

United States  
Department of  
Agriculture



Office of  
the Chief  
Economist

Office of  
Energy Policy  
and New Uses

Agricultural  
Economic  
Report  
Number 843

February 2008

# Farm-Based Anaerobic Digesters as an Energy and Odor Control Technology

## Background and Policy Issues

William F. Lazarus



Photo credit: PhotoDisc.

---

The U.S. Department of Agriculture (USDA) prohibits discrimination in all its programs and activities on the basis of race, color, national origin, age, disability, and, where applicable, sex, marital status, familial status, parental status, religion, sexual orientation, genetic information, political beliefs, reprisal, or because all or a part of an individual's income is derived from any public assistance program. (Not all prohibited bases apply to all programs.) Persons with disabilities who require alternative means for communication of program information (Braille, large print, audiotape, etc.) should contact USDA's TARGET Center at (202) 720-2600 (voice and TDD).

To file a complaint of discrimination write to USDA, Director, Office of Civil Rights, 1400 Independence Avenue, S.W., Washington, D.C. 20250-9410 or call (800) 795-3272 (voice) or (202) 720-6382 (TDD). USDA is an equal opportunity provider and employer.



United States  
Department  
of Agriculture

Agricultural  
Economic  
Report  
Number 843

February 2008

A Report from the Office of Energy Policy and New Uses

---

# **Farm-Based Anaerobic Digesters as an Energy and Odor Control Technology**

## **Background and Policy Issues**

**William F. Lazarus**

### **Abstract**

This report summarizes the existing literature and analytical perspectives on farm-based digesters, highlights major efforts in the United States and Europe to expand digester usage, and discusses key policy issues affecting digester economics. The study was largely a review of the “gray literature” on digesters, and it serves as a snapshot overview of the industry. Digesters are fairly capital-intensive when viewed primarily as an energy source. On a strictly market basis, current U.S. average electricity prices do not appear to provide sufficient economic justification for digesters to move beyond a fairly limited niche. Digesters make the most sense today where the odor and nutrient management benefits are important, or where the electricity or heat has a higher-than-average value. Digester biogas is mainly methane, which is destroyed when flared or used for electricity. This methane destruction is beneficial in terms of climate change. The associated carbon credits may become a more significant farm revenue source in the future.

**Keywords:** anaerobic digester, energy, electricity, odor, policy, nutrient management, livestock

### **Acknowledgements**

This report was prepared while I was a visiting scholar with the USDA Office of Energy Policy and New Uses in 2006-07. The report grew out of a December 2006 seminar at USDA. The report would not have been possible without the help and encouragement of Roger Conway and the Office of Energy Policy and New Uses (OEPNU) staff. Jim Duffield, Kelsi Bracmort, William Hohenstein, and Marvin Duncan provided helpful

comments on the manuscript. My interest in digesters grew out of earlier work on an Environmental Quality Incentives Program-funded project from the USDA Natural Resource Conservation Service. That project and follow-up work were coordinated by staff of the Minnesota Project, Inc., nonprofit in St. Paul, Minnesota, and involved a number of University of Minnesota staff as well as other agency and utility staff. Deborah Allen, Fantu Bachewe, Amanda Bilek, Roger Becker, Carl Nelson, Margot Rudstrom, David Schmidt, and Mike Schmitt have been terrific collaborators in that work. Phil Goodrich deserves a special note of thanks for sharing his insights on digester engineering and for putting up with me on our European digester tour. Finally, Dennis and Marsha Haubenschild have hosted us at their farm many times and shared their views on what it is like to actually own and operate a digester. I owe them my thanks for their cooperation and enthusiasm.

# Contents

- Summary . . . . . iv
  - What Is the Issue? . . . . . iv
  - What Did the Study Find? . . . . . iv
  - How Was the Study Conducted? . . . . . iv
  
- Introduction and Overview . . . . . 1
  
- Digesters in Europe and North America . . . . . 2
  
- U.S. Policies Related to Digesters . . . . . 5
  - Educational and Technical Assistance . . . . . 5
  - Support for Research and Feasibility Studies . . . . . 5
  - Grants, Loans, and Production Incentives . . . . . 6
  - Environmental Policy . . . . . 6
  - Distributed Power Pricing and Interconnection Policy . . . . . 6
  
- State Policies and Electric Rate Differentials . . . . . 8
  
- Technology and Economics of Farm-Based Digesters . . . . . 13
  - Biogas Use . . . . . 14
  - Feedstocks . . . . . 14
  - Digestate Utilization and Benefits Relative to Raw Manure . . . . . 15
  - Economic Assessments of Farm-Based Digesters . . . . . 17
  - Digester Economies of Size . . . . . 21
  
- Conclusions and Suggestions for Future Research . . . . . 23
  
- References Cited . . . . . 25

## Summary

Renewable energy is currently viewed as key to the energy security of the United States and as an economic opportunity for rural communities. Biofuels such as ethanol and biodiesel have been receiving most of the attention, but other renewable energy sources can also play an important role. Concern about climate change and greenhouse gases is growing, with methane from livestock production being one of the key areas where mitigation may be feasible. This report summarizes the outlook for farm-based digesters, highlights major efforts in the United States and Europe to expand digester usage, and discusses key policy issues affecting digester economics.

### What Is the Issue?

Digesters are of interest with respect to climate change, energy, air quality, water quality, and land use. However, digesters are capital-intensive and difficult to maintain. Many of the digesters installed in the 1970s went out of business. Have the bugs been worked out sufficiently to improve success rates in the future? What Government policies currently help facilitate adoption of this technology? Do those policies need fine-tuning to speed adoption further? How significant can digesters be as a source of renewable energy?

### What Did the Study Find?

Farm-based anaerobic digesters can make a significant contribution to U.S. energy security as well as help to minimize livestock odors. Digester technology has progressed as a result of a number of active development efforts in North America and Europe. The European countries have shown that biogas can supply a significant percentage of national electricity needs or can even serve as a transportation fuel if need be. However, digesters are fairly capital-intensive when viewed primarily as an energy source. On a strictly market basis, current U.S. average electricity prices do not appear to provide sufficient economic justification for digesters to move beyond a fairly limited niche. Digesters make the most sense today where the odor and nutrient management benefits are important, or where the electricity or heat has a higher-than-average value. Continued high fossil fuel prices and/or public sector support could accelerate digester adoption.

### How Was the Study Conducted?

The study was largely a review of the “gray literature” on digesters. By “gray literature” we mean publications other than peer-reviewed journal articles, such as extension monographs, slide sets, Web sites of public entities and private firms, consultant feasibility analyses, government information bulletins, and university research project reports. A substantial body of literature exists on digesters but is somewhat scattered and reflects a number of different analytical perspectives. Some of the material in this report was presented in a seminar at the U.S. Department of Agriculture in December 2006. A May 2006 study tour of digesters in Denmark, Sweden, and Germany helped shape the perspective taken in this report. The initial impetus for the study dates back to an interdisciplinary project monitoring a Minnesota dairy farm digester over several years. Followup projects looking at the feasibility of centralized digesters, digesters for smaller farms, and various biogas utilization options have also provided insights for this report.

## Introduction and Overview

Anaerobic digestion converts volatile acids in livestock manure into biogas consisting of methane (55–70 percent), carbon dioxide (30–45 percent), and small amounts of water and other compounds.<sup>1</sup> The organic matter that can be processed in anaerobic digesters includes manure from dairy, swine, beef, and poultry farms; wastewater sludge; municipal solid waste; food industry wastes; grain industry and crop residues; paper and pulp industry wastes; or any other biodegradable matter. The methane produced by this process can be used to generate electricity or for heating. Under favorable circumstances, there is also a potential for purifying the methane into a marketable, natural-gas-grade biogas suitable for household and industrial use. If we move to a “hydrogen economy,” biogas can be an excellent source of hydrogen. In addition to generating renewable energy, anaerobic digestion leads to reduced odor pollution, fewer pathogens, and reduced biochemical oxygen demand. There is little change in the nutrient value of the manure and organic matter that passes through the process, which can then be used as fertilizer.

Anaerobic digesters are relevant to concerns about climate change, energy supplies, air quality, and land use. Farm-based digesters are an attractive technology for addressing climate change because they reduce livestock-related emissions of methane, a potent greenhouse gas.<sup>2</sup> Evaluation of the greenhouse gas reduction benefits of a farm-based digester involves three considerations: how much methane is generated in the digester and then burned in the engine or flare; how much methane would have been generated otherwise if the farm had used a manure handling system that did not include a digester; and how much CO<sub>2</sub> would otherwise have been generated in producing the electricity that is replaced by the electricity generated by the digester system. Because digesters are designed to maximize methane production, they typically generate more methane than manure handling systems that do not include digesters. Calculating the greenhouse benefits based on digester output rather than output of the alternative manure handling system can result in an overestimate of the benefits. See the Winter 2006 AgSTAR Digest for more details on calculating methane destruction benefits [U.S. AgSTAR, 2006a].

The interest in digesters was initially driven by energy concerns, with biogas viewed as a source of electricity or a substitute for natural gas. Digestion converts volatile organic compounds in manure to more stable forms that can be land-applied with fewer objectionable odors; so many farm digesters have been installed to address neighbors’ complaints. Municipal sewage treatment plants tend to use digesters to reduce the volume of solids and minimize the land required for spreading sludge.

<sup>1</sup>The methane content of biogas varies depending on the amounts of carbohydrate, protein, and fats in the digestate (material being digested), and on CO<sub>2</sub> dissolution in the digester water (see Appendix A of Krich et al. (2005)).

<sup>2</sup>Discussions of greenhouse gases are often expressed in terms of carbon dioxide (CO<sub>2</sub>) equivalents, so some people are confused by the fact that a digester doesn’t reduce CO<sub>2</sub>. The methane from a digester is destroyed through combustion in an engine, flare, or other device. Combustion actually produces CO<sub>2</sub> and water (H<sub>2</sub>O). Methane (CH<sub>4</sub>) is considered to be around 23 times as powerful as CO<sub>2</sub> in its effect on global warming, however, so the overall impact of converting CH<sub>4</sub> to CO<sub>2</sub> is considered beneficial.

## Digesters in Europe and North America

Europe faced energy reductions during and after World War II and is still more dependent on imports of oil and natural gas than the United States [Lusk, 1998]. For example, Sweden has no domestic sources of oil or natural gas, and in 2004 Germany was dependent on imports for 89 percent of its natural gas consumption [U.S. Energy Information Administration, 2007a; WestStart-CALSTART, 2004]. Thus, it is not surprising that Europe has moved more aggressively to develop digesters, along with other renewable energy sources, than has the United States.

Of the European countries, Denmark, Sweden, and Germany have the best known biogas industries. Many European digesters have been designed as centralized units to serve the typically small farms. Denmark currently has around 20 centralized digesters. The number of individual farm digesters in Denmark was not reported, but the newer digesters are individual ones on larger swine operations [Al Seadi, 2000; Hjort-Gregersen, 1999]. The Al Seadi report states that: “The first biogas plants were only designed for generating energy. Later it occurred that the plants made a significant contribution to solve a range of problems in the fields of agriculture, energy and environment. Consequently, increased attention has been paid to these issues, and centralized biogas plants are now considered as integrated energy production, manure and organic waste treatment and nutrient redistribution facilities” (see p. 3 of Al Seadi). The centralized digesters described in that report all co-digest materials such as food processing waste along with livestock manure, which increases biogas output as well as solving disposal problems for other industries. The biogas from those digesters is utilized in combined heat-and-power plants, which in some cases supply heat to district heating systems in nearby villages.

