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

AgSTAR

EPA United States Environmental Protection Agency

www.epa.gov/agstar

June 2018

EPA-430-R-18-006

AgSTAR is an outreach program jointly sponsored by the U.S. Environmental Protection Agency, the U.S. Department of Agriculture (USDA), 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.

Contents

Introduction

Biogas is a valuable byproduct 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.

A biogas capture and use project is most likely to succeed where 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 energy from these management systems are also being developed.

Biogas can be collected from manure and burned to meet on-farm energy needs such as electricity, heating, and cooling. Surplus electricity or biogas can also be sold to neighboring operations or the utility grid. As of August 2017, AgSTAR estimates, 250 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: an estimated 8,100 U.S. dairy and swine operations (Table 1) could support biogas recovery systems. These systems may also be feasible at some poultry and beef lot operations as new and improved technologies for these manure types enter the market.

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

Animal Sector	Candidate Farms	Energy Generating Potential		
		MW	MWh/year	Thousands of MMBtu/year
Swine	5,409	837	6,597,520	71,484
Dairy	2,704	1,172	9,240,893	100,124
Total	**8,113**	**2,009**	**15,838,413**	**171,608**

Document Update History

This document updates AgSTAR's 2011 *Market Opportunities for Biogas Recovery Systems at U.S. Livestock Facilities*. It includes updates to USDA data and minor revisions to calculation methodologies or default factors used in calculations. For example, for swine and dairy population data, EPA used USDA's *2012 Census of Agriculture* instead of the *2007 Census of Agriculture*. For manure management system data and calculations, EPA used the updated *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990–2015*. Methane's global warming potential (GWP), which is used to estimate emission reductions, was updated from 21 to 25 times the heat trapping capacity of carbon dioxide (CO_2) to be consistent with the *Inventory* and with Intergovernmental Panel on Climate Change (IPCC) *Fourth Assessment Report: Climate Change 2007 (AR4)*.

Appendix B of this report includes data and analysis from specific swine- and dairy-producing states based on data in EPA's previous report. EPA believes that agricultural practices have not changed significantly in these states since the previous publication.

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 air and water quality benefits for managing these wastes.

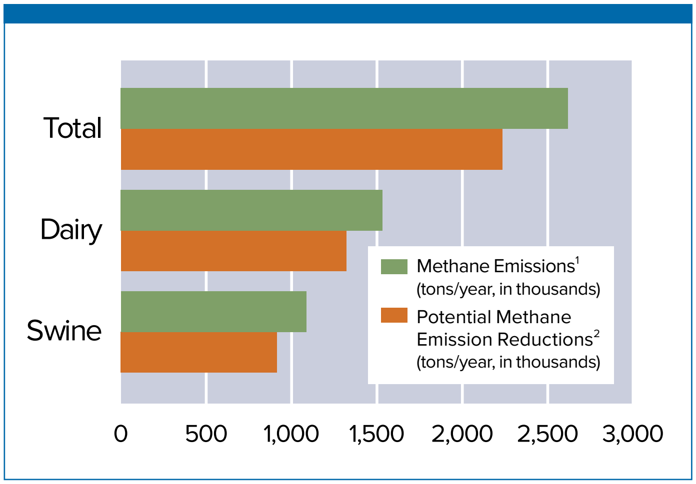
Odor control: Anaerobically digested manures produce significantly less odor than conventional storage and land application systems. Stored livestock manure's odor mainly comes from volatile organic acids and hydrogen sulfide, which has a "rotten egg" smell. In an anaerobic digester, volatile organic 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 destroyed during combustion.

Water quality protection and land conservation: Anaerobic digestion provides several water quality and land conservation 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 biochemical 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. In addition to protecting local water resources, implementing anaerobic digesters on livestock facilities improves soil health. The addition of digestate to soil increases the organic matter content, reduces the need for chemical fertilizers, improves plant growth, and alleviates soil compaction. In addition, digestion converts nutrients in manure to a more accessible form for plants to use.

Methane reduction: Digesters reduce emissions. Methane is a potent greenhouse gas with a GWP about 25 times more powerful than that of carbon dioxide over 100 year. In 2015, EPA estimates, livestock and poultry manure was responsible for approximately 10 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 could reduce their methane emissions by about 85 percent—2.2 million tons per year.

The use of biogas to generate energy can also offset fossil fuel use, which in turn lowers emissions of CO_2, another critical greenhouse gas.

Figure 1. 2015 Methane Emissions and Potential Reductions at Swine and Dairy Operations Where Anaerobic Digesters Are Economically Feasible



[1] Emissions based on 2015 values from EPA's *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990–2015*.

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

Economic Benefits

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 energy use, which can take several different forms. Biogas can be used as a direct fuel source for heating, boilers, chillers, or drying, or upgraded to a cleaner gas and used as vehicle fuel or put into natural gas pipelines for sale. It can also be combusted in an engine-generator to produce electricity, which can power on-farm operations or be 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. Harnessing power from anaerobic digestion gives farmers energy independence by allowing them to operate "off the grid." Furthermore, energy added to the grid by anaerobic digestion helps local utilities meet renewable energy goals.

Valuable byproducts: Another benefit of anaerobic digestion is the variety of byproducts that can be created from the digestate (digester effluent) solids. Examples include fertilizer, livestock bedding, and soil amendments that can be used at the farm or sold. Maximizing the value of manure through anaerobic digestion helps facilities diversify their revenue and strengthens their resiliency to market fluctuations.

Tipping fees: Where feasible, facilities may accept organic waste streams from off site, including livestock manure from neighboring farms or organic waste from local food-processing plants, groceries, restaurants, schools, or other institutions. In many cases, facilities accepting offsite waste may charge a tipping fee to manage these non-farm waste streams. In addition to boosting direct revenues, the co-digestion of non-farm organic waste streams produces additional biogas.

Renewable energy credits and greenhouse gas markets: Using biogas for energy reduces methane emissions and reduces demand for fossil fuels for heating or electricity. In 29 states plus the District of Columbia and three territories, electricity produced from biogas may qualify operations with a digester to receive renewable energy credits or a premium price for their green power.

Positive public image: The successful operation of an anaerobic digester limits the impacts of a farm on the local community and promotes a positive public image. Farms with digesters often run regular tours that educate groups about the technology and its environmental benefits. By connecting with their communities, farmers maintain good relationships with their neighbors, which is good for business and can make farm expansions more palatable.

Identifying Profitable Systems

Candidate farms for biogas recovery systems were identified using the characteristics described in Table 2. These characteristics were chosen based on AgSTAR evaluations of the technical and economic performance of successful digester systems operating on commercial-scale swine and dairy farms. (Appendix A offers details on the methodology for identifying candidate farms and estimating their energy production potential.)

Table 2. Typical Characteristics for Profitable Biogas Recovery Systems

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

[1] Assuming total solids content below 15 percent and at least weekly manure collection.

[2] Swine confinement houses in cool regions, such as the upper Midwest, commonly use deep pits under slatted floors. Biogas systems are not currently used with deep pits, which would need to be modified to remove manure more often before biogas capture and use systems 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.

Note that AgSTAR did not conduct a site-specific cost analysis; site conditions such as energy contracts, environmental permitting requirements, and other variables will affect the economic feasibility of projects. This report does not include poultry farms in its assessment of market potential—biogas from poultry operations is briefly discussed on page 11.

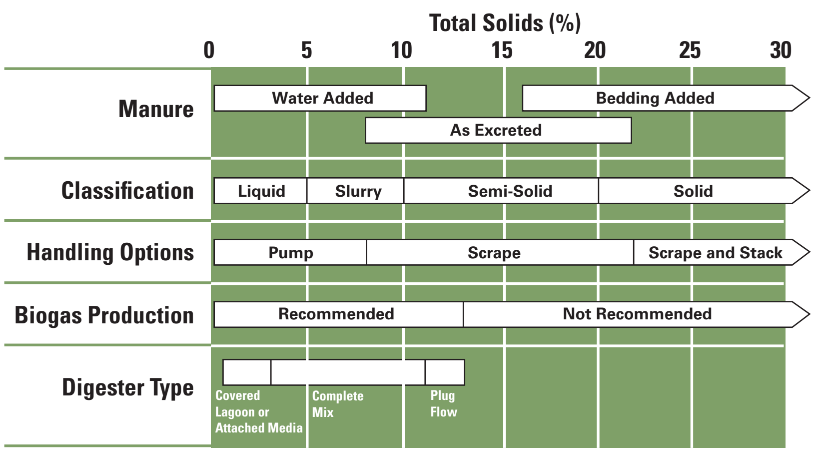
As shown in Table 1, biogas recovery systems are potentially profitable for more than 8,100 dairy and swine facilities in the United States. These facilities are large operations that use liquid or slurry manure handling systems, and collect manure often from animal confinement areas as described in Table 2.

Profitability depends on the ability to recover 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. 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.

Manure management method: Current digester systems are designed for manure in a liquid, slurry, or semi-solid state (Figure 2). Collection frequency also influences the feasibility of biogas recovery systems. Collecting manure at least weekly minimizes the loss of the biodegradable organic matter that is converted

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



into biogas during storage prior to digestion. Confined swine and dairy operations typically remove manure as often as every few hours to every few days. In other animal sectors (e.g., poultry and beef operations), use of dry manure management systems means manure is typically collected no more than three to four times per year.

Energy costs: The value of biogas depends on the price of the energy it replaces (e.g., electricity, fuel oil, liquefied petroleum gas [LPG], natural gas).

Typically, biogas generates electricity for onsite use, and any excess is sold to the local electric utility. This strategy provides three possible sources of income:

- **Avoided cost of electricity:** The 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 use 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.

Although electricity generation is the most common use for captured biogas, upgrading biogas to pipeline-quality natural gas is becoming more popular. Upgrading the biogas requires special processing equipment to remove water, carbon dioxide, and hydrogen sulfide. Renewable natural gas (RNG) may be injected into local utilities' pipeline systems, serving as a revenue source for projects. Some states, such as California, may offer financial incentives for qualified projects to cover interconnection costs and to encourage use of low-carbon fuels. RNG can also be used as vehicle fuel in the form of compressed natural gas (CNG) or liquefied natural gas (LNG), which can yield significant cost savings on fleet truck fueling or other transportation costs. For instance, Fair Oaks Farms, in northwest Indiana, runs a fleet of over 40 CNG-fueled milk trucks with the methane produced from their digesters. Each of these trucks travels around 270,000 miles a year, and the CNG replaces 2 million gallons of diesel annually.

Energy Production Potential

Nationally, swine and dairy operations could generate nearly 16 million megawatt-hours (MWh) of electricity each year—equivalent to more than 2,000 MW of electrical grid capacity or about 5.4 million MMBtu[1] of displaced fossil fuel use. According to the U.S. Department of Energy, the average price of electricity was about 11 cents per kilowatt-hour (kWh) as of September 2017.[2] Using this rate, swine and dairy operations

1 MMBtu = 1,000,000 Btu

2 U.S. DOE EIA. 2017. Table 5.6.A. Average Price of Electricity to Ultimate Customers by End-Use Sector. In *Electric Power Monthly with Data for September 2017*. U.S. Department of Energy, Washington, D.C. Available at https://www.eia.gov/electricity/monthly/archive/november2017.pdf.

could generate $1.7 billion annually in avoided electricity purchases.

If captured biogas were directed to RNG or CNG applications instead of power generation, AgSTAR estimates, there is enough methane production potential from candidate swine and dairy farms to heat over 2.7 million homes or produce over 8 billion pounds of CNG annually (equivalent to 1.3 billion diesel gallons), enough to fuel nearly 150,000 refuse trucks.

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.

Table 3 identifies the 10 states with the most potential to generate electricity from swine and dairy operations. For swine, the top 10 states account for about 88 percent of the total electricity generation potential. Iowa and North Carolina, the largest pork-producing states, account for 31 and 16 percent of the total, respectively. For dairies, the top 10 states represent 79 percent of the total potential, with California accounting for 30 percent.

Figure 3: Candidate Swine Farms

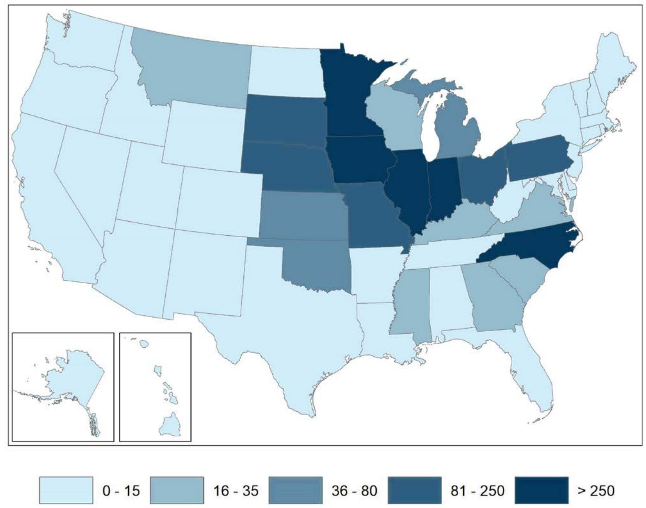
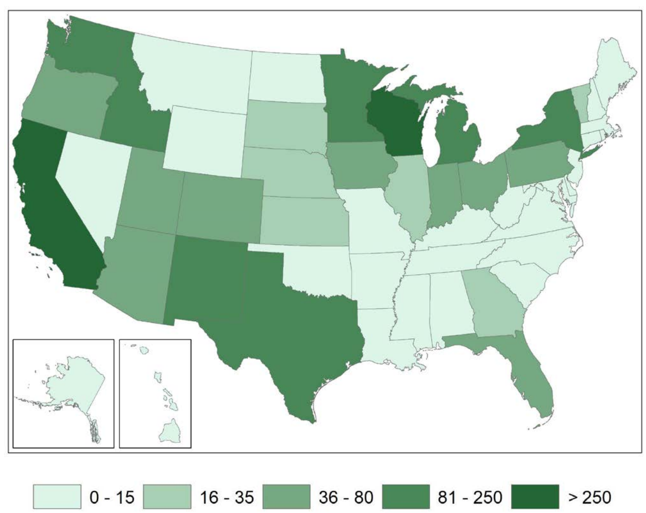


Figure 4: Candidate Dairy Farms



Appendix B, from EPA AgSTAR's 2011 report *Market Opportunities for Biogas Recovery Systems at U.S. Livestock Facilities*, offers more detail on the market potential in the swine and dairy states with the greatest potential for biogas recovery.

