ANAEROBIC DIGESTER ADOPTION ON ANIMAL FEEDING OPERATIONS

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While pursuing my master's degree, I would pass the same sculpture every day as I walked to campus. The statue included abstract metal art atop a marble bench. On the bench, the sculptor had etched this quote from Sir Isaac Newton: "If I have seen further it is by standing on the shoulders of giants." While Newton's initial motivation for penning this quote may or may not have had anything to do with education, I believe that it is very fitting that this quote, of all quotes, be given prominence on a college campus. Instruction in any form, especially at the university level, gives students the tools they need to see into their futures, realize their potential, and pursue their career goals. Outside my family, all the "giants" in my life are teachers and university faculty members. I would not be where I am today without being taught, challenged, inspired, and mentored by outstanding educators. To paraphrase Proverbs 8:10, I prefer instruction instead of silver and knowledge rather than choice gold. So to all the teachers in my past, present, and future: thank you.

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Abstract:

The livestock industry may create environmental problems such as nutrient pollution in water bodies and the discharge of greenhouse gases into the atmosphere, but anaerobic digestion could be a viable solution. In an anaerobic digester, microorganisms digest manure to produce biogas, which is mostly methane. While environmentally beneficial, limited economic feasibility has prevented them from being widely adopted. Most previous research on the economics of anaerobic digestion systems has been limited to site-specific case studies in the dairy industry.

The objectives of this research were 1) to determine the economic feasibility of anaerobic digesters and covered lagoons on swine operations, 2) to determine how government policies, co-product prices, peer group influence, farm characteristics, and farmer beliefs affect the decision to adopt anaerobic digesters, and 3) to develop a production function, a fixed cost function, and a variable cost function for methane production in an anaerobic digester. The objectives were accomplished by applying capital budgeting, contingent valuation, willingness-to-accept, and econometric methods to data collected from a nation-wide survey of dairy and hog producers.

Farm size and type were important variables for economic feasibility and for predicting the likelihood of adoption. Results showed that methane production exhibits increasing returns to scale, and average fixed and variable costs decrease with size. For swine farms, lower cost, passive systems, such as covered lagoons, could be a more promising investment when government grants and carbon trading are not available. Low-rate systems (e.g. plug flow and complete mix digesters) with higher capital costs are more economically feasible on dairy farms because of their increased productivity. While the environmental benefits of anaerobic digesters are important for predicting whether or not a producer will consider the technology for manure management, lower capital costs, co-product marketing, or government grants are needed in order to encourage more widespread adoption.

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CHAPTER I

ECONOMIC FEASIBILITY OF ANAEROBIC DIGESTERS WITH SWINE OPERATIONS

Abstract

Anaerobic digestion systems reduce greenhouse gas emissions while turning waste products into energy but are rarely adopted because capital costs make them economically infeasible for most animal operations. Past economic research is available on the application of these technologies with dairy farms. Farms have a choice between different systems, but limited information is available as to which systems are more feasible for swine. Net present values were calculated to determine the economic feasibility of anaerobic digesters and covered lagoons under different co-product and policy scenarios. Results indicate that, with no government intervention, covered lagoons can generate positive NPVs and could be more promising for swine operations.

Introduction

An increasing population requires more food and more intensive agricultural operations. As animal production facilities become larger and more concentrated, the risk of environmental and social externalities increases (Centner 2003). Environmental degradation from nutrient pollution, specifically phosphorus, consistently ranks as one of the top water quality issues in the U.S. (Carpenter et al. 1998). Excess phosphorus loading can lead to water quality problems such as hypoxia and eutrophication. Carpenter et al. (1998) argue that eutrophication is a widespread problem, and phosphorus pollution results primarily from agricultural and urban activities and is directly related to livestock stocking rates upstream.

In addition to water quality impairments, the livestock industry in the U.S. is often blamed for atmospheric environmental problems, including the discharge of methane into the atmosphere (Zaks et al. 2011). Methane is a potent greenhouse gas that could contribute to global warming (Lashof and Ahuja 1990). While livestock are not a net source of carbon dioxide, enteric fermentation and manure management account for almost 35% of anthropogenic methane emissions in the United States (USEPA 2014b). The production of livestock also requires human and fossil fuel energy. The agricultural sector accounts for approximately 19% of the energy use in the U.S. and is driven almost entirely by non-renewable energy sources (Canning et al. 2010; Pimentel et al. 1973; Pimentel and Pimentel 1996; Pimentel et al. 2008).

Another non-renewable resource that is important for production agriculture is phosphorus. Phosphorus is essential for plants to grow, and the process of growing food crops is fundamental for human survival. Unfortunately, phosphorus is a resource that is mostly obtained from mined rock phosphate, and these reserves are declining, causing the cost of extraction, processing, and shipping to increase (Cordell, Drangert, and White 2009; Shu et al. 2006). There is also concern that phosphorus, like oil, will reach its peak in production and then decline (Cordell, Drangert, and White 2009). This could cause high food prices and/or increased food scarcity.

Although research has shown the finite nature of world phosphorus reserves, thousands of tons of this valuable nutrient are lost each year due to over-application of fertilizer[1], erosion, runoff from agricultural lands, and discharges from water reclamation facilities (WRFs). The estimated average annual flux of total phosphorus from the Mississippi (and Atchafalaya) River Basin to the Gulf of Mexico is approximately 140,000 metric tons (Aulenbach et al. 2007). Not only is this a loss of a valuable nonrenewable resource, but this delivery of phosphorus also propagates algal blooms, which deplete dissolved oxygen and create a hypoxic zone in the Gulf of Mexico (Aulenbach et al. 2007).

Anaerobic digestion could be a viable solution to the environmental and resource concerns created by confined animal agriculture. An anaerobic digester processes manure under anaerobic conditions (without oxygen). Anaerobic digestion systems alleviate greenhouse gas emissions by capturing and combusting methane. These systems can also precipitate and divert mineral phosphorus (as struvite, or magnesium ammonium phosphate, $NH_4MgPO_4 \cdot 6H_20$) in a more concentrated form (Burns, Moody, and Shepherd 2006; Çelen et al. 2007; Shu et al. 2006; Uysal, Yilmazel, and Demirer 2010; Yilmazel and Demirer 2011). By doing this, the nutrients can be shipped further because struvite is concentrated and more

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[1] According to Zhang and Raun (2006), phosphorus (P) fertilization increases the risk of water pollution. This risk of water pollution is greater when the soil test phosphorus (STP) index is above 120 (P is 100% sufficient in soils with STP index ≥ 65). However, they also point out that "continued input of P to fields with high STP are not a risk to water quality if there is no runoff, no neighboring bodies of water, quality of the water body is not limited by P, or the concentration of soluble-P in runoff is reduced to acceptable levels with buffer strips" (Zhang and Raun 2006).

nutrient-dense than manure, and fertilizer transportation costs are reduced. According to Yilmazel and Demirer (2011) and others, struvite releases nutrients slowly and has a low solubility in water. Phosphorus inputs with low water solubility are less likely to impair water quality (Zhang and Raun 2006). Since phosphorus and nitrogen are removed during struvite precipitation, the remaining swine slurry effluent is safer for the environment.

Anaerobic digesters also have the potential to produce value-added co-products that could include soil amendments, livestock bedding, and liquid that can be used as fertilizer (Zaks et al. 2011; Bishop and Shumway 2009). However, despite the potential environmental and economic benefits, anaerobic digestion systems are not common in the United States. Currently only 239 of the almost 20,000 (~1%) confined animal feeding operations (CAFOs) in the United States have anaerobic digestion systems, and the swine industry accounts for only 29 of these systems (USEPA 2012; USEPA 2014).

The potential environmental benefits of anaerobic digestion systems are only one side of a very complex economic issue. The economics, and more specifically the capital costs, of these systems are often blamed for their limited adoption, and most current literature on the economic feasibility of anaerobic digestion systems has focused on the *dairy* industry (Lazarus and Rudstrom 2007; Kruger et al. 2008; Stokes, Rajagopalan, and Stefanou 2008; Bishop and Shumway 2009; Wang et al. 2010; DeVuyst et al. 2011). For example, Bishop and Shumway (2009) performed a financial analyses of a dairy farm digester in the Pacific Northwest and found reduced capital costs from government grants, additional revenue streams from co-products like electricity, fiber, nutrients, and co-digestion of food waste are important for obtaining sufficient return on investment. Lazarus and Rudstrom (2007) studied the economic feasibility of an anaerobic digestion system on a Minnesota dairy farm and determined that the profitability of the digester was primarily due to favorable electricity pricing and financial assistance from government agencies.

Although most previous research on anaerobic digestion has focused on the dairy industry, it is also important to understand the potential for these systems on swine operations and to determine the type of digester that is the most economically feasible. Digesters produce methane at a higher and more constant rate, whereas covered lagoons require lower maintenance, materials, and construction costs. Therefore, understanding the tradeoff between better performance and lower costs associated with digesters and covered lagoons, respectively, could help producers who are interested in implementing this technology. The primary objective of this study is to determine the economic feasibility of anaerobic digesters and covered lagoons on swine operations. The second objective is to determine the physical parameters, co-products, and/or government policies that are required to achieve economic feasibility with each type of system. To accomplish these objectives, net present values were calculated to gauge the economic performance of anaerobic digesters and covered lagoons. Co-product marketing scenarios were formulated, and sensitivity analyses were used to determine how the economic feasibility of the digesters and covered lagoons are affected under different economic, co-product, and policy scenarios.

Theory

A discrete-choice optimization problem for a risk neutral producer that wants to determine the economic feasibility of extracting methane and other co-products from manure produced at a swine animal feeding operation (AFO) can be defined as:

$$\max_{n,d} NPV = \sum_{i=1}^{n} \sum_{t=0}^{T} \left[\frac{p_{it} E(y_{itd}) - w_{itd} x_{itd}}{(1 + r_t)^t} \right] - C_{id} \qquad \text{(I.1)}$$

s.t. $NPV > 0$

where n is a choice variable for the outputs that the producer wishes to produce, where, $i = 1$ is recovered methane, $i = 2, \ldots n$ are any additional value-added co-products, d is the method used for handling swine manure, where $d = 1, 2$ (1 = anaerobic digester, 2 = covered lagoon), r_t is the discount rate for the t^{th} year, $E(y_{itd})$ is the expected amount of the co-product that is extracted in units/year, p_{it} is the price of each output in \$/unit, w_{itd} is the variable cost of the inputs required to produce each co-product in \$/unit, x_{itd} is the input, or physical parameter, required to achieve the i^{th} co-product in units/year, and C_{id} is the fixed cost of producing each co-product in \$.

Data

A survey instrument was used to collect primary data for this study. The survey was distributed to all swine producers known to have anaerobic digesters with the help of the U.S. Department of Agriculture (USDA) National Agricultural Statistics Service (NASS). Swine operations that currently use anaerobic digestion technology on their farms were asked to answer a five-section survey. The three sections used in this study included: introductory questions, physical parameters and digester design, and economic considerations. Survey participants were asked to share cost, revenue, and production data from their anaerobic digester. Qualtrics Survey Software was used to create and administer the survey online and a paper version of the survey was also sent in an attempt to generate additional responses.

On December 20, 2013, a postcard was sent. The postcard described the research objectives, requested help with the study, and provided a link to the online survey platform. Since the response rate was not adequate after sending the first postcard, a survey packet was distributed on January 24, 2013. The survey packet included a cover letter, a paper version of the survey, and a business reply envelope. While the response generated from the paper survey was better than with the postcard, a second postcard reminder was sent on February 12, 2014. The final paper survey response was received on May 9, 2014, and the online survey was deactivated on May 16, 2014.

Of the 29 swine operations that operate anaerobic digesters in the United States, as identified by the USEPA AgSTAR Program, eight responded to the survey (USEPA 2014b). Digesters are typically found on larger animal feeding operations. All swine operations included in this study had a total hog inventory of 1,000 head or more. As shown in table I.1, the eight completed surveys generated a response rate of almost 30%. Two respondents operated covered lagoons, while the other six operated complete mix ($n = 1$) or plug flow ($n = 5$) anaerobic digesters. While all anaerobic digesters perform the same, basic functions, there are several types that are used when handling manure, and the most common ones are split into three categories: passive systems, low rate systems, and high rate systems[2] (Hamilton 2013). For the purposes of this study and in order to protect the confidentiality of the survey respondents, the two covered lagoons were grouped together, representing the

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[2] For passive systems, methane recovery is added to existing manure management or treatment infrastructure. In low rate systems, manure is the primary source of methane-forming microorganisms. High rate systems differ in that methane-forming microorganisms are added to and contained in the digester to increase methane production efficiency (Hamilton 2013).

“passive, low cost” digesters, and the complete mix and plug flow digesters were grouped together, representing the “low rate, high cost” digesters. Table I-2 includes a summary of selected respondent, farm, and digester characteristics.

The mean number of years that the digesters or covered lagoons were operational was similar for both groups. Some of the swine farms included in this study reported that they also raise dairy cattle and that manure was not the only material entering the digestion system. The complete mix and plug flow anaerobic digesters had an average of 25% food production or processing waste in the digester input stream. Both covered lagoons only processed swine manure. The average loading rate for the anaerobic digesters was higher than the average loading rate for the covered lagoons. While this is partially due to the fact that swine manure slurry has higher water content, the addition of dairy manure and food production or processing waste could allow the anaerobic digesters to produce methane at an even higher rate than the covered lagoons. Food wastes have twice the methane yield per pound of volatile solids when compared to manure (15 ft^3/lb VS vs. 7 ft^3/lb VS) (Goldstein 2012). However, since most anaerobic digesters and covered lagoons in the U.S. are designed to treat animal wastes, the addition of food or other organic wastes that do not have similar physical, biological, and chemical compositions could disrupt the system, so careful consideration must be taken when adding food waste to an anaerobic digester or covered lagoon.

Procedure

Net present value (NPV), as specified in equation (I.1), was used to gauge and compare the economic performance of digesters and covered lagoons. Since all anaerobic digesters produce methane, NPV was calculated for the average anaerobic digester and covered lagoon on the basis of only methane production. Additional co-products, such as electricity generation, struvite, and soil amendments, were added to the analysis for those operations that reported co-product marketing. Some of the agricultural operations included in this study also reported trading carbon credits on the Chicago Climate Exchange (CCX) prior to 2010 and receiving renewable energy tax credits and/or state or federal government grants. Therefore, any benefits from government policies and/or carbon trading were also added to the analysis as co-products. All possible co-products, except methane, and their corresponding prices are listed in table I-3.

Economic Analysis: Revenues from Methane, Electricity, Struvite, and other Co-Products

According to the survey results, the methane generated by the anaerobic digesters and covered lagoons was flared, used for furnace fuel, injected into an internal combustion engine for electricity generation, and/or compressed and used for vehicle fuel (compressed natural gas, CNG). The resulting annual revenue and/or cost savings from all of these practices, with the exception of electricity generation, is included in figure I-1 under the 'Methane' heading. Methane can also be injected into an internal combustion engine/generator to produce electricity used on-farm, offsetting the cost (retail price) a producer must pay for electricity (Zaks et al. 2011). Any electricity not consumed on the farm can be sold back to the utility (or back "on the grid") for a wholesale price. All of the anaerobic digesters in this study produce methane that is injected into an electric generator, and one of the covered lagoons reported electricity generation as a part of the system. All operations that produce electricity from methane either sell the electricity off the farm at a wholesale price and/or use it to offset their own (retail) costs of electricity. The average price that this electricity was sold is included in table I.3 as *wholesale* electricity. The average price paid for electricity is included in table I.3 as *retail* electricity.

If the electricity generated from the anaerobic digester or covered lagoon was sold off-farm (or "back on the grid"), the wholesale price paid for electricity ($/kWh) was multiplied by the installed capacity (kW) and the number of hours in a year to get the total revenue generated by electricity production ($/yr). It is unlikely that electricity generators will continually run at full capacity. Generators will be shutdown periodically for repairs and maintenance. For the calculations in this study, it was assumed that the generators operate and produce electricity at 85% of the reported installed capacity of the system in order to account for times when the generator is not operating or is operating as less than full capacity. If the electricity was not sold off-farm, but instead used on-farm to offset costs, the retail price per kWh was multiplied by the installed capacity and the number of hours in a year to get the total cost savings. In some cases, electricity was used on-farm to offset costs and sold off-farm to generate revenue. In this case, survey respondents were asked to specify what percentage of the electricity was used on- and off-farm. The equation for calculating total annual benefits from electricity production was specified as

$$E(y_{2d}) = [(AR + CS) \times 24 \times 365]_d \tag{I.2}$$

$$\begin{aligned} \text{s.t. } AR &= \alpha p_w(0.85K) \\ CS &= \beta p_r(0.85K) \end{aligned}$$

where $E(y_{2d})$ is the total benefits from producing electricity in \$/year, *AR* is the revenue from selling electricity off-farm in \$/hour, *CS* represents the cost savings from producing electricity on-farm in \$/hour, α is the proportion of electricity used off-farm, p_w is the wholesale price of electricity in \$/kWh, *K* is the installed capacity of the electricity generator in kW, β is the proportion of electricity used on-farm, and p_r is the retail price of electricity in \$/kWh. Survey respondents provided electricity production and pricing information. The average annual revenue and cost savings for the anaerobic digesters and covered lagoons are included in figure I-1.

Anaerobic digestion systems could potentially precipitate mineral phosphorus (as struvite) if a struvite precipitator is added to the system (Burns, Moody, and Shepherd 2006; Çelen et al. 2007; Shu et al. 2006; Uysal, Yilmazel, and Demirer 2010; Yilmazel and Demirer 2011). Precipitation of struvite could reduce manure and nutrient transportation costs. Using similar methods as Fleming, Babcock, and Wang (1998) to compute costs of transporting, spreading, and incorporating manure, an equation for transportation cost savings resulting from the precipitation of struvite was specified as

(I.3)

$$\pi_{3d} = \varphi_k \left(\sum_{k=1}^{K} P_k N_k - \sum_{k=1}^{K} \sum_{j=1}^{J} Q_j H_j \left[r_B + Z r_A \left(D + 2\sqrt{A_{kj}/640} \right) \right] \right)$$

where π_{3d} is the value of transportation cost savings in \$/year, P_k is the price of nutrient k in \$/ton, where $k = 1$ is nitrogen and $k = 2$ is phosphorus, N_k is the quantity of nutrient k produced per year in ton/year, Q_j is the quantity of manure (or struvite) produced by breeding or feeding stock j in gallons/AU/year, where j equals 1 for nursery pigs, 2 for grow-to-finish pigs, 3 for breeding sows, 4 for dairy cows, and 5 for dairy heifers, H_j is the number of animal units (AU) contributing manure, r_A is the unit mile charge in \$/gallon-mile, r_B is the base charge in \$/gallon, Z is an indicator variable and equals 2 for slurry systems (round trip for hauling vehicle) or 1 for liquid waste (pumped, no return trip required), D is the average distance traveled to spread manure over spreadable land that accepts manure in miles, A_{kj} is the spreadable area of cropland that accepts manure in acres/year, and φ_k represents the portion (%) of nutrient k precipitated out or remaining in the manure.