Danish legislation has encouraged the centralized digesters, which are common in that country [Al Seadi et al., undated]. Manure storage is required, and is often integrated with digesters. There are limits on manure application rates based on nitrogen (N) levels (digestion increases N availability, providing more immediate benefit from the N that is allowed). Industrial processors have incentives to deliver wastes to digesters and pay tipping fees. Power companies are required to purchase digester electricity at regulated prices. Biogas is exempted from energy taxes. Grants, subsidized loans, and production subsidies are also available for digesters.

The Swedish biogas industry is unique in its emphasis on the use of biogas as a fuel for vehicles designed to run on compressed natural gas [WestStart-CALSTART, 2004; Krich et al., 2005]. The biogas production and distribution system was developed with the involvement of all the players—farmers, waste haulers, technology providers, national and municipal governments, transit authorities, energy providers, vehicle manufacturers, and consumers. Transit buses are the “anchor customers,” and Volvo bi-fuel vehicles also use the biogas, which is upgraded to as high as 97-percent methane. The Krich et al. report states that four plants in Sweden are currently upgrading biogas to biomethane.<sup>3</sup> The WestStart-CALSTART report states that only the Laholm plant injects its biomethane directly into the national natural gas distribution grid. The other plants distribute the gas through dedicated pipelines to biogas

<sup>3</sup>“Biomethane” refers to biogas that has been upgraded to natural gas quality.



refueling stations or inject “partially cleaned” biogas into “town gas” pipeline networks for residential use.

Germany currently has at least 2,700 digesters, operating with a combined electrical generating capacity of 650 megawatts [Effenberger, 2006]. Some observers have estimated the number of German digesters in late 2007 to be as high as 4,000. They supply 0.8 percent of Germany’s electricity needs (all renewable fuels combined provide 9.4 percent). Energy crops such as corn silage are a more common digester feedstock in Germany than in Denmark or Sweden. Effenberger cites one study that suggests energy crops may supply almost half of the total feedstock of digesters in the German State of Thuringia.

Farm-based digesters first became popular in the United States during the 1970s oil crisis. One of the first American digesters was installed in Iowa in 1972 [Mattocks and Wilson, 2004]. Around 70 digesters were installed on U.S. farms between 1970 and 1990, but most of those early designs failed or were taken out of service [Mattocks and Wilson, 2004; Roos, 2002; Lusk, 1998]. Energy prices declined in the late 1980s and 1990s, and it is unclear whether the success rate might have been higher if prices had remained at the levels of the early 1980s. In year-2000 dollar terms, West Texas crude oil prices reached \$50/barrel in 1982 and then declined to near \$10 in 1999 before climbing past the \$50 level again in 2006 [U.S. Energy Information Administration, 2007b]. Digesters are not the only renewable energy technology that has seen large numbers of systems cease to operate. For example, nearly 30 percent of biomass-burning power plants built since 1985 are currently nonoperational [Peters, 2007].

A total of 111 farm digesters were operating in the United States in 2007. Most of these digesters generate electricity, with an estimated output of 215 million kilowatt-hours equivalent of useable energy. Others simply flare off the biogas for odor control, use it for heating, or upgrade the gas for injection into the natural gas pipeline [Ball, 2007]. AgSTAR estimates that around 7,000 large dairy and swine operations could operate profitable biogas systems, with a generating potential of 722 megawatts—0.1 percent of total U.S. electrical generating capacity, or enough to supply almost 1 million homes [U.S. AgSTAR, 2006a].

The number of operating digesters in the United States is somewhat difficult to track. When a digester is installed, it is often publicized, especially if public support was provided. So, new digesters are generally identified and counted. When a digester ceases to operate, however, that status change may not become known until such time as someone does a comprehensive survey. Another potential source of confusion is that some large farms have installed several digesters, so when a count is done one must be clear about whether the number of farms or the number of digesters was counted.

Two surveys of digesters by Kramer in seven Midwestern States 2 years apart, in 2002 and 2004, show the dynamic nature of digester installations [Kramer, 2004]. Of 23 digesters on 19 farms with digesters in 2002, 18 digesters on 14 farms were still operating in 2004, while 5 had ceased to operate. Ten more digesters on six farms were under construction or in startup. In many cases, systems that are no longer operational did not

fail (defined as ceasing to operate) because of technology shortcomings, but because the farmer was unwilling to continue operating the Anaerobic Digestion (AD) system given the operation and maintenance costs.

Dairy producers who have digesters are reported to be almost universally pleased with them, although the motivation for installing them varies. A survey of 64 producers across the United States and 10 in California found that reducing odor and improving air and water quality were the main motivations for digester installation [Hettinga, 2007; U.S. AgSTAR, 2007b]. Electricity generation was viewed as a secondary benefit. Negotiating with the local electrical utility was the biggest challenge faced by these producers and, in many cases, discouraged them from installing digesters that had been planned. The national sample consisted of the producers who had received USDA Section 9006 grants in 2003 or 2004. By the time of the survey, 27 (40%) of the digesters were operational or under construction. Twenty eight (45%) were still in the planning stages or the producers were undecided whether to install them, while nine (15%) had decided not to move forward with installation. Financing also proved to be difficult for many in the national group and obtaining permits was more difficult for the California group.

Canada is also developing a digester industry, which was initiated largely by health concerns. One activity of the Canadian government to address the environmental problems posed by livestock manure is the ManureNet Web site, a collection of over 23,000 links on digesters, manure, and nutrient management [Agriculture and Agrifood Canada, 2005]. ManureNet includes information on digesters, organized into topics such as government programs, technology providers and consultants, digester designs, electricity net metering, impacts of antibiotics on digester performance, pathogen reduction, and economic assessments.

## **U.S. Policies Related to Digesters**

Federal, State and local policies have been instrumental in digester development in the United States. Policies relating to digesters include educational and technical assistance, grants and production incentives, distributed power generation policy, environmental policy, and support for research and development.

### **Educational and Technical Assistance**

One Federal digester support program is AgSTAR, a voluntary effort jointly sponsored by the U.S. Environmental Protection Agency (EPA), the U.S. Department of Agriculture (USDA), and the U.S. Department of Energy [U.S. AgSTAR, 2007a]. The AgSTAR program provides publications and technical tools, including a handbook and software for doing initial economic evaluations. The program helps interested livestock producers to identify potential project developers, suppliers, and partners, and conducts workshops and conferences.

One recent AgSTAR product is a protocol for rigorous evaluations of digester designs. The protocol was used to compare manure use in two typical upstate New York dairy farms, one with a digester and one without [Martin, 2004]. While the two-farm sample is obviously small, this side-by-side comparison provides insights into how a digester changes the manure effluent. For example, digestion reduced volatile solids, chemical oxygen demand, and pathogen levels. Ammonia N was increased in the effluent, with the addition presumably coming from the mineralization of the organic N. Martin did not report ammonia emissions into the atmosphere from the effluent, although total N losses from the manure storage structure were measured as less than from the undigested manure. Ammonia emitted into the atmosphere is a concern because it contributes to eutrophication of surface waters and nitrate contamination of groundwaters, and is a precursor of fine particulate matter (PM2.5) air pollution [U.S. Environmental Protection Agency, 2004; Shih et al., 2006].

The USDA Natural Resources Conservation Service also provides technical assistance on digesters, including conservation practice standards and a technical note on energy production costs [USDA Natural Resources Conservation Service, 2004; USDA Natural Resources Conservation Service, 2007; Beddoes et al., 2007].

### **Support for Research and Feasibility Studies**

Other Federal support for digesters includes basic research by the USDA Agricultural Research Service (ARS). The ARS facility at Beltsville, MD, recently installed a set of small digesters designed for replicated studies of digester feedstocks such as food wastes [U.S. AgSTAR, 2004]. State and local governments have also provided funding for basic research, as well as feasibility studies, such as the California biomethane study [Krich et al., 2005] and centralized digester studies in King County, Washington [Environmental Resource Recovery Group, LLC, 2003], Michigan [Frazier, Barnes & Associates, LLC, 2006], and Minnesota [Sebesta Blomberg & Associates, Inc., 2005].

## Grants, Loans, and Production Incentives

The main Federal sources of financial support for digesters are (1) the 2002 Farm Bill section 9006 grants (up to 25 percent of project costs) and guaranteed loans (up to 50 percent), and (2) the Renewable Electricity Production Credit (REPC) [USDA, 2007; Office of the Law Revision Counsel, U.S. House of Representatives, 2004]. Environmental Quality Improvement Program (EQIP) cost-share funds are also available for digesters that address pollution problems (see, for example, USDA Natural Resources Conservation Service, 2003). Since 2003, the 9006 grants for digesters have amounted to around \$26 million and have leveraged \$123 million in private investment. Ninety-one digesters have been funded. Of those, 19 are operational. Six more are nearing completion, and the other 66 are still under development [Lusk, 1995]. A number of other funding sources are discussed in a feasibility study of a Minnesota digester by Sebesta Blomberg & Associates, Inc. (2005).

Digesters are considered “open-loop biomass” for the purpose of the REPC, which is available at 0.9 cents/kwh for the first 5 years of digester operation. The REPC is also reduced by up to half the amount of Government grants (such as section 9006), subsidized financing, and other credits, so a livestock producer receiving a section 9006 grant for 25 percent of the project cost would need to consider that tradeoff. The REPC is currently set to expire on December 31, 2008 [North Carolina Solar Center, 2007a]. Some States, such as Minnesota, offer their own per-kwh production incentives and low-interest loans for digesters.

## Environmental Policy

The U.S. Environmental Protection Agency is currently monitoring air emissions from the livestock industry under a 2005 consent agreement, to help determine how to regulate those emissions [U.S. Environmental Protection Agency, 2005]. While the regulatory scheme is not yet determined, digesters may well be one of the technologies that could be installed to reduce emissions of volatile organic compounds. Hydrogen sulfide, ammonia, and particulate matter are also being monitored.

Farm-based digesters may play an important role in the Methane to Markets Partnership, a voluntary, nonbinding framework for international cooperation to reduce methane emissions [Methane to Markets Partnership, 2007]. The partnership will focus on key technologies, market assessment, project financing, country-specific needs, cooperative opportunities, and communication and outreach. Agriculture, coal mines, landfills, and oil and gas systems are being targeted. Livestock waste management is the main focus of the agricultural work.