Table 3. Top 10 States for Electricity Production 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 (1,000 MMBtu/Year)	Energy Generation Potential (1,000 MWh/Year)
Swine Farms					
Iowa	2,174	331	24.30	22,430	2,070
North Carolina	761	192	12.21	11,266	1,040
Minnesota	691	64	7.64	7,052	651
Illinois	345	47	5.45	5,030	464
Indiana	302	34	4.11	3,795	350
Missouri	129	31	3.45	3,183	294
Nebraska	154	27	3.33	3,077	284
Oklahoma	45	49	3.26	3,013	278
Kansas	58	24	2.50	2,311	213
Ohio	226	15	1.73	1,594	147
Remaining 40 states	**525**	**102**	**9.46**	**8,733**	**806**
Swine Total:	**5,409**	**915**	**77**	**71,484**	**6,598**
Dairy Farms					
California	799	431	32.64	30,125	2,780
Idaho	179	138	11.56	10,668	985
Wisconsin	358	88	9.02	8,323	768
Texas	126	102	7.10	6,553	605
New Mexico	88	83	6.26	5,780	533
Washington	122	54	4.80	4,428	409
Michigan	138	47	4.79	4,420	408
Arizona	56	59	3.84	3,544	327
New York	126	32	3.29	3,033	280
Colorado	58	31	2.72	2,514	232
Remaining 40 states	**655**	**254**	**22.47**	**20,737**	**1,914**
Dairy Total:	**2,704**	**1,320**	**108**	**100,124**	**9,241**
Overall:	**8,113**	**2,234**	**186**	**171,608**	**15,838**

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 goose production. Most poultry operations reduce manure moisture content by evaporation, 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, there are currently seven 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 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 (six to seven flocks per year are cycled through), with total removal every one to three years. This infrequent removal cycle results in loss of a substantial amount of the organic matter that is the source of biogas under anaerobic conditions. Meanwhile, 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 use two-story houses that provide long-term manure storage under cages in the upper story. 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 storage. In most operations, liquid would have to be added to create a manure slurry.

- 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 running under the cages; this moves the manure to the end of the house, where it is placed into a 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 keep the nitrogen in the manure until it is applied to the soil, assuming appropriate land application systems are used.

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,** using data from U.S. Department of Agriculture (USDA) reports.

2. **Estimate manure management practices,** using data from EPA *Inventory of U.S. Greenhouse Emissions and Sinks*. (The *Inventory* report, in turn, was developed with data from 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 the same methodologies found in *Inventory of U.S. Greenhouse Emissions and Sinks*. It was assumed that, when a farm converts 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.

Sections below discuss these steps in more detail, including data sources and calculation methodologies.

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 *2012 Census of Agriculture*.[1]

Census data were 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 were 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, 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

1 USDA NASS. 2014. *2012 Census of Agriculture*. National Agriculture Statistics Service, Washington, DC.

animals in each undisclosed county was then input into the state-level maps. Note that these profiles reflect the older census data and that not all profiled states will match up with the top 10 states listed in Table 3.

2. Estimating Manure Management Practices

This analysis primarily relied on the manure management system data discussed in EPA's *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990–2015*,[2] for which the key data sources were USDA's *2012 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: 1990–2015*.[3] These methodologies were developed by the 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:

$$\text{methane} = \text{population} \times VS_E \times MCF \times B_0 \times 0.041$$

where

methane	=	total methane emissions from different animal types in different states and manure management systems, pounds (lb) per year
population	=	animal population
VS_E	=	total volatile solids excretion rate, lb VS per animal per year
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

2 U.S. EPA. 2017. *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990–2015*. Report No. EPA 430-P-17-001. Office of Atmospheric Programs, Washington, D.C.

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.

Table A-1 shows example data for two types of manure management systems. 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 of the animal, the state-specific animal population, and the number of days per year. For dairy cattle, regional VS excretion rates per animal per year 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 6.6 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 an anaerobic digester would collect and combust is greater than the amount of methane produced by the baseline manure management systems because digesters are designed to optimize methane production.

5 USDA. 1996. *Agricultural Waste Management Field Handbook*. Natural Resources Conservation Service, Washington, D.C.

6 U.S. EPA. 2017. *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990–2015*. Report No. EPA 430-P-17-001. Office of Atmospheric Programs, 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.

8 Morris, G.R. 1976. *Anaerobic Fermentation of Animal Wastes: A Kinetic and Empirical Design Fermentation*. M.S. thesis. Cornell University, Ithaca, New York.

Table A-1. Methane Emission Reduction Impacts

Factors	Storage Tank or Pond	Anaerobic Lagoon
Number of cows	500	500
Total VS excretion rate (VS_E), lb VS/animal/year	6,170	6,170
B_0[a], ft^3 CH_4/lb VS	3.84	3.84
MCF for California, decimal[b]	0.34	0.73
CH_4 density, lb CH_4/ft^3	0.041	0.041
CH_4 emissions/emission reduction from biogas capture and use,[c,d] tons CH_4/yr	82.6	179.4
Equivalent reduction in CO_2 emissions,[e] tons CO_2e/yr	2,064	4,485

[a] The B_0 and MCF values were obtained from EPA's *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2015*.

[b] The MCF values shown here and in Table A-2 are rounded. The values calculated in this example use the actual values; calculated values vary based on rounding.

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

$$CH_4 \text{ Emissions} = \text{Number of cows} \times VS_E \times MCF \times B_0 \times 0.041 \text{ lbs} \times 1 \text{ ton}/2{,}000 \text{ lb}$$

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

[e] CH_4 has approximately 25 times the heat trapping capacity of CO_2.

$$CO_2 \text{ equivalents } (CO_2e) = CH_4 \text{ Emissions} \times 25$$

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 $VS = \text{number of cows} \times VS_E$	3,084,881
CH_4 production, ft^3 CH_4/yr $CH_4 \text{ production} = VS \times 3.84 ft^3 \, CH_4/\text{lb VS added}$	11,845,945
electricity generation potential, kWh/yr electricity generation potential = CH_4 production x 923 Btu/ft^3 x kWh/3.413 Btu x 0.35 x 0.9 (0.35 is the engine efficiency and 0.9 is the online efficiency)	1,009,127
reduction in utility carbon dioxide emissions,[e] ton/yr emissions reduction = electricity generation potential x 1,641 lb x MWh/1000 kWh × 1 ton/2,000 lb	828

[e] Based on 1,641 pounds of carbon dioxide emitted per MWh generated, which is the national weighted average CO_2 marginal emission rate for 2016 from EPA's Avoided Emissions and Generation Tool (AVERT). CO_2 emission rates vary across the United States depending on local electricity generation sources.

Table A-2. Methane Conversion Factors by State for 2015 (percent)

State	Dairy		Swine	
	Anaerobic Lagoon	Tank/Pond	Anaerobic Lagoon	Tank/Pond and Deep Pit
Alabama	78	42	78	41
Alaska	49	15	49	15
Arizona	79	58	78	49
Arkansas	77	37	78	40
California	73	34	73	33
Colorado	66	22	68	24
Connecticut	71	26	71	26
Delaware	76	33	76	33
Florida	82	60	81	58
Georgia	78	44	78	42
Hawaii	77	58	77	58
Idaho	68	25	65	22
Illinois	73	30	73	29
Indiana	71	27	72	28
Iowa	70	26	70	26
Kansas	76	34	76	33
Kentucky	75	33	75	33
Louisiana	80	50	80	50
Maine	65	21	65	21
Maryland	75	31	75	32
Massachusetts	69	24	70	25
Michigan	68	24	69	24
Minnesota	68	24	69	24
Mississippi	79	45	78	43
Missouri	75	32	74	32
Montana	60	19	63	21
Nebraska	72	27	72	28
Nevada	70	26	71	28
New Hampshire	66	22	66	23
New Jersey	74	30	75	31
New Mexico	74	32	72	29
New York	67	23	68	24

(continued on next page)

Table A-2. Methane Conversion Factors by State for 2015 (percent) (continued)

State	Dairy		Swine	
	Anaerobic Lagoon	Tank/Pond	Anaerobic Lagoon	Tank/Pond and Deep Pit
North Carolina	76	35	78	41
North Dakota	67	23	67	23
Ohio	71	27	72	28
Oklahoma	78	40	77	37
Oregon	65	23	65	23
Pennsylvania	71	27	72	28
Rhode Island	71	26	71	26
South Carolina	78	43	79	44
South Dakota	69	25	70	25
Tennessee	76	34	76	36
Texas	78	42	78	45
Utah	66	22	69	25
Vermont	64	21	64	21
Virginia	73	30	76	33
Washington	65	23	67	24
West Virginia	72	28	72	28
Wisconsin	67	23	68	24
Wyoming	62	20	63	21

5. Estimating Potential Electricity Yield from Methane Production

This report's estimates of the biogas production potential from dairy cow and swine manure are based on the following approach:

- **Methane production.** Based on previously observed values[9,10] 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 3.84 ft^3 of methane per pound of total VS added to the system, based on the value used in EPA's greenhouse gas inventory.
- **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 Btu per ft^3 methane.
- **Engine and online 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 online operating rate of 90 percent (to account for downtime due to maintenance and repair).
- **Heating value ratio.** The heating value ratio is 0.9638 ft^3 of natural gas to 1 ft^3 of methane, which assumes higher heating values of 1,012 Btu/ft^3 for methane and 1,050 Btu/ft^3 for natural gas.
- **Homes heated.** The total methane production was multiplied by the heating value ratio of natural gas to methane to determine the volume of RNG available for use in residential heating applications. It was assumed the average household using natural gas for heat consumes 66,000 ft^3 natural gas per year.[11]
- **Refuse trucks fueled.** AgSTAR assumed a methane to CNG conversion factor of 0.0451 lb CNG/ft^3 CH_4, based on higher heating values of 1,012 Btu/ft^3 for methane and 22,453 Btu/lb for CNG.[12]

AgSTAR also assumed a gallon gasoline equivalent (GGE) factor of 5.66 lb CNG/GGE,[13] and assumed an average annual fuel usage of 9.877 GGE per refuse truck per year.[14]

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 U.S. DOE EIA. 2013. 2009 Residential Energy Consumption Survey: Consumption & Expenditures Tables. Table CE2.1.

12 U.S. DOE. 2014. Alternative Fuels Data Center—Fuel Properties Comparison. Available at https://www.afdc.energy.gov/fuels/fuel_comparison_chart.pdf.

13 Ibid.

14 U.S. DOE. 2015. Alternative Fuels Data Center Maps and Data —Average Annual Fuel Use of Major Vehicle Categories. Available at https://www.afdc.energy.gov/data/10308.

Appendix B

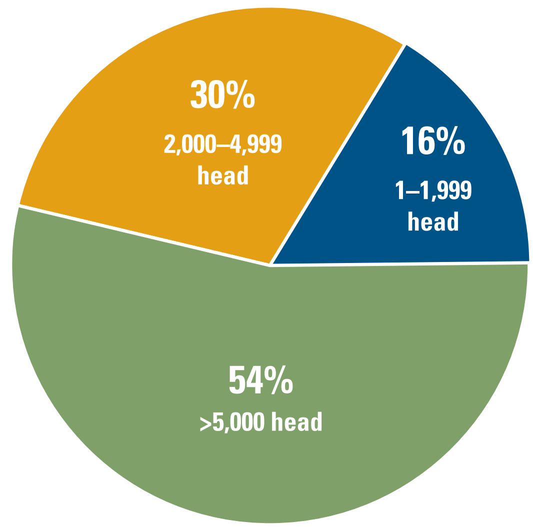
Profiles of Swine and Dairy States with Biogas Energy Recovery Potential

The data and analysis shown in Appendix B are from EPA AgSTAR's 2011 report *Market Opportunities for Biogas Recovery Systems at U.S. Livestock Facilities*. EPA believes that agricultural practices have not changed significantly in these states since the previous publication..

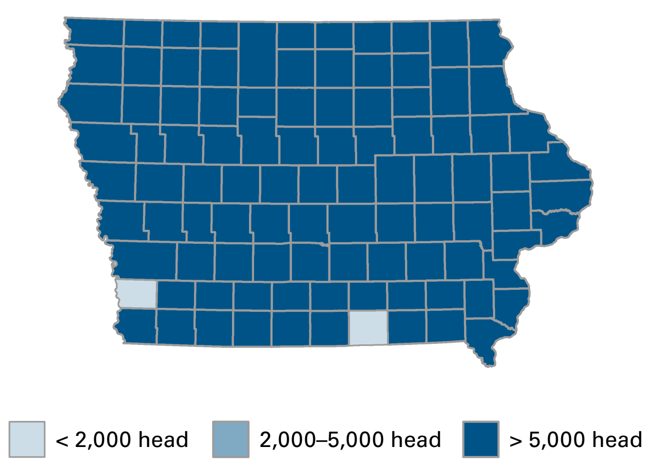
Market Opportunities to Generate Electricity with Anaerobic Digestion (2007)	
Total number of swine operations	8,330
Total number of mature swine (000 head)	19,295
Number of feasible swine operations[1]	1,997
Number of mature swine at feasible operations (000 head)	13,824
Methane emission reduction potential (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.