Research has shown that the process of struvite precipitation can extract 90-95% of the available phosphorus and about 15% of the available nitrogen in livestock manure (Burns, Moody, and Shepherd 2006; Çelen et al. 2007; Shu et al. 2006; Uysal, Yilmazel, and Demirer 2010; Yilmazel and Demirer 2011; Sommer et al. 2013). A recoverability factor of 0.9 was used to give a conservative estimate of the phosphorus recovered as struvite. Since fertilizer is available in a more concentrated form after struvite precipitation, a farmer could transport the material further. On the other hand, since the nutrients are more concentrated, shorter distances could be utilized to transport the same amount of nutrients. After struvite precipitation, the farmer will still have the processed manure, which will contain some nutrients (approximately 85% N and 10% P, by weight of manure) and will need transported a shorter distance for storage, disposal, or marketing (e.g. animal bedding, soil organic matter). Each of these considerations could affect transportation cost calculations. For this study, we assume that the remaining manure is applied to cropland.

Parameters values for variables H_j and D were obtained from survey participants. Manure and nutrient production, Q_j and N_k, were estimated based on swine and dairy waste characteristics provided by USDA (2008), and A_{kj} was calculated following methods by MWPS (1985). Parameter values for all other variables were given by Fleming, Babcock, and Wang (1998) and Ribaudo et al. (2003). Cost estimates r_A and r_B were converted to 2014 dollars using the Consumer Price Index (table I.3). Fleming, Babcock, and Wang (1998) and Ribaudo et al. (2003) provide different manure characteristic and cost estimates depending on the type of manure storage and management adopted by the livestock operation. Survey participants indicated whether their manure (pre- or post-treatment) was stored in a pit, lagoon, and/or other slurry storage, and it was assumed that any manure transported and land-applied was also incorporated into the soil. All variable descriptions and values used to estimate equation (I.3) are included in tables B.1 and B.2 in the appendix. A more detailed example of these calculations is also included in the appendix.

Precipitating mineral phosphorus as struvite and utilizing the remaining manure nutrients allows for avoided costs of purchasing fertilizer and/or the ability to market the manure or struvite as fertilizer to others. While struvite is primarily known as phosphorus fertilizer, it also contains nitrogen. The fertilizer equivalent of struvite is approximately $6-29-0$, as $\mathrm{N}-\mathrm{P_2O_5}-\mathrm{K_2O}$ (Bridger, Salutsky, and Starostka 1962). USDA (2013) lists average U.S. farm prices of selected N and P fertilizers. The price of superphosphate (44-46% phosphate) as of March 2013 was $701/ton, and the price of nitrogen solutions (30% nitrogen) was $410/ton (USDA 2013). USDA (2013) fertilizer prices were used for manure and struvite nutrients. Since the amount and value of the nutrients from manure and struvite will be the same, the primary benefit to the swine producer could be realized through the transportation cost savings resulting from concentrating nutrients as struvite.

Manure transportation calculations are based on the assumption that AFOs require land to dispose of annual manure (and nutrient) production. The land area (A_{kj}) required for manure disposal was calculated based on the amount of manure excreted by animal units on the farm, the nutrient content of the manure, and the nutrient utilization of the receiving crop. The equation for total cropland required for manure (or struvite) application was written as

(I.4)

$$A_{kj} = \sum_{j=1}^{J} \frac{Q_j H_j \rho_{kj}}{\mu_k}$$

where ρ_{kj} is production of nutrient k by animal j in lb/gallon manure, μ_k is the crop nutrient utilization in lb/ac of nutrient i, and all other variables are the same as above. For each type of breeding or feeding stock on each farm included in this study, USDA (2008) gives volume of manure and pounds of nutrients produced per animal unit per day. This information was used to calculate ρ_{kj}.

Crop nutrient utilization depends on the type of crop planted and the expected yield of the crop. In the regions where the eight swine AFOs are located, corn is one of the primary row crops, so it was the crop of choice for manure transportation calculations. The average yield in these areas was approximately 150 bushels per acre. For a yield of 150 bu/ac, corn nutrient utilization is 185 lb N/ac and 80 lb P_2O_5/ac (MWPS 1985). The area of land required for each nutrient was calculated, and the larger of the two areas was selected for transportation cost calculations in equation (I-3). Selecting the larger land area follows the assumption that the producer wants to maximize the use of nutrients in animal manure, prevent over-application of N, and avoid the buildup of P in the soil. Manure management laws in each of the states included in this study assert that manure nutrient application cannot exceed crop N requirements.[3] Application of phosphorus may be greater than crop requirements when soil tests indicate low phosphorus levels but must not exceed crop requirements when soil tests indicate phosphorus levels that are adequate for the crop. However, laws governing land application of manure P become more stringent when the land is within a certain distance of surface water (typically 100 to 1,000 feet, depending on the state and the type of water body). Applying manure over the larger land area will meet the

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[3] Individual state laws are not cited here in order to protect survey respondent confidentiality. However, the U.S. EPA provides information and resources for individual state animal feeding operation laws, regulations, policies, and guidance, including those for manure management, at http://www.epa.gov/agriculture/anafolaw.html.

crop nutrient requirements for one of the nutrients but may not be sufficient for the other nutrient. If soil tests and crop requirements indicate additional nutrients are needed, then commercial fertilizer can be used as a supplement.

According to Beal, Burns, and Stalder (1999), a swine facility will produce 113 kg struvite/yr-AU. The volume of struvite (in gallons/year) was calculated using the density of struvite (15 lb/gal) and unit conversion factors. The volume of struvite was inserted into equations (I-3) and (I-4) in place of Q_j to determine the costs of transporting, spreading, and incorporating struvite fertilizer. The difference in the cost of transporting manure and the cost of transporting struvite was calculated for each farm and averaged in order to obtain the transportation cost savings for the anaerobic digestion systems and covered lagoons (figure I-1). A more detailed example of transportation cost calculations is provided in appendix B.

The anaerobic digesters and covered lagoons also reported revenue and/or cost savings from the production of compost soil amendments. The price for soil amendments was based on national average wholesale prices for similar products, such as peat moss, potting soil, and compost. In addition to price information, survey respondents were asked to report revenue and cost-savings information, and these values are included in figure I-1.

Economic Analysis: Government Intervention

Only one anaerobic digester operator and one covered lagoon operator reported no help in the form of government grants when paying for their system. Government grants were given to producers to pay for a percentage of the capital costs of constructing the anaerobic digesters or covered lagoons. The average of those reporting assistance through government grants is included in figure I-2 and was included in the NPV analysis.

Some of the agricultural operations included in this study also reported benefiting from carbon trading on the Chicago Climate Exchange (CCX) (tables 3 and 5). Farms and businesses in the U.S. cannot trade on the European Climate Exchange (ECX) at this time, but the ECX does present a price of carbon that can be used for economic analysis. The price at which carbon is traded on the ECX is also similar to the price that carbon could be traded in the United States in the near future due to recent actions by state governments. For example, in 2006 the State of California passed the Global Warming Solutions Act (AB 32), which instituted a cap-and-trade program to reduce greenhouse gas emissions. The California Air Resources Board (ARB) approved the Climate Action Reserve and the American Carbon Registry to serve as offset project registries for the compliance offset program under the cap-and-trade program. Supply and demand models of the carbon offset market forecast trading occurring at around \$5 to \$15/tonne (Borenstein et al. 2014).

Under Executive Order 12866, the social cost of carbon was determined to allow agencies to include the social benefits of reducing carbon dioxide (CO_2) emissions into cost-benefit analysis or regulatory actions that impact global emissions (U.S. Government 2013). While the social cost of carbon is not currently an actual price obtained on the market, it does pose an interesting question. Can we accurately "estimate the monetized damages associated with an incremental increase in carbon emissions in a given year" (U.S. Government 2013)? If so, what are the cost savings associated with offsetting those damages? The actual price obtained for carbon credits on the CCX from 2003 to 2010 were much less than the government-specified social cost of carbon (SCC)[4]. The U.S. Government (2013) used three integrated assessment models that included changes in net agricultural productivity, human

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[4] This could be due to the carbon cap being below the socially optimal level. If the cap on carbon emissions tightens, the market price of carbon could increase.

health, property damages from increased flood risk, and the value of ecosystem services due to climate change, among other parameters, to estimate an average SCC at discount rates of 2.5%, 3%, and 5%. The SCC of \$12/tonne (table I-3) is estimated at a discount rate of 5%, and the SCC of \$39/tonne is estimated at a 3% discount rate[5].

According to Ackerman and Stanton (2012), the SCC has widely acknowledged limitations and is not an observable price in any actual market. It is rather a shadow price that measures the marginal benefit of emissions reductions and is deduced from an analysis of climate dynamics and economic impacts. Under the Obama administration, the higher the SCC is set, the more stringent the regulatory standards on greenhouse gas emissions (Ackerman and Stanton 2010). To determine the potential effects of the swine methane emissions being priced at the SCC, the amount of methane captured and combusted on each farm, resulting in offset carbon emissions, was calculated.

While the survey instrument did not elicit methane production rates, enough information was generated to calculate the potential carbon offset for each swine operation. Tchobanoglous et al. (2014) explains that the volume of methane gas produced by swine manure can be estimated using the universal gas law, which is

$$V = \frac{nRT}{P} \tag{I-5}$$

where V is the volume of gas occupied by the gas in liters (L), n is the moles of gas, R is the universal gas law constant, $0.08205 \text{ atm} \cdot \text{L/g mole} \cdot \text{K}$, T is temperature in degrees Kelvin (°K = 273.15 + °C), and P is absolute pressure in atm. 1. The operations with anaerobic digesters reported that they employ some type of temperature control mechanism for their

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[5] According to the U.S. Government (2013), a discount rate of 3% is typically used because "the 3% discount rate is the central value, and so the central value that emerges is the average SCC across models at the 3% discount rate."

digester and that the digesters consistently run at a temperature ranging between 98°F and 103°F (36.7°C – 39.4°C). Therefore, the average temperature of 100.5°F, or 38°C, was used in equation 5 for all anaerobic digesters. Both operations with covered lagoons specified that their systems operate at ambient air temperature. Following Tchobanoglous et al. (2014), an absolute pressure of 1.0 atm (standard pressure) was included in the equation. Values for all variables in equation (I-5) are given in tables B.1 and B.2.

Methane (CH_4) is produced from the anaerobic oxidation of chemical oxygen demand (COD), and COD is related to the VS content of the organic material entering the digester. One mole of CH_4 is produced from 64 grams of COD, and literature on the digestibility of livestock manure typically provides a COD:VS ratio between 1 and 2 (Moody et al. 2011; Hamilton 2013; Tchobanoglous et al. 2014). Survey respondents provided the average loading rate of manure for their anaerobic digester or covered lagoon in lb VS /day. Equation (I-5) and supplemental information from literature were used to calculate ultimate, or theoretical, methane yield. Specific methane yield, which "indicates the potential of substrates to produce methane under perfect laboratory conditions," was calculated similarly, but with lower methane yield values. Methane yield from the anaerobic digesters and covered lagoons was estimated by multiplying the specific methane yield by a conversion factor ranging between 0.6 and 0.9. Conversion efficiencies of 0.9, 0.8, and 0.7 were used for the complete mix, plug flow, and covered lagoon systems, respectively. A more detailed example of methane yield calculations is provided in appendix B.

After the amount of methane, in liters CH_4/day, was determined, conversion factors were used to obtain methane yield in tons/year and tonnes/year. Methane tons (or tonnes) can then be converted into carbon dioxide tons (or tonnes) using the carbon dioxide equivalent for methane. The Intergovernmental Panel on Climate Change (1996) determined that the global warming potential of methane is 21 times that of carbon dioxide. Multiplying the resulting average amount of offset carbon dioxide equivalent for each type of digester by the price provided for trading carbon credits on the European Climate Exchange (ECX) yields estimated revenues, which are shown in figure I-1.

The value of the carbon offsets according to the Obama administration can also be calculated in a similar fashion by using the social costs per tonne of carbon provided in table I-3. While the SCC estimates the monetized damages on society associated with an incremental increase in carbon emissions, it is also the value of damages avoided by emissions reduction. In this study, the SCC prices, like the price on the ECX, are assumed to be possible prices that a farmer could receive for his or her carbon offsets.

It is also important to note that imposing the SCC on the entire economy could increase electricity rates. Several studies have described this phenomenon, which is known as price "pass-through" (Kim, Chattopadhyay, and Park 2010). Depending on how electricity prices are determined (regulated or market) and how carbon credits are distributed (e.g. auction vs. free distribution), policies that regulate carbon emissions could result in the prices of electricity increasing by 1% to 15% (Paul, Palmer, and Woerman 2013; Bird, Holt, and Carroll 2008). However, the current study does not account for the potential rise in electricity prices resulting from policies like the Global Warming Solutions Act and the SCC.

Economic Analysis: Fixed and Variable Costs

Respondents were asked to identify all components included in their covered lagoon or anaerobic digestion system. Along with the main vessel (covered lagoon or digester), some systems also included one or more of the following: solids separator/sludge thickener, electricity generator, boiler/furnace, post treatment apparatus, gas conditioning/processing unit, flare, external heater, gas storage unit, manure storage unit, an/or agitator (or stirrer). Respondents were also asked to provide a capital investment cost that included the cost of all components in the system. After converting all capital cost values to 2014 dollars, the mean size, capital costs, and variable costs were calculated for the anaerobic digesters and covered lagoons. As expected, the average cost for the anaerobic digesters was larger than the average costs for the covered lagoons. Variable costs include the average annual costs associated with the operation, labor, maintenance, and repairs of each system (see figure I-2).

As stated previously, the NPV was first calculated for the average anaerobic digester and covered lagoon on the basis of only methane production. Therefore, costs had to be adjusted. The total cost of the system was reduced for only methane production because the system would not include an electricity generator set. The estimated fixed and variable costs for electric generator sets, given the desired installed capacity, were obtained from RSMeans (2014). Installed capacities for each anaerobic digester and covered lagoon were provided by the survey respondent. The cost estimates for the electricity generator set were subtracted from the cost values provided by the survey respondents, and the resulting costs estimates used for scenarios that excluded electricity generation are in figure I-2.

It was more difficult to determine the fixed and variable costs of recovering phosphorus via struvite precipitation because, while the technical literature for struvite extraction is becoming more prevalent (Çelen 2007; Uysal, Yilmazel, and Demirer 2010), the economics of this technology have not been thoroughly researched. In addition to the already established anaerobic digester or covered lagoon system, the set-up for struvite precipitation consists of a reactor container (with a tapered bottom), stirring system, stand mechanism, filter, pipes, and fittings (Etter 2009). The technical literature was used to estimate the sizes and types of materials needed to construct the struvite precipitator, and RSMeans (2014) provided the cost estimates for materials and construction (Çelen 2007; Etter 2009; Uysal, Yilmazel, and Demirer 2010).

Previous studies have shown that increasing the pH (to approximately 9.0) of livestock wastewater can significantly increase the amount of organic phosphorus extracted, but the addition of magnesium (along with increased pH) is necessary for optimum phosphorus recovery and struvite precipitation (Çelen et al. 2007; Yilmazel and Demirer 2011). Estimated variable costs for this study were derived from literature on existing struvite extraction applications for municipal waste water reclamation, and the amounts and costs of chemicals required to maintain pH and magnesium at levels necessary for optimal extraction of phosphorus as struvite were also considered (Shu et al. 2006). The variable cost of the chemicals required for extracting struvite was \$1.65/day, or about \$600/year. The variable costs of operating and maintaining a struvite precipitator were the same as the variable costs of operating and maintaining an electric generator set and are shown in figure I-2 (RSMeans 2014).

Sensitivity analyses were used to determine how the economic feasibility of the digester is affected by including each of the co-products, government incentive programs, phosphorus extraction, and carbon trading (or carbon offset) scenarios. Costs were assumed to remain unchanged for all other co-product marketing and government policy scenarios. The only sources of change were whether or not electricity was generated and phosphorus was precipitated as struvite. After calculating average costs and revenues, equation (I-1) was used to determine the net present value (NPV) of the digester under the different scenarios. A discount rate of 4% and a project life span of 25 years were used, which are consistent with previous literature (Bishop and Shumway 2009; Tchobanoglous et al. 2014; USACE 2011). Since anaerobic digestion systems or covered lagoons could be risky investments for farms, and many farms borrow money to implement these systems, an additional sensitivity analysis was performed by calculating NPVs at a discount rate of 10%.

Results and Discussion

Figure I-1 summarizes revenue information for the anaerobic digesters and covered lagoons. For all revenue sources except methane and co-products, the anaerobic digesters are more productive. While anaerobic digesters are known to produce methane and co-products at a higher and more consistent rate, it appears that most of the methane produced by the anaerobic digesters is used to generate electricity. Figure I-2 depicts the fixed costs, variable costs, and government grants for the anaerobic digesters and covered lagoons. While government grants are technically a source of revenue, they are included with the costs because they are allocated as a percentage of the fixed cost of each system. Although provided in figure I-2, government grants were not included in the NPV analysis for the systems with struvite precipitation since that was a hypothetical scenario. The fixed costs for anaerobic digesters are about twice as large as the fixed costs for covered lagoons. Fixed costs are also significantly larger than the variable costs of each system. When government grants are applied to the anaerobic digestion systems, the costs of the systems are reduced by half and draw closer to the fixed costs of the covered lagoon systems.

It is also clear from figures 1 and 2 that the three largest potential revenue sources are electricity generation, carbon credits, and government grants. Therefore, it may be important for swine producers who are interested in anaerobic digestion to understand the likelihood or feasibility of benefiting from each of these co-product markets and/or government policies. The U.S. Department of Energy maintains a Database of State Incentives for Renewables & Efficiency (DSIRE), which lists 14 different financial incentives and regulatory policies that promote renewable energy at the state or local level. Figure I-3 summarizes the concentration of these policies in each state. A state received a point for having a state-wide policy and another point for policies on the local level. Only policies dealing with renewable electricity production, GHG emission offsets, and grants were considered. Generally, revenues for renewable electricity are dependent on state policies, and as shown in figure I-3, some states offer more financial incentives and regulatory policies than others. As for carbon credits, California recently passed the Global Warming Solutions Act. Although the act was passed in California, it is expected that carbon trading to would occur on a national level. Supply and demand models of the carbon offset market forecast trading at around $10 to $15/MT (Borenstein et al. 2014).

