Investing in Methane Digesters on Pennsylvania Dairy Farms: Implications of Scale Economies and Environmental Programs

Elizabeth R. Leuer, Jeffrey Hyde, and Tom L. Richard

A stochastic capital budget was used to analyze the effect of net metering policies and carbon credits on profitability of anaerobic digesters on dairy farms in Pennsylvania. We analyzed three different farm sizes—500, 1,000, and 2,000 cows—and considered the addition of a solids separator to the project. Results indicate that net metering policies and carbon credits increase the expected net present value (NPV) of digesters. Moreover, the addition of a solids separator further increases the mean NPV of the venture. In general, the technology is profitable only for very large farms (1,000+ cows) that use the separated solids as bedding material.

Key Words: anaerobic digester, stochastic capital budget model, dairy farm, alternative energy

For a host of reasons, U.S. scientists, government leaders, and citizens are increasingly seeking alternative sources of energy. Green energy sources are those that do not emit harmful pollutants and/or that are renewable. Anaerobic digesters (AD), found on dairy, hog, and poultry farms across the United States, represent potential sources of green energy. AgSTAR, a U.S. Environmental Protection Agency (U.S. EPA) program, whose goal is to increase the number of anaerobic digesters on farms in the United States, estimates there are 6,900 swine and dairy farms that could utilize digesters (U.S. EPA 2002a). However, the operating costs and benefits of AD adoption vary greatly from farm to farm, while the investment costs are very large. Therefore, the objective of this research is to compare the profitability of several digester scenarios. Unlike most previous research, which consists of analyses of specific, individual farms (i.e., case studies), we use a model to compare several scenarios, including the application of benefits realized by farms via net metering laws and carbon credits.

Literature Review

Anaerobic digestion is the process by which manure generates biogas, a mixture of methane (CH_4) and carbon dioxide (CO_2), without the presence of oxygen. Manure is made up of water and solids. The solids, often referred to as total solids (TS), consist of volatile solids (VS) and ash. When manure enters the digester, the VS are digested by several types of bacteria. In the early stages of digestion, one type of bacteria breaks the manure into simple fatty acids, carbon dioxide, and hydrogen. The simple fatty acids and hydrogen are then converted by a different type of bacteria into methane and more CO_2. To operate correctly, the digester must maintain the appropriate temperature and a pH level (approximately 6.4–7.4) that is conducive to the growth of these microorganisms (Converse 2001, Lusk 1998).

The biogas can be flared (i.e., burned) or used to generate electricity or heat. The electricity produced in an engine-generator can be used on the farm and/or sold to a utility. If the biogas is used

Elizabeth Leuer is Graduate Assistant and Jeffrey Hyde Associate Professor in the Department of Agricultural Economics and Rural Sociology at the Pennsylvania State University in University Park, Pennsylvania. Tom Richard is Associate Professor in the Department of Agricultural and Biological Engineering, also at the Pennsylvania State University in University Park, Pennsylvania.

The authors wish to thank Joshua Duke, co-editor of this journal, and two anonymous reviewers for helpful suggestions that improved the clarity of the paper. We also thank Pat and Deb Topper for sharing their experiences from working with digesters and farms. Finally, we thank USDA/CSREES for financial support of this work.

Agricultural and Resource Economics Review 37/2 (October 2008) 188–203

for heat, it is typically burned in a boiler, creating hot water (Lusk 1998). Alternatively, a farm could choose to sell its methane to a natural gas company, but it would need to remove the CO_2 (approximately 40 percent of the biogas mix), clean up impurities, and connect to the natural gas pipeline (Krich et al. 2005). Because of the expense of purchasing an engine-generator or boiler, a farm typically selects one or the other, while few sell biogas directly.

There are three types of digesters primarily discussed in the literature: covered lagoon, complete mix, and plug-flow (Wilkie 2005). The type of digester a farm selects depends upon the composition of the manure and other materials entering the digester. A covered lagoon digester requires manure that is 0.5 to 3.0 percent TS, while a complete mix digester operates with manure between 3 and 10 percent TS. Plug-flow digesters can handle the thickest manure and are recommended for manure that is 10 to 14 percent TS (U.S. EPA 2002b).

For example, a dairy in Florida that uses a flush water system for cleaning would most likely install a covered lagoon because the material entering the digester would be significantly watered down. A dairy farm in Pennsylvania, on the other hand, would most likely utilize a scrape system for cleaning, which means the manure's consistency would not change during the cleaning process. A dairy with a system like this would most likely install a plug-flow digester that could handle thicker manure. For the purposes of this analysis we assume a plug-flow digester, which is the most common digester type in Pennsylvania.

While scientists have understood anaerobic digestion for about 300 years, digesters first appeared on farms in the United States in the 1970s (Lusk 1998). Many of these digesters failed from either a technical or financial perspective (Lusk 1998, Garrison and Richard 2005). AgSTAR lists several causes for a digester's failure (U.S. EPA, undated), which include

- farmers lacking the skills and time necessary to keep the digester functioning,
- incorrect equipment for the digester,
- digester designs that were not customized to fit the farm's manure-handling practices,
- high maintenance and repair costs due to design,
- limited educational opportunities or technical support for the digester manager,
- diminished monetary returns or no returns, and
- attrition of farms due to non-digester factors.

Similarly, Scruton, Weeks, and Achilles (2004b) list, as reasons for failed digesters, problems with digester design, cash flow issues, low prices received for electricity, excessive maintenance requirements, and little specialized support for installation or servicing. Additionally, Kramer (2004) and Lorimor and Sawyer (2004) cite equipment and management problems as reasons for non-operational digesters.

The price of the digester continues to be the greatest hurdle to widespread adoption. In 2002, AgSTAR estimated that digester costs range between \$200 and \$450 per 1,000 pound animal unit (U.S. EPA 2002b). It is unclear if this covered only the digester or the entire digester project. Kramer (2004) provided an estimate of \$417 to \$763 per cow on farms generating electricity. In early 2007, one industry representative estimated this cost to be even higher, ranging from approximately \$890 to \$1,760 per cow, depending on whether the farm included a separator. This large increase was attributed to inflation (McEliece 2007). In focus group meetings in Iowa, a low economic return was the biggest concern of farmers considering adoption (Garrison and Richard 2005).

In recent years, some opportunities to increase digester returns have emerged. For example, in 2006, Pennsylvania passed net metering laws. Prior to this, farms were often paying the utility company each month for energy they used during any time in which electricity use exceeded on-farm production (i.e., peak periods) (Birge 2007). In addition to charging farms for electricity use, some utility companies would add a "standby" or "demand" charge to the farm's utility bill. Under net metering, the utility must consider the total electricity generated by the farm compared to the farm's consumption throughout the month. If the farm does not meet its own electricity needs, it is billed by the utility for the electricity needed to meet the shortfall. If the amount generated is greater than the amount consumed, the farm avoids payment on the electricity it uses. In addition, the farm may sell the excess electricity to the utility at a rate negotiated with the power company (Pennsylvania Public Utility Commission 2006).