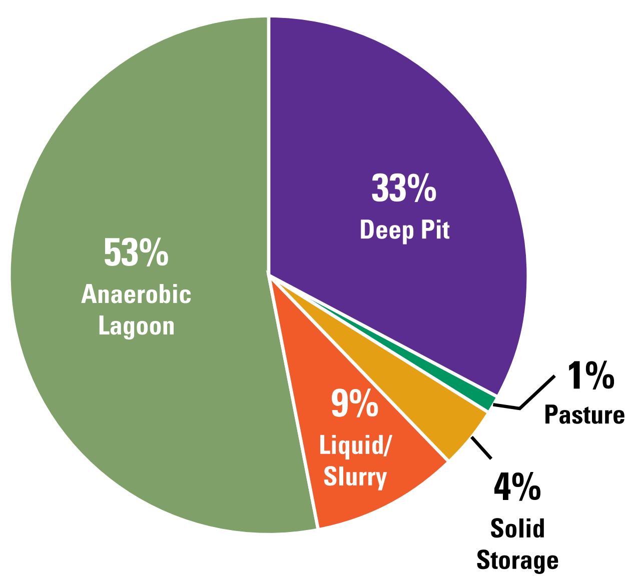
Swine Farm Size



Swine Population by County



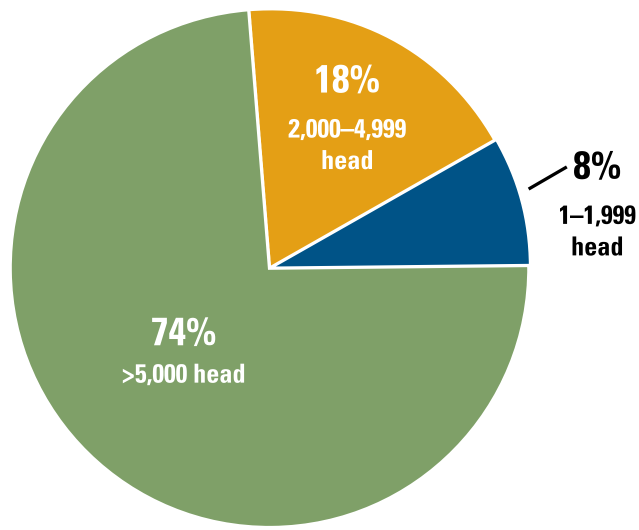
Swine Manure Managed in Each Waste Management System



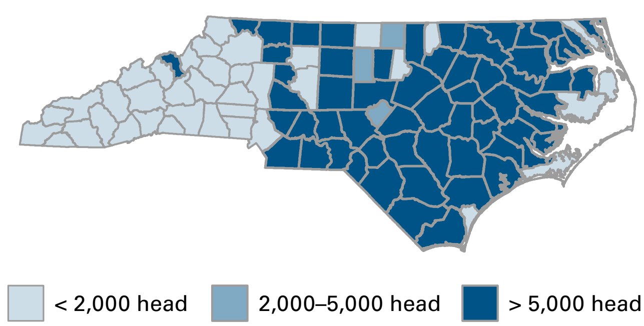
Market Opportunities to Generate Electricity with Anaerobic Digestion (2007)	
Total number of swine operations	2,836
Total number of mature swine (000 head)	10,134
Number of feasible swine operations[1]	939
Number of mature swine at feasible operations (000 head)	8,471
Methane emission reduction potential (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.

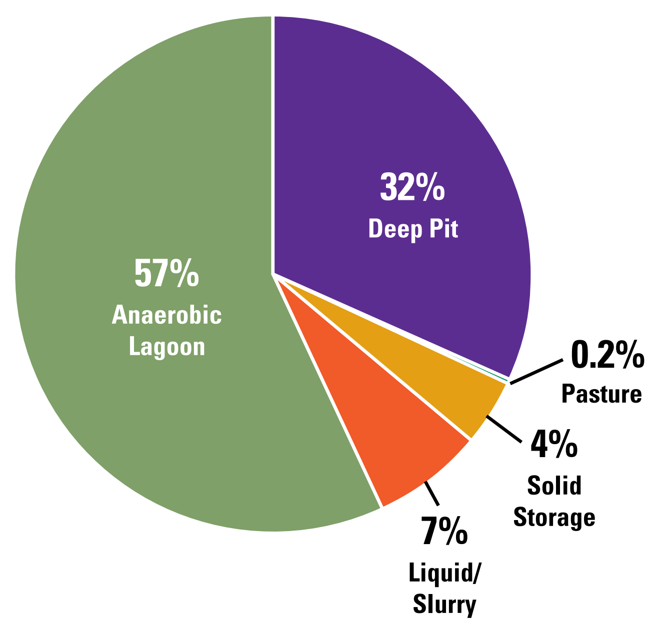
Swine Farm Size



Swine Population by County



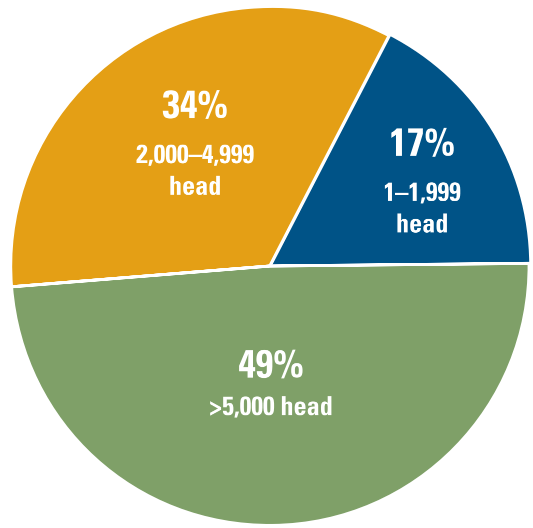
Swine Manure Managed in Each Waste Management System



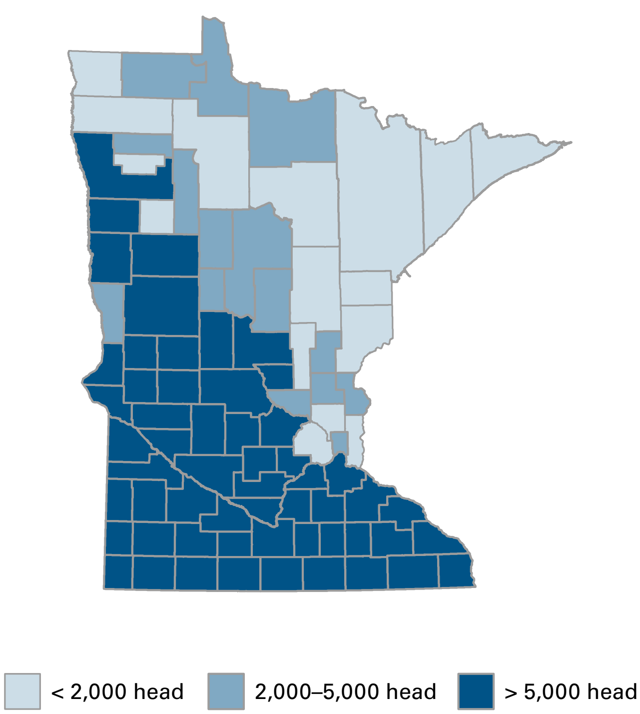
Market Opportunities to Generate Electricity with Anaerobic Digestion (2007)	
Total number of swine operations	4,382
Total number of mature swine (000 head)	7,652
Number of feasible swine operations[1]	707
Number of mature swine at feasible operations (000 head)	4,692
Methane emission reduction potential (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.

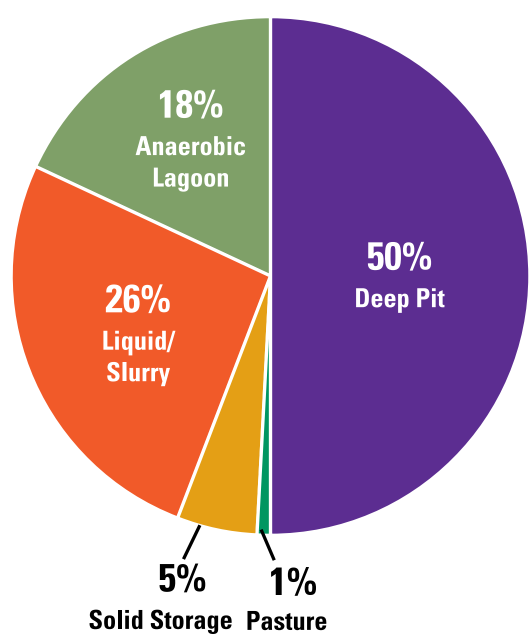
Swine Farm Size



Swine Population by County



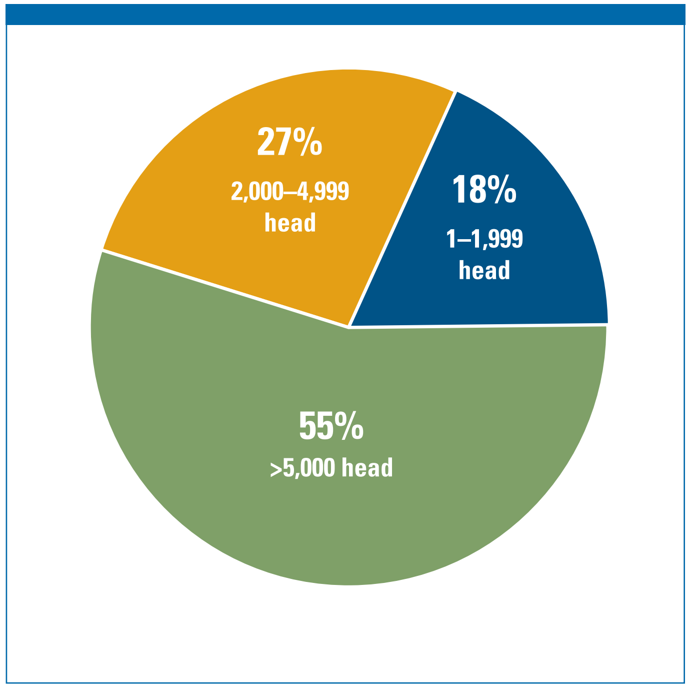
Swine Manure Managed in Each Waste Management System



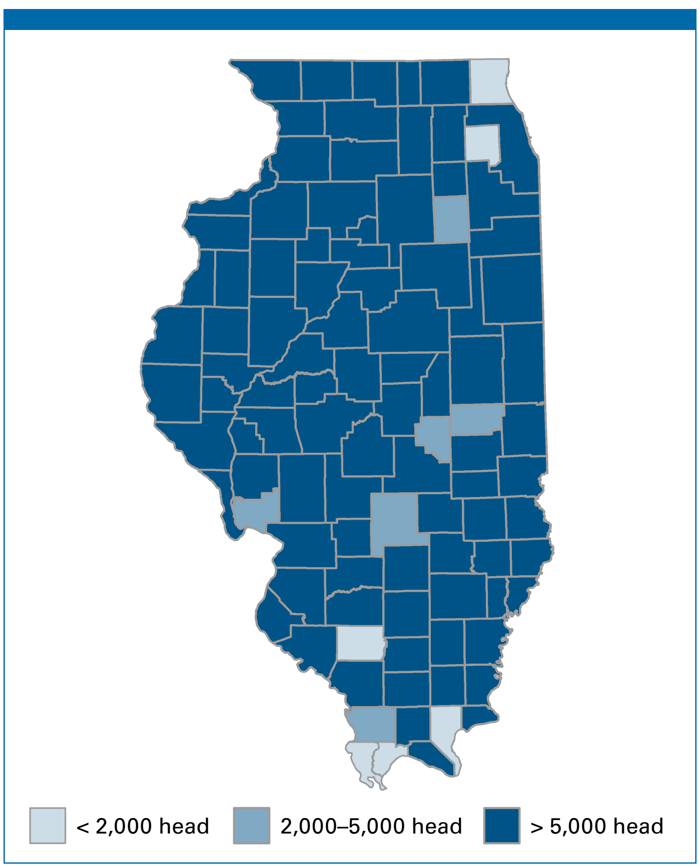
Market Opportunities to Generate Electricity with Anaerobic Digestion (2007)	
Total number of swine operations	2,864
Total number of mature swine (000 head)	4,299
Number of feasible swine operations[1]	350
Number of mature swine at feasible operations (000 head)	2,746
Methane emission reduction potential (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.

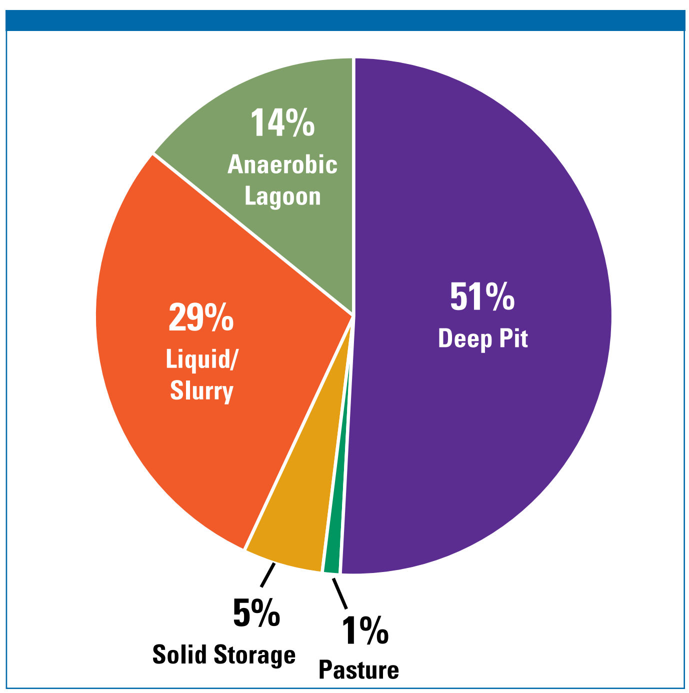
Swine Farm Size



Swine Population by County



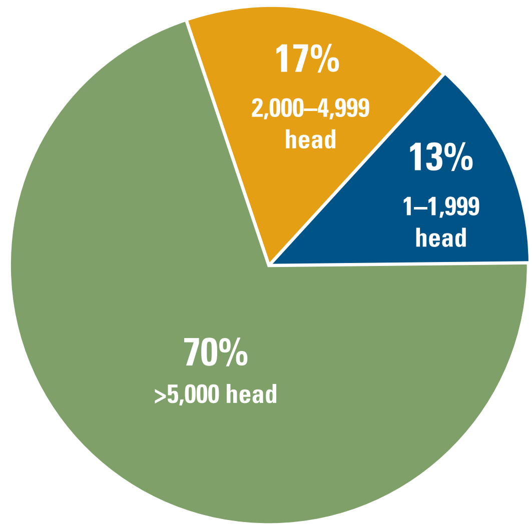
Swine Manure Managed in Each Waste Management System



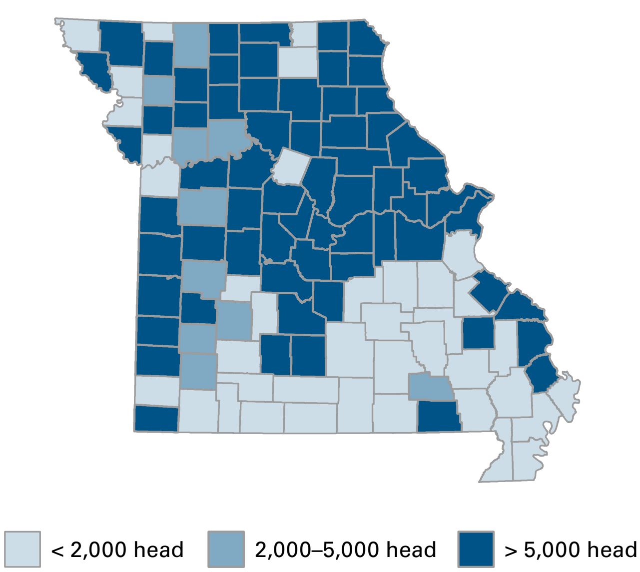
Market Opportunities to Generate Electricity with Anaerobic Digestion (2007)	
Total number of swine operations	2,999
Total number of mature swine (000 head)	3,101
Number of feasible swine operations[1]	154
Number of mature swine at feasible operations (000 head)	2,277
Methane emission reduction potential (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.