Due to the large capital investment required to purchase an anaerobic digester or covered lagoon system, net present values (NPVs) for the production of only methane are negative (Table I-4). Therefore, it is not likely that a hog farm would adopt an anaerobic digester or covered lagoon for manure management if it could produce only methane. These results correspond with similar studies carried out in the dairy industry (Bishop and Shumway 2009; Wang et al. 2011).

Net present values remained negative for all scenarios that did not include electricity generation. The addition of co-product markets, such as solid and/or liquid fertilizer, compost soil amendments, and carbon trading on the CCX were not enough to overcome the large capital costs of digester/lagoon installation. On average, carbon trading on the Chicago Climate Exchange (CCX) only generated $730 revenue per year for anaerobic digesters and about $218 revenue per year for covered lagoons. While some of the survey respondents reported trading carbon credits on the CCX, all trading would have occurred prior to December 2010, when all trading of carbon credits on the Climate Exchange ceased. Electricity generation was added in scenario 2, but still did not produce a positive NPV for either type of system. Most economic feasibility analyses of anaerobic digestion systems on dairy farms have included the production of methane and electricity and have also found that anaerobic digesters are not economically feasible (Bishop and Shumway 2009; Garrison et al. 2003), and the results of this study, applied to swine operations, agree with the previous literature. However, producing methane and electricity along with other co-products on a swine operation does produce a positive NPV for anaerobic digesters and covered lagoons.

Even without the assistance of government grants, the net present value for the covered lagoon that produces methane, electricity, and soil co-products is positive and larger than the same NPV for anaerobic digesters. The application of struvite precipitation with an anaerobic digestion or covered lagoon system is not a common practice on animal feeding operations. This technology is expensive and primarily used for municipal and experimental purposes. Costs of struvite precipitation were too large to make their addition to the anaerobic digestion or covered lagoon system economically feasible without other revenue sources. After the struvite is precipitated out, the remaining manure must still be shipped for disposal and/or land application, so the transportation cost savings are small when compared to some of the other revenue sources. When added to the analysis, struvite precipitation decreased, rather than increased, the NPV. Other studies have indicated that the primary benefits generated from the precipitation of struvite included reduced reliance on chemicals and maintenance and cleaning cost savings due to decreased struvite incrustations on equipment (Maaß, Grundmann, and von Bock von Polach 2014; Shu et al. 2006). While outside the scope of this analysis, these considerations could be included in future studies of anaerobic digestion with struvite precipitation on swine operations.

The addition of government grants made less difference in the NPV of the covered lagoon system because the initial costs and the percent paid by the government were smaller than the corresponding values for the anaerobic digesters. However, the addition of government grants resulted in a positive NPV for the complete mix and plug flow anaerobic digestion systems, which was larger than the NPV for the covered lagoon. Carbon trading on the ECX increased the net present values for all scenarios, and this increase was enough to make the NPV for anaerobic digestion systems positive without government assistance in the scenarios where methane and electricity were also produced. Similar results were obtained when adding the SCC, and the NPV for anaerobic digesters was larger than the NPV for covered lagoons in all scenarios that included carbon trading.

To provide a more realistic picture of what agricultural producers may require for such an uncertain investment, NPVs were also calculated with a discount rate of 10%, and these results are presented in table I-5. Government grants were necessary to obtain a positive NPV at a higher rate of return for the anaerobic digesters and covered lagoons in all scenarios except for when methane, electricity, and co-products were produced in conjunction with selling carbon credits on the SCC. In all scenarios that produced a positive NPV, the NPV was larger for the anaerobic digester than for the covered lagoon, which is due to the anaerobic digesters receiving larger government grants and producing more carbon credits. For all scenarios, precipitating struvite had a negative effect on the NPV of both systems.

Conclusions

In the absence of government grants for capital investment and carbon trading, the covered lagoon was able to achieve a larger net present value than the anaerobic digester when the cost of capital was assumed to be 6%. At this time, the ability to precipitate mineral phosphorus as struvite as a part of an anaerobic digestion or covered lagoon system is still somewhat hypothetical, and transportation cost savings are not enough to improve economic feasibility.

Having the ability to trade on the ECX and valuing carbon offsets with the government-specified “Social Cost of Carbon”, along with methane, co-product, and electricity markets, did result in positive NPVs for anaerobic digesters and covered lagoons. These scenarios are only theoretical, but it is important to understand how carbon trade policy and/or government mandates on the cost of carbon could affect the economic feasibility of renewable energy systems on swine farms. Unlike electricity generation and struvite precipitation, carbon trading requires no additional costs to the producer. With an anaerobic digester or covered lagoon, methane is already captured, and most systems include a flare. Having the ability to trade or sell carbon credits could improve the economic feasibility of anaerobic digesters and covered lagoons. While more expensive, anaerobic digesters obtained positive NPVs when only producing methane, electricity, and carbon for trading at the ECX and SCC prices. Anaerobic digesters are designed to have more control over the parameters that affect methane production (e.g. temperature, retention time, microbial activity). Because of this, anaerobic digesters extract and capture more methane at a more consistent rate and could benefit more from carbon trading than covered lagoons.

In summary, co-products, such as electricity generation and soil amendments are required to make covered lagoons a potentially viable option for handling swine manure. When co-product markets, electricity generation, and government grants are available, anaerobic digesters and covered lagoons both resulted in positive NPVs. However, a positive NPV does not necessarily guarantee economic feasibility for all agricultural operations. Cost of capital and desired rate of return on investment vary among producers and could have a significant effect on whether or not an anaerobic digester or covered lagoon project is pursued. Since carbon trading is limited in the U.S., struvite precipitation is not a wide-spread technology, and government grants for renewable energy technologies vary among states, covered lagoons could have more potential than anaerobic digesters on swine operations. As stated earlier only about 1% of farms in the U.S. operate anaerobic digesters or covered lagoons. These digesters and lagoons exist either because the producers received government grants or the producers are willing to accept relatively low returns on capital. As the results of this study show, anaerobic digesters and covered lagoons are not economically feasible at a 10% discount rate with no grants and no carbon credits. However, covered lagoons are more promising than anaerobic digesters.

While covered lagoons may produce methane and other co-products at a slower and more inconsistent rate than anaerobic digesters, the benefits of the system could be enough to cover the lower costs of construction and maintenance. Overall, in order to make anaerobic digesters or covered lagoons work, they will need lower costs, co-products such as struvite and electricity generation, and government subsidies. Otherwise, they will remain a marginal investment at best. Since larger government grants are typically applied to anaerobic digesters (rendering their fixed costs close to the costs of covered lagoons), covered lagoons seem more promising than anaerobic digesters, and capital costs of covered lagoons are still too high, one policy recommendation could be to reallocate government subsidies for renewable energy production on swine AFOs to focus on covered lagoons.

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Table I.1. Swine Survey Response Statistics

Sample Statistic	Value
Hog farms in the U.S.[a]	10,363
Survey population	29
Sample size	29
Responses	8
Completed responses	8
Response rate	27.6%

[a] Farm size ≥ 1,000 head (inventory), 2012 Census of Agriculture

Table I-2. Mean Respondent Farm and Digester Demographics

Digester Type	Years Operating Digester	Farm Size (AU)	Diversified Livestock Production	Manure Input (%)
Complete mix/plug flow	8	3,078	Yes	75
Covered lagoon	9	2,018	No	100

Table I-3. Potential Anaerobic Digester Co-products

Revenue or Cost-Saving Source	Units	Price $/unit
Wholesale electricity[a]	kWh	0.043
Retail electricity[a]	kWh	0.075
P fertilizer[b]	ton	701
N fertilizer[b]	ton	410
Base manure handling charge – hauled[c]	gallon	0.0088
Base manure handling charge – pumped[c]	gallon	0.0071
Unit mile manure hauling charge[c]	gallon-mile	0.00123
Unit mile manure pumping charge[c]	gallon	0.001025
Bulk soil amendment[d]	cu yd	25
Carbon trading on CCX[e]	ton	0.10
Carbon trading on ECX[f]	tonne	5.12
Social cost of carbon[g]	tonne	12
Social Cost of carbon[h]	tonne	39

[a] Mean prices, as reported by survey respondents
[b] USDA (2013)
[c] Fleming, Babcock, and Wang (1998) and Ribaudo et al. (2003)
[d] Price estimated from various sources
[e] Chicago Climate Exchange (2012)
[f] European Climate Exchange (2014)
[g] For regulatory analysis – under Executive Order 12866, $r = 5\%$ (2013)
[h] For regulatory analysis – under Executive Order 12866, $r = 3\%$ (2013)

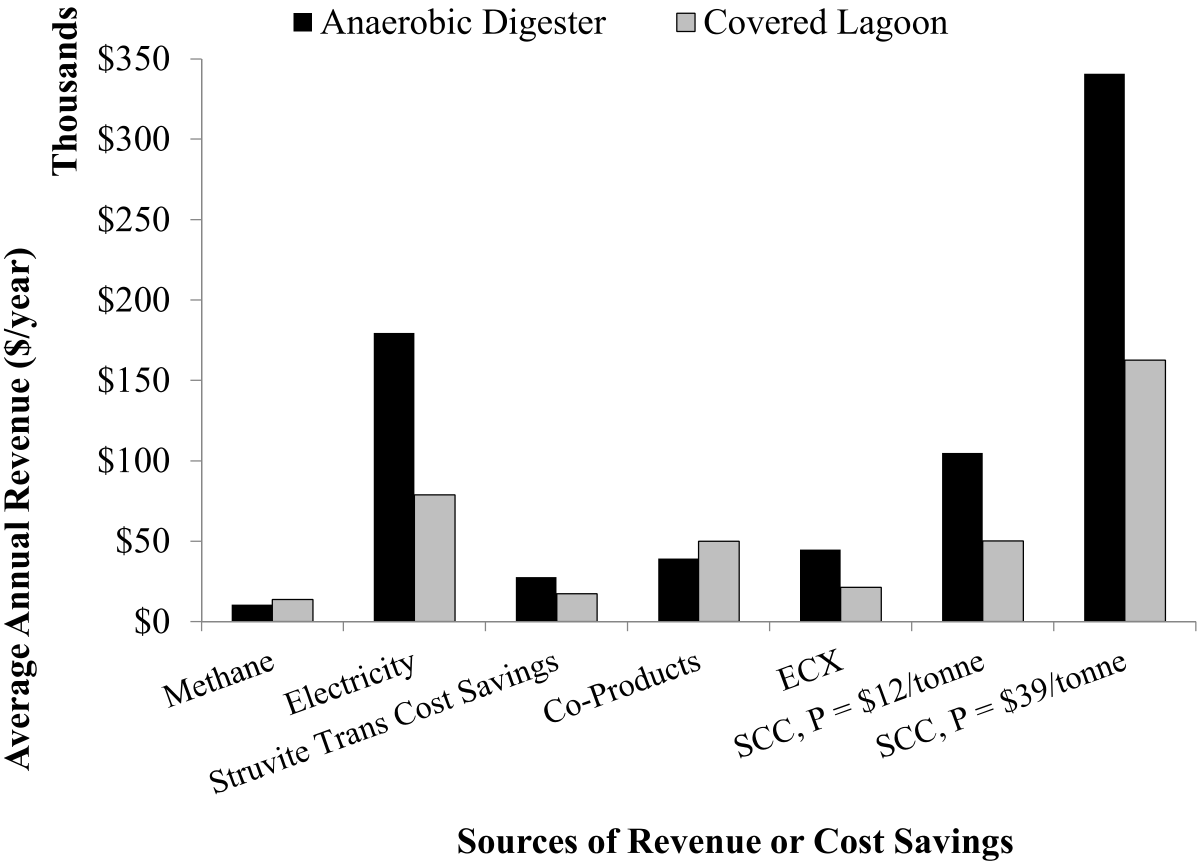

Figure I-1. Mean annual revenues

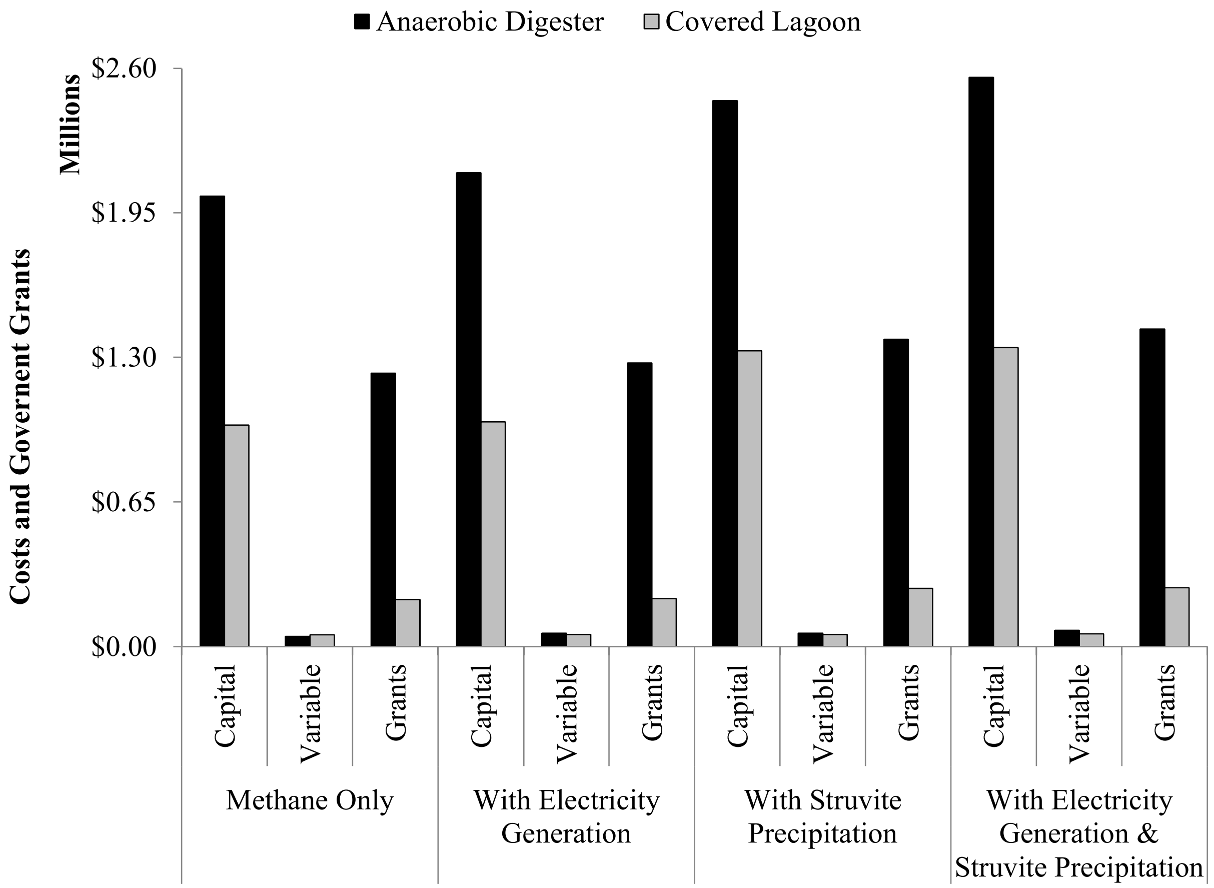

Figure I-2. Mean fixed and variable costs

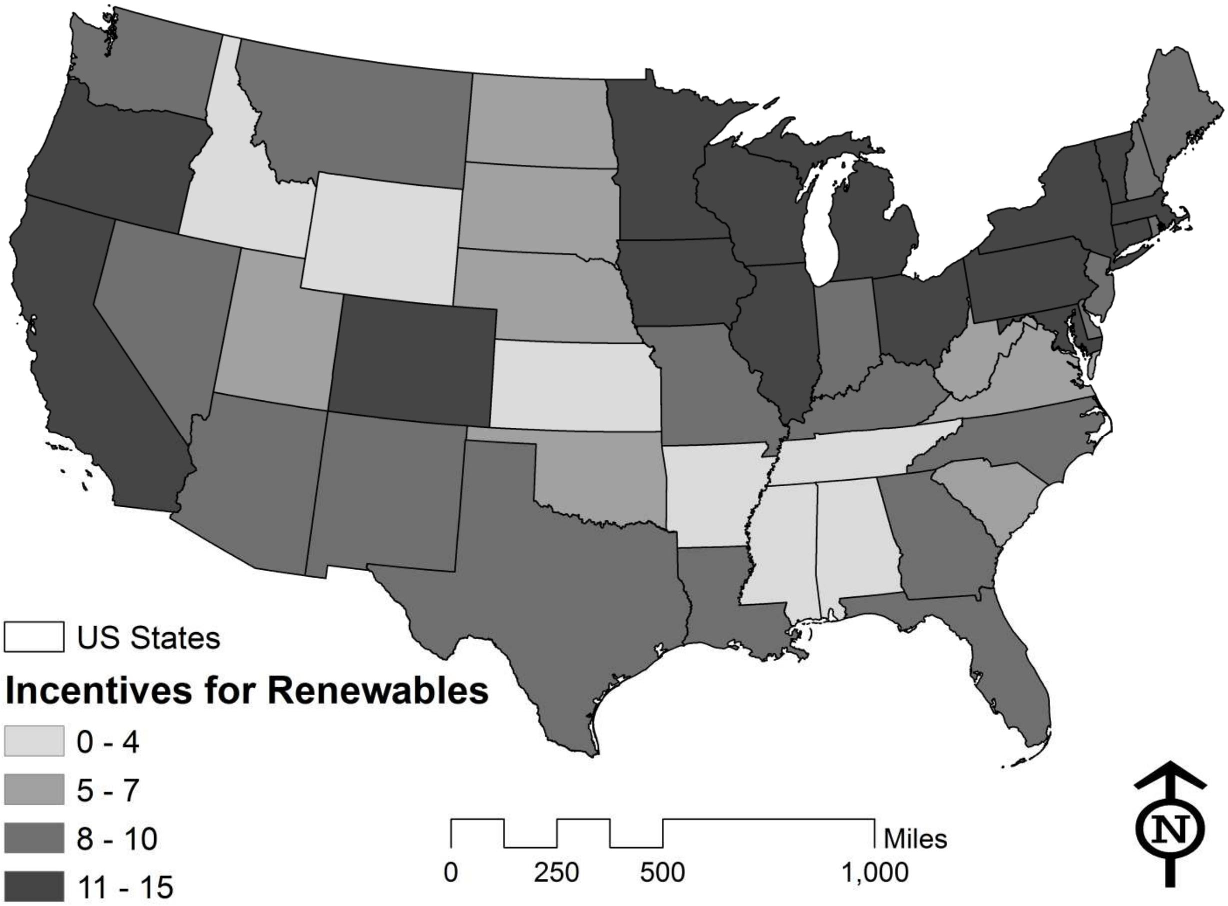

Figure I-3. Number of financial incentives and regulatory policies that promote renewable energy in each U.S. state (USDOE 2014)