In addition to net metering laws, carbon credits and solid separators may improve the net economic returns of digesters. Farms that implement a digester are eligible for valuable carbon credits if they are reducing their emissions of greenhouse gases (Subler 2006). For instance, a farm with an open cover lagoon that builds a digester is eligible for carbon credits because it is reducing methane emissions. Carbon credits can also be received for generation of renewable energy (Six 2006).[1] A solids separator does exactly what its name describes: it separates the liquid and solid portions of the manure. The liquid portion is stored, but the digested solids have value as bedding or soil amendments (Goodrich 2005).

Within academia, digester economics have been examined on a case-by-case basis by various researchers. Martin et al. (2003), Martin (2004, 2005), and Lazarus and Rudstrom (2003, 2007) explored the profitability of digesters, but focused on one or two case studies. Stokes, Rajagopalan, and Stefanou (2006) performed a similar analysis for a dairy farm in Pennsylvania. Lusk (1998) documents 23 digesters and briefly discusses the costs and benefits associated with each case. Likewise, Kramer (2004) published a casebook on 11 digesters located throughout the upper Midwest. As case studies, the lessons learned may not be relevant to a generalized group of representative farms.

Various capital budget models are available to calculate the net present value (NPV) of digesters. The University of Florida as well as the University of California-Davis offer online resources to calculate the NPV of digesters (de Vries et al. 2007 and California Biomass Collaborative 2007).[2] AgSTAR offers free software, FarmWare, to analyze the costs and benefits of digesters (AgSTAR, undated).

In addition to FarmWare, AgSTAR offers other resources for farmers considering digester implementation. One report highlights the benefits of digesters and identifies key factors necessary for a farm to successfully operate a digester. Benefits they identified included biogas, fertilizer/soil amendments, odor control, greenhouse gas reduction, ammonia control, and water quality protection. While each of these items is thoroughly explained, a cash value is not assigned to any of them (U.S. EPA 2002a).

Furthermore, AgSTAR suggests that successful digesters are dependent upon the farm's size (number of animals), manure management, and local energy markets. Dairies with greater than 500 head of cattle are more likely to find a digester to be cost-effective. Additionally, a farm must have a steady flow of manure in order for the digester to operate, and it is imperative that a use for the biogas be identified (U.S. EPA 2002a).

This report also suggests that centralized, or "community," digesters may provide a way for smaller farms to benefit from an anaerobic digester. The four main benefits of centralized digesters include economies of scale, marketing leverage, additional financing opportunities, and third party management. Economies of scale are cited as a benefit of increased biogas production capacity, which indicates that digesters on larger farms might experience these as well. AgSTAR does not indicate a minimum profitable scale (U.S. EPA 2002a).

Questions of scale can be considered even beyond the community to a regional scale. Ghafoori and Flynn (2006a) analyzed nine community digester scenarios for a county in Canada. They compiled industry data to calculate a scale factor to adjust investment costs in their model. Each scenario used manure from all of the 61 confined feeding operations in the county, but the number, size, and locations of digesters varied across the scenarios. The scenario with one centralized digester had the lowest cost per unit of power produced. Ghafoori and Flynn comment that it appears that only the capital costs of a community digester are scaleable, while the transportation costs associated with hauling the manure to the digester are not.

In a different study, Ghafoori and Flynn (2006b) offered an economic analysis of a pipeline for a community digester that uses manure from beef cattle. The pipeline would run from each participating farm to the digester. In this way, the farm would not need to transport manure to a centrally located digester. Their objective was to determine if a pipeline provided a more cost-effective way, compared to trucking, to move manure to a centrally located digester. They found that pipeline transport exhibits economies of size and that costs are minimized when manure is

---

[1] For every 1,000 kWh (1 mW) a farm generates, it receives an alternative energy credit. The farm can sell this credit to a utility or as a carbon credit.

[2] The spreadsheet from the University of Florida is found at http://dairy.ifas.ufl.edu/tools/Digester1.1.xls. The spreadsheet from the University of California-Davis is available at http://faculty.engineer[-]ing.ucdavis.edu/jenkins/CBC/Calculator/EconModules/EconCalculatorBiogas.xls.

between 12 and 14 percent TS. Furthermore, a two-way pipeline, which is a pipeline that can either pump manure into the digester or send effluent back to the farm, was more cost-effective than two separate pipelines.

The results in each of Ghafoori and Flynn's studies are potentially generalizable to community digester scenarios. Conversely, these results may not necessarily be applicable to the farm-based digester context addressed here.

Limited analysis of net-metering laws has been completed. Scruton, Weeks, and Achilles (2004a) discussed Vermont's net-metering law and its effect on digester profitability, but only mention how it would affect a 750-cow dairy.

Shih et al. (2006) identified and analyzed three hypothetical market-based policies to increase digester adoption. Their model was based on three sizes of digesters—400, 500, and 1,000 head of dairy cattle—in two different climates, warm and cold. The cost of each of the six digesters was calculated based on a scale factor they calculated. While this is a nice feature, it should be noted that the scale factor is based on a regression line fit to only four observations.

Their first market-based policy called for farmers to receive greenhouse gas (GHG) credits for reducing methane emissions. This credit was the numerical difference between pre-digester methane emissions and CO_2 emissions from biogas combustion post-digestion. The GHG credits were assigned a value of $11 per ton of carbon dioxide equivalent, which is based on data from Europe and the northeastern United States. This price is higher than the Chicago Climate Exchange's (CCX) carbon credit price (Chicago Climate Exchange 2007). Because Pennsylvania dairy farmers are most likely to utilize the CCX, Shih et al.'s (2006) price significantly overstates the market price that these farmers are likely to receive.

Their second policy rewarded farms that reduce ammonia emissions. Ammonia emissions were calculated in two steps. In the first step, the annual ammonia emission reduction on a farm was calculated. In the second step, this reduction was multiplied by the population it affects and a coefficient associated with the health benefit of this reduction. This yields the monetary benefit.

Their final policy examined expanding net metering laws, so that in addition to traditional net metering laws, farms would also receive $0.06 per kilowatt-hour (kWh) for any extra electricity sold back to the grid. While their paper cited farms receiving this rate, other sources (e.g., Lazarus and Rudstrom 2003 and 2007, Garrison and Richard 2005) indicate that farms should anticipate a lower price.

Based on the scale factor and policies outlined above, Shih et al. (2006) found that all six of the digester scenarios yield positive net benefits annually. Smaller herd sizes received fewer benefits than larger herd sizes, and farmers in warmer climates realized more benefits than farmers in cold climates.