## Distributed Power Pricing and Interconnection Policy

While distributed power policy is too complex to describe fully here, a few of the key aspects relating to digester electricity will be noted. A long-standing Federal law regulating distributed electrical generators such as

digesters is the 1978 Public Utility Regulatory Practices Act (PURPA), which requires utilities to interconnect with qualifying facilities and to buy the electricity at the utility's avoided cost. The definition of a "qualifying facility" relates to size, which generally may not exceed 80 megawatts, and fuel use, which must be mainly biomass, waste, or renewable or geothermal resources. "Avoided costs" means the incremental costs to an electric utility of electric energy or capacity or both which, but for the purchase from the qualifying facility or qualifying facilities, such utility would generate itself or purchase from another source [Regulations Under Sections 201 and 210 of the Public Utility Regulatory Policies Act of 1978 With Regard to Small Power Production and Cogeneration, 18 U.S.C. 292.101 et seq., undated; Cogeneration and small power production, 16 U.S.C. 824a-3]. Derivation of avoided costs involves an energy component and a capacity component. Capacity planning must consider the 10 succeeding years [Availability of electric utility system cost data, 18 U.S.C. 292.302]. The Energy Policy Act of 2005 loosened the requirements on utilities to purchase electricity from small producers who have nondiscriminatory access to wholesale electricity markets. There is a rebuttable presumption that qualifying facilities below 20 megawatts do not have nondiscriminatory access to the market [Termination of obligation to purchase from qualifying facilities, 18 U.S.C. 292.309].

The value of digester electricity is an important factor in economic feasibility, and negotiating favorable terms with local utilities for valuing avoided purchases and excess sales has long been a concern. The United States and the European countries have followed somewhat different paths in encouraging renewable sources of electricity. In the United States, the Federal Government and the States have tended to set quantitative mandates or targets, while European countries have tended to set minimum purchase prices ("feed-in tariffs") that utilities must pay suppliers of renewable electricity. Kildegaard argues that the minimum-price approach is more efficient [Kildegaard, 2006].

## State Policies and Electric Rate Differentials

Farm-based digesters can be found in most of the States with significant dairy or swine industries. California, New York, Pennsylvania, and Wisconsin are the only States with more than five digesters each, however [Ball, 2007]. What explains the popularity of digesters in those States?

Digesters are a technology that produces electricity, requires large volumes of livestock manure, and minimizes livestock odors, so it could be expected that States with high electricity rates and/or large livestock operations would be likely to explore digester development. Data are not available on the value of the electricity generated at most farm-based digesters, except for a few situations discussed in the economic assessment section below. Most States have adopted rules implementing PURPA [National Rural Electric Cooperative Association, 2005]. For example, Minnesota's implementation language is in Minnesota Statutes section 216B.164 [Cogeneration and Small Power Production, Minnesota Statutes 216B.164, 2006].

The Kildegaard paper describes the rulemaking procedure that the Minnesota Public Utility Commission has followed to set rates and interconnection standards for distributed electricity [Kildegaard, 2006]. The most difficult problem has been to arrive at the value of the backup generating capacity that the utility must provide in case the distributed facility shuts down, in particular, how the distributed facilities affect the utilities' need to meet projected future demand growth and over what timeframe. A white paper by the National Rural Electric Cooperative Association provides a rural electric cooperative's perspective on the question of how to value distributed generation [National Rural Electric Cooperative Association, 2005]. That paper argues that distributed generation is in danger of being oversold, and that it poses genuine safety and reliability risks, and can pose economic risks to some incumbent utilities and their consumers.

State incentives include renewable electricity portfolio minimums that may induce utilities to offer attractive prices for digester electricity, particularly in States where wind resources are not good enough to make wind farms feasible. For example, Minnesota provides a 1.5-cent/kwh production incentive and low-interest construction loans for digesters [Minnesota Department of Agriculture, 2007; Minnesota Department of Commerce, 2007]. The California Energy Commission's Dairy Power Production Program was mentioned above [Marsh and LaMendola, 2006]. A description of every State's programs is beyond the scope of this analysis—see the Database of State Incentives for Renewable Energy for State program details [North Carolina Solar Center, 2007b]. An analysis of experiences in 11 States with tradable renewable credits, also known as green tags or renewable energy credits, is provided in Fitzgerald et al. (2003).

Local governments sometimes require new or expanded livestock facilities to install digesters for odor control. Electricity may then be generated as a side benefit, or the farm may decide to just flare the gas. Local policies vary widely, but in Minnesota large new feedlots typically must have public hearings before they are permitted (see, for example, the feedlot ordinance for

Nicollet County, Minnesota [Department of Environmental Services, Nicollet County, Minnesota, 2007]). Digesters are not explicitly required in that ordinance, but might be one of a range of technologies that the feedlot operator and officials could consider in addressing concerns raised by the public.

The avoided costs that PURPA required utilities to use as a basis for payment rates generally are not public information, but retail electric rates may serve as a proxy for avoided costs. Retail electric rates are a function of utility costs for generation, transmission, and distribution. Assuming that the main costs avoided are for generation and that transmission and distribution costs are relatively constant across States, average retail electricity rates are likely to provide at least a rough estimate of the variation in avoided costs across States. Table 1 gives a breakdown of the 2006 average retail electricity rates in the 23 States that had a total of 111 digesters [Ball, 2007]. The most recent electricity rates available for Denmark and Germany (for 2004) are shown for comparison. The numbers of milk cows as of January 2007 and the 2006

Table 1

**State Electricity Rates Compared With the U.S., Danish, and German Averages, with Numbers of Milk Cows, Pigs, and Digesters**

	Average retail electricity rates, cents/kwh <sup>1</sup>			Dairy cows (000)	Pig crop (000)	Number of digesters in 2007
	All sectors	Residential	Industrial			
U.S. total	8.83	10.55	6.12	9,129	105,259	111
California	12.15	12.20	9.71	1,790	330	15
Connecticut	14.79	17.27	11.70	19	5	2
Florida	10.50	11.43	7.72	130	56	1
Idaho	4.66	6.10	3.10	502	50	1
Illinois	7.19	8.79	4.73	103	7,377	4
Indiana	6.45	8.69	4.86	166	4,858	3
Iowa	6.71	9.58	4.87	210	16,583	3
Maryland	10.78	10.47	12.05	60	64	1
Michigan	8.24	9.83	6.13	324	1,765	3
Minnesota	6.81	8.66	5.31	455	10,209	2
Mississippi	7.55	8.83	5.60	22	695	1
Nebraska	5.83	7.32	4.41	60	6,514	1
New York	14.33	16.92	9.17	628	149	16
North Carolina	7.68	9.80	5.35	48	20,048	3
Oregon	6.71	7.62	4.89	115	52	5
Pennsylvania	8.48	10.54	6.38	550	1,676	16
Texas	10.16	12.89	7.51	347	1,651	3
Utah	6.06	7.43	4.40	86	1,365	2
Vermont	11.48	13.84	8.10	140	5	4
Virginia	6.78	8.75	4.81	100	548	1
Washington	6.51	6.99	5.17	235	48	2
Wisconsin	8.09	10.59	5.90	1245	935	20
Wyoming	5.49	8.27	4.37	7	377	2
Denmark, 2004		28.30	9.60			
Germany, 2004		19.80	7.70			

<sup>1</sup>The U.S. electricity prices are for October 2006. The latest Danish and German rates available through the EIA are for 2004.

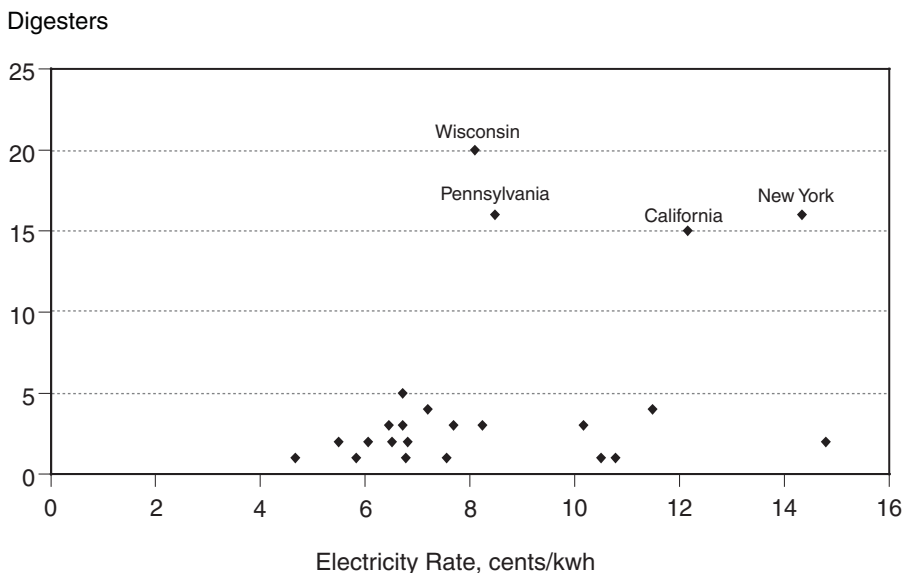
Sources: The electricity rates are from the U.S. Energy Information Administration. Milk cow and pig crop numbers are from the USDA National Agricultural Statistics Service. The digester numbers are from the AgSTAR 2007 Update.

pig crops are also indicated. Figure 1 shows how the digester numbers relate to the electricity rates.

California, Florida, Maryland, Texas, and Vermont, like New York and Connecticut, have double-digit electricity rates. California also has the most dairy cows, concentrated on quite large operations in an area where air quality is a concern. Dairy farm digesters are one part of a broader energy and waste management project in the “Inland Empire” region of California that lies east of Los Angeles [Inland Empire Utilities Agency, 2006]. The California Energy Commission’s Dairy Power Production Program provides construction buydown grants and electrical generation incentive grants; to date, 14 projects have been approved for grants totaling \$5,792,370. The projects have an estimated generating capacity of 3.5 megawatts. Five dairy farm digesters funded by this program have been operating long enough to be described in 90-day evaluation reports in 2006, with others evaluated in 2005 [Marsh and LaMendola, 2006].

Wisconsin is interesting in that the State has more digesters than California but cheaper electricity (8.09 cents compared to 12.15 cents/kwh). A comprehensive discussion of each State’s situation is beyond the scope of this paper, but a few possible reasons can be identified for the popularity of digesters in Wisconsin. One factor is that Wisconsin was one of the first States to enact a renewable electricity portfolio standard [North Carolina Solar Center, 2007b]. States further west, such as Minnesota, are relying mainly on wind as a source of renewable electricity, but Wisconsin’s wind resources are not as good, so there is more of a need for digesters to meet that requirement. Also, Wisconsin is the second-ranked dairy State in the United States. The Wisconsin dairy industry has been consolidating into larger operations with new facilities, so the addition of a digester to a facility construction plan may be a logical step. Many of the Wisconsin digesters are plug-flow designs,

Figure 1  
**U.S. Digesters by State in 2007 Compared With October 2006 Average Retail Electricity Rates**





which will work with dairy manure and are less costly than the complete-mixed digester designs that are generally used with swine manure, so that investment requirements are somewhat less than for States where swine is the predominant livestock type.

Aside from the retail electricity rates, State policies on distributed power pricing and interconnection also differ among States and, some authors argue, can greatly affect the economic viability of digesters and other distributed power generation sources. Contractual arrangements for digesters operating in parallel with electric utilities tend to be of three types: “buy all-sell all,” “surplus sale,” and “net metering” [U.S. AgSTAR, 2006b, chapter 5]. In a buy all-sell all arrangement, the utility usually offers an avoided cost rate for all electricity generated, whether the amount generated exceeds usage on the farm or not. In a surplus-sale arrangement, excess generation is sold at the avoided cost rate, while excess usage is purchased at the retail rate. This allows the farm to realize the retail value of the amount used on the farm. However, some utilities impose “demand” or “standby” charges to pay for the availability of electricity to the farm when the generator is not running. At least one digester operator avoids standby charges by purchasing electricity on an interruptible basis. He runs a backup generator (separate from the digester generator) for 80 to 100 hours of peak demand per year when requested by the utility, and so also has the backup generator available when the digester generator needs servicing [U.S. AgSTAR, 2007b].