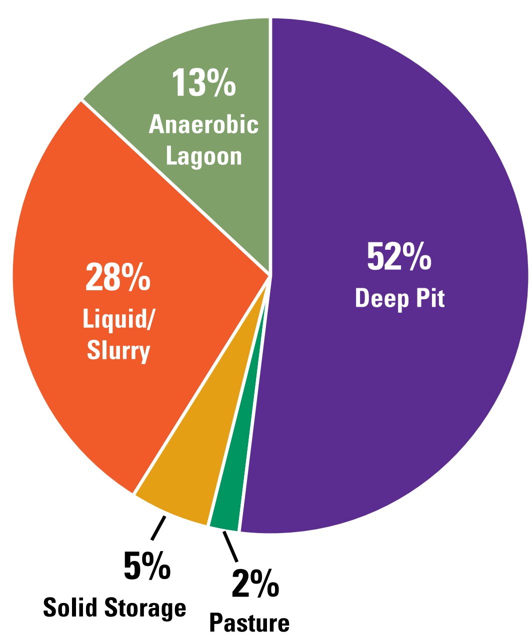
Swine Farm Size



Swine Population by County



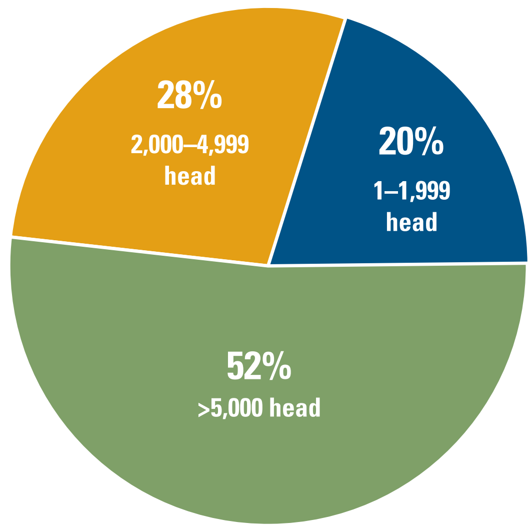
Swine Manure Managed in Each Waste Management System



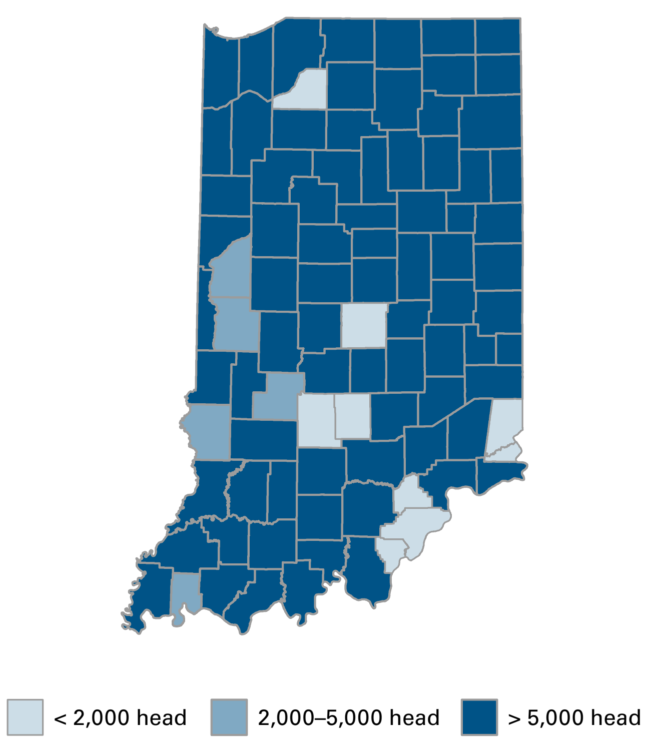
Market Opportunities to Generate Electricity with Anaerobic Digestion (2007)	
Total number of swine operations	3,420
Total number of mature swine (000 head)	3,669
Number of feasible swine operations[1]	296
Number of mature swine at feasible operations (000 head)	2,238
Methane emission reduction potential (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.

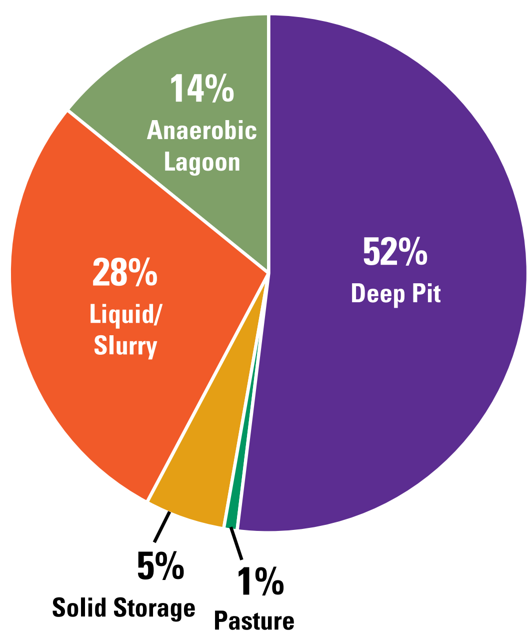
Swine Farm Size



Swine Population by County



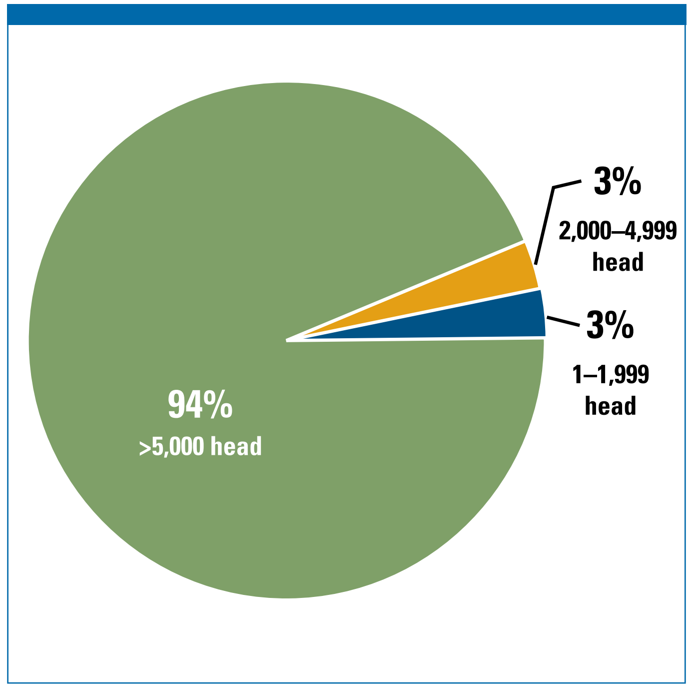
Swine Manure Managed in Each Waste Management System



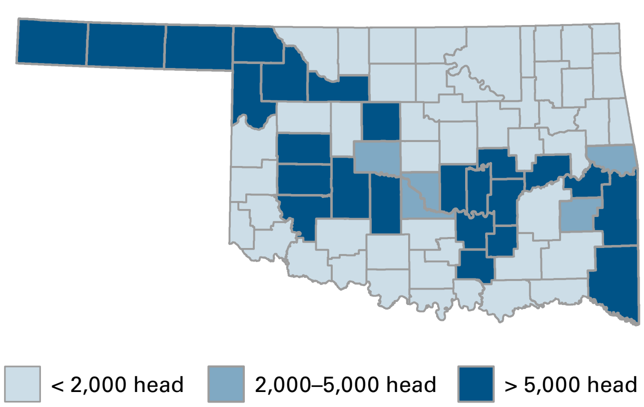
Market Opportunities to Generate Electricity with Anaerobic Digestion (2007)	
Total number of swine operations	2,702
Total number of mature swine (000 head)	2,398
Number of feasible swine operations[1]	56
Number of mature swine at feasible operations (000 head)	2,207
Methane emission reduction potential (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.

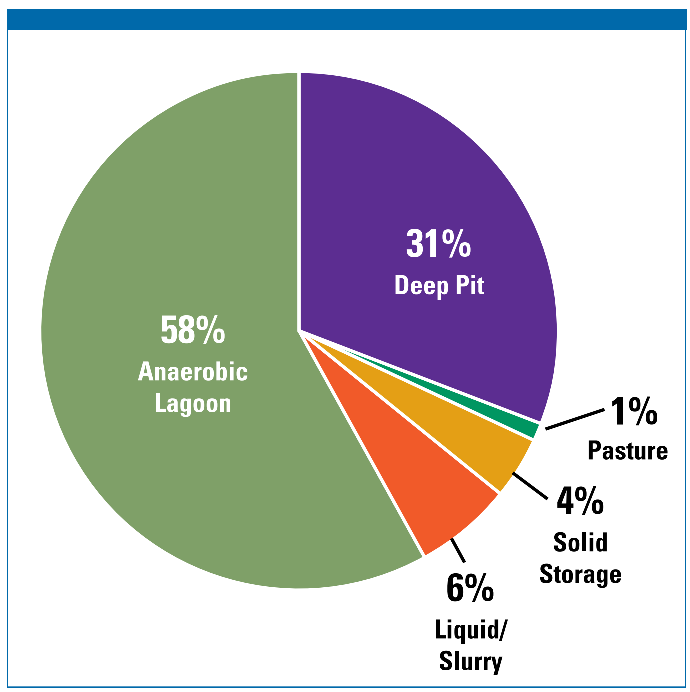
Swine Farm Size



Swine Population by County



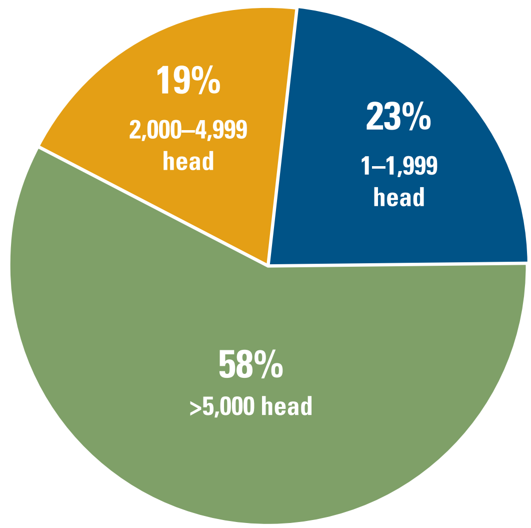
Swine Manure Managed in Each Waste Management System



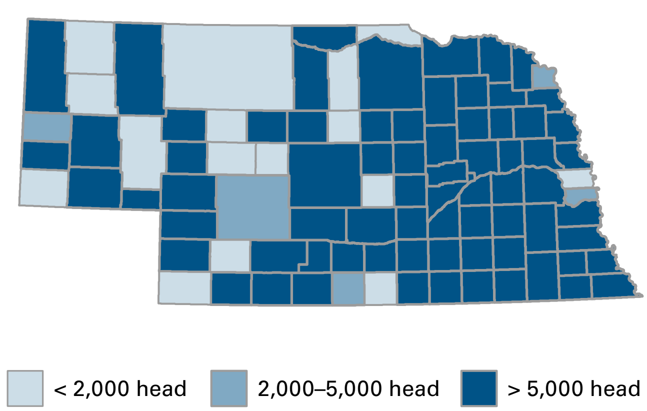
Market Opportunities to Generate Electricity with Anaerobic Digestion (2007)	
Total number of swine operations	2,213
Total number of mature swine (000 head)	3,269
Number of feasible swine operations[1]	177
Number of mature swine at feasible operations (000 head)	2,052
Methane emission reduction potential (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.