The body of literature suggests a need for a thorough analysis of investment profitability across alternative herd sizes. Researchers have used various sources of investment costs that differ over time and production companies. More importantly, however, there is a clear need for assessing investment profitability in light of net metering laws and carbon credit trading. Earlier studies that addressed these issues did not include these components in a manner that reflects the policies and markets that have emerged. Thus, this research represents a richer treatment of those issues within a methodological framework that provides more robust results relative to previous work.

Materials and Methods

A stochastic capital budgeting model is employed to analyze the problem. Hyde and Engel (2002) used a similar method to compare traditional milking parlors to robotic milking systems. Using Monte Carlo simulations, they determined the break-even NPV required for a farmer to be more profitable using robotic milkers than traditional means of milking. Similarly, our research also utilizes Monte Carlo simulations, but we derive the probability of NPV being greater than or equal to zero. Our research also differs because rather than comparing two different technologies, we simply analyze the additional income and expenses from a single technology.

Economic Benefits

The economic benefits of a digester are defined by several factors. As is standard with capital budgeting, we assess only the marginal cash flows associated with the investment. For example, while milk production is a part of farm income, it is not impacted by the digester, so it is excluded as a benefit (or cost) to the digester. The sale of electricity, however, exists only if a digester is operating.

There are several factors that may be included as benefits, depending upon decisions made by the farmer. In this section, we briefly describe each source of benefits. Later, we discuss how each benefit is valued within the context of this research.

Electricity avoided. Once the firm begins to generate electricity, it is able to avoid purchasing at least a portion of its electricity from the utility. The value of the benefit depends upon the retail price of electricity.

Electricity sold. The digester may produce more electricity than the farm can use. When this occurs, the excess electricity may be sold to a utility. Often this is at a price well below the retail rate.

Bedding savings. If a farm opts to utilize a solids separator, the solids may be sold for bedding or used to replace current bedding materials. We assume that bedding materials are used on-farm.

Separated solids sales. A farm may also choose to sell composted separated solids as a soil amendment. The value of the compost depends upon many factors, including how long it has been composted. We calculate the cost of preparing the solids for sale by accounting for the opportunity cost of land used to dry the solids and the cost of operating a tractor to turn the solids (Rynk et al. 1992).

Carbon credits. Carbon credits have been traded on the CCX since 2003. Each credit traded at the CCX represents a reduction of one metric ton of carbon dioxide (CO_2) equivalent. Although firms (including farms) are not required to participate, they do have the option of buying or selling credits at the current market price (Chicago Climate Exchange 2007). In our context, farms that switch from an anaerobic manure lagoon to a digester are eligible for carbon credits. A farm can receive credits only if its digester reduces methane emissions. For example, if prior to digester implementation, the farm's manure handling system was emitting methane, the implementation of a digester will reduce the farm's methane emissions (Subler 2006).

Carbon credits are calculated by finding the minimum of either the methane captured/combusted by the digester or the per head default emissions factor issued by the CCX. Methane captured/combusted can fluctuate between farms, so we simply used the CCX's baseline figure for Pennsylvania of 4.41 carbon credits per lactating cow per year (McComb 2007). The baseline figures vary depending on the state, animal species, and animal size.

Renewable energy certificates (RECs). If a farm with a digester generates alternative energy, it can receive an REC for every megawatt hour (1,000 kWh) of energy it produces. Farms in Pennsylvania may sell these to utility companies, if allowable under contract, or sell them as carbon credits. We assume that farmers receive additional carbon credits for renewable energy. For each megawatt produced, a farm receives 0.4 carbon credits (Subler 2006).

Some research suggests that the fertilizer value of the effluent is different from the influent. Consistent with Mehta (2002), we have chosen not to place a dollar value on this potential benefit. Most sources agree that the amount of phosphorous and potassium remains the same pre- and post-digestion (Ndegwa et al. 2005, Converse 2001, Lusk 1998). Additionally, the total nitrogen in the manure remains the same after digestion, but the distribution of nitrogen containing compounds changes (Ndegwa et al. 2005, Lusk 1998). Digestion breaks down organic nitrogen into a form that is more immediately available to plants. Martin et al. (2003) and Martin (2005) found that the increase in ammonia nitrogen (NH_4-N) after digestion was statistically significant. However, the values of these changes are difficult to quantify. Consequently, we may be slightly understating the benefits associated with the digester.

There may be additional benefits, such as odor reduction, waste heat, or weed-seed reduction. However, the exact nature of the benefits is neither well understood nor easily quantifiable. Additionally, while something like odor reduction may be part of a farm's decision to adopt this technology and is certainly a social benefit, our analysis focuses strictly on the farm's monetary benefits from implementation of a digester.

Economic Costs

There are only two streams of costs in our model. These relate to the purchase of the system as well as its operation and maintenance.

Capital cost. This is a one-time expense incurred at the beginning of the project's life. Depending upon the scenario, this may include the cost of the digester as well as a solids separator. Our estimates include costs for the mix tank, raw manure pumping and mixing, total site piping, digester, engine building, engine generator, hydrogen sulfide filter, installation labor, utility charge, startup, contingencies, engineering/site assistance/grant work required, construction observation and assistance, travel, and insurance and performance bonds. The cost of a separator is included in the scenarios where applicable (McEliece 2007).

Operating and maintenance. Labor and parts are needed to maintain and operate the digester over time. In our model, this cost occurs in each of t time periods and is assumed to be constant over time.

Net Present Value Calculations

The NPV is calculated by subtracting the total discounted economic costs from the total discounted economic benefits. A positive NPV indicates that a project is expected to generate positive profits. The net present value is defined as

$$\text{NPV} = \sum_{t=0}^{T} \left[\left(\text{Benefits} - \text{Costs} \right)_t / (1+\delta)^t \right],$$

where t = 0 to T indexes time, and T may vary across digester systems. The net cash flows in each time period, t, are discounted at a rate of δ. The standard decision rule is that investment should occur when a project's NPV exceeds zero.

Variables and Parameters

Each component of the economic benefits and costs is calculated using parameters and variables. Parameters are constant within a simulated scenario and variables are randomly generated within a scenario. This section details the parameters and variables included in our model.

Model parameters. Parameters are those items that remain unchanged within a given simulated scenario, although some, such as herd size, may change across scenarios (Table 1). We assess herd sizes of 500, 1,000, and 2,000 lactating cows. The digester's costs changed with herd size (McEliece 2007). By varying herd size, we are able to draw conclusions regarding economies of scale in digester adoption.

If a farm installs a digester, it must decide if it wants to add a solids separator to the project. A separator's cost increases as herd size increases. Of course, if a farm selects the "no separator" option, the cost of the separator is zero.

Model variables. Variables are defined as those items that change within a given simulated scenario (Table 2). We assign a distribution to each variable based on information and data found in the literature.