Net metering allows customer/generators, such as farm digester operators, to spin their meters backwards, in effect paying the customer/generator the retail rate for the electricity they generate but do not immediately consume. If customers generate more electricity than they use over a specified period, they are typically paid for the net excess generation at the utility’s avoided cost, or at the wholesale rate. In some cases, however, they are paid at the retail rate, or their excess electricity may be granted to the utility with no payment [Chapman, 2006; New Rules Project, 2007]. Lack of net metering may not necessarily be a barrier to digester installation if the other terms of the electricity sales agreement are favorable, but availability of net metering with a favorable payment for excess generation might help stimulate digester adoption. The Energy Policy Act of 2005 requires States to offer some type of net metering (see 109th Congress, 2005, Title XII, Subtitle E, section 1251), but the specifics are regulated by the States. Maximum sizes of generators that qualify for net metering, and maximum percentage of total utility capacity vary by State; digesters qualify in some States and not in others. Most digesters have generators of at least 100 kilowatts, so a net metering maximum below that level is unlikely to help promote digesters. Of the four States with more than five digesters, California and New York have net metering caps greater than 100 kilowatts. California has a 1-megawatt maximum, whereas New York’s maximum for digesters is 400 kilowatts [Chapman, 2006]. Wisconsin’s and Pennsylvania’s caps are too low to be beneficial to digesters—Wisconsin’s limit is 20 kilowatts, whereas Pennsylvania has a 10-kilowatt cap [North Carolina Solar Center, 2007b; Chapman, 2006].

New York and Connecticut have the highest electricity rates of the States with significant digester activity. The New York State Legislature formed the New York State Energy Research and Development Authority

(NYSERDA) in 1975 with funding from an assessment on utilities [New York State Energy Research Development Agency, 2007]. Since that time, Cornell University has had an active research and extension program on digesters. The program is responsible for developing the plug-flow digester design, which has lower capital costs and is easier to operate than the early complete-mix digesters [Lusk, 1998]. The Cornell program has issued papers on a variety of topics, including biogas processing, use of manure solids for dairy cow bedding, and operating experience and economic comparisons of digesters on a number of New York dairy farms [Cornell Manure Management Program, 2007].

The Central Vermont Public Service Corporation is encouraging dairy farm digesters by offering financial incentives, along with a 4-cent/kwh premium on digester electricity. The 4-cent premium is a voluntary addition that over 2,500 consumers have chosen to pay on their electric bills [Dunn, 2007]. So far, one Vermont farm is operating a digester under the program.

As a possible adjunct to the electricity being generated by digesters in California, the potential for producing biomethane from dairy manure and other wastes has been studied [Krich et al., 2005]. Krich includes biogas-upgrading cost estimates, based on information from four Swedish upgrading plants, and a discussion of prospects for siting farm digesters to feed the biomethane into existing compressed natural gas outlets. The feasibility of operating centralized digesters in California has also been analyzed [Hurley, Ahern, and Williams, 2006].

Pennsylvania also has relatively cheap electricity, but it has 16 digesters. Pennsylvania has a relatively large number of rural residences interspersed with its livestock operations, so urban sprawl-related odor concerns may have been a more significant motivation for digesters there than in the more rural States further west. Illinois and Iowa have low electricity rates, but large swine industries, with odor concerns related to urban encroachment that were the motivation for early digesters [Lusk, 1998]. While North Carolina's electricity rates are relatively low, North Carolina State University has an active livestock waste management research program, funded via an agreement between the North Carolina Attorney General and six large swine operations to preserve and enhance water quality [North Carolina State University, 2007]. This research focuses on innovative digester designs along with other technologies for air and water quality preservation and enhancement. Oregon and Washington have low-cost electricity, but they have water quality concerns that have motivated digester development [Environmental Resource Recovery Group, LLC, 2003; Port of Tillamook Bay, 2006].

## Technology and Economics of Farm-Based Digesters

Digester technology is discussed in detail in many of the references mentioned above. This section will highlight only a few common themes and issues particularly relevant to energy policy. For more details, a reader might start with the AgSTAR handbook for general background; the Martin protocol description, with and without comparison on performance measures; Lusk for historical perspective; Krich et al. on biomethane; and the Marsh and LaMendola reports on startup issues [U.S. AgSTAR, 2006b; Krich et al., 2005; Martin, 2006; Martin, 2004; Lusk, 1998; Marsh and LaMendola, 2006].

The three main designs for farm-based digesters are the covered anaerobic lagoon, plug-flow, and complete mix (or continually stirred tank reactor) (see, for example, Krich et al., 2005). Digester temperature must be regulated, so anaerobic digesters are also classified by working temperature. Those that work at temperatures between 95 and 105 degrees Fahrenheit are called mesophilic, whereas those that work between 120 and 140 degrees are known as thermophilic. Covered lagoons operate at “psychrophilic” temperatures lower than 95 degrees. They are lower in cost and are commonly used where odor control is the main objective. However, in some warmer locations covered lagoon digesters are successfully used to produce energy. Digestion also occurs naturally at temperatures lower than 95 degrees in ponds, swamps, and open lagoons.

The solids content of the material to be digested is an important criterion in the choice of digester design. Plug-flow digesters work best at a solids content of 11–13 percent, so they work well with dairy manure from operations that collect it by scraping or other methods that do not add much additional water. Complete-mix digesters work at a wider range of 2–10 percent solids, which makes them suitable for a greater variety of materials, including swine manure and processing wastes as well as dairy manure. For more dilute wastes such as those in municipal sewage treatment plants or flush manure systems, “fixed-film” or “filter” digesters are designed to retain the bacteria on some type of medium long enough to break down the waste rather than allowing it to be immediately flushed out of the system. See the Sebesta report for a discussion of several newer digester designs [Sebesta Blomberg & Associates, Inc., 2005].

It is not practical to run the manure from all livestock through digesters. The potential for methane production from livestock waste depends on: (1) size of the farm operation, (2) freshness of the waste, and (3) concentration of digestible materials in the manure. EPA AgSTAR staff have identified 500 dairy cows or 2,000 head of swine as the minimum for which a digester is likely to provide positive financial returns [U.S. AgSTAR, 2007]. Forty percent of the dairy cows and approximately 75 percent of the swine are on operations larger than the AgSTAR figures. Free-stall dairy operations with daily-scraped alleys work well with digesters because the manure does not get mixed with dirt or stones and is moved into the digester while fresh. Drylot dairies, beef, sheep, and poultry operations work less well because the manure may decompose before it is scraped. Flushed manure collection

systems also produce less gas because the digestible materials are diluted. Deep-pitted swine-finishing buildings would need to be modified to remove manure more frequently before a digester would be practical.

## **Biogas Use**

Most farm-based digesters use the biogas output to fuel internal combustion engines that generate electricity. The electricity is most valuable when used on-farm, but many digester systems have the capacity to generate more than the farm needs. The economic feasibility of selling the extra electricity to the local utility varies widely.

If the number of digesters with internal combustion engine generators were greatly increased in the United States, emissions of the regulated air pollutant NO<sub>x</sub> could become an issue. Lean-burn engines with relatively low NO<sub>x</sub> emissions are currently available in sizes of 350 kilowatts or more, but that is larger than most individual farm digesters currently in use (see Krich et al. (2005), pp. 36-37). Microturbines are another widely discussed option, but they have not been used successfully on digesters because biogas impurities corrode the engines. Fuel cells would be cleaner, if they could be developed to the point of commercial feasibility.

Mesophilic and thermophilic digesters typically use engine heat to heat the digester. Engine heat is also often used for heating farm buildings, barn alleys, and water. The biogas can also be burned directly for space heating, which is most common at small digesters where an engine would be uneconomical.

As mentioned earlier, in Sweden biogas is being upgraded, injected into the natural gas grid, and used as a transportation fuel [WestStart-CALSTART, 2004]. Biogas is also being used in combined heat and power plants in villages in Denmark. Krich et al. evaluated the feasibility of this use in the United States.

Two digester installations, in Texas and Wisconsin, began marketing biogas that had been upgraded to biomethane or “renewable natural gas” in 2007 [Smith, 2007; Agri-Waste Energy, Inc., 2007]. The Texas facility, Huckabay Ridge, is located at a dairy manure composting plant. This location provided a large volume of manure, but has added complications in material handling and maintaining the desired solids levels compared to locating at a dairy farm. Huckabay Ridge has also experienced startup problems with gas cleanup and compression equipment and problems with the digester chemical balance that were caused by delays in acquiring a permit for land application of separated liquids, but those problems have now apparently been solved [USDA Natural Resources Conservation Service, 2007].

## **Feedstocks**

Livestock manure is the main feedstock for farm-based digesters, but there are other important feedstocks, including organic wastes from nonfarm sources like food processing industries, as well as energy crops that are digested without going through livestock first. Almost half of the 2005 biogas production in Thuringia State, Germany, was from energy crops

[Effenberger, 2006]. The biogas potential of different feedstocks varies widely [Effenberger, 2006; Steffen et al., 1998].

Nonfarm industries that have organic wastes to dispose of will sometimes pay tipping fees to a farm digester to accept the waste. For the digester enterprise, the tipping fees can be an important side benefit of accepting this feedstock, making the difference between profit and loss (see, for example, the comparison of New York State farm digesters by Wright et al. (2004) and the analysis of centralized Danish digesters by Nielsen and Hjort-Gregersen [Wright et al., 2004; Nielsen and Hjort-Gregersen (undated)]). Industrial organic wastes are an important digester feedstock in Europe [Al Seadi, 2000; WestStart-CALSTART, 2004]. European digesters that accept industrial waste are required to either operate at thermophilic temperatures or pasteurize the wastes at high temperatures before digestion to ensure the destruction of pathogens [Bendixen, undated]. Pasteurization is reported to have the side benefit of speeding up gas production. The required pasteurization tanks and heat exchangers likely add to capital investment and operating costs, but the magnitude of the added cost is not detailed in any of the publicly available economic analyses identified for this report. Another potential concern is that on livestock farms with small land bases, the livestock manure alone may already have too much nitrogen and phosphorus for the cropland available. Imported nonfarm organic wastes would contain additional nutrients, which could exacerbate the cropland nutrient imbalance. The tipping fees and added gas output need to be weighed against potentially greater manure hauling costs to take the effluent to more distant cropland, where the nutrients can be utilized.

## **Digestate Utilization and Benefits Relative to Raw Manure**

Digestion is generally considered to reduce odor during land application of the digestate because the odor-causing volatile organic compounds are converted to more stable forms during digestion. (See pages H-119 through H-123 of Jacobson et al. for principles and empirical studies of the impact of digestion on odor [Jacobson, Moon, Bicudo, Janni, and Noll, 2007]). The reduced odor potential may have economic value to the livestock operation when spread on the operation's own cropland if it minimizes the chance of neighbors' complaints or nuisance lawsuits. The reduced odor may also make the digestate more marketable to crop farms. The economic analyses of U.S. digesters reviewed for this report have not included estimates of the economic value of reduced odor, however.