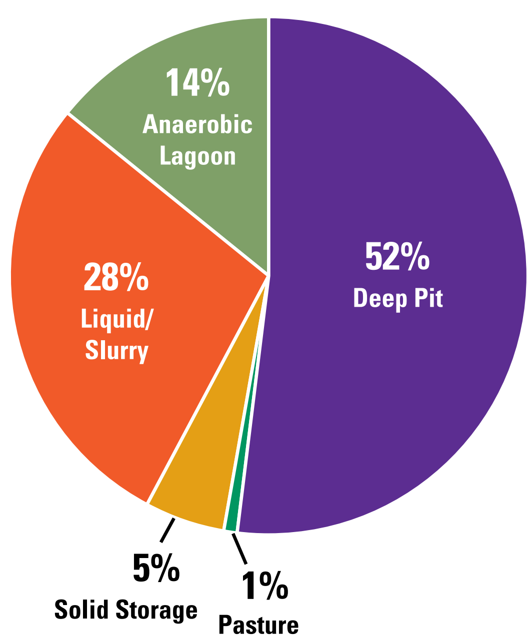
Swine Farm Size



Swine Population by County



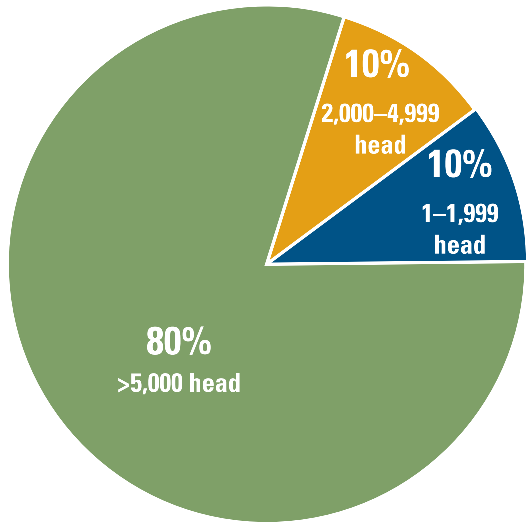
Swine Manure Managed in Each Waste Management System



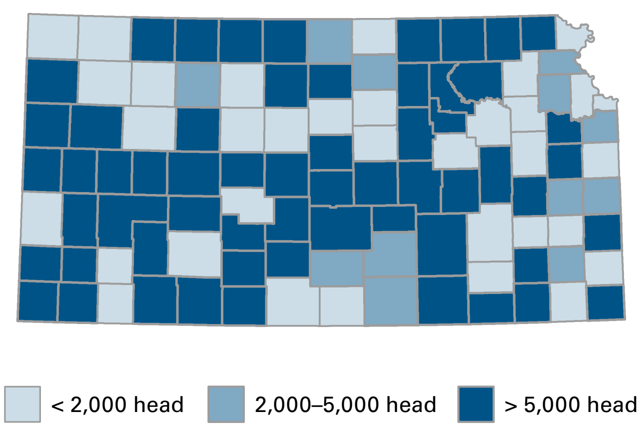
Market Opportunities to Generate Electricity with Anaerobic Digestion (2007)	
Total number of swine operations	1,454
Total number of mature swine (000 head)	1,885
Number of feasible swine operations[1]	80
Number of mature swine at feasible operations (000 head)	1,508
Methane emission reduction potential (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.

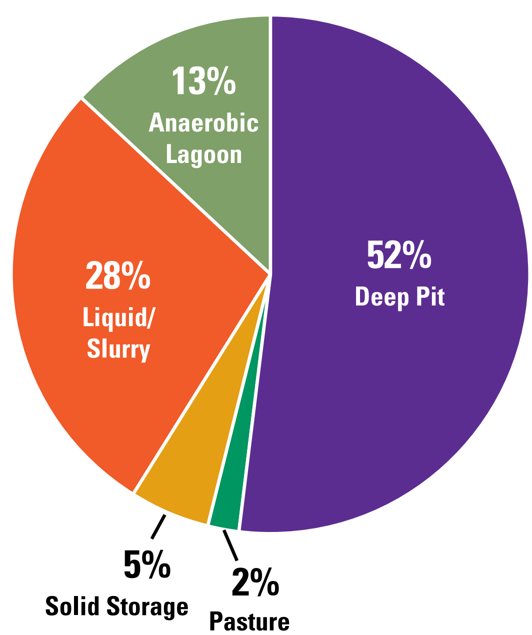
Swine Farm Size



Swine Population by County



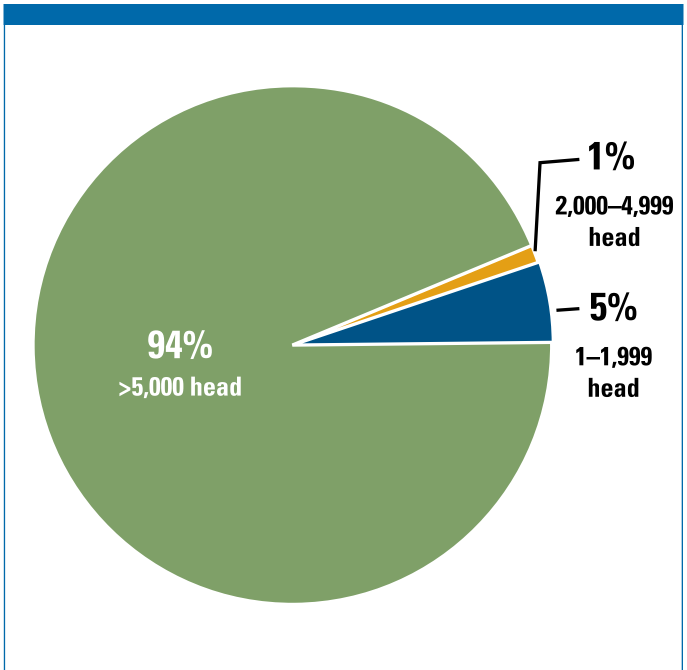
Swine Manure Managed in Each Waste Management System



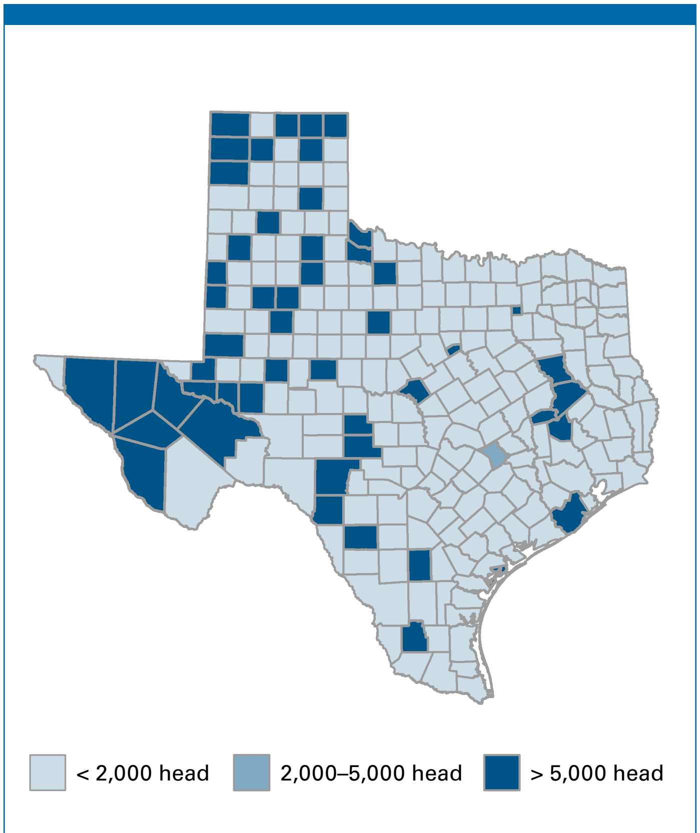
Market Opportunities to Generate Electricity with Anaerobic Digestion (2007)	
Total number of swine operations	4,471
Total number of mature swine (000 head)	1,156
Number of feasible swine operations[1]	10
Number of mature swine at feasible operations (000 head)	1,057
Methane emission reduction potential (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.

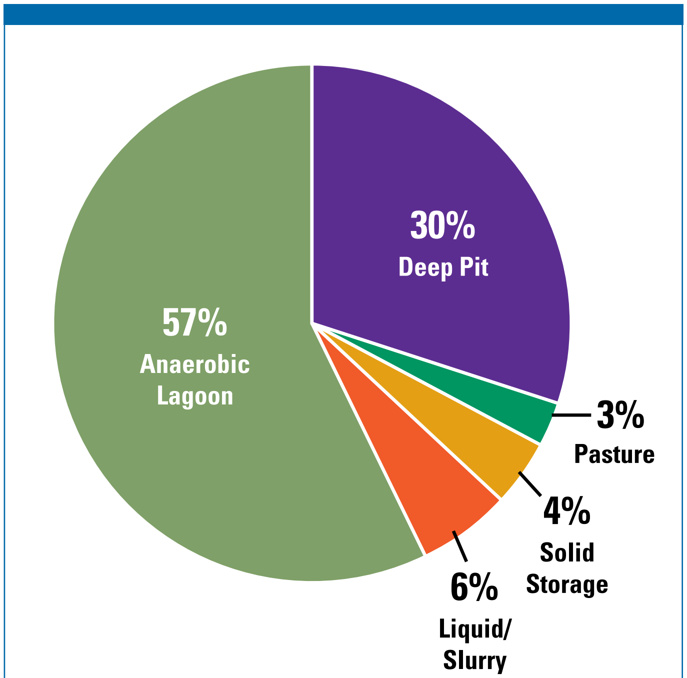
Swine Farm Size



Swine Population by County



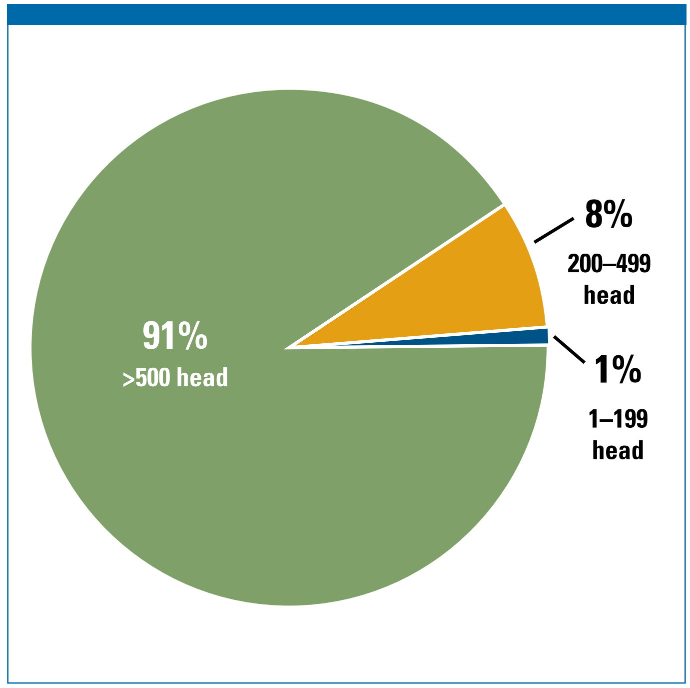
Swine Manure Managed in Each Waste Management System



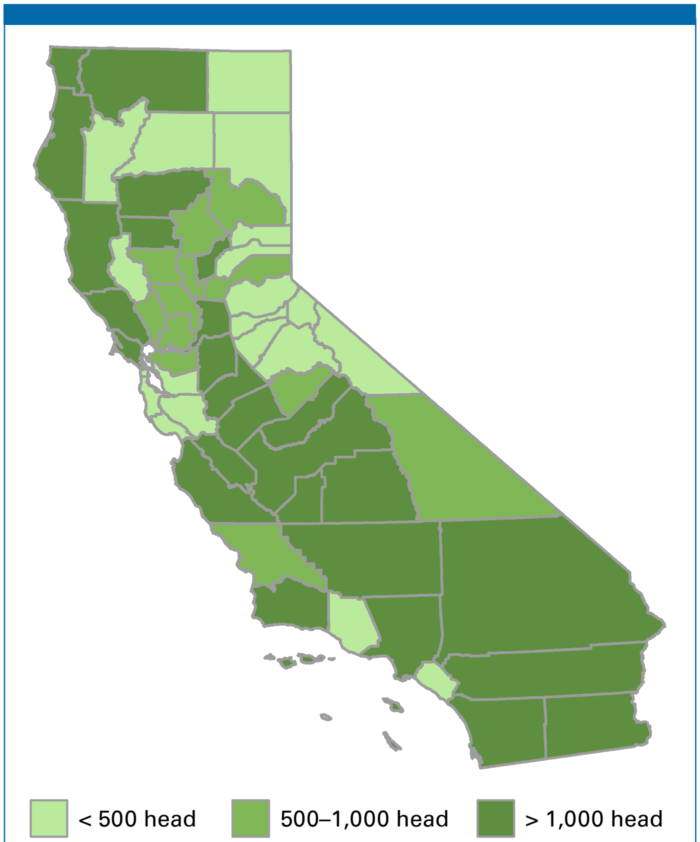
Market Opportunities to Generate Electricity with Anaerobic Digestion (2007)	
Total number of dairy operations	2,165
Total number of mature dairy cows (000 head)	1,841
Number of feasible dairy cow operations[1]	889
Number of mature dairy cows at feasible operations (000 head)	1,352
Methane emission reduction 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.