Under the Pennsylvania net metering regulation, the farm avoids payment for all electricity generated by a methane digester. The value of this benefit is a function of the retail price of electricity. Based upon U.S. Department of Energy (U.S. DOE) data on the residential price of electricity from 1985 to 2005, we specify a triangular distribution with a minimum and mode of \$0.0739 and maximum of \$0.0967 per kWh (U.S. DOE 2006).

Digester operators must decide if they want to install a solids separator. If so, they must decide if they will utilize the solids for bedding on the farm or sell them as compost. Weeks (2002) estimated that each cow's manure would provide approximately one cubic foot per day of separated solids. He indicates that this is more than enough to provide for bedding for cattle. Furthermore, he comments that the average bedding purchase on a farm is approximately \$50–\$100 per cow per year. These numbers are supported by Gooch et al. (2006), who found that farms can save between \$60–\$100 per cow per year on bedding purchases.[3] Without data to clarify further the nature of the distribution, we specify a uniform

[3] There are concerns that using digested manure solids may increase pathogens, thereby increasing mastitis cases in the herd (Cornell Waste Management Institute 2006). Clearly, if herd health declines as a result of using manure solids for bedding, this is a cost a farm would incur. However, because scientists are in the early research stages of this problem and this health cost is difficult to quantify, we do not include this potential cost as part of our analysis.

Table 1. Parameters Specified in the Model

Parameter	Units	Value(s)	Data Source(s)
Herd size	Milk cows	500, 1,000, 2,000	Assumed
Downtime of digester	Percent	10	Assumed
Digester cost[a]	$	500 cows – 804,087 1,000 cows – 1,072,879 2,000 cows – 1,774,599	McEliece (2007)
Separator cost	$	500 cows – 74,780 1,000 cows – 76,500 2,000 cows – 115,625	McEliece (2007)
Price realized for sale of electricity	$/kWh	0.01, 0.03 (base case), 0.05, 0.10	Lazarus and Rudstrom (2003) and Garrison and Richard (2005)
Cost to turn compost[b]	$/cubic yard	500 cows – 1.33 1,000 cows – 1.22 2,000 cows – 1.09	Rynk et al. (1992) and U.S. Department of Agriculture (2007)
Opportunity cost of land given up for compost[c]	$/acre	46.50	Pennsylvania Agricultural Statistics Service (2006)
Farm electricity use	kWh/cow/year	811	Ludington and Johnson (2003)
Engine efficiency	Percent	25	Lusk (1998), Giesy et al. (2005), and U.S. EPA (undated)
Carbon credit value	$/metric ton of CO_2 equivalent	3.70	Chicago Climate Exchange (2007)
Operation and maintenance cost	$/kWh generated	0.015	Lazarus and Rudstrom (2003) and Krich et al. (2005)
Discount rate	Percent	8	Assumed

[a] Digester costs include separate mix tank, raw manure pumping and mixing, total site piping, digester, hydrogen sulfide filter, installation labor estimate, utility charge estimate, startup cost, contingencies, engineering/site assistance/grant-required work, construction observation and assistance, travel, and insurance and performance bond (McEliece 2007).

[b] We indexed suggested figures from Rynk et al. (1992) using data from U.S. Department of Agriculture (2007) and Pennsylvania Agricultural Statistics Service (2006). This cost assumes that a farm uses an 85 hp tractor with a loader attachment (1 yard bucket) to turn the compost 4 times per year (Rynk et al. 1992).

[c] Martin (2004) writes that a 550-cow farm sells 1,825 cubic yards of compost per year or roughly 3.3 cubic yards per cow per year. Additionally, we used Rynk et al. (1992) to determine the amount of land necessary to compost digested solids.

distribution with a minimum of $50 and maximum of $100.

Wright and Ma (2003) indicate that one could charge $10 per cubic yard of compost generated, while in Martin's (2004) case study, a farm received an average of $16 per cubic yard of compost generated. The length of time the solids are able to compost affects the final product's quality. The longer they dry, the more the quality improves, which results in a higher price. Since there were limited data available and the quality is dependent upon a menu of other decisions, we estimated that a farm could charge between $9 and $16 per cubic yard (distributed uniformly) of composted materials. This allowed us to capture uncertainty associated with both quality and market price. As already mentioned, there are costs associated with drying the solids, and these are included in our calculation. We used Rynk et al.'s (1992) method to compute these costs.

The amount of methane in the biogas depends upon a collection of factors, including bedding material, digester management, digester type, and herd diet. Wilkie (2005) writes that biogas is ap-

Table 2. Variables Specified in the Model

Parameter/Variable	Units	Specified Distribution	Source(s)
Retail electricity price	$/kWh	Triangular: 0.0739, 0.0739, 0.0976 [a]	U.S. Department of Energy (2006)
Bedding savings	$ saved/cow/year	Uniform: 50, 100 [b]	Gooch et al. (2006) and Weeks (2002)
Value of compost created	$/cubic yard	Uniform: 9, 16	Martin (2004) and Wright and Ma (2003)
Amount of methane in biogas	Percent	Triangular: 55, 60, 80	Lusk (1998), Wilkie (2005), Shih et al. (2006), and U.S. EPA (2002b)
Biogas	Cubic feet/lb. VS	Triangular: 3, 5, 8	Wright (2001) and Engler et al. (1999)
Life expectancy	Years	Triangular: 10, 15, 20	Lusk (1998) and U.S. EPA (undated)
Total solids	Percent	Triangular: 11, 13.33, 14	ASAE (2005), U.S. EPA (2002b), and U.S. EPA (undated)
Pounds of manure	Pounds/cow/day	Triangular: 110, 160, 150	ASAE (2005), U.S. EPA (undated), and VanHorn et al. (1994)

[a] Triangular (minimum, most likely, maximum).
[b] Uniform (minimum, maximum).

proximately 60 percent methane, while Shih et al. (2006) and U.S. EPA (2002b) cite that methane makes up 60–70 percent of biogas. Lusk (1998) suggests 55–80 percent as a range of expected methane production. Thus, we specify a triangular distribution with minimum of 55 percent, mode of 60 percent, and maximum 80 percent methane gas.

The cubic feet of biogas produced per pound of volatile solids (VS) may vary. Wright (2001) estimates that one pound of VS produces 3 to 7 cubic feet of biogas. Similarly, Engler et al. (1999) calculate that it takes one pound of VS to produce 3 to 8 cubic feet of biogas. Accordingly, we assign a triangular distribution with minimum 3, maximum 8, and most likely 5 cubic feet of biogas produced per pound of VS.

FarmWare 3.0 uses a 15-year life span in its estimation of a plug-flow digester's profitability (AgSTAR, undated). Lusk (1998) comments that well-designed plug-flow digesters will last 20 years. We specify a triangular distribution for life span with a minimum of 10 years, most likely 15 years, and maximum of 20 years.