Pathogen reduction is another frequently cited benefit of digestion. Martin's two-farm comparison found a 99.9-percent reduction in fecal coliforms and *Mycobacterium avium paratuberculosis* [Martin, 2004]. The California spinach recall in 2006 demonstrates the potential food supply disruption and costs that pathogens can cause. No studies have been identified that have quantified the economic benefit of pathogen reduction, however, or the percentage reduction that would be required in order to provide an economic benefit in a given situation.

Many of the farm digester systems described in the literature include separators that extract manure solids that may be used as a bedding material in dairy farm free-stall barns, or sold as a soil amendment for landscaping or gardening. Separation also may help reduce manure application costs because the remaining liquid can be applied at higher per acre rates on cropland close to the livestock facility, since separation removes some of the nutrients from the liquid. The solids are nutrient-dense but have less volume, so they can be hauled to fertilize distant fields at less cost than hauling the original manure. There appear to be few empirical economic assessments of solids separators that document the impact on land-application costs.

These benefits of solids separators can be achieved without incorporating a digester in the system. For that reason, the AgSTAR digester evaluation protocol recommends setting boundary conditions for digester evaluations that leave out the separator part of the system [Martin, 2006]. One reason to include the separator in digester evaluations is that many dairy farms that do not have digesters use sand bedding, and sand tends to settle out in a digester and reduce capacity until it is cleaned out, which can be an expensive process [Moser and Langerwerf, 2004]. A farm operator who might not otherwise consider a separator may decide to install one as part of a digester system so that the solids are available to replace the sand that can no longer be used.

Manure solids bedding is controversial because of concerns that it might increase mastitis problems in dairy cows. The concern is greatest in warm and moist conditions. Determining the impact on mastitis is complicated by a number of factors, including different ways of measuring the concentration of bacteria in bedding (by weight on a wet or dry basis or by volume); changes in bacterial levels in bedding during the time it sits in the stall; the relationship between bacteria in the bedding and on teat ends; and the impact of bacteria in bedding and on teat ends on the occurrence of mastitis and on milk quality. These aspects of solids bedding for dairy animals are summarized in a recent literature review by the Cornell Waste Management Institute [Cornell Waste Management Institute, 2006]. The mastitis associated with factors such as bedding is termed “environmental mastitis,” as opposed to “contagious mastitis.” A common way of detecting mastitis is to estimate the somatic cell count (SCC) of a milk sample, which consists mainly of white blood cells, or leucocytes. A high SCC count is correlated with reduced milk production, and reduces the milk’s value for uses such as cheesemaking. A high bulk tank SCC count generally indicates a problem with contagious mastitis. Herds with lower bulk tank SCC counts have lower levels of subclinical mastitis and better udder health. However, leucocytes in the udder help protect it from other sources of mastitis, so low SCC counts may predispose cows to environmental mastitis. The literature review suggests that more research is needed to clarify the impact of bedding type on mastitis, in the context of the many other management factors on a typical dairy farm.

The economic value of separated and composted manure solids as an off-farm soil amendment appears to vary widely, depending on the seller’s marketing expertise and location. Compost may have a higher market value if sold as a replacement for fertilizer, fungicide, or sand-based golf course topdressing material rather than as a substitute for peat moss. In an online publication, Alexander (2004) provides some example prices for

these products that might be useful for anyone who is considering their use [Alexander, 2007].

A centralized digester was recently proposed to serve an estimated 15 dairy farms in King County, Oregon, with a total of 6,075 cows [Environmental Resource Recovery Group, LLC, 2003]. A followup study examined the feasibility of marketing the digested manure solids from that digester [Terre-Source LLC, 2003]. The Terre-Source study found that a number of the original study's assumptions were not realistic. It found that the cost of handling the solids, which had been estimated at \$5 per ton, was actually \$10–\$15 per ton at a similar operation. It also found that equipment and storage space may also have been underestimated. The followup study further concluded that a 3–5 year ramp-up period would be needed to develop the solids market before the projected price could be achieved. Marketing staff would be needed. The solids volume would be reduced due to solids degradation and moisture loss, there might be odor problems, and sulfides in the solids might need to be dealt with (see Terre-Source, p. 22).

Discussion of solids marketing raises a question about the potential size of the U.S. market for digested manure solids, assuming that the number of digesters becomes greatly expanded and that it proves profitable to market the solids throughout the United States (obviously a long way from the current situation.) The Canadian Sphagnum Peat Moss Association claims to supply over 98 percent of the peat moss used in the United States and to have sold 10.3 million m<sup>3</sup> to the United States in 1999 for almost \$170 million [Canadian Sphagnum Peat Moss Association, 2007]. That works out to \$16.50/m<sup>3</sup>. A study by Hurley et al. (2006) assumes a solids production rate of around 17 yd<sup>3</sup>/cow/year or 13 m<sup>3</sup>/cow/year [Hurley, Ahern, and Williams, 2006]. If the market for manure solids could be expanded to replace, say, 25 percent of that peat moss, that would be around 2.5 million m<sup>3</sup>. This would equal the supply from digesters for around 200,000 dairy cows, assuming that all of the digesters were for dairy rather than swine or poultry. There were 9 million dairy cows in the United States in 2005, so that would be 2 percent of the total dairy herd.

## **Economic Assessments of Farm-Based Digesters**

A number of digesters have been described in case study reports and other publications over the past two decades (see, for example, Kramer, 2004; Lusk, 1998; Lusk, 1995; Martin, 2005; Martin, 2004; Wright et al., 2004). The ManureNet Web site lists 32 other North American and European studies under the “Economic Assessments” heading [Agriculture and Agrifood Canada, 2005]. The capital costs from 38 digesters described in Kramer, Wright et al., and the two Lusk reports have been summarized in Beddoes et al. The latter report found that on average 36 percent of total investment on these digesters was for the electrical generation equipment, suggesting that substantial cost savings may be possible in situations where the biogas can be used for heating rather than to produce electricity.

Methodologies and the amount of economic information on revenues and operating costs vary across these studies, however, making an overall assess-

ment difficult. Martin (2006) suggests that, "...the decision to construct and operate manure-based biogas systems depends ultimately on the anticipated ability to at least recover any internally derived capital investment with a reasonable rate of return and service any debt financing over the life of the system. Otherwise, other investment opportunities become more attractive unless the need for environmental quality benefits, such as odor control, justify the net cost of system operation." It is fairly common for these studies to provide the size and capital cost of the digester. Data are published less often on biogas output, electricity prices, and maintenance costs. It is axiomatic that any technology can be profitable if subsidized heavily enough, so information on grants and operating subsidies received for digesters is important, but it is not always provided.

Few of the published economic assessments appear to be peer reviewed, so accuracy and any bias toward excessively optimistic or conservative assumptions are difficult to evaluate. Even when assessments include comprehensive sets of actual operating performance data, the assessments are usually done fairly early in the expected useful life. Future costs for engine overhauls, flexible cover replacements, and other maintenance, along with gas output declines as the digester fills up with sludge, are difficult to predict, as are future electrical rates.

A few overall conclusions can be drawn from the studies that are relatively recent and complete. First, under current economic conditions digester profitability appears marginal when manure is the primary feedstock, when electricity is the primary source of value, when not all of the electricity can be used onsite, when electricity retail rates (as a proxy for utility avoided costs) are around the national average, and when subsidies are minimal or are left out of the analysis. Second, there are digesters that appear to be operating profitably or that may not be quite covering financial costs, but that are viewed as successful because they are providing nonmonetary benefits such as odor control.

Livestock operations often expand over time depending on profitability, so determining the optimal size for a digester that is expected to operate for 10 years or more can be difficult. Martin discusses one digester that was oversized in anticipation of a dairy herd expansion that did not happen. In this situation, the profitability of a digester can be analyzed two ways: (1) as operating at less than full capacity, or (2) as if it were operating at full capacity. The second approach gives an indication of the potential of the technology, but it may be worth also looking at the as-operating performance, given that future farms may not always be able to anticipate expansion with certainty.

A digester located at the ML dairy farm in New York is profitable [Wright et al., 2004]. The estimated annual revenues are reported as \$287,685, which is over half the total capital cost of \$490,269. Profitability in this case is largely the result of tipping fees and expanded gas production from off-farm food processing wastes that the farm is accepting for digestion. The profitability projections are based on a relatively favorable electricity price of 10 cents/kwh. Wright also mentions that this farm has received grants, but the amounts were not specified. Another New York digester, at AA Dairy, was analyzed by both Wright et al. and Martin [Martin, 2004]. Wright and



colleagues base their analysis on a 10-cent/kwh electricity price, but Martin notes that around a third of the electricity was excess sold to the utility for a lower price, which averaged around 5.25 cents/kwh. That digester is profitable in the Wright calculations (at the 10-cent/kwh price) and would have a 7.5-year payback in the Martin calculations as operated, or 2.8 years if it could be operated at full capacity. In the author’s calculations, AA Dairy does not quite cover the digester costs if the revenue is recalculated based on the electricity price information from Martin. The Wright article describes three other New York digesters that were losing money. The AA Dairy digester was also described as receiving a grant, although the amount was not specified.

The Haubenschild Farms digester in Minnesota has also been profitable [Lazarus and Rudstrom, 2007]. This digester received grants and subsidized financing, and received a 7.3-cent electricity price for its sales in the first 5 years of operation. In contrast, the Tillamook, Oregon, centralized digester has had financial difficulties during its first few years of operation, due partly to higher-than-expected manure transportation costs and lower-than-expected revenue from solids sales [DeVore, 2006].

The investment required to generate electricity via a farm-based digester is somewhat higher than for two other non-fossil-fuel-based electrical generation technologies, a wind generator or an advanced nuclear power plant (table 2). The nuclear costs, from the U.S. Energy Information Administration, are obviously speculative since no nuclear plants have been built in the United States for many years. The investment amounts are shown per cow (for the digesters), per kilowatt of generating capacity. In interpreting the measures of the wind generator’s per kilowatt production capacity, it is important to

Table 2  
**Capital Investments Made for Selected Dairy Farm Digesters Compared With a Wind Generator and an Advanced Nuclear Plant**

	Cows	Generating capacity, kw	Investment/cow	Investment/kw capacity	Investment/kw output
AA Dairy, NY, 1998	950	140	\$374	\$2,536	\$2,941
ML Dairy, NY, 2001	550	130	\$446	\$1,886	\$4,118
Haubenschild Dairy, MN, 1999	740	135	\$663	\$3,632	\$3,632
Tillamook (central), OR, 2003	4,000	500	\$425	\$3,400	\$3,723
Four California dairies average, 2005 <sup>1</sup>	3,176	267	\$561	\$3,774	NA
Wind generator, 2005	NA	1,650	NA	\$1,003	\$2,866
Advanced nuclear, 2002	NA	1,000,000	NA	\$2,117	NA

<sup>1</sup>The average herd size for the four California dairies includes heifers and bulls, but not calves. Marsh and LaMendola also prepared a report on the centralized digester at the Inland Empire facility, which was an upgrade to an existing digester. The investment at that facility was somewhat cheaper on a per cow basis but more expensive per kilowatt of generating capacity. Investment per kw of output was not calculated for these four digesters because they had only been operating for 90 days, so the output numbers provided may not be indicative of longer-run performance.