Table I-4. NPVs for Anaerobic Digesters and Covered Lagoons on Swine Farms at $r = 6\%$

No.	Revenue Source Scenario	Anaerobic Digester	Covered Lagoon
1	Methane + struvite	(2,738,665)	(1,642,400)
2	Methane + struvite + ECX	(2,166,661)	(1,369,399)
3	Methane only	(2,486,631)	(1,495,183)
4	Methane + ECX	(1,914,627)	(1,222,182)
5	Methane + struvite + co-products	(2,237,979)	(1,003,233)
6	Methane + struvite + SCC12	(1,398,036)	(1,002,568)
7	Methane + struvite + co-products + ECX	(1,665,975)	(730,231)
8	Methane + co-products	(1,985,945)	(856,016)
9	Methane + SCC12	(1,146,002)	(855,351)
10	Methane + electricity + struvite	(719,597)	(676,703)
11	Methane + co-products + ECX	(1,413,941)	(583,014)
12	Methane + electricity + struvite + ECX	(147,593)	(403,702)
13	Methane + electricity	(1,083,043)	(529,474)
14	Methane + struvite + co-products + SCC12	(897,350)	(363,400)
15	Methane + electricity + ECX	(971,751)	(475,400)
16	Methane + co-products + SCC12	(645,316)	(216,183)
17	Methane + electricity + struvite + co-products	(218,912)	(37,536)
18	Methane + electricity + struvite + SCC12	621,032	(36,871)
19	Methane + electricity + struvite + co-products + ECX	353,092	235,466
20	Methane + electricity + co-products	33,455	109,694
21	Methane + electricity + SCC12	265,590	110,359
22	Methane + electricity + co-products + struvite + gov't grants	$1,294,184	$228,409
23	Methane + struvite + SCC33	$1,618,363	$437,068
24	Methane + electricity + co-products + ECX	$605,459	$382,696
25	Methane + electricity + co-products + gov't grants	$1,308,338	$325,019
26	Methane + electricity + struvite + co-products + SCC12	$1,121,717	$602,297
27	Methane + electricity + co-products + struvite + grants + ECX	$1,866,188	$501,411
28	Methane + SCC33	$1,870,397	$584,285
29	Methane + electricity + co-products + gov't grants + ECX	$1,880,342	$598,021
30	Methane + electricity + co-products + SCC12	$1,374,084	$749,527
31	Methane + electricity+ co-products + struvite + grants + SCC12	$2,634,813	$868,242
32	Methane + struvite + co-products + SCC33	$2,119,049	$1,076,236
33	Methane + electricity + co-products + gov't grants + SCC12	$2,648,967	$964,852
34	Methane + co-products + SCC33	$2,371,083	$1,223,453
35	Methane + electricity + struvite + SCC33	$3,637,431	$1,402,765
36	Methane + electricity + SCC33	$3,281,989	$1,549,995
37	Methane + electricity + struvite + co-products + SCC33	$4,138,116	$2,041,933
38	Methane + electricity + co-products + SCC33	$4,390,483	$2,189,163
39	Methane + electricity+ co-products + struvite + grants + SCC33	$5,651,212	$2,307,878
40	Methane + electricity + co-products + gov't grants + SCC33	$5,665,366	$2,404,488

Table I-5. NPVs for Anaerobic Digesters and Covered Lagoons on Swine Farms at $r = 10\%$

No.	Revenue Source Scenario	Anaerobic Digester	Covered Lagoon
1	Methane + struvite	($2,656,033)	($1,551,770)
2	Methane + struvite + ECX	($2,249,871)	($1,357,921)
3	Methane only	($2,352,540)	($1,350,218)
4	Methane + ECX	($1,946,379)	($1,156,369)
5	Methane + struvite + co-products	($2,300,512)	($1,097,918)
6	Methane + struvite + SCC12	($1,704,096)	($1,097,446)
7	Methane + struvite + co-products + ECX	($1,894,351)	($904,069)
8	Methane + co-products	($1,997,020)	($896,366)
9	Methane + SCC12	($1,400,604)	($895,894)
10	Methane + electricity + struvite	($1,253,148)	($870,355)
11	Methane + co-products + ECX	($1,590,859)	($702,517)
12	Methane + electricity + struvite + ECX	($846,986)	($676,505)
13	Methane + electricity	($1,386,590)	($668,794)
14	Methane + struvite + co-products + SCC12	($1,348,576)	($643,594)
15	Methane + electricity + ECX	($1,307,566)	($630,398)
16	Methane + co-products + SCC12	($1,045,083)	($442,042)
17	Methane + electricity + struvite + co-products	($897,627)	($416,503)
18	Methane + electricity + struvite + SCC12	($301,211)	($416,031)
19	Methane + electricity + struvite + co-products + ECX	($491,466)	($222,653)
20	Methane + electricity + co-products	($593,802)	($214,942)
21	Methane + electricity + SCC12	($553,598)	($214,470)
22	Methane + electricity + co-products + struvite + grants	$615,469	($150,558)
23	Methane + struvite + SCC33	$437,749	($75,208)
24	Methane + electricity + co-products + ECX	($187,641)	($21,093)
25	Methane + electricity + co-products + gov't grants	$267,855	$383
26	Methane + electricity + struvite + co-products + SCC12	$54,309	$37,821
27	Methane+ electricity + co-products + struvite + grants + ECX	$1,021,630	$43,292
28	Methane + SCC33	$741,242	$126,344
29	Methane + electricity + co-products + gov't grants + ECX	$1,087,242	$194,232
30	Methane + electricity + co-products + SCC12	$358,135	$239,382
31	Methane + electricity+ co-products + struvite + grants + SCC12	$1,567,405	$303,766
32	Methane + struvite + co-products + SCC33	$793,270	$378,644
33	Methane + electricity + co-products + gov't grants + SCC12	$1,633,018	$454,707
34	Methane + co-products + SCC33	$1,096,762	$580,196
35	Methane + electricity + struvite + SCC33	$1,840,634	$606,207
36	Methane + electricity + SCC33	$1,588,247	$807,768
37	Methane + electricity + struvite + co-products + SCC33	$2,196,155	$1,060,059
38	Methane + electricity + co-products + SCC33	$2,499,980	$1,261,620
39	Methane + electricity +co-products + struvite + grants + SCC33	$3,709,251	$1,326,004
40	Methane + electricity + co-products + gov't grants + SCC33	$3,774,863	$1,476,945

Appendix A: Graphical Representation of NPV Results

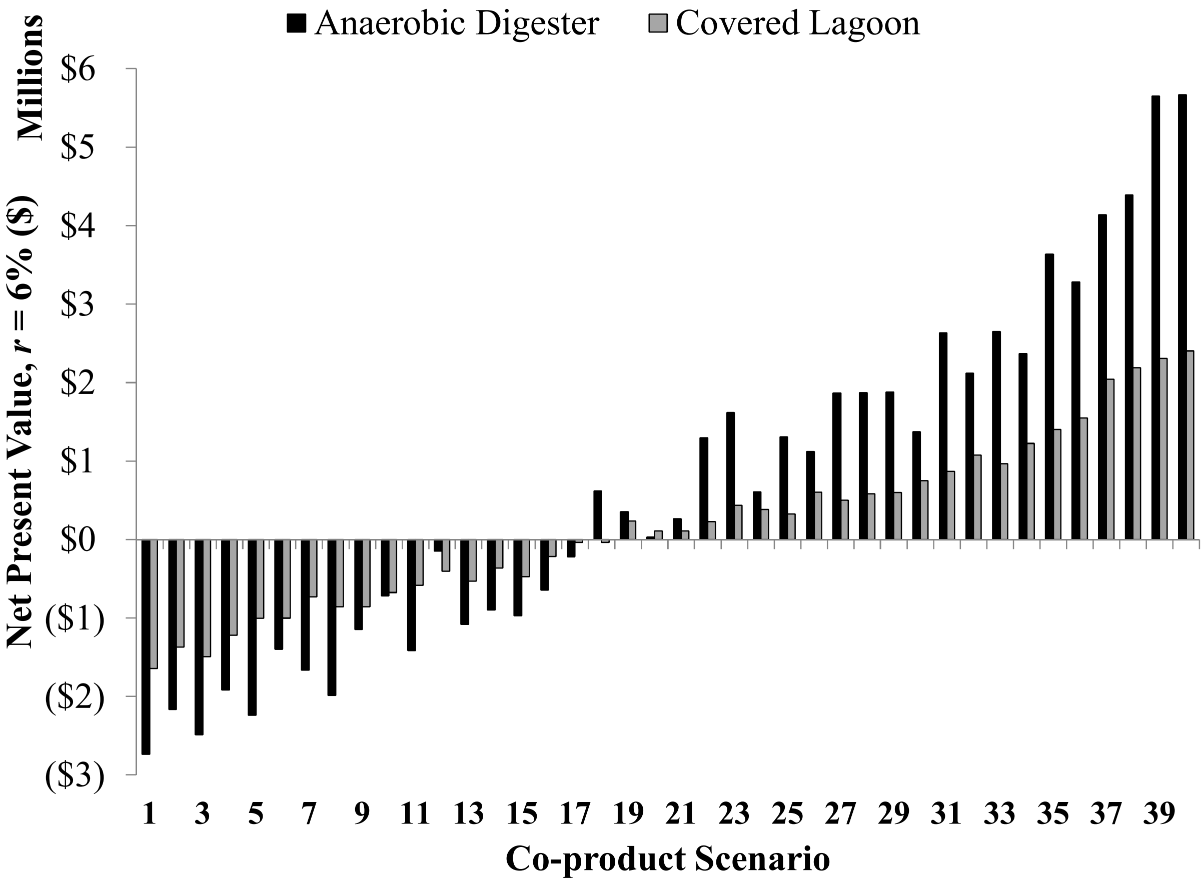

Figure A.1 Net present values at 6% discount rate. Co-product scenario numbers correspond to those specified in Table I-4.

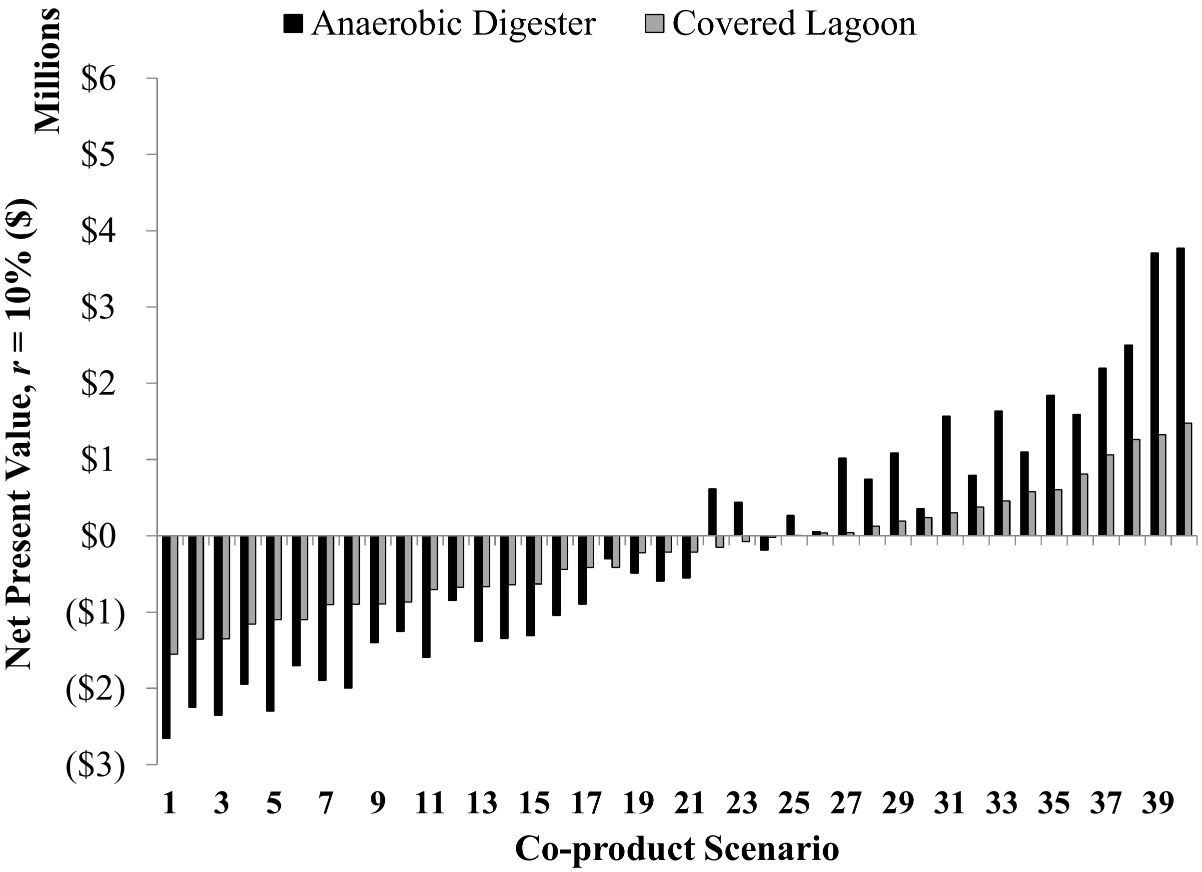

Figure A.2 Net present values at 10% discount rate. Co-product scenario numbers correspond to those specified in Table I-5.

Appendix B: Equation Variables

Table B.1. Variables for Anaerobic Digester Calculations

Variable	Description	Units	Mean	Standard Deviation
Q^a	quantity of manure hauled	gal/AU/yr	3,533	1,846
H^a	number of animals	AU	3,078	3,138
$r_A{}^{b,c}$	unit mile charge	\$/gal-mile	0.001196	--
Z^a	1 for liquid waste	--	1	0
	2 for slurry systems	--	2	0
$r_B{}^{b,c}$	base charge	\$/gal	0.0075	--
D^a	avg distance traveled	miles	1.15	0.6
n^d	moles of gas	mole	1	--
R^d	universal gas constant	$\mathrm{atm \cdot L/g\ mole \cdot K}$	0.08205	--
T^e	temperature	°K	311.15	
P^d	absolute pressure	atm	1	--

[a]Source: survey instrument

[b]Souce: Fleming, Babcock, and Wang. (1998)

[c]Source: Ribaudo et al. (2003)

[d]Source: Tchobanoglous et al. (2014)

[e]Source: USDA (2008)

Table B.2. Variables for Covered Lagoon Calculations

Variable	Description	Units	Mean	Standard Deviation
Q^{a}	qty of manure hauled	gal/AU/yr	2,908	970
H^{a}	number of animals	AU	2,018	2,034
$r_A{}^{b,c}$	unit mile charge	\$/gal-mile	0.001128	--
Z^{a}	1 for liquid waste	--	1	0
	2 for slurry systems	--	2	0
$r_B{}^{b,c}$	base charge	\$/gal	0.0068	--
D^{a}	avg distance traveled	miles	0.5	0.4
n^{d}	moles of gas	mole	1	--
R^{d}	universal gas constant	$\mathrm{atm} \cdot \mathrm{L/g\ mole} \cdot \mathrm{K}$	0.08205	--
T^{e}	temperature	°K	298.15	
P^{d}	absolute pressure	atm	1	--

[a]Source: survey instrument

[b]Souce: Fleming, Babcock, and Wang (1998)

[c]Source: Ribaudo et al. (2003)

[d]Source: Tchobanoglous et al. (2014)

[e]Source: USDA (2008)

Appendix C: Example Calculations

The objective of this section is to further describe the methodology for estimating methane yield and the amount of carbon offset by the anaerobic digestion systems. The volume of methane gas produced by swine (or dairy) manure can be estimated using the universal gas law (Tchobanoglous et al. 2014):

(I-5)
$$V = \frac{nRT}{P}$$

where V is the volume occupied by the gas in liters (L), n is the moles of gas, R is the universal gas law constant, $0.08205\ \text{atm} \cdot \text{L/g mole} \cdot$ K, T is temperature in degrees Kelvin (°K = 273.15 + °C), and P is absolute pressure in atm.