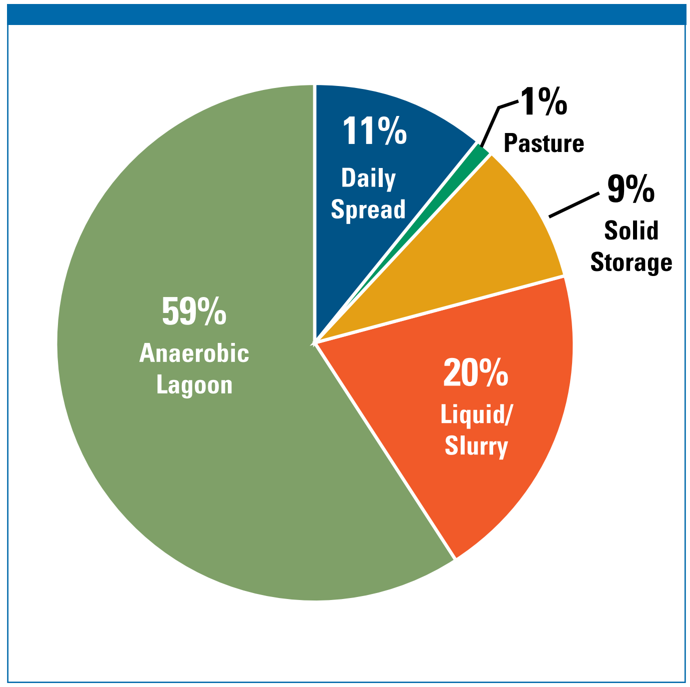
Dairy Farm Size



Dairy Population by County



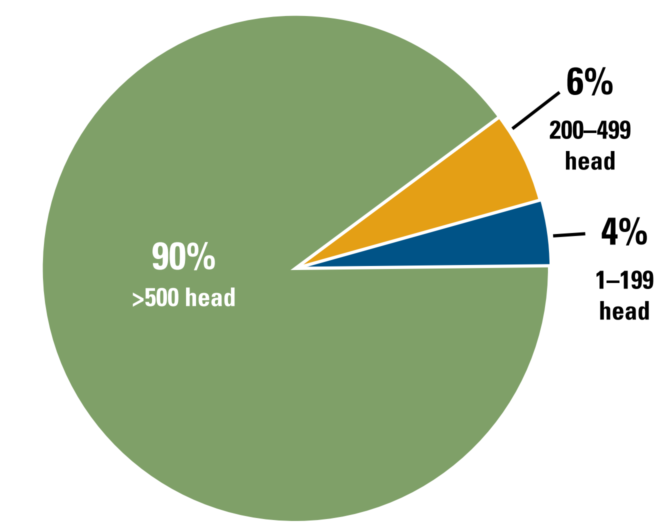
Dairy Manure Managed in Each Waste Management System



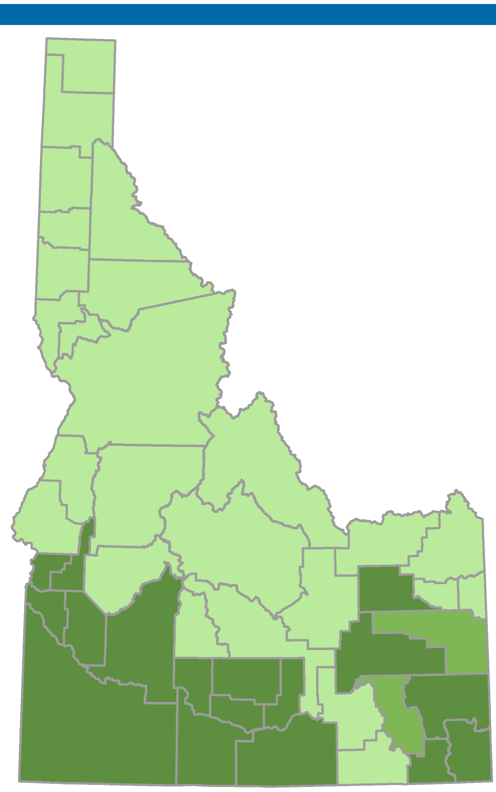
Market Opportunities to Generate Electricity with Anaerobic Digestion (2007)	
Total number of dairy operations	811
Total number of mature dairy cows (000 head)	536
Number of feasible dairy cow operations[1]	203
Number of mature dairy cows at feasible operations (000 head)	430
Methane emission reduction 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.

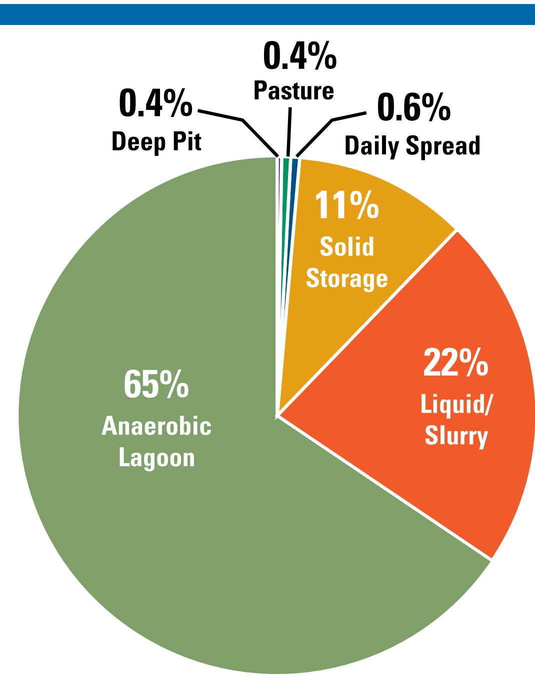
Dairy Farm Size



Dairy Population by County



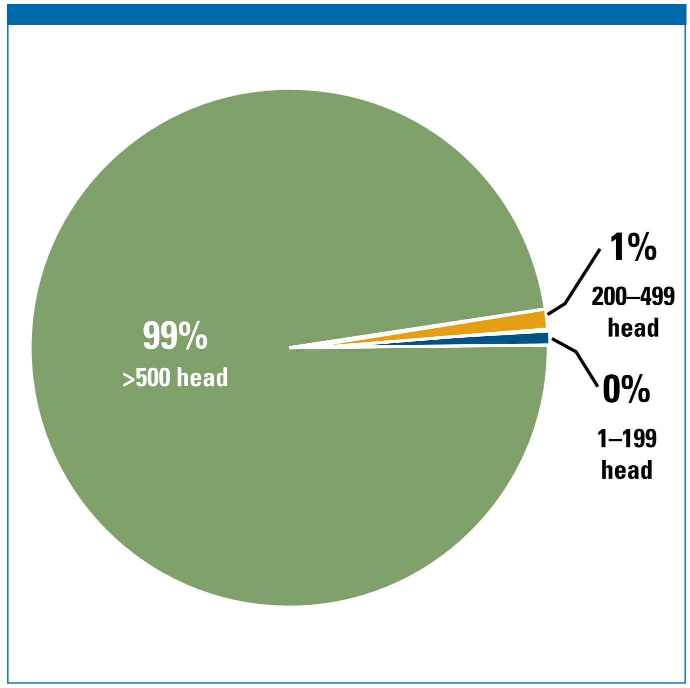
Dairy Manure Managed in Each Waste Management System



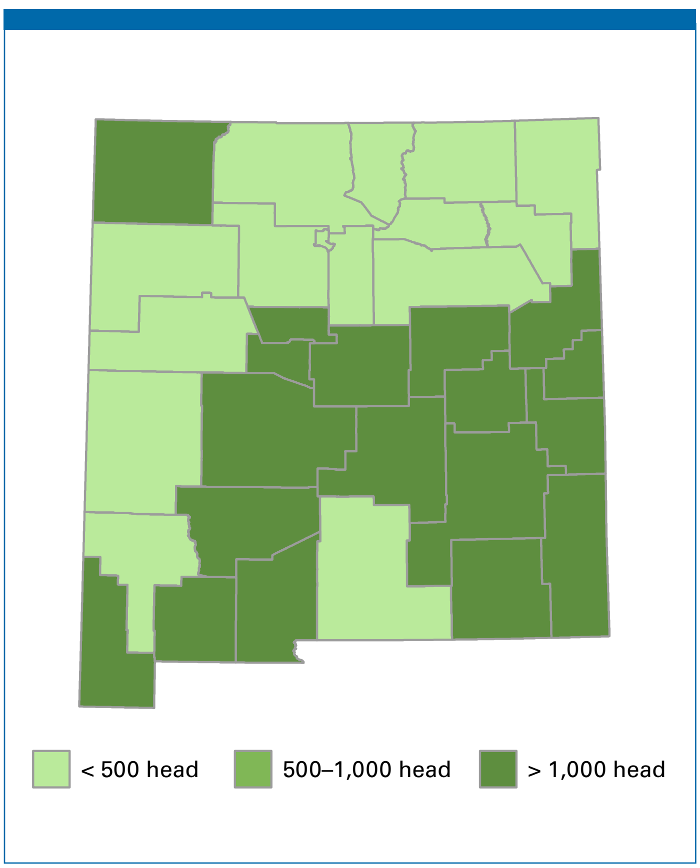
Market Opportunities to Generate Electricity with Anaerobic Digestion (2007)	
Total number of dairy operations	272
Total number of mature dairy cows (000 head)	326
Number of feasible dairy cow operations[1]	110
Number of mature dairy cows at feasible operations (000 head)	261
Methane emission reduction 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.

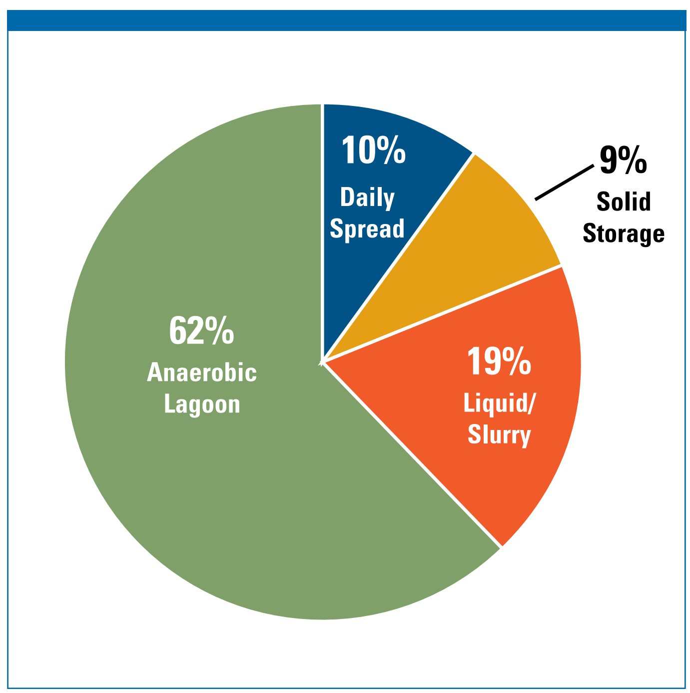
Dairy Farm Size



Dairy Population by County



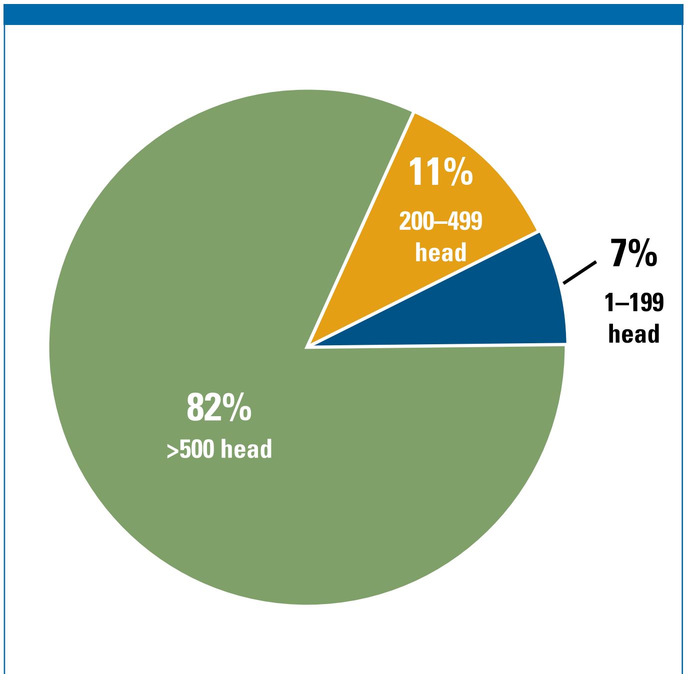
Dairy Manure Managed in Each Waste Management System



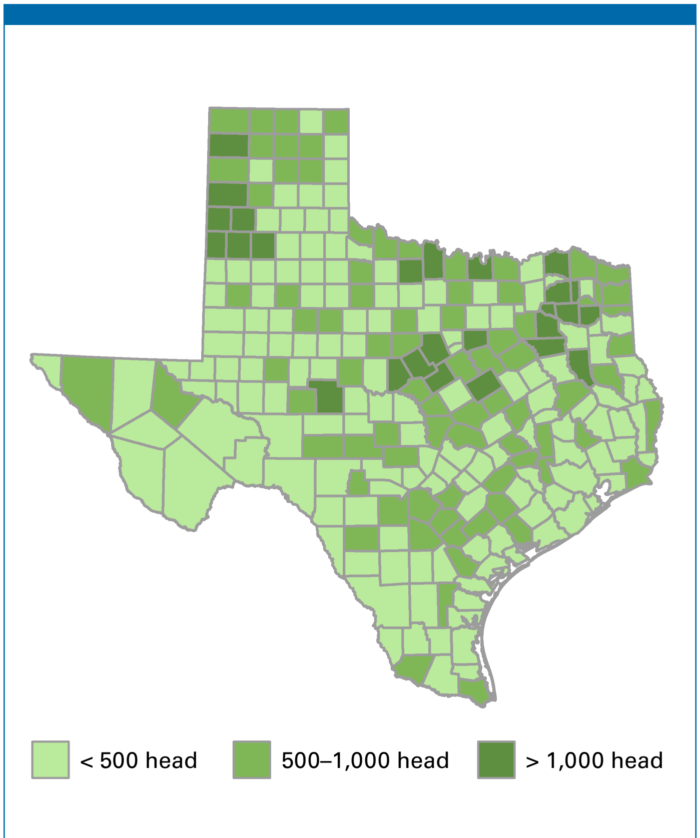
Market Opportunities to Generate Electricity with Anaerobic Digestion (2007)	
Total number of dairy operations	1,293
Total number of mature dairy cows (000 head)	404
Number of feasible dairy cow operations[1]	155
Number of mature dairy cows at feasible operations (000 head)	266
Methane emission reduction 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.