Sources: The AA Dairy is described by both Wright et al., (2004) and Martin, (2004). The ML Dairy data are from Wright et al. The Haubenschild data are from Lazarus and Rudstrom (2007). The Tillamook data are from DeVore (2006). The California dairy data are from Marsh and LaMendola (2006). The wind generator data are from Tiffany (2005). The nuclear plant data are from the Energy Information Administration (undated).

remember that a wind generator produces only when the wind is blowing. The last column of the table adjusts the wind amount for an assumed 35-percent capacity factor to make it more comparable with the digesters. The digester investment/kw of output numbers is calculated by taking the estimated annual electricity output from the reports, divided by 365 days and 24 hours.

Table 3 shows several profitability measures calculated for the four digesters compared with the wind generator, with the electricity price assumed as an average of the electricity purchases avoided and the excess sales. The profitability of the Haubenschild digester considers the investment buydown from the grant as well as the benefit of a zero-interest loan. The amounts of grants received by AA and ML Dairies are not included.

Figure 2 is a graphical representation of the costs and benefits for these four digesters versus the wind generator. The investments, costs, and benefits were annualized and then divided by annualized total cost for comparability, using the assumptions described in Lazarus and Rudstrom [Lazarus and Rudstrom, 2007]. The bottom line on the graph shows annualized operating costs, with annualized total costs as the top line. The stacked bars show the various revenue sources. The ML and AA benefits were provided only as undifferentiated totals, rather than by breaking out co-generated heat and solids or digestate value as was done for the Haubenschild and Tillamook digesters. Finally, carbon credit trading may offer a way to internalize the greenhouse gas reduction externality presented by farm digesters. Haubenschild Farms has also recently begun selling carbon credits through an intermediary to the Chicago Climate Exchange, although the annualized value of the credits appears negligible in Figure 2 partly because the sale was not arranged until the digester had been operating for most of its estimated useful life [Bilek, 2006; Haubenschild, 2006]. In present value terms, the production tax credits for which the wind generator is eligible are larger relative to the electrical market value than are the grants and interest subsidy that the Haubenschild digester received.

Digester biogas and electricity, like other renewable energy sources, compete with fossil fuels. Hence, the economic feasibility of farm-based digesters will be dictated to a large extent by the direction of fossil fuel prices in the future. The oil price swing from \$50 per barrel in the early 1980s to \$10 in the late 90s and up to over \$100 in 2007 was accompanied by a rash of digester terminations, followed by a recent resurgence of interest in digesters.

Table 3

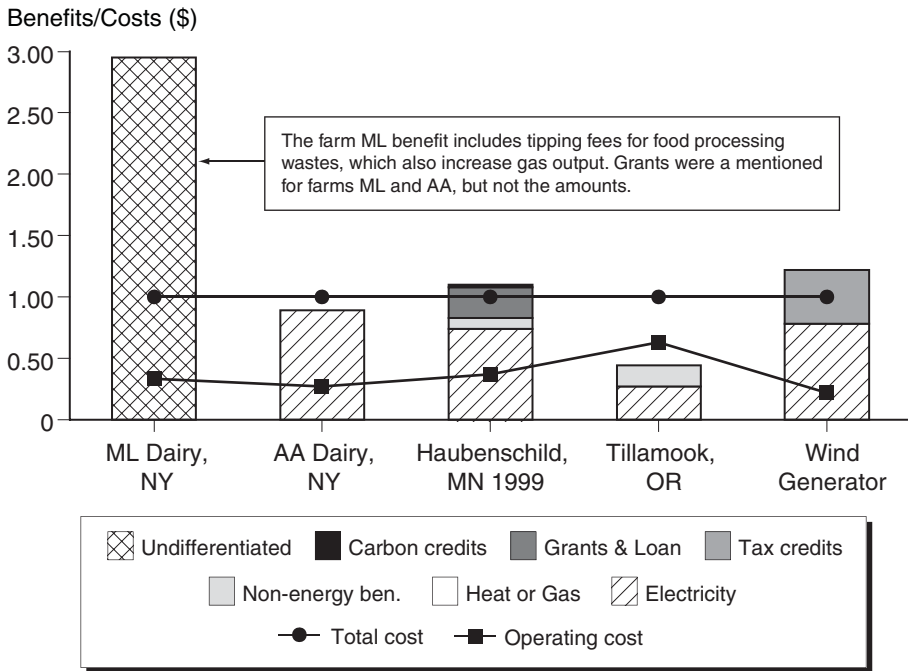
**Electricity Price and Profitability Indicators for Selected Dairy Farm Digesters Compared With a Wind Generator**

	Electricity price, \$/kwh	Payback, years	Return on assets	NPV, annualized
ML Dairy, NY, 2001	0.100	2	39%	\$134,463
AA Dairy, NY, 1998	\$0.086	8	3%	\$(3,495)
Haubenschild Dairy, MN, 1999	\$ 0.058	4	12%	\$9,392
Tillamook (central), OR, 2003	\$0.047	10+	<-10%	\$(247,666)
Wind generator, 2005	\$ 0.033	7	9%	\$31,034

Sources: The AA Dairy is described by both Wright et al., (2004) and Martin, (2004). The ML Dairy data are from Wright et al. The Haubenschild data are from Lazarus and Rudstrom, 2007. The Tillamook data are from DeVore (2006). The California dairy data are from Marsh and LaMendola (2006). The wind generator data are from Tiffany (2005).

Figure 2

**Comparison of Economic Assessments of Selected Dairy Farm Digesters Compared With a Wind Generator Under Minnesota Conditions**



Looking ahead, prospects seem good for digesters given that further fossil fuel price increases seem likely, but history suggests that the downside risk cannot be discounted entirely.

The renewable electricity portfolio minimums enacted in many States are stimulating the interest of utilities in all forms of renewable electricity, including that from digesters, but here wind electricity is a competitor. For example, competition from wind electricity appears to be placing an implicit ceiling on digester electricity rates in Minnesota, where wind generators are being installed at a rapid rate. A common rate for wind electricity is 3.3 cents/kwh on a 20-year flat-price contract [Tiffany, 2005].

**Digester Economies of Size**

The relationship between digester size and capital cost is difficult to estimate at present due to the small number of operating digesters, differences in digester design, and inflation over time. AgSTAR staff have estimated the cost-size relationship for 15 dairy plug-flow digesters with flexible covers and internal combustion engine-generator sets, based on dairy herd size [U.S. AgSTAR, 2006a]. They arrived at the regression equation:

Plug-Flow/Flexible Cover/Dairy:  

$$y = 226.69x + 288,936 \text{ (} R^2 = 0.76 \text{)}$$

The individual farm data are provided only as a scatterplot, so specifics are not available but, based on the scatterplot, 14 of the 15 farms appear to be between 100 and 2,200 cows. The other farm has 7,000 cows. The total

capital cost and per cow cost for some representative herd sizes implied by this relationship are:

Table 4

**Cost-Size Relationship for Dairy Farm Plug-Flow Digesters**

Dairy herd size	Capital cost - total	Per cow cost
x	y	y / x
100	\$311,605	\$3,116
500	402,281	805
2,000	742,316	371
7,000	1,875,766	268

They also estimated cost-size relationships for dairy and swine covered lagoon digesters, but the observations were more limited—five dairy and three swine lagoons. Those regressions were:

Lagoon, dairy:  $y = 233.43x + 38,056$  ( $R^2 = 0.967$ )

Lagoon, swine:  $y = 63.863x + 35,990$  ( $R^2 = 9792$ )

They did not estimate the cost-size relationship for complete-mix digesters, which tend to be larger and more costly than plug-flow designs.

A feasibility analysis of three hypothetical, centralized, scraped-manure, complete-mix digesters for large California dairies provides some information on the cost-size relationship at larger sizes [Hurley, Ahern, and Williams, 2006]. The 1.5-megawatt digester required 9,000–10,600 cows with the manure trucked up to 1 mile (one way), while the 10-megawatt size required 48,200–63,500 cows with a haul distance of up to 4 miles. Hurley’s per cow capital cost estimates for the 100 percent participation scenario are roughly double the AgSTAR equation estimate for the largest plug-flow digester (see their table 4-5):

Table 5

**Cost-Size Relationship for Large Dairy Farm Complete-Mix Digesters**

Dairy herd size	Capital cost - total	Per cow cost
9,100	\$5,364,712	\$590
27,120	14,135,387	521
50,774	26,216,241	516

Part of Hurley et al.’s higher costs may be for the trucks and loading/unloading facilities that would not be required for an individual farm digester. They found the difference in required electricity prices between a 1.5-megawatt digester and a 10-megawatt one to be 0.5–1.25 cents/kwh depending on assumptions about financing terms and farm participation rate. For example, with 100 percent of the farms participating near the digester location, and a 9-percent interest rate, 9.75 cents/kwh would be required for a 1.5-megawatt digester and 8.50 cents for a 10-megawatt one.

## Conclusions and Suggestions for Future Research

One conclusion of this analysis is that farm-based digesters are a multifaceted technology that offers a range of benefits. The benefits tend to appeal to different policy constituencies, which can become confusing. Digesters are a source of renewable energy. They destroy methane, a greenhouse gas that contributes to global warming. Future digester installations can help address the Nation's energy situation, but their contribution is likely to be small. Odor concerns have been the main motivation for many of the existing digesters. Aside from odor, other factors conducive to economic viability are where the biogas can replace large, onsite retail purchases of electricity or heat; where the digester electricity is sold to the grid in a region with higher-than-average electricity prices; or where offsite organic wastes are available. Evidence so far suggests that digesters do not reduce ammonia emissions, and may increase them slightly. There are other technologies and practices that can address ammonia emissions, such as biofilters and soil injection of manure. Digesters have been included in some large manure handling systems that have been constructed to address water quality concerns; however, it appears that other components of those systems, such as solids separators, are the components that offer most of the water quality benefits. Digesters do not significantly reduce total nutrients in the effluent.

This analysis of existing literature indicates that public funding support and technical assistance along with private entrepreneurship are resulting in advances in digester technologies. Continued growth in the industry can be expected. The expanded application of biogas, in particular conversion to natural gas that can be put on existing pipelines, is already underway at facilities in Wisconsin and Texas.

The concept of integrating farm-based digesters with ethanol plants in a relatively closed system, where the ethanol co-products supply livestock, which then supply biogas to heat the ethanol plant, seems promising. Indications so far are that the associated livestock operation needs to be relatively large and/or the ethanol plant fairly small compared to industry norms for such a design to work, so it will be interesting to see how this possibility affects overall economies of size and structure of the livestock and ethanol industries.

Two other questions for future research are: 1) How much is digester technology improving over time? and 2) Will those improvements along with policy and market shifts lead to more rapid digester adoption in the future? Regarding the first question, in a certain sense basic digester technology has not changed much since the 1970s. The digester is still a covered tank into which manure or other wastes react to produce biogas, which is then often burned in an internal combustion engine to generate electricity. However, changes are apparent in some areas of digester technology. Hydrogen sulfide removal from biogas is one such area of active academic research and commercial development (see, for example, an evaluation of micro-aeration [Duangmanee, 2007]. New digester designs are also being adopted, such as induced blanket digesters and biogas-mixed plug-flow digesters [Martin and Roos, 2007; Sebesta Blomberg & Associates, Inc., 2005]. Digester moni-

toring and control systems have also improved, in part due to availability of the Internet and cellular phone technology [Goodrich, 2007].