1. We first calculate the volume occupied by *one mole* of methane (CH_4). The operations included in this study all reported that they employ some type of temperature control mechanism for their anaerobic digester and that the digesters consistently run at a temperature ranging between 98°F and 103°F (36.7°C – 39.4°C). Therefore, we use the average temperature of 100.5°F, or 38°C, in equation 5. Following Tchobanoglous et al. (2014), an absolute pressure of 1.0 atm (standard pressure) was included in the equation:

$$V = \frac{(1\ \text{mole})(0.082056\,\text{atm} \cdot \text{L/g mole} \cdot \text{K})(273.15 + 38)}{1.0\ \text{atm}} = 25.35\ \text{L/mole.}$$

2. Methane is produced from the anaerobic oxidation of chemical oxygen demand (COD). One mole of CH_4 is produced from 64 grams of COD (Tchobanoglous et al. 2014). Thus, the amount of CH_4 produced per unit of COD converted under anaerobic conditions at 38°C is

$$(25.35\,\text{L/mole}\ \text{CH}_4)/(64\,\text{g COD/mole}\ \text{CH}_4) = 0.396\,\text{L}\ \text{CH}_4/\text{g COD.}$$

3. We can estimate ultimate methane yield by determining the oxygen equivalent of biomass in g COD/g VS (volatile solids), or the ratio of COD to VS. Literature on the digestibility of livestock manure typically provides a COD:VS ratio between 1 and 2. Moody et al. (2011) and Hamilton (2013) present COD:VS ratios of 1.8 for swine manure and 1.2 for dairy manure (recall that some of the farms included in this study operated a diversified operation with dairy cows/heifers and swine breeding and/or feeding stock). Methane yield per gram of VS is

$$\left(\frac{0.396\ \mathrm{L\ CH_4}}{\mathrm{g\ COD}}\right)\left(\frac{1.8\ \mathrm{g\ COD}}{1\ \mathrm{g\ VS}}\right) = 0.7128\ \mathrm{L\ CH_4/g\ VS}\ \ \text{swine manure, and}$$

$$\left(\frac{0.396\ \mathrm{L\ CH_4}}{\mathrm{g\ COD}}\right)\left(\frac{1.2\ \mathrm{g\ COD}}{1\ \mathrm{g\ VS}}\right) = 0.4752\ \mathrm{L\ CH_4/g\ VS}\ \text{dairy manure.}$$

4. Survey respondents provided the average loading rate of manure for their anaerobic digester or covered lagoon in lb VS /day. USDA 2008 also provides data for pounds VS produced per animal per day for swine feeding and breeding stock and for dairy cows and heifers, which could be used to estimate a loading rate if the data were not available. First, the loading rate is converted from lb VS/d to g VS/d. The ultimate methane yield is calculated as

$$\left(\frac{0.7128\ \mathrm{L\ CH_4}}{\text{g VS swine manure}}\right)\left(\frac{4{,}422{,}522\ \mathrm{g\ VS}}{\mathrm{d}}\right) = 3{,}152{,}373\ \ \mathrm{L\ CH_4/d}\ \ \text{and}$$

$$\left(\frac{0.4752\ \mathrm{L\ CH_4}}{\text{g VS dairy manure}}\right)\left(\frac{4{,}422{,}522\ \mathrm{g\ VS}}{\mathrm{d}}\right) = 2{,}101{,}582\ \ \mathrm{L\ CH_4/d}.$$

The ultimate methane yield is the maximum amount of methane produced per mass of oxygen demand removed (Hamilton 2013). However, we know from laboratory bench-scale and field experiments that not all the oxygen demand contained in manure is removed during digestion and converted into methane. Specific methane yield is based on laboratory biochemical methane potential (BMP) analyses. Moody et al. (2011) and Hamilton (2013) report specific methane yield values of 0.13 L CH_4/g VS for swine manure and 0.24 L CH_4/g VS for dairy manure. However, the swine manure samples represent the low extremes for swine manure because they appeared to be partially digested due to age and weathering. Specific methane yield for swine and dairy manure are similar and typically between 0.2 and 0.3 L CH_4/g VS. A specific methane yield of 0.25 L CH_4/g VS was used in this study for swine and dairy manure. Digester methane conversion is not 100% efficient. Therefore, in order to estimate the methane yield from an anaerobic digester, we need to multiply the specific methane yield by a conversion factor ranging between 0.6 and 0.9. For this study, conversion efficiencies of 0.9, 0.8, and 0.7 were used for the complete mix, plug flow, and covered lagoon systems, respectively. This example will estimate methane production in a complete mix that processes swine manure (table C.1).

Table C.1. Loading Rate and Methane Yield Estimates for Complete Mix Digester on a Swine Farm

Loading Rate lb VS/d	Loading Rate g VS/d	Ultimate Methane Yield L CH_4/d	Specific Methane Yield L CH_4/d	Digester Methane Yield L CH_4/d
9,750	4,422,522	3,152,373	788,093	709,284

5. The next step is to convert the volume of methane produced into cubic feet:

$$E(y_{11}) = \left(\frac{709{,}284 \text{ L CH}_4}{\text{d}}\right)\left(\frac{1 \text{ ft}^3}{28.3168 \text{ L}}\right) = 25{,}180 \ \text{ft}^3\text{CH}_4/\text{d}.$$

6. The density of methane is 0.66 kg/m^3, which allows us to convert methane yield to tonnes/year:

$$25{,}180 \ \frac{\text{ft}^3}{\text{d}} \times \frac{0.0283168 \text{ m}^3}{1 \text{ ft}^3} \times \frac{0.66 \text{ kg}}{1 \text{ m}^3} \times \frac{1 \text{ tonne}}{1{,}000 \text{ kg}} \times \frac{365 \text{ d}}{1 \text{ yr}} = 172 \ \text{tonnes CH}_4/\text{yr}.$$

7. Methane generated by an anaerobic digester or covered lagoon is captured and burned through a flare or in an internal combustion electricity generator. Combusting methane, generates carbon credits. Methane tonnes (or tons) can be converted into carbon dioxide tonnes (or tons) using the carbon dioxide equivalent for methane. The Intergovernmental Panel on Climate Change (1996) determined that the global warming potential of methane is 21 times that of carbon dioxide:

$$172\ \text{tonnes methane/yr} \times 21 = 3{,}607\ \text{tonnes carbon/yr.}$$

The objective of this section of appendix C is to present an alternative method for estimating methane yield from an anaerobic digester. Tchobanoglous et al. (2014) provide another equation for methane yield from an anaerobic digester, which is

(C.1) $$V_{CH_4} = (0.35)[(S_0 - S)(Q)(1kg/10^3 g) - 1.42P_x]$$

where V_{CH_4} is the volume of methane produced at standard conditions (0°C and 1 atm) in m^3/day (d), 0.35 is the theoretical conversion factor for the amount of methane produced, in m^3, from the conversion of 1 kg of biodegradable COD (bCOD) at 0°C (conversion factor at 35°C = 0.40), Q is the flowrate in m^3/day, S_0 is bCOD in the influent in g/m^3, S is bCOD in the effluent in g/m^3, 1, and P_x is the net mass of cell tissue produced per day in kg/d.

The mass of biological solids synthesized daily, P_x, can be estimated using

(C.2) $$P_x = \frac{YQ(S_0 - S)(1\ \mathrm{kg}/10^3\ \mathrm{g})}{1 + b(SRT)}$$

where Y is the yield coefficient in gVSS/g bCOD, b is an endogenous coefficient in d^{-1} (typical values range from 0.02 to 0.04 d^{-1}), SRT is the solids retention time in days, and the other terms are as previously defined. Equation C.2 was not used for this study because data on bCOD in the influent and effluent streams of each digester and covered lagoon were not obtained from survey participants. However, it is included here as an alternative method for future studies.

One variation of equation C.2 was derived by Sharvelle (2010), and could have been used for this paper or others. This equation is specified as

(C.3) $$V_{CH_4} = 5.65\eta F\left[1 - 4.2\left(\frac{Y}{1 + b\theta_c}\right)\right]$$

where V_{CH_4} is the volume of methane produced from an anaerobic digester or covered lagoon in ft^3/d, η is the conversion efficiency of the system (typically about 0.6-0.9), F is the applied biological oxygen demand (BOD) in lb/d, Y is the effective yield of the microorganisms in lb cells/lb BOD, b is the decay rate (typically about 0.03 d^{-1}), and θ_c is the mean cell residence time in days. The steps used to estimate methane yield and carbon offset credits are listed below.

1. For the complete mix digester, we set $\eta = 0.9$.
2. Table B.1 summarizes biological oxygen demand (BOD) data for excreted swine manure in pounds per animal per day for feeding and breeding stock. This information was used to calculate *F*.

Table C.2. Swine Waste BOD Characterization – As Excreted

		Sow				
		Gestating 440 lb	Lactating 423 lb	Boar 440 lb	Nursery Pig 27.5 lb	Grow to Finish 154 lb
Component	Units					
BOD	lb/d-a	0.37	0.84	0.29	0.09	0.32

All calculations are based on current inventory, as reported by survey respondents. Current inventory, as opposed to annual production, is more applicable here because we need to know how much manure is entering the digester (or covered lagoon) on a *daily* basis. For the purposes of this example and to protect the identity of study participants, we will manufacture a hypothetical hog farm that has 4,400 nursery pigs, 8,040 grow to finish pigs, 720 dairy cows, and 780 dairy heifers. The applied BOD for this farm is calculated as a weighted average:

$$
\begin{aligned}
F = {} & (0.09\ \text{lb BOD/d} - \text{a})(4{,}400\ \text{nursery pigs}) \\
& + (0.32\ \text{lb BOD/d} - \text{a})(8{,}040\ \text{grow to finish pigs}) \\
& + (2.9\ \text{lb BOD/d} - \text{a})(720\ \text{dairy cow}) \\
& + (1.2\ \text{lb BOD/d} - \text{a})(780\ \text{dairy heifers})
\end{aligned}
$$

$$F = 5{,}993\ \text{lb BOD/d}.$$

3. The effective yield was determined based on the kinetics of the system and the composition of the material entering the digester. Organic decomposition, and hence methane production, depends on the percent distribution (by weight) of carbohydrates, proteins, and fatty acids in the material entering the digester. For example, food waste is made up of 50% protein, 40% carbohydrates, and 10% fatty acids. Each of these organic materials is assigned a stoichiometric equation coefficient for conversion into methane via the anaerobic digestion process, and the weighted average is taken to determine the effective yield for each material. The effective yields for livestock manure and food waste were combined using a weighted average to determine the total effective yield for the material entering the anaerobic digester or covered lagoon. To calculate the effective yield (*Y*), we have to know additional information on the composition of swine manure. According to Tchobanoglous et al. (2014), manure is composed of 60% protein, 40% carbohydrates, and 0% fatty acid.

Table C.3. Coefficients for Stoichiometric Equations for Anaerobic Treatment of Manure

Waste component	Typical Chemical Formula	*Y* g VSS/g BOD removed	*b* d^{-1}
Proteins	$C_{16}H_{24}O_5N_4$	0.056	0.02
Carbohydrates	$C_6H_{10}O_5$	0.20	0.05
Fatty acids	$C_{16}H_{32}O_2$	0.042	0.03

Using this information, we calculate the effective microorganism yield as

$$Y = (0.6)(0.056\ \mathrm{gVSS/gBOD}) + (0.4)(0.20\ \mathrm{gVSS/gBOD})$$

$$+ (0)(0.042\ \mathrm{gVSS/gBOD})$$

$$Y = 0.1136\ \mathrm{lb\ cells/lb\ BOD}.$$

4. The decay rate is calculated in a similar fashion:

$$b = (0.6)(0.02\ \mathrm{d}^{-1}) + (0.4)(0.05\ \mathrm{d}^{-1}) + (0)(0.03\ \mathrm{d}^{-1})$$

$$b = 0.032\ \mathrm{d}^{-1}.$$

5. For complete mix and plug flow digesters, the mean cell residence time (θ_c) is equivalent to retention time (θ) because cells leave with the processed manure. Retention times for complete mix systems range from 10 to 30 days, while retention times for plug flow systems typically range between 30 and 60 days. Since complete mix and plug flow systems were combined into one data set for "anaerobic digester", a mean cell residence time of 30 days was used for all anaerobic digester methane yield calculations.
6. Methane yield for this example can then be calculated as

$$E(y_{11}) = 5.65(0.85)(5{,}993)\left[1 - 4.2\left(\frac{0.1136}{1 + (0.032\ \mathrm{d}^{-1})(30\ \mathrm{d})}\right)\right]$$

$$E(y_{11}) = 21{,}775\ \mathrm{ft}^3\mathrm{CH}_4/\mathrm{d}.$$

7. The density of methane is $0.66\ \mathrm{kg/m}^3$, which allows us to convert methane yield to tonnes/year:

$$21{,}775\ \frac{\mathrm{ft}^3}{\mathrm{d}} \times \frac{0.0283168\ \mathrm{m}^3}{1\ \mathrm{ft}^3} \times \frac{0.66\ \mathrm{kg}}{1\ \mathrm{m}^3} \times \frac{1\ \mathrm{tonne}}{1{,}000\ \mathrm{kg}} \times \frac{365\ \mathrm{d}}{1\ \mathrm{yr}} = 149\ \mathrm{tonnes\ CH}_4/\mathrm{yr}.$$

8. Methane generated by an anaerobic digester or covered lagoon is captured and burned through a flare or in an internal combustion electricity generator. Combusting

methane, instead of releasing it into the atmosphere, generates carbon credits. Methane tonnes (or tons) can be converted into carbon dioxide tonnes (or tons) using the carbon dioxide equivalent for methane. The Intergovernmental Panel on Climate Change (1996) determined that the global warming potential of methane is 21 times that of carbon dioxide:

$$149\ \text{tonnes methane/yr} \times 21 = 3{,}129\ \text{tonnes carbon/yr.}$$

Note that the amount of carbon offset each year, as calculated in Section B.1, was 3,528. The percent difference between the two calculation methods was 12%.

References

Sharvelle, S. 2010. Estimation of Methane & AD Technology Selection. Unpublished (Course Documents), Colorado State University.

This section outlines the calculations completed for determining transportation cost savings resulting from the precipitation of struvite. A more detailed version of equation (I-3) for calculating costs of transporting, spreading, and incorporating manure and the corresponding transportation cost savings resulting from the precipitation of struvite was specified as

(I-3)

$$
\begin{aligned}
\pi_{3d} = \Bigg\{ & \varphi_{struvite,k} \left(\sum_{k=1}^{K} P_k N_k - \sum_{k=1}^{K} \sum_{j=1}^{J} Q_j H_j \left[r_B + Z r_A \left(D + 2\sqrt{A_{kj}/640} \right) \right] \right) \\
& + \varphi_{manure,k} \Bigg(\sum_{k=1}^{K} P_k N_k \\
& - \sum_{k=1}^{K} \sum_{j=1}^{J} Q_j H_j \left[r_B + Z r_A \left(D + 2\sqrt{A_{kj}/640} \right) \right] \Bigg) \Bigg\}_{struvite,d} \\
& - \left\{ \sum_{k=1}^{K} P_k N_k - \sum_{k=1}^{K} \sum_{j=1}^{J} Q_j H_j \left[r_B + Z r_A \left(D + 2\sqrt{A_{kj}/640} \right) \right] \right\}_{manure,d}
\end{aligned}
$$

where π_{3d} is the value of transportation cost savings in \$/year, P_k is the price of nutrient k in \$/ton, where $k = 1$ is nitrogen and $k = 2$ is phosphorus, N_k is the quantity of nutrient k produced per year in ton/year, Q_j is the quantity of manure (or struvite) produced by breeding or feeding stock j in gallons/AU/year, where j equals 1 for nursery pigs, 2 for grow-to-finish pigs, 3 for breeding sows, 4 for dairy cows, and 5 for dairy heifers, H_j is the number of animal units (AU) contributing manure, r_A is the unit mile charge in \$/gallon-mile, r_B is the base charge in \$/gallon, Z is an indicator variable and equals 2 for slurry systems (round trip for hauling vehicle) or 1 for liquid waste (pumped, no return trip required), D is the average distance traveled to spread manure over spreadable land that accepts manure in miles, A_{kj} is the spreadable area of cropland that accepts manure in acres/year, and $\varphi_{struvite,k}$ and $\varphi_{manure,k}$ represent the portion (%) of nutrients precipitated out and remaining in the manure, respectively.

The first step was to calculate the costs associated with transporting manure. Manure nutrient transportation cost calculations present an interesting example of supply and demand. The livestock supply the manure, with embedded nutrients, and the surrounding cropland or pasture demand nutrients for the production of food and fiber crops. For this study, we assume that AFOs require land to dispose of annual manure nutrient production. However, we also recognize that the crops that accept the manure have nutrient utilization requirements. Recall from equation (I-3) that net benefits resulting from utilizing manure nutrients and transporting nutrients from the farm to the field can be specified as

(C.4)
$$\pi_{31} = \sum_{k=1}^{K}\sum_{j=1}^{J} P_k N_{kj} - \sum_{k=1}^{K}\sum_{j=1}^{J} Q_j H_j \left[r_B + Z r_A \left(D + 2\sqrt{A_{kj}/640} \right) \right]$$

where π_{31} is the net benefit in \$/year, P_k is the price of nutrient k in \$/ton, where $k = 1$ is nitrogen and $k = 2$ is phosphorus, N_{kj} is the quantity (tons) of nutrient k produced per year by breeding or feeding stock j, where j equals 1 for nursery pigs, 2 for grow-to-finish pigs, 3 for breeding sows, 4 for dairy cows, and 5 for dairy heifers, Q_j is the quantity of manure (or struvite) produced in gallons/AU/year, H_j is the number of animal units (AU) contributing manure, r_A is the unit mile charge in \$/gallon-mile, r_B is the base charge in \$/gallon, Z is an indicator variable and equals 2 for slurry systems (round trip for hauling vehicle) or 1 for liquid waste (pumped, no return trip required), D is the average distance traveled to spread manure over spreadable land that accepts manure in miles, and A_{kj} is the spreadable area of cropland that accepts manure in acres/year.

1. Farm Data

Calculating manure generated on a farm begins with the number and types of animals on the farm. Table C.4 gives the number, in animal units, and types of animals on a farm with an anaerobic digester.

Table C.4. Hypothetical Farm with Anaerobic Digester, $n = 6$

Animal Units, H_j (AU)					Manure Hauling Distance, D (miles)
Nursery Pigs	Grow to Finish Pigs	Sows	Dairy Cows	Dairy Heifers	
400	3,000	0	1,000	850	1.5

2. Manure Production and Composition

USDA (2008) provides the values listed in table B.5 for dairy and swine manure characterization. These values are used to estimate the quantity of manure produced by breeding or feeding stock j in gallons/AU/year, or Q_j, and the quantity of nutrient k produced per year in ton/year, or N_{kj}.

Table C.5. Dairy and Swine manure Characterization – As Excreted

Component	Units	Nursery Pigs	Grow to Finish Pigs	Sows[a]	Dairy Cows[b]	Dairy Heifers
Manure	lb/d/AU	88	65	42	148	54
Manure	ft^3/d/AU	1.4	1.1	0.69	2.4	0.87
Manure[c]	gal/d/AU	10.5	8.2	5.2	18.0	6.5
N	lb/d/AU	0.92	0.54	0.305	0.97	0.26
P	lb/d/AU	0.15	0.09	0.09	0.17	0.04

[a] Average of values for gestating and lactating sows
[b] Assumed lactating cows, producing 75 lb milk/d
[c] Calculated using conversion factor: 7.48052 gal/ft^3

For equation (C.4), manure production in gal/d/AU was multiplied by 365 days to get annual manure production (Q_j) in gal/yr/AU. Dairy and swine daily nutrient production was also multiplied by 365 days and the number of AU on the farm. After obtaining the amount of manure nutrients per animal group in lbs/yr, the value was converted to tons (i.e. 2000 lb/ton) to obtain annual nutrient production (N_{kj}) in tons/yr, as shown in table B.6.