The American Society of Agricultural Engineers (ASAE) estimates that a lactating dairy cow produces 150 pounds of manure per day, of which 20 pounds (13.3 percent) are TS and 17 pounds (11.3 percent) are VS. This means that VS are approximately 85 percent of the TS. Furthermore, a plug-flow digester operates best with 11–13 percent TS (ASAE 2005, U.S. EPA 2002b). We use a triangular distribution with minimum 11 percent, maximum 14 percent, and most likely 13.33 percent to estimate the volume of TS in relation to manure.

The amount of manure produced by each cow is variable. Although the ASAE estimates 150 pounds per day, VanHorn et al. (1994) estimate that the average Holstein dairy cow produces 125 pounds of manure per day. The U.S. Environmental Protection Agency offers an even lower figure: 112 pounds per 1,400-pound dairy cow per day (U.S. EPA 1999). Based on these estimates, we specify a triangular distribution with minimum 110 pounds, maximum 160 pounds, and most likely 150 pounds of manure per day per lactating cow.

Stochastic Simulations

Our basic capital budgeting model was developed in Microsoft Excel. To execute the Monte Carlo simulations, we used @Risk, an Excel add-in. @Risk allows one to specify distributions for a model's stochastic input variables. We used a constant seed value across simulations, such that the simulated values were constant across simulations. Thus, we were able to directly compare scenarios without being concerned that differences may be due in part to the randomness of the simulation technique. Within each simulation, 10,000 iterations were performed. The simulated results converged to stable distributions within this number of iterations.

Results

In presenting the results, we provide the mean of the simulated distribution of net present values [E(NPV)] for each scenario. Additionally, we provide the probability of an iteration having a positive NPV within each scenario. These values provide a clear understanding of the expected NPV of the project as well as the variability of NPVs over the simulation.

In those scenarios that do not include net metering, we estimate that 30 percent of the farm's electricity is subject to the retail rate each month, but that excess electricity is sold to the utility at a rate of $0.03 per kilowatt-hour. This is consistent with Garrison and Richard's (2005) work, which used $0.025 per kWh, and Lazarus and Rudstrom's (2003) work, which used $0.0317 per kWh.

Digester with No Solids Separator

The net returns of a methane digester are highly negative if a solids separator is not employed (Table 3). Mean NPVs range from about -$970,000 to -$600,000. In these cases, the benefits of net metering and/or carbon credits may offset some of these large losses, but the results are still highly negative in the absence of a solids separator.

Digester with a Solids Separator

As mentioned previously, the farmer may purchase a solids separator to work with the methane digester. Once separated, the solids have a value that depends upon their use. Generally, the solids can be used as bedding, either on the farm or sold off the farm, or they can be composted and sold as a soil amendment. In this section, we analyze the results of the investment decision under each alternative. Again, we analyze the choice across three herd sizes as well as the existence of net metering and carbon credit sales.

The results clearly indicate that methane digester adoption is unprofitable at all herd sizes when the solids are used (or sold) as composted material (Table 4). Without either net metering or carbon credit sales, the mean NPV ranges between -$525,000 and -$455,000. At herd sizes of 1,000 and 2,000 cows, the benefits associated with both carbon credit sales and net metering effectively increase the NPV, though not by an amount that causes the mean NPV of either distribution to be positive. For the very largest herds, however, the NPV is positive in approximately 33 percent of the simulated iterations.

In comparison to the compost option, using (or selling) the separated solids as bedding is significantly more profitable (Table 5). For the 500-cow herds, however, the technology remains unprofitable, even when the farm is able to take advantage of net metering and sell its carbon credits. At the assumed input values, the 1,000-cow herd realizes a mean NPV greater than zero when solids are used as bedding and the farmer sells carbon credits and takes advantage of net metering.

The largest gains are realized by the 2,000-cow herd in this analysis. Without selling carbon credits or taking advantage of net metering, the largest farms realize a large, positive NPV, and about two-thirds of all iterations resulted in a positive NPV. Thus, the technology is profitable for most dairy farms in that size range under the assumptions made in our analysis. When either carbon credit sales or net metering is considered for the 2,000-cow herd, the probability of a positive NPV exceeds 80 percent. When both are considered, that probability is nearly 95 percent and the mean NPV is over $500,000.

Sensitivity Analyses

The results shown thus far are dependent upon some underlying assumptions of our model. It is important to assess the sensitivity of our results to alternative assumptions. Because the value of the digester is negative for 500-cow herds in all analyses discussed thus far, we do not discuss results for that herd size in the remainder of this paper.

Sensitivity to the market value of carbon credits. The market value of carbon credits is $3.70 in our model. As is true for most other markets, this price could increase or decrease. Price changes

Table 3. Simulation Results of Investment in Digester with No Solids Separator

Herd Size	Base		Base with Carbon Credits		Base with Net Metering		Base with Carbon Credits and Net Metering	
	P (NPV > 0)	E(NPV)	P (NPV > 0)	E(NPV)	P (NPV > 0)	E(NPV)	P (NPV > 0)	E(NPV)
500	0.0%	-$603	0.0%	-$564	0.0%	-$551	0.0%	-$512
1,000	0.0%	-$670	0.0%	-$593	0.0%	-$566	0.0%	-$489
2,000	0.0%	-$969	0.0%	-$815	0.0%	-$761	0.0%	-$608

Notes: All dollar values are in $1,000 units. All probabilities relate to the percentage of simulated results that exceed zero.

Table 4. Simulation Results of Investment in Digester with a Solids Separator and Solids Used as Compost

Herd Size	Base		Base with Carbon Credits		Base with Net Metering		Base with Carbon Credits and Net Metering	
	P (NPV > 0)	E(NPV)	P (NPV > 0)	E(NPV)	P (NPV > 0)	E(NPV)	P (NPV > 0)	E(NPV)
500	0.0%	-$523	0.0%	-$485	0.0%	-$471	0.0%	-$433
1,000	0.0%	-$434	0.0%	-$358	0.0%	-$331	0.9%	-$254
2,000	0.8%	-$454	6.3%	-$300	11.4%	-$247	32.8%	-$93

Notes: All dollar values are in $1,000 units. All probabilities relate to the percentage of simulated results that exceed zero.

Table 5. Simulation Results of Investment in Digester with a Solids Separator and Solids Used as Bedding

Herd Size	Base		Base with Carbon Credits		Base with Net Metering		Base with Carbon Credits and Net Metering	
	P (NPV > 0)	E(NPV)	P (NPV > 0)	E(NPV)	P (NPV > 0)	E(NPV)	P (NPV > 0)	E(NPV)
500	0.0%	-$364	0.0%	-$326	0.0%	-$312	0.0%	-$274
1,000	23.3%	-$120	39.3%	-$43	45.1%	-$16	62.5%	$61
2,000	68.5%	$169	83.7%	$322	87.5%	$376	94.9%	$530

Notes: All dollar values are in $1,000 units. All probabilities relate to the percentage of simulated results that exceed zero.

might be driven by policies, general shifts in public perceptions of environmental issues, or other reasons. Therefore, we assess the effects of higher ($5.00) and lower ($2.40) market prices for the carbon credits.