One suggestion for future research is to consider applying the concept of an “experience curve” to digester technology. The idea is to quantify technological learning over an extended period of time and to identify the drivers underlying the improvements. If there is learning, production costs will tend to decline by a fixed percentage with each doubling in cumulative production. An analysis of the dry mill ethanol industry found that cumulative dry grind ethanol production doubled 7.2 times over the period 1983–2005, while ethanol processing costs (without corn and capital costs) declined by 45% after adjusting for inflation [Hettinga, 2007]. The progress ratio of this curve was estimated as  $0.87 \pm 0.01$ , indicating that ethanol processing costs declined 13 percent per doubling in cumulative production. As profitability data become available for more digesters, it might be possible to test for a change in costs over time. Such an analysis would be complicated by the range of motivating factors for digester installations and the different sources of value involved.

## References Cited

- Cogeneration and Small Power Production, Minnesota Statutes 216B.164.
- Availability of electric utility system cost data, 18 U.S.C. 292.302.  
Accessed 7/16/2007.
- Cogeneration and small power production, 16 U.S.C. 824a-3.  
Accessed 7/16/2007.
- Termination of obligation to purchase from qualifying facilities, 18 U.S.C. 292.309. Accessed 7/16/2007.
- Regulations Under Sections 201 and 210 of The Public Utility Regulatory Policies Act of 1978 With Regard to Small Power Production and Cogeneration, 18 U.S.C. 292.101 et seq. Accessed 7/16/2007.
- 109th Congress. Energy Policy Act of 2005, P.L. 109-58.  
Accessed 7/18/2007.
- Agri-Waste Energy, Inc., *Turning Animal Waste into Energy* (Web page), <http://www.agriwasteenergy.com/home.html>, 2007, accessed 11/9/2007.
- Agriculture and Agrifood Canada, *ManureNet Canada: Manure Digesters Background Information* (Web page), [http://res2.agr.ca/initiatives/manurenet/en/man\\_digesters\\_back.html](http://res2.agr.ca/initiatives/manurenet/en/man_digesters_back.html), 2005, accessed 6/28/2005.
- Al Seadi, T., Hjort-Gregersen, K., and Holm-Nielsen, J. B. Impact of the Legislative Framework on the Implementation and Development of Manure Based, Centralised Co-Digestion Systems in Denmark. undated.
- Al Seadi, Teodorita. Danish Centralized Biogas Plant Descriptions. 2000. Bioenergy Department, University of Southern Denmark. <http://websrv5.sdu.dk/bio/pdf/rap2.pdf>.
- Alexander, Ron, *Strategies for Increasing the Value of Biosolids Compost* (Web page), [www.alexassoc.net](http://www.alexassoc.net), 2004, accessed 2/5/2007.
- Ball, Jeffrey. Gas Leak: Kyoto's Caps On Emissionism Hit Snag In Marketplace. Wall Street Journal, A1. 12/3/2007.
- Beddoes, Jenifer C., Bracmort, Kelsi S., Burns, Robert T., and Lazarus, William F. An Analysis of Energy Production Costs from Anaerobic Digestion Systems on U.S. Livestock Production Facilities, Technical Note No. 1. 10/2007. USDA Natural Resources Conservation Service. [http://directives.sc.gov.usda.gov/media/pdf/TN\\_BIME\\_1\\_a.pdf](http://directives.sc.gov.usda.gov/media/pdf/TN_BIME_1_a.pdf).
- Bendixen, H. J. Hygiene and Sanitation Requirements in Danish Biogas Plants, unpublished mimeo. undated.
- Bilek, Amanda. Trading Carbon Credits From Methane Digester. In *Business* 28(4), 16. 7/2006-8/31/2006.

Canadian Sphagnum Peat Moss Association, *Welcome To The Canadian Sphagnum Peat Moss Association* (Web page), [www.peatmoss.com](http://www.peatmoss.com), undated, accessed 1/12/2007.

Chapman, Shaun. Freeing the Grid: How Effective State Net Metering Laws Can Revolutionize U.S. Energy Policy. 11/2006. Network for New Energy Choices. <http://www.newenergychoices.org/uploads/netMetering.pdf>.

Cornell Manure Management Program, *Manure Treatment: Anaerobic Digestion* (Web page), <http://www.manuremanagement.cornell.edu/HTMLs/AnaerobicDigestion.htm>, undated, accessed 1/31/2007.

Cornell Waste Management Institute. Using Manure Solids as Bedding: Literature Review. 12/2006. <http://cwmi.css.cornell.edu/beddinglit-review.pdf>.

Department of Environmental Services, Nicollet County, Minnesota, *Nicollet County Zoning Ordinance – Feedlot Sections* (Web page), <http://www.co.nicollet.mn.us/dept/9/Nicollet%20County%20Feedlot%20Ordinance.pdf>, undated, accessed 2/2/2007.

DeVore, George. Tillamook, Oregon Methane Energy Development Program. 4/24/2006. <http://www.epa.gov/agstar/pdf/conf06/devore.pdf>.

Duangmanee, Thanapong Jack. Micro-Aeration for Sulfide Removal in Anaerobic Treatment of High-Solid Wastewater. AgSTAR National Conference. 11/27/2007.

Dunn, David J., *Diversifying Vermont Farms through Renewable Generation* (Web page), <http://www.epa.gov/agstar/pdf/conf06/dunn.pdf>, 2006, accessed 2/1/2007.

Effenberger, Mathias. Biogas Opportunities—Pathways and Wrong Tracks to Success. Organic Inputs and Renewable Energy: Learning from the European Biogas Model. 4/6/2006. [http://www.omafra.gov.on.ca/english/engineer/facts/bg\\_pres4.pdf](http://www.omafra.gov.on.ca/english/engineer/facts/bg_pres4.pdf).

Environmental Resource Recovery Group, LLC. Anaerobic Digesters for King County Dairies, Final Report for King County, Washington. 6/2003. <http://dnr.metrokc.gov/wlr/lands/2003-anaerobic-digesters-report.htm>.

Fitzgerald, Garrett, Wiser, Ryan, and Bolinger, Mark. The Experience of State Clean Energy Funds with Tradable Renewable Certificates. 11/2003. [http://eetd.lbl.gov/ea/ems/cases/TRC\\_Case\\_Study.pdf](http://eetd.lbl.gov/ea/ems/cases/TRC_Case_Study.pdf).

Frazier, Barnes & Associates, LLC. Feasibility Study: West Michigan Regional Liquid Livestock Manure Processing Center (LLMPC). 4/25/2006. [http://www.michigan.gov/documents/CIS\\_EO\\_West\\_Michigan\\_Centralized\\_AD\\_Feasibility\\_Study2006\\_165007\\_7.pdf](http://www.michigan.gov/documents/CIS_EO_West_Michigan_Centralized_AD_Feasibility_Study2006_165007_7.pdf).



- Goodrich, P. Professor, Department of Bioproducts and Biosystems Engineering, University of Minnesota. Personal communication about experiences with remote monitoring and control of digester operation. 11/20/2007.
- Haubenschild, D. personal communication about carbon credit sales. 12/2006.
- Hettinga, Willem. Technological Learning in U.S. Ethanol Production: Quantifying Reductions in Production Costs and Energy Use, Master Thesis. 5/2007. The Netherlands, Energy & Resources Track, Utrecht University.
- Hjort-Gregersen, Kurt. Centralized Biogas Plants Integrated Energy Production, Waste Treatment and Nutrient Redistribution Facilities. 1999. Danish Institute of Agricultural and Fisheries Economics. <http://webserv4.sdu.dk/bio/pdf/centra.pdf>.
- Hurley, S., Ahern, J., and Williams, D., *Clustering of Independent Dairy Operators for Generation of Bio-Renewable Energy: A Feasibility Analysis, A Report Prepared for the California Institute for the Study of Specialty of Crops* (Web page), <http://cissc.calpoly.edu/research/dairy-grant-final-report-7-31-06-exec-summary-2.pdf>, 2006, accessed 12/4/2006.
- Inland Empire Utilities Agency, *Inland Empire Dairy Manure to Energy "Cow Power" Renewable Energy Program* (Web page), <http://www.epa.gov/agstar/pdf/conf06/clifton.pdf>, 2006, accessed 12/4/2006.
- Jacobson, Larry D., Moon, Roger, Bicudo, Jose, Janni, Kevin, and Noll, Sally, *Generic Environmental Impact Statement on Animal Agriculture: A Summary of the Literature Related to Air Quality and Odor* (Web page), [http://www.eqb.state.mn.us/geis/LS\\_AirQuality.pdf](http://www.eqb.state.mn.us/geis/LS_AirQuality.pdf), 2005, accessed 6/11/2007.
- Kildegaard, A. "Renewable Energy Policy in Minnesota: Can We Change the Subject?" *CURA Reporter* (2006):3-8.
- Kramer, Joseph M. Agricultural Biogas Casebook 2004 Update. 9/2004. Resource Strategies, Inc., 22 North Carroll Street, Suite 300, Madison, WI 53703. <http://www.rs-inc.com/deliverables.asp>.
- Krich, Ken, Augenstein, Don, Batmale, JP, Benamann, John, Rutledge, Brad, and Salour, Dara. Biomethane from Dairy Waste: A Sourcebook for the Production and Use of Renewable Natural Gas in California. 7/2005. Sustainable Conservation. [http://www.suscon.org/news/biomethane\\_report/Full\\_Report.pdf](http://www.suscon.org/news/biomethane_report/Full_Report.pdf).
- Lazarus, W. and M. Rudstrom. "The Economics of Methane Digester Operations on Minnesota Dairy Farms." *Review of Agricultural Economics* 2(2007):349–364.

- Lusk, P. Methane Recovery from Animal Manures: A Current Opportunities Casebook. 1995. Washington, DC, U.S. Department of Energy, Regional Biomass Energy Program, National Renewable Energy Laboratory.
- Lusk, P. Methane Recovery from Animal Manures: The Current Opportunities Casebook, 3rd Edition. 9/1998. National Renewable Energy Laboratory. <http://www.nrel.gov/docs/fy99osti/25145.pdf>.
- Marsh, Michael L. H. and LaMendola, Tiffany. Dairy Methane Digester System 90-Day Evaluation Reports—Eden-Vale, Hilarides, Koetsier, and van Ommering Dairies, and Inland Empire Utilities Agency. 12/2006. Modesto, California, prepared by: Western United Resource Development, Inc., for the California Energy Commission. <http://www.energy.ca.gov/pier/iaw/reports/index.html>.
- Martin, J. H. Jr. and Roos, K. F. Comparison of the Performance of a Conventional and a Modified Plug-Flow Digester for Scraped Dairy Manure. International Symposium on Air Quality and Waste Management for Agriculture, ASABE Publication Number 701P0907cd. 9/16/2007.
- Martin, John H. A Comparison of Dairy Cattle Manure Management With and Without Anaerobic Digestion And Biogas Utilization. 6/17/2004. Washington, DC, AgSTAR Program, U.S. Environmental Protection Agency. <http://www.epa.gov/agstar/pdf/nydairy2003.pdf>.
- Martin, John H. An Evaluation of a Mesophilic, Modified Plug-Flow Anaerobic Digester for Dairy Cattle Manure. 7/20/2005. Washington, DC, AgSTAR Program, U.S. Environmental Protection Agency. [http://focusonenergy.com/data/common/dmsFiles/W\\_RW\\_REFR\\_GordondaleFeasReport.pdf](http://focusonenergy.com/data/common/dmsFiles/W_RW_REFR_GordondaleFeasReport.pdf).
- Martin, John H. A Protocol for Quantifying and Reporting the Performance of Anaerobic Digestion Systems for Livestock Manures. 9/2006. Washington, DC, AgSTAR Program, U.S. Environmental Protection Agency. [http://www.epa.gov/agstar/pdf/assessing\\_digester\\_perform\\_protocol.pdf](http://www.epa.gov/agstar/pdf/assessing_digester_perform_protocol.pdf).
- Mattocks, Richard and Wilson, Richard. Latest Trends in Anaerobic Digestion in North America. Biocycle Fourth Annual Conference. 11/2004.
- Methane to Markets Partnership, *Methane to Markets* (Web page), <http://www.methanetomarkets.org/>, undated, accessed 2/26/2007.
- Minnesota Department of Agriculture, *FAQs about the MDA Methane Digester Loan Program* (Web page), <http://www.mda.state.mn.us/feed-lots/digester.htm>, undated, accessed 2/2/2007.
- Minnesota Department of Commerce, *Renewable and Efficiency Incentives* (Web page), <http://www.state.mn.us/portal/mn/jsp/content.do?id=-536881350&subchannel=-536881511&sc2=null&sc3=null&contentid=536885915&contenttype=EDITORIAL&programid=536885394&agency=Commerce>, undated, accessed 2/2/2007.

