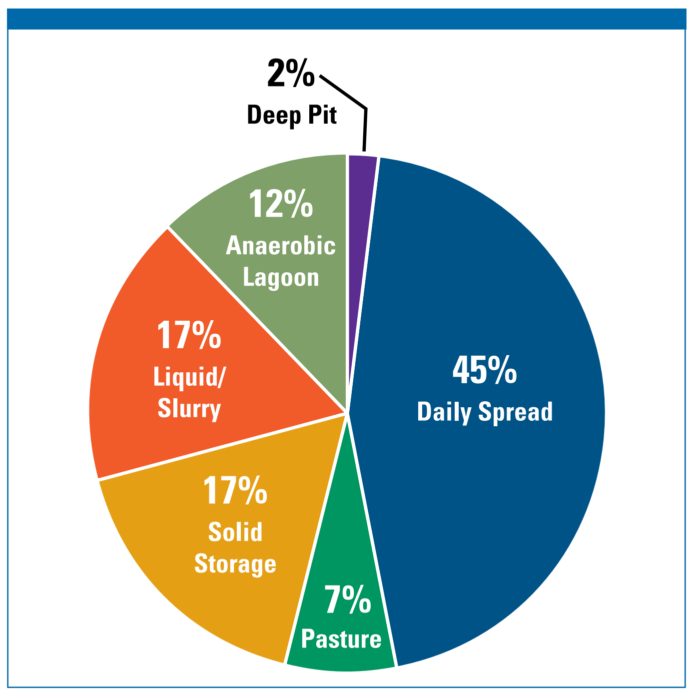
Dairy Farm Size



Dairy Population by County



Dairy Manure Managed in Each Waste Management System

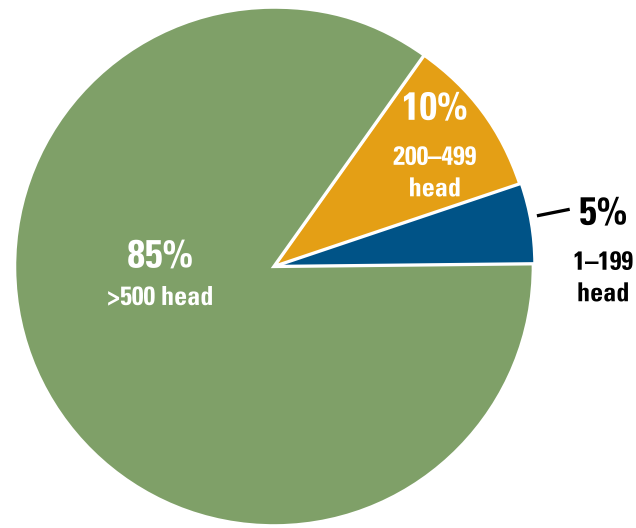


Market Opportunities to Generate Electricity with Anaerobic Digestion (2007)

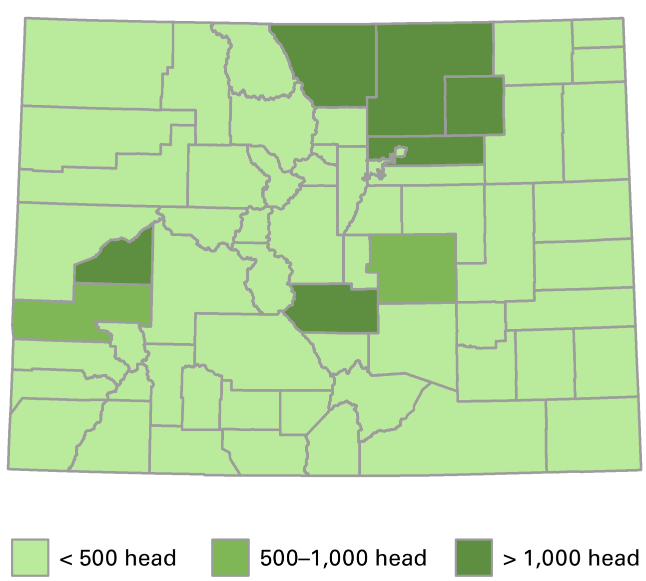
Total number of dairy operations	449
Total number of mature dairy cows (000 head)	127
Number of feasible dairy cow operations[1]	54
Number of mature dairy cows at feasible operations (000 head)	97
Methane emission reduction potential (000 tons/year)	22
Methane production potential (billion ft^3/year)	2.0
Electricity generation potential (000 MWh/yr)	174

[1] Anaerobic digestion was considered feasible at all existing operations with flushed or scraped freestall barns and drylots with at least 500 dairy cows.

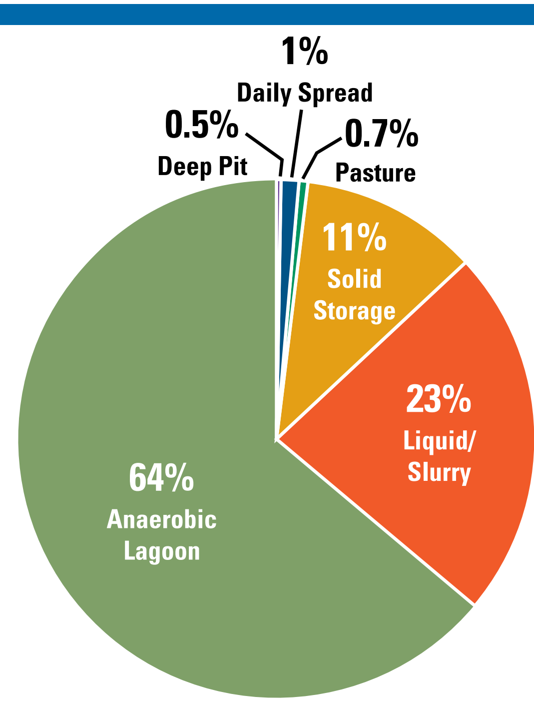
Dairy Farm Size



Dairy Population by County



Dairy Manure Managed in Each Waste Management System



AgSTAR is an outreach program jointly sponsored by the U.S. Environmental Protection Agency, the U.S. Department of Agriculture, and the U.S. Department of Energy. The program encourages the use of biogas recovery technologies at confined animal feeding operations that manage manure as liquids or slurries. These technologies reduce emissions of methane (a potent greenhouse gas), generate clean energy, and achieve other environmental benefits. For additional information, please visit our website at www.epa.gov/agstar.