While an increase in carbon credit values does increase the mean NPV and the probability that the NPV will be greater than zero, the results are fairly insensitive to the increase analyzed here (Table 6). For 2,000-cow farms selling solids as compost, the probability of a positive NPV increases, but more than half of all iterations remained negative. The 2,000-cow farms that used the solids as bedding have an increase of about $54,000 in mean NPV, while the increase for 1,000-cow farms using the solids as bedding increases by about $27,000.

Similarly, a decrease in the value of carbon credits also results in a decrease of the mean NPV and probability of the NPV being greater than

Table 6. Sensitivity of Results to the Price of Carbon Credits

Herd Size	Solids Use	Carbon Credit Price	Pr (NPV > 0)	E(NPV)
1,000	Bedding	$5.00	68.5%	$88
		$3.70	62.5%	$61
		$2.40	56.3%	$34
	Compost	$5.00	1.8%	-$227
		$3.70	0.9%	-$254
		$2.40	0.4%	-$281
2,000	Bedding	$5.00	96.7%	$584
		$3.70	94.9%	$530
		$2.40	92.9%	$476
	Compost	$5.00	42.2%	-$39
		$3.70	32.8%	-$93
		$2.40	24.5%	-$147

Note: All dollar values are in $1,000 units. All probabilities relate to the percentage of simulated results that exceed zero.

zero, but this decline is minimal. 1,000-cow farms utilizing the bedding option continue to have a positive mean NPV, but the probability of a negative NPV falls close to 50 percent in this scenario.

Sensitivity to the price received for electricity. Although our base assumption is that the farmer received $0.03 per kWh of electricity sold, it is possible that a farm could receive more or less than this. Thus, we explored the impact of the price received for excess electricity on the distribution of NPV for the 1,000- and 2,000-cow herds that opt for a separator.

An increase to $0.05 per kWh makes the digester profitable on the 2,000-cow farm when solids are used as compost (Table 7). However, even with a price of $0.10 per kWh for a 1,000-cow herd selling solids, the probability of the NPV being positive is less than 50 percent. At $0.05 per kWh, a 2,000-cow herd that uses the solids for bedding has a 97.5 percent probability of being profitable. Because this probability is quite large, we do not include the results at $0.10 per kWh for this scenario.

Sensitivity to changes in the capital costs at startup. The costs of purchasing and installing the digester and solids separator are quite significant. Digester costs have risen in recent years due to increases in the costs of labor, concrete, steel, and shipping (McEliece 2007). However, because of the increased interest in sources of renewable energy, there may be grants and subsidies available for farmers interested in installing digesters. In that case, the farmer does not bear the total investment cost of the digester. Because of this uncertainty in capital costs, we examine the impacts of a 10 percent increase and a 10 percent decrease in capital costs. Each of these analyses assumes that the farmer is selling carbon credits and using net metering.

The results indicate that the distribution of NPVs is quite sensitive to the capital costs, as one might expect given that they are not discounted in the model (Table 8). A grant or subsidy in the amount of 10 percent of the investment cost can have a very significant impact on the profitability of the digester. However, these are large grants, ranging from about $115,000 for the 1,000-cow herd to about $200,000 for the 2,000-cow herd.

Sensitivity to composting costs. From the previous analyses, it appears that opting for solids as bedding is more profitable than selling the solids as compost. There is a cost to producing and selling the compost, and we explored the relationship between the cost of composting the materials and the distribution of NPVs to determine if changing these costs would significantly affect the NPV

Table 7. Sensitivity of Results to the Price of Electricity Received by Farmers

Herd Size	Solids Use	Electricity Price ($/kWh)	Pr (NPV > 0)	E(NPV)
1,000	Compost	$0.00	0.0%	-$369
		$0.03	0.9%	-$254
		$0.05	10.2%	-$177
		$0.10	49.0%	$15
2,000	Compost	$0.00	5.0%	-$324
		$0.03	32.8%	-$93
		$0.05	57.7%	$60
		$0.10	82.0%	$444
1,000	Bedding	$0.00	36.6%	-$55
		$0.03	62.5%	$61
		$0.05	75.6%	$137
		$0.10	88.8%	$329
2,000	Bedding	$0.00	81.8%	$299
		$0.03	94.9%	$530
		$0.05	97.5%	$683

Notes: All dollar values are in $1,000 units. All probabilities relate to the percentage of simulated results that exceed zero.

Table 8. Sensitivity of Results to the Initial Digester Capital Cost

Herd Size	Solids Use	Capital Cost	Pr (NPV > 0)	E(NPV)
1,000	Bedding	10% decrease	85.2%	$175
		Base	62.5%	$61
		10% increase	37.4%	-$54
	Compost	10% decrease	9.6%	-$139
		Base	0.9%	-$254
		10% increase	0.0%	-$369
2,000	Bedding	10% decrease	99.4%	$719
		Base	94.9%	$530
		10% increase	84.3%	$341
	Compost	10% decrease	66.5%	$96
		Base	32.8%	-$93
		10% increase	9.3%	-$282

Notes: All dollar values are in $1,000 units. All probabilities relate to the percentage of simulated results that exceed zero.

distribution. The results indicate that these costs have little effect on the NPV of the digester project (Table 9). All scenarios in which the solids are composted show a large, negative mean NPV.

Sensitivity to expected life of the digester. Because a 2,000-cow herd that utilizes solids for bedding yielded the greatest probability of being profitable, we conducted further analysis on this

Table 9. Sensitivity of Results to Changes in the Cost of Composting Solids

Herd Size	Composting Costs	Pr (NPV > 0)	E(NPV)
1,000	10% decrease	1.0%	-$251
	Base	0.9%	-$254
	10% increase	0.9%	-$257
2,000	10% decrease	34.0%	-$87
	Base	32.8%	-$93
	10% increase	31.7%	-$99

Notes: All dollar values are in $1,000 units. All probabilities relate to the percentage of simulated results that exceed zero.

scenario to determine the impacts of the expected life of a digester and, thus, the time to pay back a project with these specifications. Although the digester's life span averages 15 years throughout our analysis, the mean NPV is positive when the life span (now entered as a model parameter) is shorter than 15 years (Table 10). At 10 years, for example, the project has a positive mean NPV, but when the digester is useful for fewer than 10 years, the project has a negative mean NPV.