Table C.6. Annual Manure and Nutrient Production

Component	Units	Nursery Pigs	Grow to Finish Pigs	Sows	Dairy Cows[a]	Dairy Heifers	Total
Manure, Q_j	gal/yr/AU	3,833	2,993	1,898	6,570	2,373	17,666
N	lb/yr/AU	335.8	197.1	111.3	354.1	94.9	1,093
P	lb/yr/AU	54.8	32.9	32.9	62.1	14.6	197
N, N_{1j}	ton/yr	67	39	0	71	19	219
P, N_{2j}	ton/yr	11	7	0	12	3	39

[a] Assumed lactating cows, producing 75 lb milk/d

3. Estimating Fertilizer Value of Manure

USDA (2013) lists average U.S. farm prices of selected N and P fertilizers (table C.7). The price of superphosphate (44-46% phosphate) as of March 2013 was \$701/ton, and the price of nitrogen solutions (30% nitrogen) was \$410/ton (USDA 2013).

Table C.7. Potential Anaerobic Digester Co-products

Revenue or Cost-Saving Source	Units	Price \$/unit
N fertilizer[a]	ton	410
P fertilizer[a]	ton	701

[a] USDA (2013)

Values in table C.7 were multiplied by values in table B.6 to obtain revenues for manure nutrients as

$$\sum_{k=1}^{K}\sum_{j=1}^{J} P_k N_{kj} = (\$410/\text{ton N})(580\text{ ton N/yr}) + (\$701/\text{ton P})(97\text{ ton P/yr})$$

$$= \$306{,}185/\text{yr}.$$

4. Land Required to Dispose of Annual Manure Production

Recall that the equation for total cropland required for manure (or struvite) application was written as

(I-4)
$$A_{kj} = \frac{Q_j H_j \overline{\rho_{kJ}}}{\mu_k}$$

where ρ_{kj} is production of nutrient k by animal j in lb/gallon manure, μ_k is the crop nutrient utilization in lb/ac of nutrient i, and all other variables are the same as above. Values for Q_j and H_j are provided in tables C.6 and C.4, respectively. Production of nutrients in lb/gallon manure is given by the quotient of daily nutrient production in lb/day/AU and daily manure production in gal/day/AU (table C.6).

Example:
$$\rho_{11} = \frac{0.92\text{ lb N/d/AU}}{10.5\text{ gal manure/d/AU}} = 0.088\text{ lb N/gal manure}$$

Table C.8. Nutrient Production, ρ_{kj}

Component	Units	Nursery Pigs	Grow to Finish Pigs	Sows	Dairy Cows[a]	Dairy Heifers
N	lb/gal manure	0.088	0.066	0.059	0.054	0.040
P	lb/gal manure	0.014	0.011	0.017	0.009	0.006

[a] Assumed lactating cows, producing 75 lb milk/d

Crop nutrient utilization depends on the type of crop planted and the expected yield of the crop. In the regions where the eight swine AFOs are located, corn is one of the primary row crops, so it was the crop of choice for manure transportation calculations. The average yield in these areas was approximately 150 bushels per acre. For a yield of 150 bu/ac, corn nutrient utilization is 185 lb N/ac and 80 lb P_2O_5/ac (MWPS 1985).

Table C.9. Crop Nutrient Utilization

Crop to be grown	Corn
Expected yield, bu/ac	150
N required, lb/ac	185

P required, lb/ac	80

We calculate the land area required for disposal of manure nutrients based on the supply of manure nutrients per livestock type and the demand, or nutrient utilization, of the crop to be grown (in this case, corn).

Example:

$$A_{11} = \frac{(3{,}833\ \mathrm{gal/yr-AU})(400\ \mathrm{AU})(0.088\ \mathrm{lb\ N/gal\ manure})}{185\ \mathrm{lb\ N/ac}} = 729\ \mathrm{ac/yr}$$

Table C.10. Land Required for Nutrient Disposal

Component	Units	Nursery Pigs	Grow to Finish Pigs	Sows	Dairy Cows[a]	Dairy Heifers	Total
N	ac/yr	729	3,196	0	1,914	436	6,272
P	ac/yr	274	1,232	0	776	155	2,436

[a] Assumed lactating cows, producing 75 lb milk/d

In order to prevent over application of manure nutrients and to maximize the use of nutrients in the manure, we select a land area of 6,272 acres/year for nutrient disposal. This will supply all of the crop's N requirements, but the producer may need additional fertilizer to meet crop P requirements.

5. Distance Traveled

If survey participants responded that their manure was land applied, they were asked how far the manure was transported for land application. This distance is represented by D in equation (I-4). Once manure arrives at the field, it continues to be transported until all manure is applied. The method for computing average distance traveled within and between fields is described (in detail) as "searchable area" by Fleming, Babcock, and Wang (1998). For this example, the average one-way distance traveled within the cropland area calculated in the previous section is

$$2\sqrt{A_{kj}/640} = 2\sqrt{(6{,}272\ \mathrm{ac/yr})/640} = 6.3\text{ miles}$$

6. Estimating Manure Transportation Costs

Table C.11 provides the remaining variables needed to compute manure transportation costs for equation (I-3). Values for these variables are provided by Fleming, Babcock, and Wang (1998) and survey participants.

Table C.11. Remaining Variables for Manure Transportation Calculations

Variable	Description	Units	Mean
r_A	unit mile charge	\$/gal/mile	0.001196
Z	1 for liquid waste	--	1
	2 for slurry systems	--	2
r_B	base charge	\$/gal	0.0075
D	distance traveled to field	miles	1.5

Manure transportation costs are calculated as

$$\sum_{k=1}^{K}\sum_{j=1}^{J} Q_j H_j \left[r_B + Zr_A\left(D + 2\sqrt{A_{kj}/640}\right)\right]$$

$$= [(3{,}833 \text{ gal manure/yr/AU})(400 \text{ AU}) + (2{,}993 \text{ gal/yr/AU})(3{,}000 \text{ AU})$$

$$+ (6{,}570 \text{ gal/yr/AU})(1{,}000 \text{ AU})$$

$$+ (2{,}373 \text{ gal/yr/AU})(850 \text{ AU})]\Big\{\$0.0075/\text{gal}$$

$$+ (2)(\$0.001196/\text{gal/mile})\left[1.5 \text{ miles} + 2\sqrt{(6{,}272 \text{ ac/yr})/640}\right]\Big\}$$

$$= \$497{,}794/\text{yr}$$

7. Estimating Annual Net Benefits

Annual net benefits, or costs, are the difference between the revenues from manure nutrients and the costs of transportation:

$$\pi_{31} = \$306{,}185/\text{yr} - \$390{,}034/\text{yr} = -\$191{,}609/\text{yr}.$$

This section provides a more detailed description for calculating the transportation costs associated with precipitated struvite. Recall from equation (I-3) that net benefits resulting from utilizing and transporting struvite from the farm to the field can be specified as

(C.5)

$$\pi_{31} = \varphi_{struvite,k}\left(\sum_{k=1}^{K} P_k N_k - \sum_{k=1}^{K}\sum_{j=1}^{J} Q_j H_j \left[r_B + Z r_A\left(D + 2\sqrt{A_{kj}/640}\right)\right]\right)$$

$$+ \varphi_{manure,k}\left(\sum_{k=1}^{K} P_k N_k - \sum_{k=1}^{K}\sum_{j=1}^{J} Q_j H_j \left[r_B + Z r_A\left(D + 2\sqrt{A_{kj}/640}\right)\right]\right)$$

where π_{31} is the value of transportation cost savings (note that this is not a *net* benefit because the precipitation of struvite incurs additional costs to the system) in \$/year, P_k is the price of nutrient k in \$/ton, where $k = 1$ is nitrogen and $k = 2$ is phosphorus, N_{kj} is the quantity (tons) of nutrient k produced per year by breeding or feeding stock j, where j equals 1 for nursery pigs, 2 for grow-to-finish pigs, 3 for breeding sows, 4 for dairy cows, and 5 for dairy heifers, Q_j is the quantity of manure (or struvite) produced in gallons/AU/year, H_j is the number of animal units (AU) contributing manure, r_A is the unit mile charge in \$/gallon-mile, r_B is the base charge in \$/gallon, Z is an indicator variable and equals 2 for slurry systems (round trip for hauling vehicle) or 1 for liquid waste (pumped, no return trip required), D is the average distance traveled to spread manure over spreadable land that accepts manure in miles, A_{kj} is the spreadable area of cropland that accepts manure in acres/year, and $\varphi_{struvite,k}$ and $\varphi_{manure,k}$ represent the portion (%) of nutrients precipitated out and remaining in the manure, respectively.

1. Farm Data

Calculating struvite generated on a farm begins with the number and types of animals on the farm. Table C.12 gives the number, in animal units, and types of animals on a farm with an anaerobic digester.

Table C.12. Hypothetical Farm with Anaerobic Digester, $n = 6$

Animal Units, H_j (AU)					Struvite Hauling Distance, D (miles)
Nursery Pigs	Grow to Finish Pigs	Sows	Dairy Cows	Dairy Heifers	
400	3,000	0	1,000	850	1.5

2. Struvite Production and Composition

USDA (2008) provides the values listed in table C.13 for dairy and swine manure characterization. These values are used to estimate the quantity of struvite produced by breeding or feeding stock j in gallons/AU/year, or Q_j, and the quantity of nutrient k produced per year in ton/year, or N_{kj}.

Table C.13. Dairy and Swine Manure Characterization – As Excreted

Component	Units	Nursery Pigs	Grow to Finish Pigs	Sows[a]	Dairy Cows[b]	Dairy Heifers
Manure	lb/d/AU	88	65	42	148	54
Manure	ft^3/d/AU	1.4	1.1	0.69	2.4	0.87
Manure[c]	gal/d/AU	10.5	8.2	5.2	18.0	6.5
N	lb/d/AU	0.92	0.54	0.305	0.97	0.26
P	lb/d/AU	0.15	0.09	0.09	0.17	0.04

[a] Average of values for gestating and lactating sows
[b] Assumed lactating cows, producing 75 lb milk/d
[c] Calculated using conversion factor: 7.48052 gal/ft^3

According to Beal, Burns, and Stalder (1999), a swine facility will produce 113 kg struvite/yr/AU. The volume of struvite (in gallons/year) was calculated using the density of struvite (15 lb/gal) and unit conversion factors.

$$Q_j = \left(\frac{113 \text{ kg struvite}}{\text{yr AU}}\right)\left(\frac{2.20462 \text{ lb}}{\text{kg}}\right)\left(\frac{1 \text{ gal struvite}}{15 \text{ lb}}\right) = 16.6 \text{ gal struvite/yr/AU}.$$

While it may be a fragile assumption, the value of 16.6 gal struvite/yr/AU was used for each animal type. Table C.14 gives daily and annual struvite production estimates.

Table C.14. Dairy and Swine Struvite Characterization

Component	Units	Nursery Pigs	Grow to Finish Pigs	Sows[a]	Dairy Cows[b]	Dairy Heifers
Struvite, Q_j	gal/d/AU	0.045	0.045	0.045	0.045	0.045
Struvite, Q_j	gal/yr/AU	16.6	16.6	16.6	16.6	16.6
N	lb/d/AU	0.138	0.081	0.046	0.15	0.039
P	lb/d/AU	0.135	0.081	0.081	0.15	0.036
N	ton/yr	11.1	6.5	3.7	11.7	3.1
P	ton/yr	10.8	6.5	6.5	12.3	2.9

[a] Average of values for gestating and lactating sows
[b] Assumed lactating cows, producing 75 lb milk/d

Research has shown that the process of struvite precipitation can extract 90-95% of the available phosphorus and about 15% of the available nitrogen in livestock manure (Burns, Moody, and Shepherd 2006; Çelen et al. 2007; Shu et al. 2006; Uysal, Yilmazel, and Demirer 2010; Yilmazel and Demirer 2011; Sommer et al. 2013). A recoverability factor of 0.9 was used to give a conservative estimate of the phosphorus recovered as struvite. These values are represented by $\varphi_{struvite,k}$. The percent nutrient precipitated from manure was multiplied by the value of manure nutrient content in table C.13 to get struvite nutrient content in lb/d/AU (table C.14). After obtaining the amount of struvite nutrients per animal group in lbs/yr, the value was converted to tons (i.e. 2000 lb/ton) to obtain annual nutrient production in tons/yr, as shown in table C.14.

3. Estimating Fertilizer Value of Struvite

USDA (2013) lists average U.S. farm prices of selected N and P fertilizers (table B.8). The price of superphosphate (44-46% phosphate) as of March 2013 was

$701/ton, and the price of nitrogen solutions (30% nitrogen) was $410/ton (USDA 2013).

Values in table C.14 were multiplied by values in table C.7 to obtain revenues for struvite nutrients as

$$\sum_{k=1}^{K}\sum_{j=1}^{J} P_k \varphi_{struvite,k} N_{kj}$$

$$= (\$410/\text{ton N})(32.8\text{ ton N/yr}) + (\$701/\text{ton P})(35.5\text{ ton P/yr})$$

$$= \$38{,}316/\text{yr}.$$

4. Land Required to Dispose of Annual Struvite Production

Recall that the equation for total cropland required for manure (or struvite) application was written as

(I-4)
$$A_{kj} = \frac{Q_j H_j \overline{\rho_{kJ}}}{\mu_k}$$

where ρ_{kj} is production of nutrient k by animal j in lb/gallon manure, μ_k is the crop nutrient utilization in lb/ac of nutrient i, and all other variables are the same as above. Values for Q_j and H_j are provided in tables C.14 and C.12, respectively. Production of nutrients in lb/gallon manure is given by the quotient of daily nutrient production in lb/day/AU and daily struvite production in gal/day/AU (table C.14).

Example:
$$\rho_{11} = \frac{0.138\text{ lb N/d/AU}}{0.045\text{ gal struvite/d/AU}} = 3.03\text{ lb N/gal struvite}$$

Table C.15. Nutrient Production, ρ_{kj}

Component	Units	Nursery Pigs	Grow to Finish Pigs	Sows	Dairy Cows[a]	Dairy Heifers
N	lb/gal struvite	3.03	1.78	1.01	3.20	0.86
P	lb/gal struvite	2.97	1.78	1.78	3.36	0.79

[a] Assumed lactating cows, producing 75 lb milk/d

Notice that when we compare values from tables C.8 and C.15, nutrients are much more concentrated (i.e. more nutrients in a gallon of struvite than in a gallon of manure.

Again, crop nutrient utilization depends on the type of crop planted and the expected yield of the crop.

Table C.16. Crop Nutrient Utilization

Crop to be grown	Corn
Expected yield, bu/ac	150
N required, lb/ac	185
P required, lb/ac	80

We calculate the land area required for disposal of struvite nutrients based on the supply of struvite nutrients per livestock type and the demand, or nutrient utilization, of the crop to be grown (in this case, corn).

Example:

$$A_{11} = \frac{(16.6\ \mathrm{gal/yr/AU})(400\ \mathrm{AU})(3.03\ \mathrm{lb\ N/gal\ struvite})}{185\ \mathrm{lb\ N/ac}} = 109\ \mathrm{ac/yr}$$

Table C.17. Land Required for Nutrient Disposal

Component	Units	Nursery Pigs	Grow to Finish Pigs	Sows	Dairy Cows	Dairy Heifers	Total
N	ac/yr	109	479	0	287	65	941
P	ac/yr	246	1,109	0	698	140	2,193

Just as for manure, we select the larger land area (2,193 acres/year) for struvite application. For this scenario, all crop P requirements are met, but N requirements will need to be supplemented with commercial fertilizer.

5. Distance traveled is calculated as described in the previous section, using equation (I-4).
6. Estimating Manure Transportation Costs

Table C.18 provides the remaining variables needed to compute manure transportation costs for equation (I-3). Values for these variables are provided by Fleming, Babcock, and Wang (1998) and survey participants.

Table C.18. Remaining Variables for Manure Transportation Calculations

Variable	Description	Units	Mean
r_A	unit mile charge	\$/gal/mile	0.001196
Z	1 for liquid waste	--	1
	2 for slurry systems	--	2
r_B	base charge	\$/gal	0.0075
D	distance traveled to field	miles	1.5

Struvite transportation costs are calculated as

$$\sum_{k=1}^{K}\sum_{j=1}^{J} Q_j H_j \left[r_B + Z r_A \left(D + 2\sqrt{A_{kj}/640} \right) \right]$$

$$= (16.6 \text{ gal struvite/yr/AU})(5{,}250 \text{ AU}) \Big\{ \$0.0075/\text{gal}$$

$$+ (2)(\$0.001196/\text{gal/mile}) \left[1.5 \text{ miles} + 2\sqrt{(2{,}193 \text{ ac/yr})/640} \right] \Big\}$$

$$= \$1{,}738/\text{yr}.$$

7. Additional Manure Production and Composition

USDA (2008) provides the values listed in table C.19 for dairy and swine manure characterization. These values are used to estimate the quantity of manure produced by breeding or feeding stock j in gallons/AU/year, or Q_j, and the quantity of nutrient k produced per year in ton/year, or N_{kj}.

Table C.19. Dairy and Swine Manure Characterization – As Excreted

Component	Units	Nursery Pigs	Grow to Finish Pigs	Sows[a]	Dairy Cows[b]	Dairy Heifers
Manure	lb/d/AU	88	65	42	148	54
Manure	ft^3/d/AU	1.4	1.1	0.69	2.4	0.87
Manure[c]	gal/d/AU	10.5	8.2	5.2	18.0	6.5
N	lb/d/AU	0.92	0.54	0.305	0.97	0.26
P	lb/d/AU	0.15	0.09	0.09	0.17	0.04

[a] Average of values for gestating and lactating sows

[b] Assumed lactating cows, producing 75 lb milk/d

[c] Calculated using conversion factor: 7.48052 gal/ft^3

Since struvite precipitation can extract 90-95% of the available phosphorus and about 15% of the available nitrogen in livestock manure, we assume that the remaining 10% phosphorus and 85% nitrogen remain in the manure. The percent nutrient remaining in the manure was multiplied by the value of manure nutrient content in table C.19 to get manure nutrient content in lb/d-AU (table C.20). After obtaining the amount of manure nutrients per animal group in lbs/yr, the value was converted to tons (i.e. 2000 lb/ton) to obtain annual nutrient production in ton/yr, as shown in table C.20.