- Moser, M. and Langerwerf, L., *Langerwerf Dairy Digester Facelift: What We Found When We Took Apart a 16 Year-old Dairy Plug Flow Digester* (Web page), [http://www.epa.gov/agstar/resources/lag\\_cons.html](http://www.epa.gov/agstar/resources/lag_cons.html), undated, accessed 12/20/2004.
- National Rural Electric Cooperative Association. White Paper on Distributed Generation. 12/2/2005. <http://www.nreca.org/Documents/PublicPolicy/DGWhitepaper.pdf>.
- New Rules Project, *Net Metering of Electricity* (Web page), <http://www.newrules.org/electricity/nmeter.html>, undated, accessed 1/5/2007.
- New York State Energy Research Development Agency, *About NYSERDA* (Web page), <http://www.nyserda.org/About/default.asp>, 2007, accessed 1/31/2007.
- Nielsen, L. H. and Hjort-Gregersen, K. Socio-Economic Analysis of Centralised Biogas Plants. undated. Danish Research Institute of Food Economics, C/o University of South Denmark, Niels Bohrsvej 9, DK-6700 Esbjerg, Denmark.
- North Carolina Solar Center, *Renewable Electricity Production Tax Credit* (Web page), [http://www.dsireusa.org/library/includes/incentive2.cfm?Incentive\\_Code=US13F&State=federal&currentpageid=1&ee=0&re=1](http://www.dsireusa.org/library/includes/incentive2.cfm?Incentive_Code=US13F&State=federal&currentpageid=1&ee=0&re=1), 2007a, accessed 3/13/2007a.
- North Carolina Solar Center, *DSIRE Database of State Incentives for Renewables & Efficiency* (Web page), [dsireusa.org](http://www.dsireusa.org), 2007b, accessed 2/21/2007b.
- North Carolina State University, *Waste Management Programs* (Web page), [http://www.cals.ncsu.edu/waste\\_mgt/](http://www.cals.ncsu.edu/waste_mgt/), undated, accessed 1/31/2007.
- Office of the Law Revision Counsel, U.S. House of Representatives. Internal Revenue Code, Electricity produced from certain renewable resources.
- Peters, Jerome. Debt Financing. Biomass Finance & Investment Summit. 1/18/2007-1/19/2007.
- Port of Tillamook Bay, *Bio-Gas Methane Facility—Hooley Digester* (Web page), <http://www.potb.org/methane-energy.htm>, undated, accessed 12/4/2006.
- Roos, K. Status and Issues Facing the Anaerobic Digester Industry Relative to the U.S. Livestock Market. Wisconsin Manure Biogas Symposium, (Proceedings available on CD from the University of Wisconsin Center for Dairy Profitability, Madison, Wisconsin). 4/4/2002.
- Sebesta Blomberg & Associates, Inc. Methane Digester Economic & Technical Feasibility Study, West River Dairy & City of Morris. 10/2005. Agricultural Utilization Research Institute (AURI) Center for Producer-Owned Energy.

- Shih, Jih-Shyang, Burtraw, Dallas, Palmer, Karen, and Siikamaki, Juha. Air Emissions of Ammonia and Methane from Livestock Operations: Valuation and Policy Options, Discussion Paper 06-11. 2006. Resources for the Future. [http://agecon.lib.umn.edu/cgi-bin/pdf\\_view.pl?paperid=21066](http://agecon.lib.umn.edu/cgi-bin/pdf_view.pl?paperid=21066).
- Smith, J. B. Manure-to-gas plant promises relief for Texas' dairy country. Waco Tribune-Herald. 7/9/2007. [http://www.news-journal.com/green/content/shared/news/stories/dairy\\_070907.html](http://www.news-journal.com/green/content/shared/news/stories/dairy_070907.html).
- Steffen, R., Szolar, O., and Braun, R. Feedstocks for Anaerobic Digestion. 1998. Austria. [http://res2.agr.ca/initiatives/manurenet/download/feedstocks\\_AD.pdf](http://res2.agr.ca/initiatives/manurenet/download/feedstocks_AD.pdf).
- Terre-Source LLC. Study to Evaluate the Price and Markets for Residual Solids from a Dairy Cow Manure Anaerobic Digester. 2003. <ftp://dnr.metrokc.gov/dnr/library/2003/kcr1540.pdf>.
- Tiffany, Douglas G. Economic Analysis: Co-generation Using Wind and Biodiesel-Powered Generators, Staff Paper P05-10. 2005. University of Minnesota, Department of Applied Economics. [http://agecon.lib.umn.edu/cgi-bin/pdf\\_view.pl?paperid=18123&ftype=.pdf](http://agecon.lib.umn.edu/cgi-bin/pdf_view.pl?paperid=18123&ftype=.pdf).
- U.S. AgSTAR. Guide to Operational Systems. 6/30/2004. <http://www.epa.gov/agstar/operational.html>.
- U.S. AgSTAR, *Market Opportunities for Biogas Recovery Systems: A Guide to Identifying Candidates for On-Farm and Centralized Systems* (Web page), [http://www.epa.gov/agstar/pdf/biogas%20recovery%20systems\\_screenres.pdf](http://www.epa.gov/agstar/pdf/biogas%20recovery%20systems_screenres.pdf), 2004, accessed 6/11/2007.
- U.S. AgSTAR. Winter 2006 AgSTAR Digest. 2006a. <http://www.epa.gov/agstar/>.
- U.S. AgSTAR. AgSTAR Handbook and Software, Second Edition. 11/3/2006b. Washington, D.C. <http://www.epa.gov/agstar/resources/handbook.html>.
- U.S. AgSTAR, *The AgSTAR Program* (Web page), <http://www.epa.gov/agstar/>, 2007a, accessed 2/22/2007a.
- U.S. AgSTAR. Anaerobic Digesters Continue Growth in U.S. Livestock Market. 11/2007b. [http://www.epa.gov/agstar/pdf/2007\\_digester\\_update.pdf](http://www.epa.gov/agstar/pdf/2007_digester_update.pdf).
- U.S. Energy Information Administration, *International Data, Natural Gas* (Web page), <http://www.eia.doe.gov/emeu/international/contents.html>, 2006a, accessed 1/30/2007a.
- U.S. Energy Information Administration, *Petroleum Spot Prices* (Web page), [http://tonto.eia.doe.gov/dnav/pet/pet\\_pri\\_spt\\_s1\\_d.htm](http://tonto.eia.doe.gov/dnav/pet/pet_pri_spt_s1_d.htm), 2007b, accessed 1/30/2007b.

- U.S. Energy Information Administration, NEMS (*Renewable Energy Modeling Summit Series*) (Web page), [http://www.epa.gov/cleanrgy/pdf/model\\_sum\\_nems\\_100202.pdf#search=%22nems%20model%22](http://www.epa.gov/cleanrgy/pdf/model_sum_nems_100202.pdf#search=%22nems%20model%22), undated, accessed 2/9/2007c.
- U.S. Environmental Protection Agency. National Emission Inventory—Ammonia Emissions from Animal Husbandry Operations, Draft Report. 1/30/2004. [http://www.epa.gov/ttn/chief/ap42/ch09/related/nh3inventorydraft\\_jan2004.pdf](http://www.epa.gov/ttn/chief/ap42/ch09/related/nh3inventorydraft_jan2004.pdf).
- U.S. Environmental Protection Agency. Consent Agreement And Final Order (Afo Air Agreement). 1/21/2005. <http://www.epa.gov/compliance/resources/agreements/caa/cafo-agr-0604.html>.
- USDA, *Section 9006: Renewable Energy and Energy Efficiency Program* (Web page), <http://www.rurdev.usda.gov/rbs/farbill/>, undated, accessed 1/9/2007.
- USDA Natural Resources Conservation Service. 2003 Minnesota EQIP Conservation Practice Payment Docket(440-V-CPM, First Edition, Amend. MN-27, May, 2003) MN515-230(48). 2003. [http://www.mn.nrcs.usda.gov/programs/eqip/2003mn\\_eqip\\_docket3.pdf](http://www.mn.nrcs.usda.gov/programs/eqip/2003mn_eqip_docket3.pdf).
- USDA Natural Resources Conservation Service. Conservation Practice Standard, Anaerobic Digester Controlled Temperature, Code 366. 8/2004. [http://efotg.nrcs.usda.gov/references/public/pa/pa366\\_std.pdf](http://efotg.nrcs.usda.gov/references/public/pa/pa366_std.pdf).
- USDA Natural Resources Conservation Service. Conservation Practice Standard, Anaerobic Digester Ambient Temperature, Code 365. 2/2007. [http://efotg.nrcs.usda.gov/references/public/WY/Anerobic\\_Digester\\_Ambient\\_Temperature\\_\\_365\\_Standard.pdf](http://efotg.nrcs.usda.gov/references/public/WY/Anerobic_Digester_Ambient_Temperature__365_Standard.pdf).
- WestStart-CALSTART. Swedish Biogas Industry Education Tour 2004: Observations and Findings. 11/12/2004 . [http://www.calstart.org/info/publications/Swedish\\_Biogas\\_%20Tour\\_2004/Swedish\\_Biogas\\_Tour\\_2004.pdf](http://www.calstart.org/info/publications/Swedish_Biogas_%20Tour_2004/Swedish_Biogas_Tour_2004.pdf).
- Wright, Peter, Inglis, Scott, Ma, Jianguo, Gooch, Curt, Aldrich, Brian, Meister, Alex, and Scott, Norman. Preliminary Comparison of Five Anaerobic Digestion Systems on Dairy Farms in New York State. 2004 ASAE/CSAE Annual International Meeting. 8/1/2004-8/4/2004. <http://www.manuremanagement.cornell.edu/Docs/ASAE%20paper%20044032%20Final.pdf>.