Conclusion

This work clearly shows that larger dairy farms are more likely to profit from methane digester technology. AgSTAR suggests that dairies with 500 cows or more will be profitable with a digester (U.S. EPA 2002a), but our findings suggest that dairies must be larger, in the range of 1,000 or 2,000 cows, to have the potential to be profitable. With the addition of a solids separator and new policies and regulations, the project becomes significantly more profitable for larger herd sizes. In addition, the option of a separator increases the probability of the investment being profitable. Using the solids as bedding for the herd further increases the profitability of the project. Net metering regulations and carbon credit sales also affect the project's profitability. While these items do increase the expected value of the project's NPV, neither, by itself, turned an unprofitable scenario (i.e., one that had a negative mean NPV) into a profitable scenario.

Additional analyses indicated that the base results are highly sensitive to the price received for excess electricity sold to the power company, the initial investment cost, and the expected life of the digester. Shih et al. (2006) also show that these variables are highly important. The variables in their study were based on hypothetical situations and potential policies, which were quite different than our assumptions. The differences are as follows:

- farms received a higher rate for excess electricity—$0.06 per kWh in Shih et al. (2006) versus $0.03 per kWh in our research;
- farms paid a lower investment cost—approximately $400 per cow on a 1,000-cow farm in Shih et al. (2006) versus approximately $1,070 for the same sized farm in this paper;
- farms experienced a longer digester life in Shih et al. (2006)—20 years—versus a uniform distribution of 10–20 years in our work.

As a result of these differences, Shih et al. (2006) found that digesters could be profitable on a dairy farm with 400 or more cows, without a separator. Our values, based on actual market and policy conditions, yielded different results than Shih et al.

Additionally, we found that our results were less sensitive to some other factors. For instance, our results fluctuated only slightly when we altered the market price of carbon credits. Furthermore, the costs of producing and selling compost from the separated solids were shown to have little effect on the distribution of NPVs for the relevant scenarios.

The analysis of carbon credits and net metering suggests that current policies are not enough for most farms, even many large ones, to profitably adopt this technology without a significant reduction in the investment cost. If renewable energy, in the form of electricity produced by methane digesters on dairy farms, is important to public policymakers, then large grants or subsidies

Table 10. Sensitivity of Results to Changes in Expected Life of the Digester for a 2,000-Cow Herd Using Solids as Bedding

Years of Useful Life	Pr (NPV > 0)	E(NPV)
12	87.1%	$293
11	74.1%	$178
10	58.4%	$54
9	37.3%	-$81
8	12.0%	-$225
7	0.2%	-$382

Notes: All dollar values are in $1,000 units. All probabilities relate to the percentage of simulated results that exceed zero.

are needed to induce investment on nearly all farms of the size commonly found in Pennsylvania and the northeastern United States. Although little attention has been given to "community digesters," which two or more farmers might use, these may provide a way to achieve scale economies across farms. It is also possible for farmers to combine efforts with other types of businesses (e.g., restaurants or cheese plants) to mix manure with other waste to be digested. Thus, investment could occur on a large scale, taking advantage of scale economies.

References

AgSTAR. Undated. "FarmWare 3.0." AgSTAR Program, U.S. Environmental Protection Agency, Washington, D.C. Available at http://www.epa.gov/agstar/resources/handbook.html (accessed May 2007).

American Society of Agricultural Engineers (ASAE). 2005. "Manure Production and Characteristics." Publication No. D384.2, ASAE, St. Joseph, MI.

ASAE [*see* American Society of Agricultural Engineers].

Birge, C. 2007. Personal communication, Pennsylvania Public Utility Commission, Harrisburg, PA.

California Biomass Collaborative. 2007. California Biomass Collaborative, Department of Biological and Agricultural Engineering, University of California, Davis. Available at http://faculty.engineering.ucdavis.edu/jenkins/CBC/Calculator/index.html (accessed May 2007).

Chicago Climate Exchange. 2007. Market data. Available at http://www.chicagoclimateexchange.com (accessed April 28, 2007).

Converse, J. 2001. "Fundamentals of Biogas Production from Dairy Manure." Presentation at Wisconsin Ad Hoc Anaerobic Digestion Committee Meeting, Wisconsin Department of Agriculture, Trade and Consumer Protection (DATCP) (May 3).

Cornell Waste Management Institute. 2006. "Using Manure Solids as Bedding." Department of Crops and Soil Sciences, Cornell University, Ithaca, NY.

de Vries, A., A. Wilkie, R. Giesy, and R. Nordstedt. 2007. "Spreadsheet to Calculate the Economic Feasibility of Anaerobic Manure Digesters on Florida Dairy Farms." University of Florida/IFAS Electronic Data Information Source (EDIS). Available at http://dairy.ifas.ufl.edu/tools/Di[-]gester1.1.xls (accessed May 2007).

Engler, C., E. Jordan, M.J. McFarland, and R.D. Lacewell. 1999. "Economics and Environmental Impact of Biogas Production as a Manure Management Strategy." Biological & Agricultural Engineering, Texas A&M, College Station, TX.

Garrison, M.V., and T.L. Richard. 2005. "Methane and Manure: Feasibility Analysis of Price and Policy Alternatives." *Transactions of the ASAE* 48(3): 1287–1294.

Ghafoori, E., and P.C. Flynn. 2006a. "Optimizing the Size of Anaerobic Digesters." Paper presented at the CSBE/SCGAB Annual Conference, Edmonton, Alberta (July 16–19).

____. 2006b. "An Economic Analysis of Pipelining Beef Cattle Manure." *Transactions of the ASABE* 49(6): 2069–2075.

Giesy, R., A. Wilkie, A. de Vries, and R. Nordstedt. 2005. "Economic Feasibility of Anaerobic Digestion to Produce Electricity on Florida Dairy Farms." Publication No. AN159, Animal Science Department, Florida Cooperative Extension Service, Institute of Food and Agricultural Sciences, University of Florida, Gainesville.

Gooch, C., J. Hogan, N. Glazier, and R. Noble. 2006. "Use of Post-Digested Separated Manure Solids as Freestall Bedding: A Case Study." Paper presented at the National Mastitis Council Annual Meeting, Tampa, Florida (January 22–25).

Goodrich, P. 2005. "Anaerobic Digester Systems for Mid-Sized Dairy Farms." The Minnesota Project, St. Paul, MN.

Hyde, J., and P. Engel. 2002. "Investing in a Robotic Milking System: A Monte Carlo Simulation Analysis." *Journal of Dairy Science* 85(9): 2207–2214.

Kramer, J. 2004. *Agricultural Biogas Casebook: 2004 Update.* Madison, WI: Resource Strategies, Inc.

Krich, K., D. Augenstein, J.P. Batmale, J. Benemann, B. Rutledge, and D. Salour. 2005. "Biomethane from Dairy Waste. A Sourcebook for the Production and Use of Renewable Natural Gas in California." Report prepared for Western United Dairymen, Modesto, CA.

Lazarus, W., and M. Rudstrom. 2003. "Financial Feasibility of Dairy Digester Systems Under Alternate Policy Scenarios, Valuations of Benefits, and Production Efficiencies: A Minnesota Case Study." Paper presented at the conference "Anaerobic Digester Technology Applications in Animal Agriculture: A National Summit," Raleigh, NC (June 2–4).