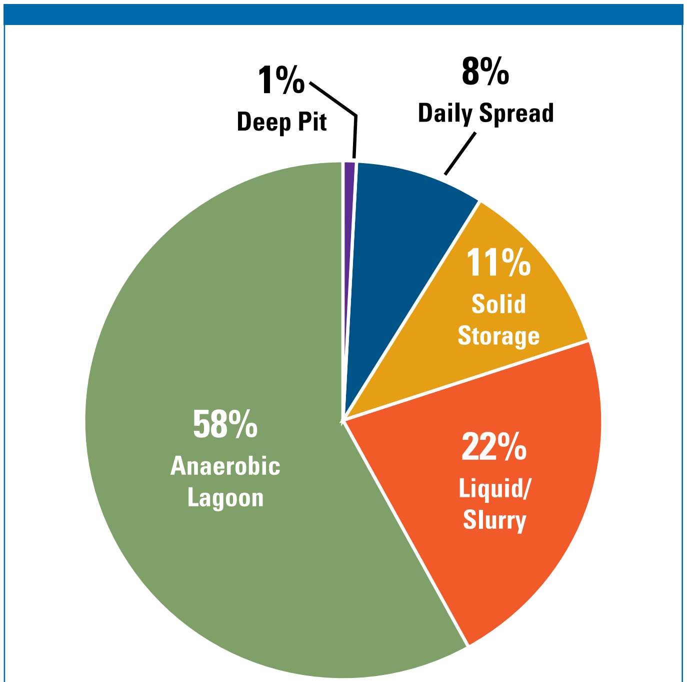
Dairy Farm Size



Dairy Population by County



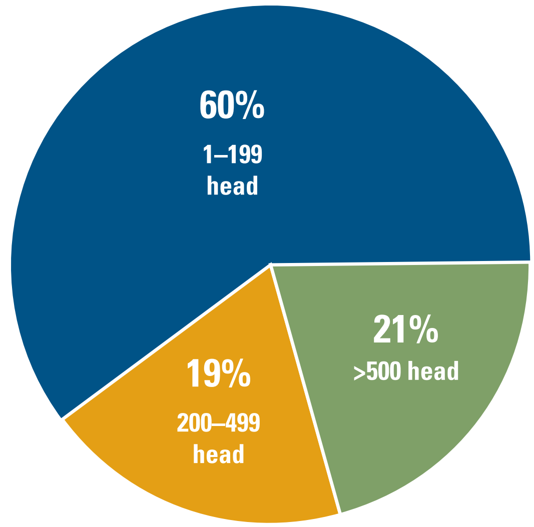
Dairy Manure Managed in Each Waste Management System



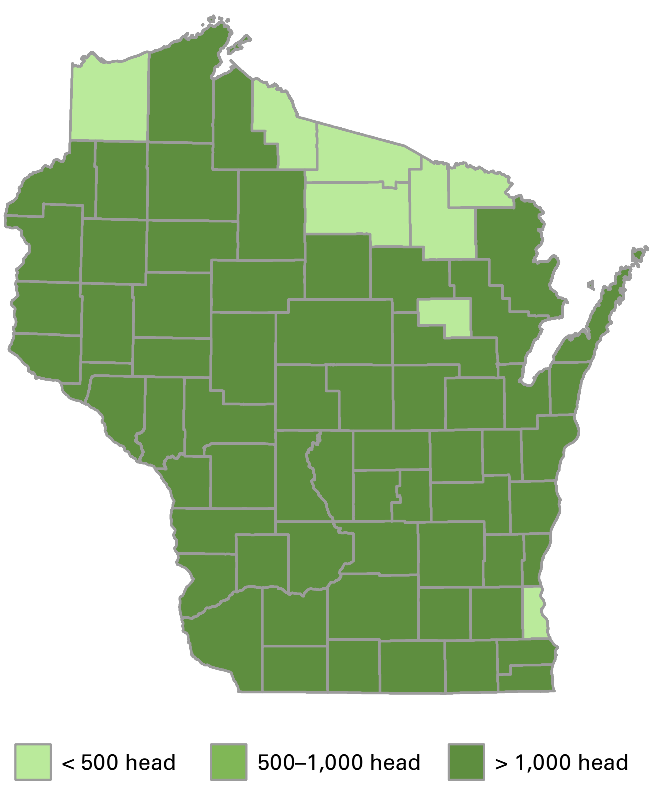
Market Opportunities to Generate Electricity with Anaerobic Digestion (2007)	
Total number of dairy operations	14,158
Total number of mature dairy cows (000 head)	1,249
Number of feasible dairy cow operations[1]	251
Number of mature dairy cows at feasible operations (000 head)	238
Methane emission reduction 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.

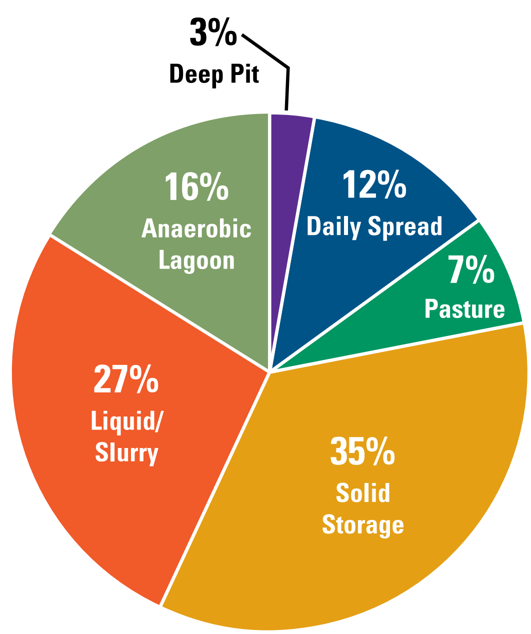
Dairy Farm Size



Dairy Population by County



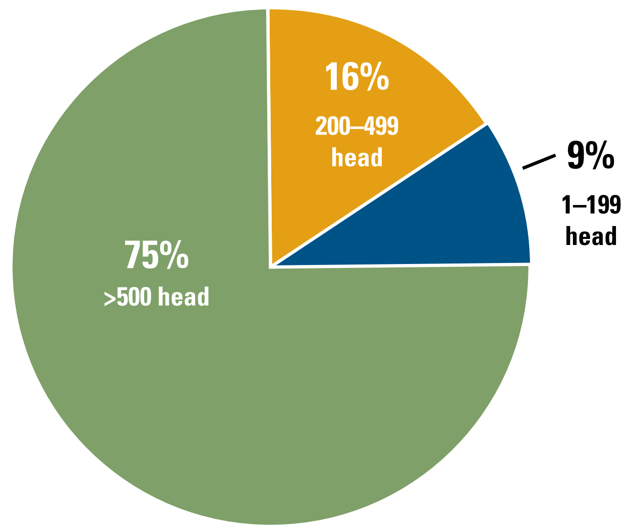
Dairy Manure Managed in Each Waste Management System



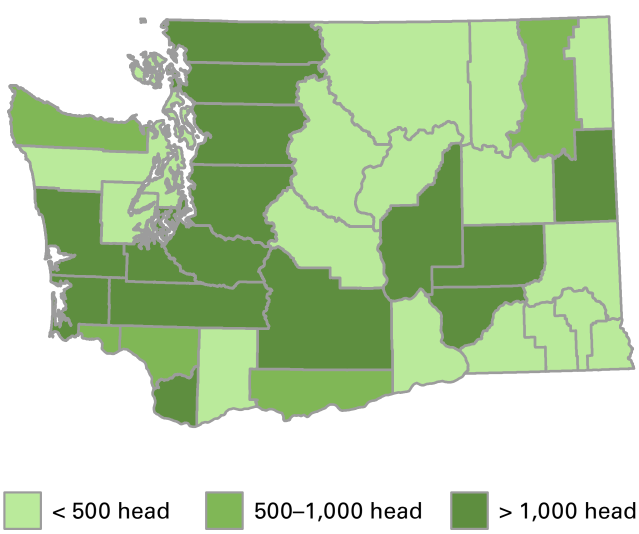
Market Opportunities to Generate Electricity with Anaerobic Digestion (2007)	
Total number of dairy operations	817
Total number of mature dairy cows (000 head)	243
Number of feasible dairy cow operations[1]	125
Number of mature dairy cows at feasible operations (000 head)	163
Methane emission reduction potential (000 tons/year)	35
Methane production potential (billion ft^3/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.

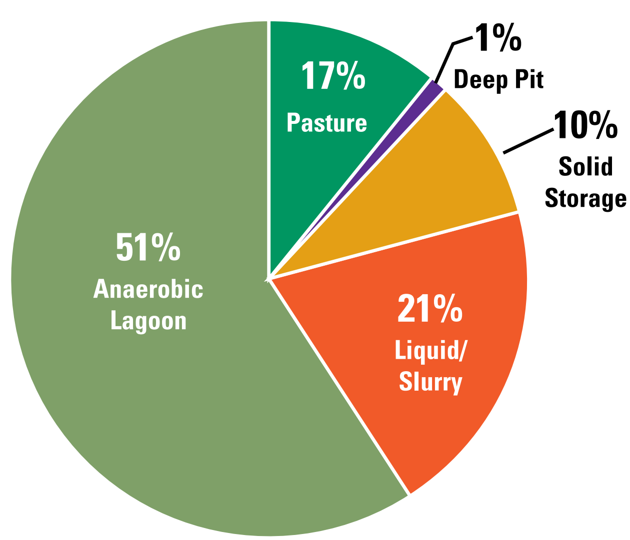
Dairy Farm Size



Dairy Population by County



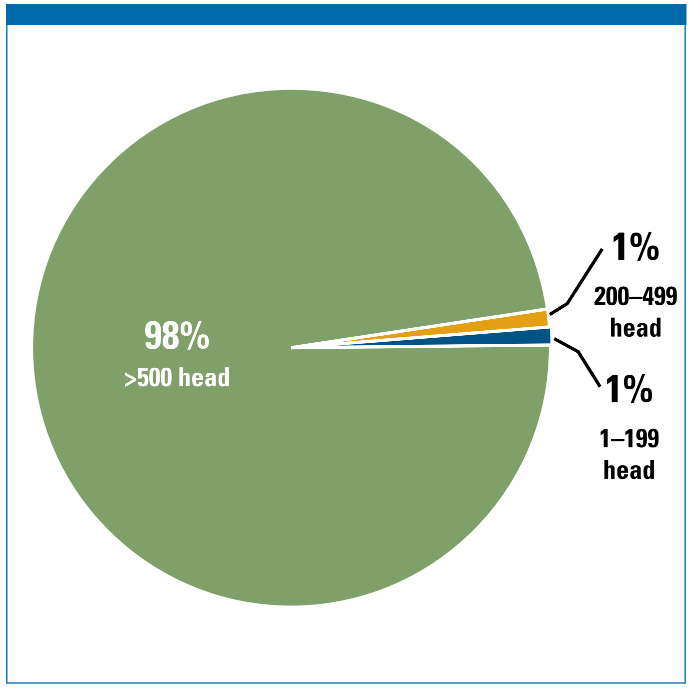
Dairy Manure Managed in Each Waste Management System



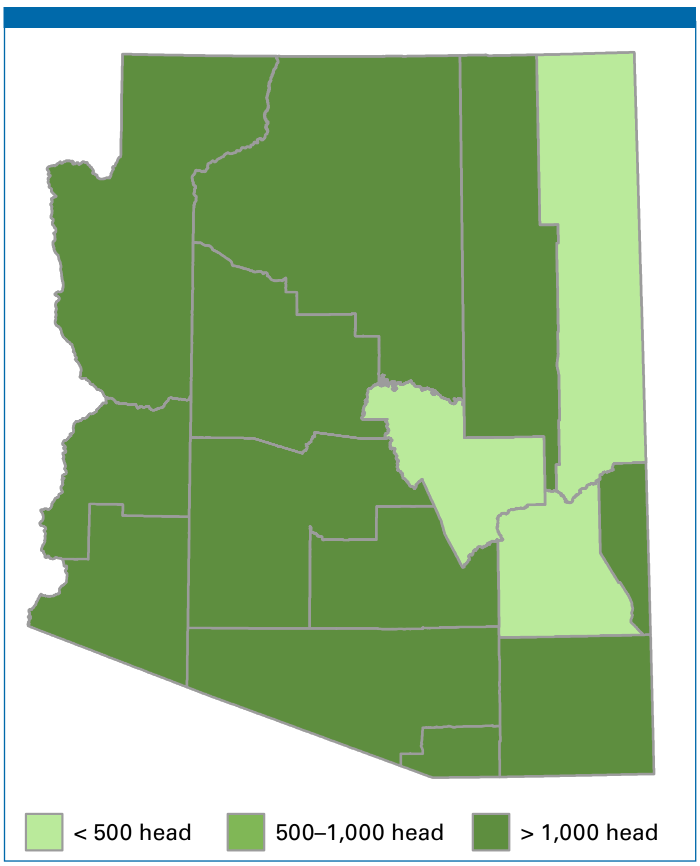
Market Opportunities to Generate Electricity with Anaerobic Digestion (2007)	
Total number of dairy operations	182
Total number of mature dairy cows (000 head)	184
Number of feasible dairy cow operations[1]	54
Number of mature dairy cows at feasible operations (000 head)	146
Methane emission reduction 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.