Table C.20. Dairy and Swine Struvite Characterization

Component	Units	Nursery Pigs	Grow to Finish Pigs	Sows[a]	Dairy Cows[b]	Dairy Heifers
Manure, Q_j	gal/d/AU	10.5	8.2	5.2	18	6.5
Manure, Q_j	gal/yr/AU	3,833	2,993	1,898	6,570	2,373
N	lb/d/AU	0.782	0.459	0.259	0.825	0.221
P	lb/d/AU	0.015	0.009	0.009	0.017	0.004
N	ton/yr	62.8	36.9	20.8	66.2	17.7
P	ton/yr	1.2	0.7	0.7	1.4	0.3

[a] Average of values for gestating and lactating sows

[b] Assumed lactating cows, producing 75 lb milk/d

8. Estimating Fertilizer Value of Remaining Manure

USDA (2013) lists average U.S. farm prices of selected N and P fertilizers (table C.7). Values in table C.20 were multiplied by values in table C.7 to obtain revenues for struvite nutrients as

$$\sum_{k=1}^{K}\sum_{j=1}^{J} P_k \varphi_{struvite,k} N_{kj}$$

$$= (\$410/\text{ton N})(186\text{ ton N/yr}) + (\$701/\text{ton P})(4\text{ ton P/yr})$$

$$= \$78{,}958/\text{yr}.$$

9. Land Required to Dispose of Annual Manure Production

Recall that the equation for total cropland required for manure (or struvite) application was written as

(I-4)
$$A_{kj} = \frac{Q_j H_j \overline{\rho_{kj}}}{\mu_k}$$

where ρ_{kj} is production of nutrient k by animal j in lb/gallon manure, μ_k is the crop nutrient utilization in lb/ac of nutrient i, and all other variables are the same as above. Values for Q_j and H_j are provided in tables C.20 and C.12, respectively. Production of nutrients in lb/gallon manure is given by the quotient of daily nutrient production in lb/day-AU and daily struvite production in gal/day-AU (table C.20).

Example:
$$\rho_{11} = \frac{0.782\text{ lb N/d} - \text{AU}}{10.5\text{ gal manure/d} - \text{AU}} = 0.074\text{ lb N/gal manure}$$

Table C.21. Nutrient Production, $\boldsymbol{\rho_{kj}}$

Component	Units	Nursery Pigs	Grow to Finish Pigs	Sows	Dairy Cows[a]	Dairy Heifers
N	lb/gal manure	0.074	0.056	0.050	0.046	0.034
P	lb/gal manure	0.001	0.001	0.002	0.001	0.001

[a] Assumed lactating cows, producing 75 lb milk/d

Again, crop nutrient utilization depends on the type of crop planted and the expected yield of the crop.

Table C.22 Crop nutrient utilization

Crop to be grown	Corn
Expected yield, bu/ac	150
N required, lb/ac	185
P required, lb/ac	80

We calculate the land area required for disposal of manure nutrients based on the supply of manure nutrients per livestock type and the demand, or nutrient utilization, of the crop to be grown (in this case, corn).

Example:

$$A_{11} = \frac{[(3{,}833 - 16.6)\ \mathrm{gal/yr - AU}](400\ \mathrm{AU})(0.074\ \mathrm{lb\ N/gal\ struvite})}{185\ \mathrm{lb\ N/ac}}$$

$$= 614\ \mathrm{ac/yr}$$

Table C.23 Land Required for Nutrient Disposal

Component	Units	Nursery Pigs	Grow to Finish Pigs	Sows	Dairy Cows[a]	Dairy Heifers	Total
N	ac/yr	614	2,702	0	1,623	692	5,331
P	ac/yr	27	123	0	77	15	243

[a] Assumed lactating cows, producing 75 lb milk/d

In order to prevent the over-application of N, a land area of 5,331 acres is selected for the spreading of the remaining manure.

10. Distance traveled is calculated with equation (I-4) and a land area of 5,331 acres.
11. Estimating Manure Transportation Costs

Table C.24 provides the remaining variables needed to compute manure transportation costs for equation (I-3). Values for these variables are provided by Fleming, Babcock, and Wang (1998) and survey participants.

Table C.24 Remaining Variables for Manure Transportation Calculations

Variable	Description	Units	Mean
r_A	unit mile charge	\$/gal/mile	0.001196
Z	1 for liquid waste	--	1
	2 for slurry systems	--	2
r_B	base charge	\$/gal	0.0075
D	distance traveled to field	miles	1.5

Manure transportation costs are calculated as

$$\sum_{k=1}^{K}\sum_{j=1}^{J} Q_j H_j \left[r_B + Z r_A \left(D + 2\sqrt{A_{kj}/640} \right) \right]$$

$$= [(3{,}833\ \text{gal manure/yr/AU})(400\ \text{AU}) + (2{,}993\ \text{gal/yr/AU})(3{,}000\ \text{AU})$$
$$+ (6{,}553\ \text{gal/yr/AU})(1{,}000\ \text{AU})$$
$$+ (2{,}356\ \text{gal/yr/AU})(850\ \text{AU})] \Big\{ \$0.0075/\text{gal}$$
$$+ (2)(\$0.001196/\text{gal/mile}) \left[1.5\ \text{miles} + 2\sqrt{(5{,}331\ \text{ac/yr})/640} \right] \Big\}$$
$$= \$266{,}916/\text{yr}.$$

12. Estimating Annual Benefits/Costs

Annual benefits (or costs) are the difference between the revenues from manure nutrients and the costs of transportation:

$$\pi_{31} = (\$97{,}165/\text{yr} - \$1{,}738/\text{yr})_{struvite} + (\$209{,}020/\text{yr} - \$475{,}471/\text{yr})_{manure}$$
$$= -\$171{,}024/\text{yr}.$$

13. Transportation cost savings

The annual transportation cost savings associated with producing struvite are calculated as

$$\pi_{3d} = -\$171{,}024/\text{yr} - (-\$191{,}609/\text{yr}) = \$20{,}585/\text{yr}.$$

Appendix D: Additional Results

At the very end of the survey, producers were asked, “In your opinion, what is the one most important thing that would have to be done to encourage more wide-spread adoption of anaerobic digestion systems?” Some of the responses were as follows:

- “Costs! Not many want to wait more than 7-10 years to pay it off.”
- “Make it cost effective to build and operate. Must see profit in 3 years, minimum.”
- “The adoption of an anaerobic digester would have to generate extra income or save on current costs that would pay for itself in 3-5 years.”
- “The digesters need to cash flow. If they pay for themselves within 20 years, most progressive farmers would have one.”
- “At least 80% of the total cost provided by others.”
- “Government to pay for 80% of the cost of putting it in.”
- “Capital costs are too high. The return on investment is insufficient unless 75%-80% of capital costs are covered by grant or other.”
- “Grant combination must cover 75% of cost.”

Not all of these responses came from swine producers who currently operate anaerobic digesters or covered lagoons. Some also came from dairy producers who operate anaerobic digesters or covered lagoons and dairy and swine producers who do not have an anaerobic digestion systems or covered lagoon on their farm. However, the responses from these producers did generate some additional research questions that are briefly examined and answered in this section of the appendix.

Net present value (NPV), which was used in this study, is more common in capital budgeting analyses because it provides concrete decision criteria. The payback period and discounted payback period methods are not typically recommended for evaluating capital investments because cash flows beyond what is necessary for recovering the initial investment are ignored. Payback period methods also do not indicate the particular payback period that maximizes wealth (Fabozzi and Peterson Drake 2009). With these methods, a shorter payback period is better than a longer payback period, but there is no rule as to which length of time is best. While there are some limitations to payback period methods, it does appear that producers are interested in the payback period of anaerobic digesters and covered lagoons. Therefore, the payback period and discounted payback period were calculated for the average anaerobic digester and average covered lagoon on the farms included in this study.

As shown in Table D.1, the payback period and discounted payback period were both shorter for the covered lagoon. These payback periods were calculated for systems that produce only methane, electricity, and other co-products. Of the producers (listed above) that mentioned payback periods, only one indicated a payback period longer than 10 years. The discounted payback periods, which consider time value of money, exceeded 20 years when using a 6% discount rate. When assuming a 10% rate, a realistic payback period did not exist.

While some respondents indicated that they thought anaerobic digesters and covered lagoons should be able to pay for themselves without government assistance, it appears that if shorter payback periods are desired, government grants are essential. Those that were in favor of government assistance suggested that a majority of the systems costs should be covered by government grants or other outside funding sources. In addition to calculating the payback period for the baseline system that produces only methane, electricity, and other co-products, producers and policy makers could benefit from understanding the levels of government assistance that cause an anaerobic digester or covered lagoon to break even within a specified payback period.

The payback period method is a type of "break-even analysis", and in finance, the break-even point is defined as "the number of units produced and sold such that the product of the units sold and unit price just covers both the variable and fixed expenses" (Fabozzi and Peterson Drake 2009, pg 379). For this application, we want to determine the percentage government grant, applied to an anaerobic digester that produces methane, electricity, and other co-products, required for the digester to break even. The lifetime of the project was set to 5, 10, 15, 20, or 25 years, which were the five different "payback periods". In the net present value framework, the government grant is added as revenue in year zero. Since the government grant is a percentage of the capital cost (also applied in year zero), the percentage grant for this case was allowed to change. For each payback period, the Solver tool in Microsoft Excel was used to solve for the percentage grant that resulted in a net present value of zero. Costs of capital were assumed to be the same as those used in the NPV analysis, and the results of this analysis are included in figure D.1.

An anaerobic digester with a 10% cost of capital would need government grants to cover 70% of the capital cost in order to break even in 5 years. A covered lagoon under the same conditions would require government grants to cover 67% of the capital investment. On average, the anaerobic digesters included in this study received government grants to cover 49% of their capitals costs. According to the results in figure D.1, this would be more than enough for the anaerobic digesters to break even in 10 years, assuming a 6% cost of capital.

If the cost of capital increases to 10%, the payback period would be closer to 15 years. For the covered lagoons, government grants covered 13% of the capital costs, but this is not enough for the covered lagoon to breakeven in less than 15 years. The covered lagoon would need grants to cover 36% of the capital costs at the 6% rate and 47% of the capital costs at the 10% rate in order to pay for itself in 10 years. If an anaerobic digester or covered lagoon was to break even in 3 years, as mentioned by a couple of the respondents, government grants would need to cover between 77 and 80% of the capital costs, depending on the system type and discount rate. Overall, covered lagoons are less expensive and need fewer government grants in order to break even. However, since anaerobic digesters are more productive, the difference in the amount of government grants required for each type of system within each payback period does not appear to be significant.

The selling of carbon credits is another benefit of anaerobic digestion that could require some government intervention. A NPV framework was used to determine the breakeven price of carbon. For this scenario, no revenues from government grants were included in year zero. Instead, beginning in year one, the anaerobic digester and covered lagoon could generate revenues from selling carbon credits. Revenues from carbon trading were added to revenues from the production of methane, electricity, and other co-products. The quantity of carbon produced was held constant while the price of carbon was allowed to change. For each payback period, Excel Solver was used to determine the price of carbon that resulted in a NPV of zero. Results from this analysis are included in figure D.2.

Although covered lagoons require lower upfront costs, the breakeven price for carbon is higher for them than for anaerobic digesters when the payback period is set to 5 years. This is primarily due to the fact that anaerobic digesters more efficiently and effectively capture methane and can produce a greater number of carbon credits. However, because of the difference in capital costs, the breakeven price of carbon decreases more rapidly over time for covered lagoons than for anaerobic digester. For a payback period of 20 years, the breakeven price of carbon required for the covered lagoons is slightly less than the price required for anaerobic digesters. For comparison, the price of carbon on the European Climate Exchange (ECX) is $5.12/tonne and the social cost of carbon (SCC) is $12/tonne when calculated at a 5% discount rate and $39/tonne with a 3% discount rate. At $5.12/tonne, the anaerobic digester and covered lagoon could achieve a payback period of 20 years when assuming a 6% cost of capital. With 10% cost of capital, neither system could be paid for in less than 25 years. If carbon credits were priced at the SCC of $12/tonne, both systems could have payback periods between 15 and 25 years, depending on the cost of capital. At the SCC of $39/tonne, both systems would have payback periods in 10 years or less.

Another scenario could arise where a producer receives government grants to pay for an anaerobic digester or covered lagoon and also trades carbon credits once the digester or covered lagoon is operational. For this scenario, the average revenues provided by government grants (as reported by survey participants) were added in year zero. Then revenues from carbon credits were again added in year one, and Excel Solver was used to determine the price of carbon that resulted in a NPV of zero within each payback period. These results are shown in figure D.3.

When the capital costs for anaerobic digesters were subsidized with government grants, the price of carbon on the ECX would be enough to achieve a payback period of 5 years under a cost of capital of 6%. With a 10% discount rate, an SCC of $12/tonne would result in a payback period of 5 years for anaerobic digesters. Under these same conditions, the covered lagoons would need 10 to 15 years for payback to occur.

From the NPV analysis, this study confirmed for the swine industry what other studies had found in the dairy industry: anaerobic digesters are not economically feasible without government subsidies. If we use a project lifetime of 25 years, covered lagoons could be more economically feasible than anaerobic digesters due to their lower capital costs. When including government assistance, it is more difficult to conclude which type of system is better for swine operations. Since government grants are based on a percentage of the capital costs, covered lagoons would require less funding. However, anaerobic digesters are more effective at capturing methane, so producers could benefit more from trading carbon credits if they implement an anaerobic digester. While it is difficult to draw conclusions using payback period methodology, this section was primarily intended to provide additional information for producers. While this section established grant levels and carbon prices required for anaerobic digesters and covered lagoons to break even, the next chapter of this dissertation uses contingent valuation methodology to determine how these policies affect producers willingness-to-accept (or adopt) digesters.

References

Fabozzi, F.J. and P. Peterson Drake. 2009. *Finance: Capital Markets, Financial Management, and Investment Management*. Hoboken, N.J.: Wiley.

Table D.1 Payback Periods for Systems that Produce Methane, Electricity, and Other Co-Products

Type of System	Payback Period years	Discounted Payback Period r = 6%, years
Anaerobic digester	13	25
Covered lagoon	12	21

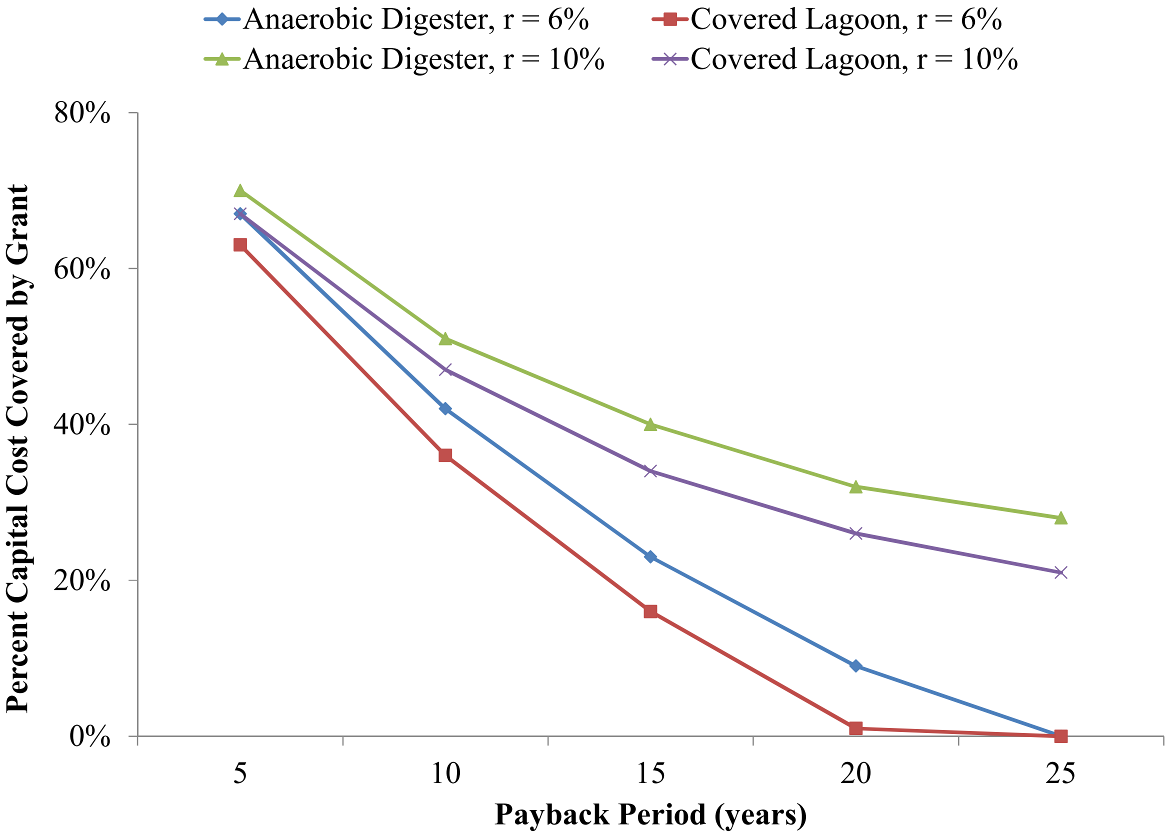

Figure D.1 The government grant (as a percentage of capital investment cost) required for an anaerobic digester or covered lagoon (producing methane, electricity, and co-products) to break even within a specified discounted payback period

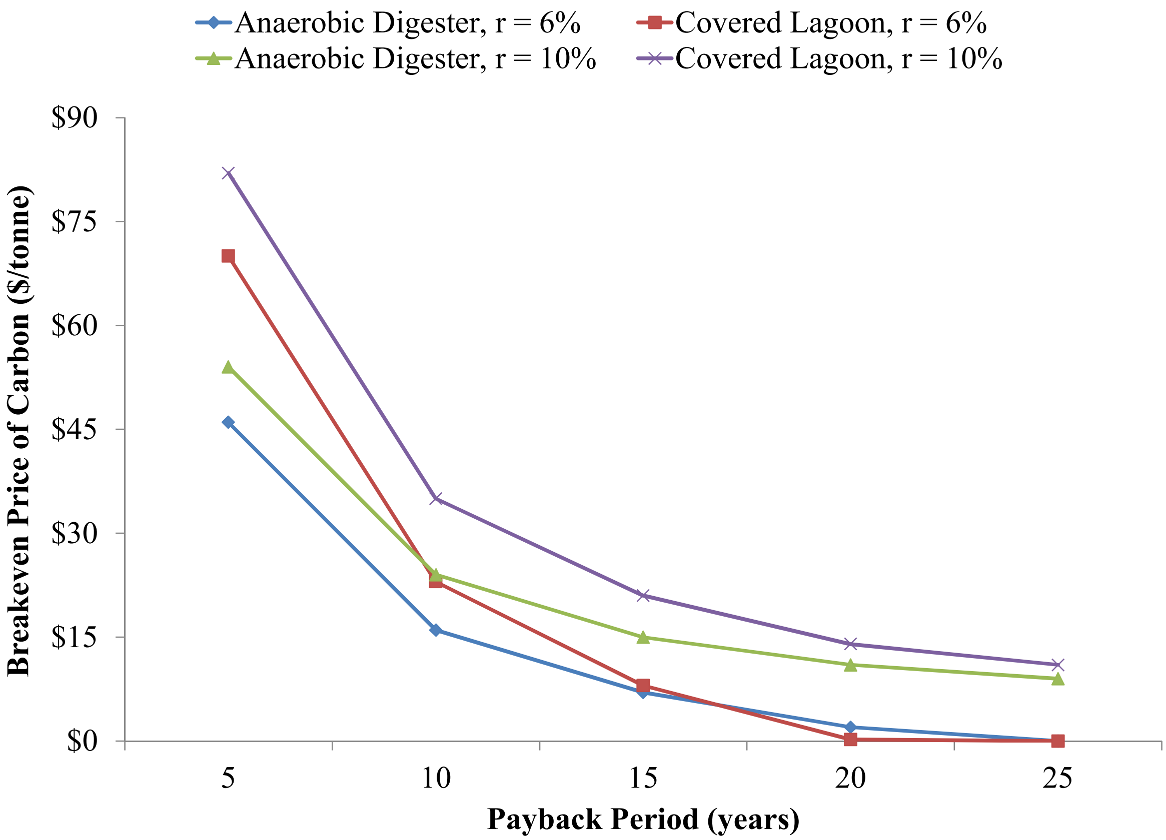

Figure D.2 The price of carbon required for an anaerobic digester or covered lagoon (producing methane, electricity, and co-products) to break even within a specified discounted payback period