____. 2007. "The Economics of Anaerobic Digester Operation on a Minnesota Dairy Farm." *Review of Agricultural Economics* 29(2): 349–364.

Lorimor, J., and J. Sawyer. 2004. "Swine USA Anaerobic Digester Performance Analysis." Cooperative Agreement No. 68-6114-9-217, Natural Resources Conservation Service, Iowa State University, Ames, IA.

Ludington, D., and E.L. Johnson. 2003. "Dairy Farm Energy Audit Summary." Report prepared for FlexTech Services, New York State Energy Research and Development Authority, Albany, NY.

Lusk, P. 1998. "Methane Recovery from Animal Manures: The Current Opportunities Casebook." Report prepared for National Renewable Energy Laboratory, Golden, CO.

Martin, J.H. 2004. "A Comparison of Dairy Cattle Manure Management with and without Anaerobic Digestion and Biogas Utilization." Report prepared for AgSTAR Program, U.S. Environmental Protection Agency, Washington, D.C.

____. 2005. "An Evaluation of a Mesophilic, Modified Plug Flow Anaerobic Digester for Dairy Cattle Manure." Report prepared for AgSTAR Program, U.S. Environmental Protection Agency, Washington, D.C.

Martin, J.H., P. Wright, S. Inglis, and K.R. Roos. 2003. "Evaluation of the Performance of a 550 Cow Plug-Flow Anaerobic Digester Under Steady-State Conditions." In *Ninth International Animal, Agricultural and Food Processing Wastes Proceedings of the 12–15 October 2003 Symposium* (Research Triangle Park, NC).

McComb, S. 2007. Personal communication, economist, Chicago Climate Exchange, Inc., Chicago, IL.

McEliece, A. 2007. Various personal communications, RCM Digesters, Berkeley, CA.

Mehta, A. 2002. "Economics and Feasibility of Electricity Generation Using Manure Digesters on Small and Mid-Size Dairy Farms." Energy Analysis and Policy Program, Department of Agricultural and Applied Economics, University of Wisconsin, Madison, WI.

Ndegwa, P.M., D.W. Hamilton, J.A. Lalman, and H.J. Cumba. 2005. "Optimization of Anaerobic Sequencing Batch Reactors Treating Dilute Swine Slurries." *Transactions of the ASAE* 48(4): 1575–1583.

Pennsylvania Agricultural Statistics Service. 2006. *Pennsylvania Agricultural Statistics 2005–2006.* Pennsylvania Field Office, National Agricultural Statistics Service, U.S. Department of Agriculture, Harrisburg, PA.

Pennsylvania Public Utility Commission. 2006. "PUC Adopts Net Metering Rules to Connect Small Alternative Energy Generators to Electric Distribution System." Pennsylvania Public Utility Commission, Harrisburg, PA.

Rynk, R., M. van de Kamp, G.B. Willson, M.E. Singley, T.L. Richard, J.J. Kolega, F.R. Gouin, L.L. Laliberty, Jr., D. Kay, D.W. Murphy, H.A.J. Hoitink, and W.F. Brinton. 1992. "On-Farm Composting Handbook." Publication No. NRAES-54, Natural Resource, Agriculture, and Engineering Services, Cooperative Extension, Ithaca, NY.

Scruton, D.L., S.A. Weeks, and R.S. Achilles. 2004a. "Net Metering's Effect on On-Farm Electrical Generation Economics." Paper presented at the conference "Renewable and Distributed Power Generation: Wind Solar and Other Sources," Ottawa, Ontario (August 3).

____. 2004b. "Strategic Hurdles to Widespread Adoption of On-Farm Anaerobic Digester." Paper presented at the conference "Dairy Manure Management Systems," Ottawa, Ontario (August 4).

Shih, J., D. Burtraw, K. Palmer, and J. Sukiyaki. 2006. "Air Emissions of Ammonia and Methane from Livestock Operations: Valuation and Policy Options." Discussion Paper No. 06-11, Resources for the Future, Washington, D.C.

Six, D. 2006. Personal communication. Controller, Environmental Credit Corporation, State College, PA.

Stokes, J.R., R.M. Rajagopalan, and S.E. Stefanou. 2006. "Investment in a Methane Digester: An Application of Capital Budgeting and Real Options." Unpublished manuscript.

Subler, S. 2006. Personal communications. President, Environmental Credit Corporation, State College, PA.

U.S. Department of Agriculture. 2007. "Agricultural Prices." National Agricultural Statistics Service, USDA, Washington, D.C. Available at http://www.nass.usda.gov/publica[-]tions/ Todays_Reports/reports/agpr0407.txt (accessed May 2007).

U.S. Department of Energy (U.S. DOE). 2006. "Average Retail Price of Electricity, 1960–2005." U.S. DOE, Washington, D.C.

U.S. Environmental Protection Agency (U.S. EPA). 1999. "U.S. Methane Emissions 1990–2020: Inventories, Projections, and Opportunities for Reductions." Office of Air and Radiation, U.E. EPA, Washington, D.C.

____. 2002a. "Market Opportunities for Biogas Recovery Systems: A Guide to Identifying Candidates for On-Farm and Centralized Systems." AgSTAR Program, U.S. EPA, Washington, D.C.

____. 2002b. "Managing Manure with Biogas Recovery Systems: Improved Performance at Competitive Costs." AgSTAR Program, U.S. EPA, Washington, D.C.

____. Undated. "AgSTAR Handbook and Software" (2nd edition). AgSTAR Program, U.S. EPA, Washington, D.C.

VanHorn, H.H., A.C. Wilkie, W.J. Powers, and R.A. Nordstedt. 1994. "Components of Dairy Management Systems." *Journal of Dairy Science* 77(7): 2008–2030.

Weeks, S.A. 2002. "Fixed-Film Anaerobic Digestion of Separated Dairy Manure: Compost Drying of Separated Manure Solids." Paper presented at the ASAE Annual International Meeting/CIGR XVth World Congress, Chicago, IL (July 28–31).

Wilkie, A.C. 2005. "Anaerobic Digestion of Dairy Manure: Design and Process Considerations." In *Dairy Manure Management: Treatment, Handling, and Community Relations*. Natural Resource, Agriculture, and Engineering Service, Cornell University, Ithaca, NY.

Wright, P. 2001. "Overview of Anaerobic Digestion Systems for Dairy Farms." Publication No. NRAES 143, Natural Resource, Agriculture and Engineering Service Cooperative Extension, Ithaca, NY.

Wright, P., and J. Ma. 2003. "Fixed Film Digester at Farber Dairy Farm: Case Study." Case Study No. AD-3, Manure Management Program, Department of Biological and Environmental Engineering, Cornell University, Ithaca, NY.