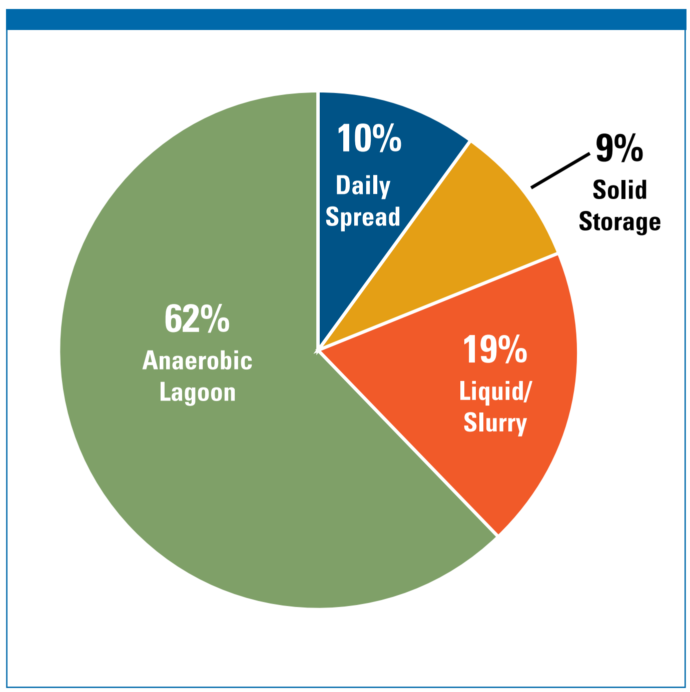
Dairy Farm Size



Dairy Population by County



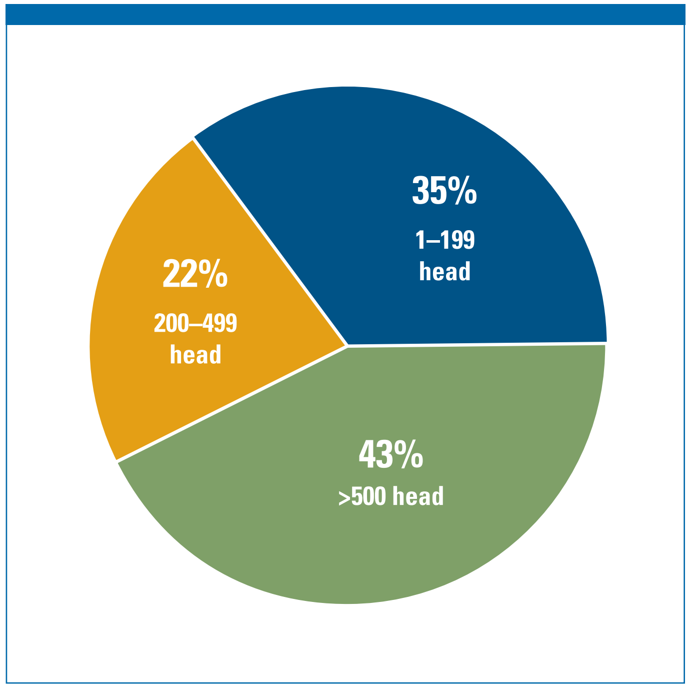
Dairy Manure Managed in Each Waste Management System



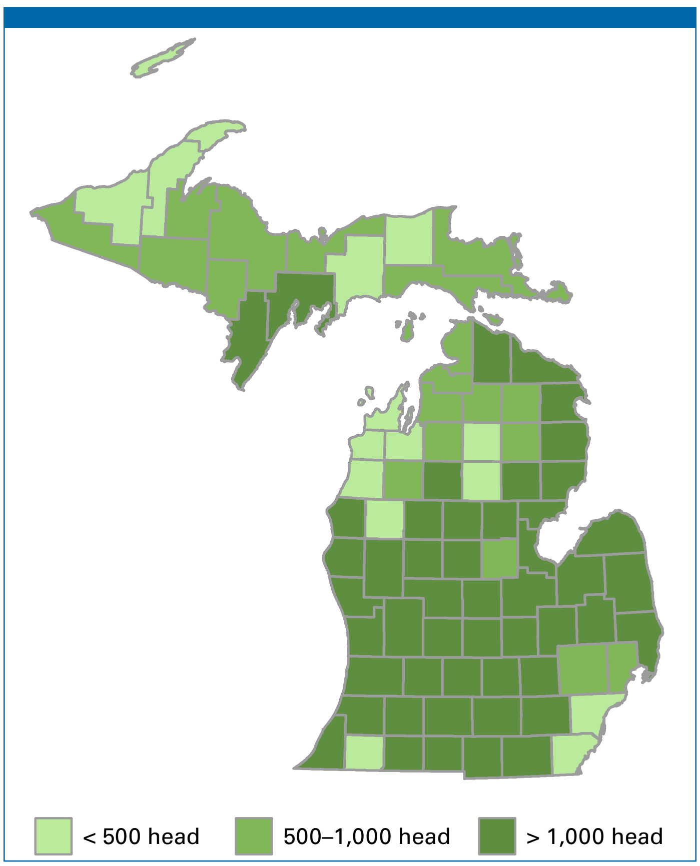
Market Opportunities to Generate Electricity with Anaerobic Digestion (2007)	
Total number of dairy operations	2,647
Total number of mature dairy cows (000 head)	344
Number of feasible dairy cow operations[1]	107
Number of mature dairy cows at feasible operations (000 head)	138
Methane emission reduction 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.

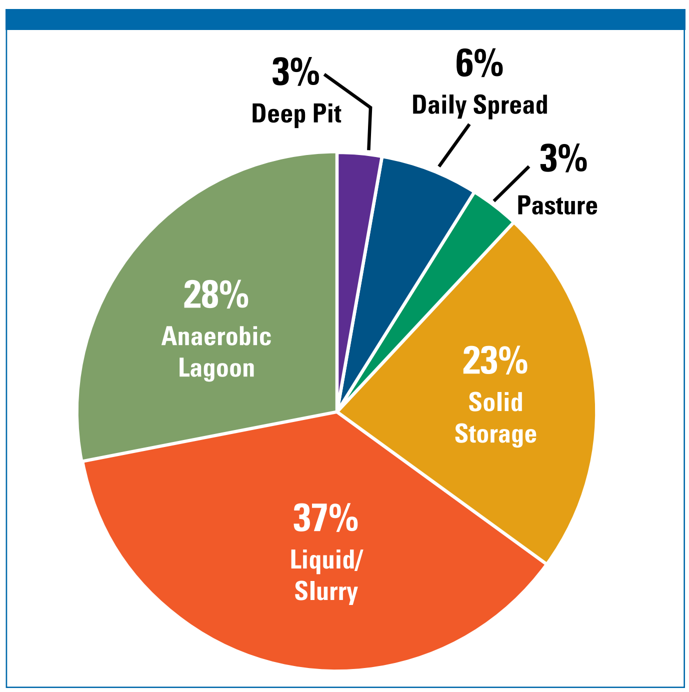
Dairy Farm Size



Dairy Population by County



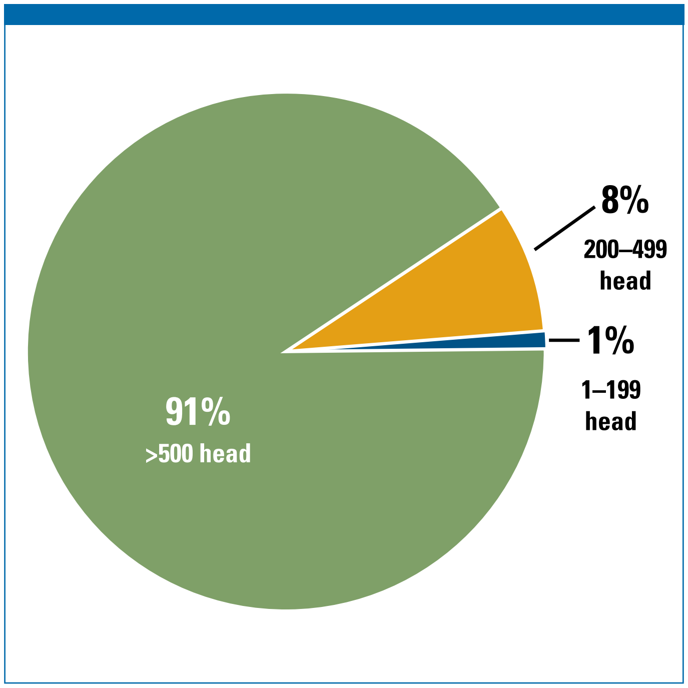
Dairy Manure Managed in Each Waste Management System



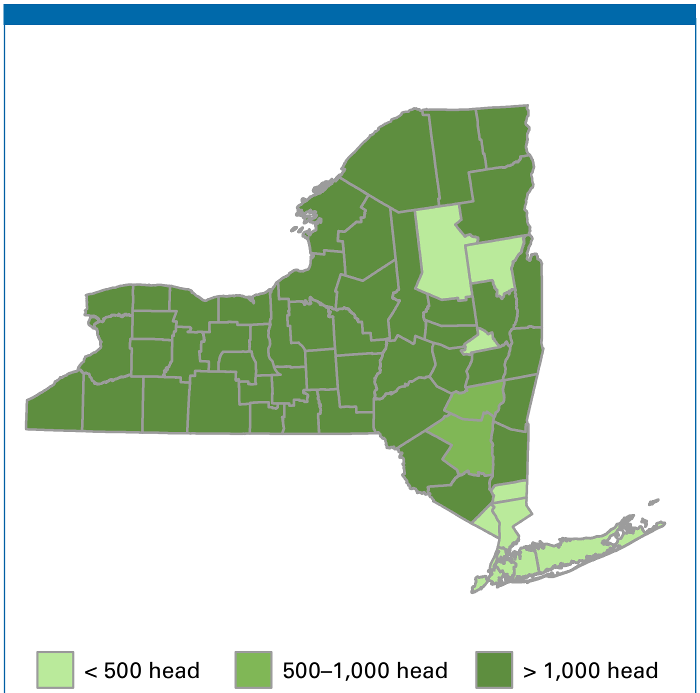
Market Opportunities to Generate Electricity with Anaerobic Digestion (2007)	
Total number of dairy operations	5,683
Total number of mature dairy cows (000 head)	626
Number of feasible dairy cow operations[1]	111
Number of mature dairy cows at feasible operations (000 head)	109
Methane emission reduction 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.

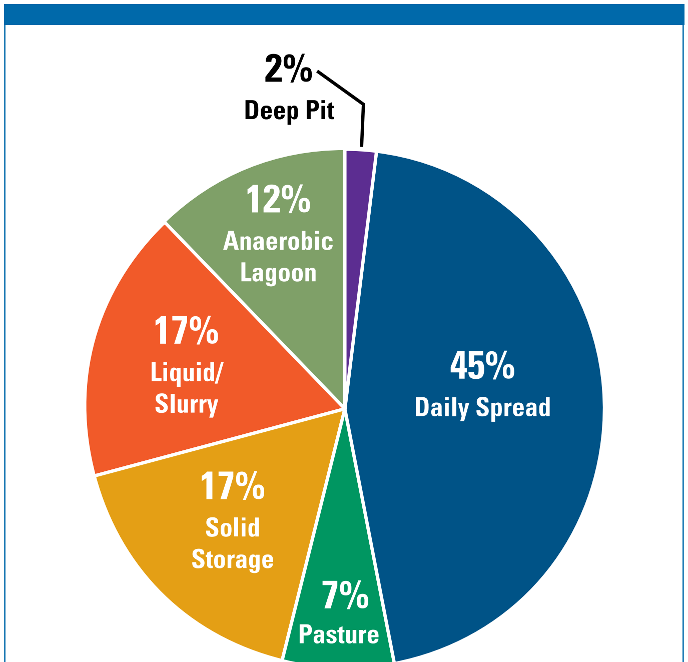
Dairy Farm Size



Dairy Population by County



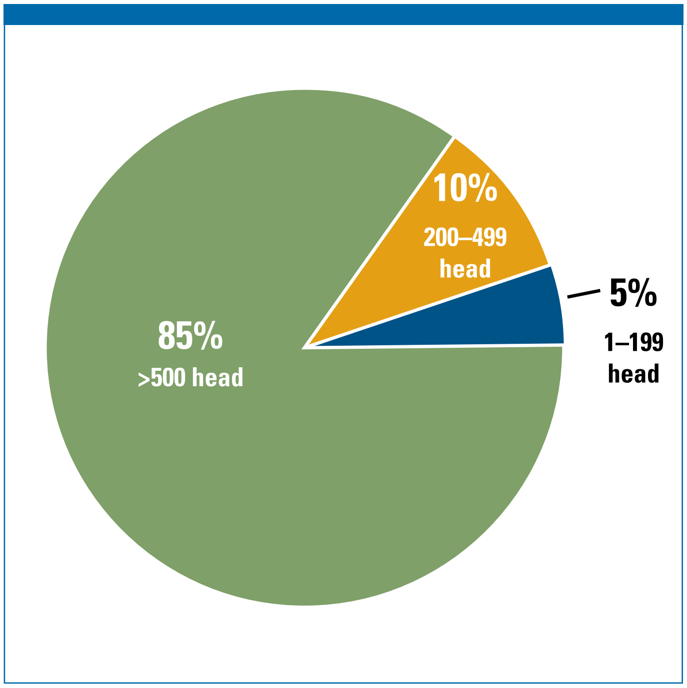
Dairy Manure Managed in Each Waste Management System



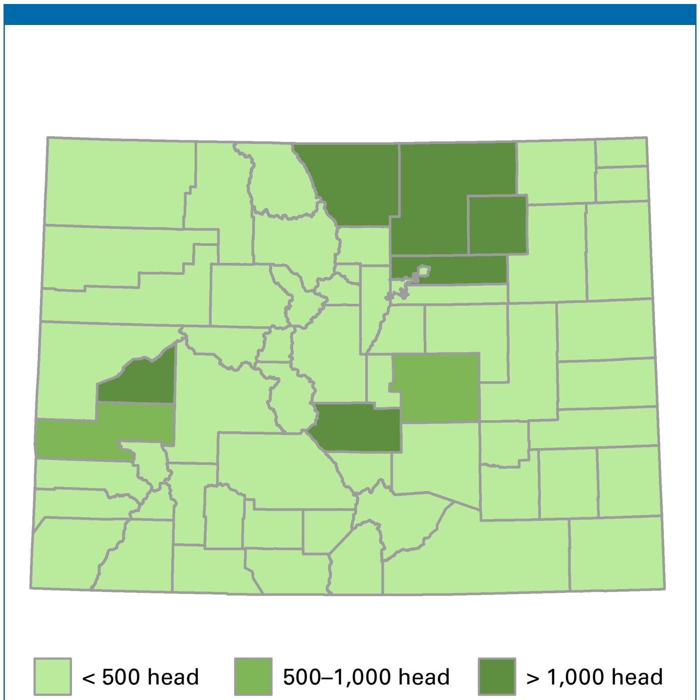
Market Opportunities to Generate Electricity with Anaerobic Digestion (2007)	
Total number of dairy operations	449
Total number of mature dairy cows (000 head)	127
Number of feasible dairy cow operations[1]	54
Number of mature dairy cows at feasible operations (000 head)	97
Methane emission reduction 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