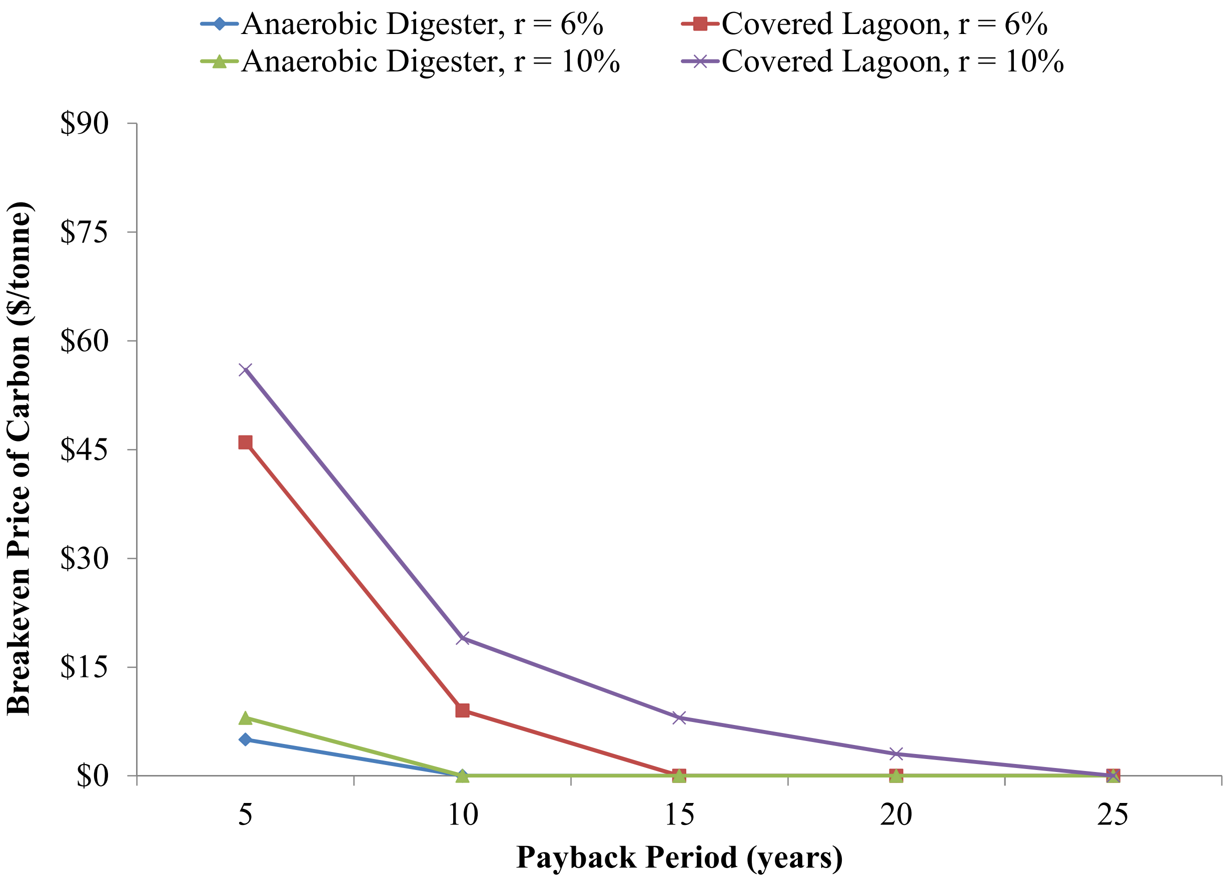

Figure D.3 The price of carbon required for an anaerobic digester or covered lagoon (producing methane, electricity, and co-products and subsidized by government grants) to break even within a specified discounted payback period

CHAPTER II

THE EFFECTS OF POLICIES AND FARMER CHARACTERISTICS ON THE ADOPTION OF ANAEROBIC DIGESTERS IN THE UNITED STATES

Abstract

Anaerobic digesters promote environmental stewardship via greenhouse gas emission abatement, waste water mitigation, and odor reduction. At the same time, high capital costs relative to potential revenue sources typically limit the economic feasibility of digesters on animal feeding operations. Using a nation-wide survey of dairy and swine producers, this study seeks to determine how government policies, peer group influences, environmental beliefs, and farm characteristics affect the decision to adopt an anaerobic digester. Results suggest that neighborhood effects, farm type and size, and nonmarket benefits of anaerobic digestion are important for predicting whether or not a producer will consider an this technology for manure management. However, the decision to actually adopt is more dependent on government policies and economic considerations.

Introduction

As animal production facilities have become larger and more intensive, the potential for environmental and social externalities increases (Centner 2003). Anaerobic digestion could be a solution to environmental and resource concerns identified for confined animal agriculture. An anaerobic digester processes manure under anaerobic conditions (without oxygen). Under these conditions, decomposition of organic waste by bacteria results primarily in carbon dioxide and methane, which can be burned to generate electricity (Tchobanoglous et al. 2014).

Although digesters can reduce greenhouse gas (GHG) emissions, produce renewable electricity, and generate other value-added products like pathogen-free animal bedding, large capital costs have typically made these systems economically infeasible (Bishop and Shumway 2009; Kruger et al. 2008; Lazarus and Rudstrom 2007; Stokes et al. 2008; Wang et al. 2010; DeVuyst et al. 2011). However, along with the approximately 238 digesters currently operating in the United States, 31 digesters were under construction on commercial livestock farms in 2013, and 17 new projects are under way in 2014 (USEPA 2014b). Since previous studies have found that digesters are not economically feasible for *most* animal feeding operations, why do some operations continue to adopt this technology?

Case studies of operational digesters show renewable energy policies and government grants contribute to the economic feasibility of anaerobic digestion systems (Bishop and Shumway 2009; DeVuyst et al. 2011; Gloy and Dressler 2010; Lazarus and Rudstrom 2007; Stokes, Rajagopalan, and Stefanou 2008; Wang et al. 2010). These policies are often adopted by states to support greater investment in and adoption of renewable energy technologies (USEPA 2014c). If the motivation for these policies is to support greater adoption, then a better understanding of anaerobic digester adoption motivation and behavior is important.

Along with government policies, one hypothesis for why anaerobic digesters are adopted is that the decision to adopt is not purely financial. As Rogers (2003) describes, when explaining the diffusion of innovations, differences in adoption are described by differences in the agents' "character", or beliefs, rather than by differences in their circumstances. Thus, adoption of an anaerobic digester could be driven by aspects of a producer's worldview, such as environmental beliefs (e.g. Bishop, Shumway, and Wandschneider 2010). Other behavioral drivers, such as peer-group influence, could also affect anaerobic digester adoption rates (Baerenklau 2005).

The objective of this study is to determine how government policies, co-product prices, peer group influence, farm characteristics, and farmer demographics and beliefs affect producers' decisions to adopt anaerobic digestion technology on animal feeding operations (AFOs). The objective was accomplished using a unique dataset, which resulted from a nation-wide survey of dairy and hog producers. Producers were asked a series of questions about their farms, their opinions of and experiences with different policies, and their willingness to accept an anaerobic digester based on policy scenarios that were developed following contingent valuation methodology. Following data collection, probit models and a bivariate probit model with sample selection were used to predict farmer adoption of anaerobic digestion as a function of electricity price, carbon credit price, or percent capital cost (of digester) covered by a government grant.

One of the primary contributions of this paper is that it is more comprehensive than most economic studies of anaerobic digestion. Most previous research has analyzed the economic feasibility of one or several anaerobic digesters using economic budgeting or real option analysis. Few studies exist that contribute to the understanding of anaerobic digestion (or other manure management) technology adoption, and those that are available only cover one state or region and focus on the dairy industry (e.g. Bishop, Shumway, and Wandschneider 2010; Poe et al. 2001; Sanders et al. 2010).

This study expands on previous research by surveying all USDA NASS dairy *and swine* estimation states (see figure II-1 for reference). Previous research has reported on the technical feasibility of anaerobic digesters on hog farms, but little is known about the economic considerations involved with adopting this technology or about the opinions of swine producers concerning anaerobic digestion (e.g. Massé, Rajagopal, and Singh 2014; Ndegwa et al. 2008). The farms surveyed included producers who currently operate anaerobic digesters, producers who previously operated anaerobic digesters (those with decommissioned digesters), third-party operators of anaerobic digesters[6], and producers who have never owned or operated an anaerobic digester. Empirical models were constructed based on demand, technology adoption, and behavioral economic theories and were designed to determine how specific policies and co-product prices affect the likelihood of anaerobic digester adoption. Instead of determining whether or not a producer will adopt, these models provide the actual price (or percent government grant) that will result in adoption of an anaerobic digester.

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[6] Third-party operators include anaerobic digester management firms, community or regional anaerobic digester (i.e. a digester that services more than one farm) operators, and university digester or waste management specialists that supervise an anaerobic digester at a cooperative farm.

Theory

From random utility theory, a farmer is assumed to maximize expected utility of profit. From a theoretical utility standpoint, a farmer is willing to accept \$$P$ to switch to a new production practice (e.g. implementing anaerobic digestion for manure management) if the farmer's utility with the new practice and incentive payment is at least as great as it was before the offer was made. Let $U_A(\pi)$ represent the expected utility of profit from adopting an anaerobic digester and $U_B(\pi)$ represent the expected utility from not adopting. If we define $U^*(\pi) = U_A(\pi) - U_B(\pi)$, the observed choice equals 1 if $U^*(\pi) > 0$ and 0 if $U^*(\pi) \leq 0$. Therefore, the choice selection reveals which one provides the greater utility but does not disclose the unobservable utilities. A common specification of the random utility model is

$$U^*(\pi) = \boldsymbol{x}'\boldsymbol{\beta} + \varepsilon \tag{II-1}$$

where $\boldsymbol{x}$ is the observable vector of exogenous explanatory variables, and $\varepsilon \sim N(\mu_\varepsilon, \sigma_\varepsilon)$ is a random error term that represents the stochastic elements that are specific to and known only by the individual, but not by the observer (Greene 2012). If the producer's choice of adopting a digester (alternative *A*) is denoted by $Y = 1$, then we infer that $U^*(\pi) > 0$ and can complete the model since the observed outcome is determined by variables in the utility functions.

Results from previous studies on the economics of anaerobic digesters indicate that random utility theory based on profit maximization alone may not be enough to explain anaerobic digester adoption decisions. For example, we would expect that $U^*(\pi) \leq 0$ if the producer's decision is only based on utility of profit. Instead, we know that at least 48 anaerobic digesters were adopted on commercial livestock farms over the last two years (USEPA 2014b). According to Nowak (1987) and Bishop, Shumway, and Wandschneider (2010) economic models do not always explain non-adoption of profitable technologies or adoption of unprofitable technologies. Chouinard et al. (2008, pg. 79) found support for the hypothesis that some producers make decisions partly based on “unobservable characteristics of the land stewardship process” and are willing to pay (or forgo profit) for conservation.

Other than the potential revenues that they generate, producers may be interested in adopting anaerobic digesters because of the environmental and social benefits that they create. Within the anaerobic digestion process, microorganisms consume chemical and biological oxygen demand. This process not only optimizes methane production, but also reduces the potential for water quality impairments. Microbial processes also produce heat that reduces the number of pathogens in the waste stream. This improves the quality of the waste leaving the digester, and allows the separated solids to be used as value-added co-products, such as animal bedding for dairy cows. Some anaerobic digesters are also equipped to remove and concentrate nutrients. This prevents the nutrients from entering water bodies, and provides the producers with a more concentrated fertilizer.

According to the USEPA (2014a) the agriculture sector is responsible for 8.1% of all greenhouse gas emissions, and enteric fermentation and manure management account for 25% and 9.4% of agricultural methane emissions, respectively. Anaerobic digestion of livestock manure reduces greenhouse gas emissions by collecting and combusting methane. Methane is 21 times more potent as a greenhouse gas than carbon dioxide (IPCC 1996). Combusting methane can generate heat and electricity for an agricultural operation, while emitting only carbon dioxide and water vapor. Anaerobic digesters also reduce odor by removing and stabilizing organic matter and capturing and burning biogas methane. Some of these environmental effects could enter the profit function as private costs or revenues (e.g. carbon trading), while others do not (e.g. reduced odor).

Bishop, Shumway, and Wandschneider (2010, pg 588) provide an example where an agent's utility is expanded to include "direct well-being effects from nonmarket goods and services" resulting from the environmental consequences of anaerobic digestion. A version of this utility function can be written as

$$U^* = U^*(\pi, e) = \boldsymbol{x}'\boldsymbol{\beta} + \varepsilon \tag{II-2}$$

where e is an environmental effect. Including an environmental effect in (II-2) assumes that producers' indifference curves could reflect a "profit-environment trade-off" and that their decisions could be based on differences in beliefs or motives rather than just differences in profit (Bishop, Shumway, and Wandschneider 2010, pg 588).

While environmental beliefs could give one explanation for why anaerobic digesters are adopted, the literature on technology adoption provides additional explanation. Baerenklau (2005) found that subjective beliefs, such as those attributed to peer-group influence, or neighborhood effects, are important in the adoption decision and in models that are used to estimate the impacts of adoption incentives. Anaerobic digestion technology is not reversible or transportable, so producers interested in this technology are dependent on learning from others who have already adopted it. Baerenklau (2005) describes this tendency to become more willing to adopt a technology after learning more about it from peers as a neighborhood effect. Figure II-2 shows how the neighborhood effect could be relevant for anaerobic digester adoption, at least at the state level. The adoption of anaerobic digesters is more prevalent in some states than in others. However, this could not only be due to the neighborhood effect but also to the fact that some states develop and implement more renewable energy financial incentives and regulatory policies than others, as shown in figure II-3.

While typically unprofitable, anaerobic digesters *could be* profitable (or an agent could perceive them as potentially profitable) depending on available co-products markets, prices for co-products, and government subsidies that help cover investment costs. Farmers, policy makers, and researchers are interested in policies that affect the prices of renewable electricity and carbon credits, and previous research has shown that government grants are particularly important for anaerobic digester profitability (e.g. Bishop and Shumway 2009; Gloy and Dressler 2010; Lazarus and Rudstrom 2007; Stokes, Rajagopalan, and Stefanou 2008). Selling renewable electricity and carbon credits and receiving government grants all do the same thing in that they contribute to a producer's income. However, the *source* of the income could matter because an individual's utility could differ depending on the policy scenario that he or she faces.

Hawkins and Wallace (2006) describe how types of income effect demand because individuals attach psychic and transaction costs to goods, and according to Moore (1945), industry stakeholders are not only concerned about a company's income. Stakeholders also want to know where the income originates, or the sources of the income. In the context of this study, one producer may adopt an anaerobic digester if they are given government grants, while another will refuse government grants and only consider adoption if the digester can pay for itself. In this example, although the latter producer would not accept government grants, he or she may be more in favor of anaerobic digesters if the renewable electricity could be sold for a certain price.

Background: Policies for Renewable Energy Technology Adoption

Several state policies support renewable energy generation, including renewable portfolio standards (RPS), interconnection standards, net metering, feed-in tariffs, and other financial incentives, such as grants, loans, rebates, and tax credits (USEPA 2014c). According to the Database of State Incentives for Renewables & Efficiency (DESIRE), 29 states, Washington DC, and 2 U.S. territories have a RPS in place. An additional eight states and two territories have renewable portfolio goals (RPGs) (USDOE 2014). Renewable portfolio standards are generally aimed at jump-starting markets for established renewable energy technologies by requiring electric utilities to provide a certain percentage of electricity from renewable resources to their customers.

With a similar objective, interconnection standards reduce uncertainty and interconnection delays by establishing uniform processes and technical requirements for connecting renewable energy sources to the electric grid. As of February 2013, 43 states and Washington DC implemented some type of interconnection policy (USDOE 2014). Net metering and feed-in tariffs ensure renewable energy producers are compensated for the electricity they produce. With net metering, when the amount of electricity produced exceeds the producer's needs, the producer is given a credit that can be used later when on-site electricity production is not sufficient to meet all energy needs.

Feed-in tariffs are pre-established premium rates for renewable power fed into the grid. In terms of government grants, some states set up public benefits funds for renewable energy to pool resources and invest in clean energy supply projects. Approximately 22 states and 2 territories offer grant programs for renewable energy infrastructure. These grants can be offered by states, local governments, local utilities, private programs, or a combination of sources.

Carbon credits are another potential income source of anaerobic digesters. Several examples of carbon trading exist in the U.S. and around the world. From 2003 to 2010, the Chicago Climate Exchange (CCX) operated as a comprehensive cap and trade program with an offsets component. The final average settlement price was \$0.05/MT, and the highest average settlement price over the existence of the CCX was \$7.40/MT in June 2008. On the world market, countries that signed and ratified the Kyoto Protocol have access to world carbon trading markets, such as the European Climate Exchange (ECX). As of May 2014, carbon was trading on the ECX for \$5.12/MT.

In 2006 the State of California passed the Global Warming Solutions Act (AB 32), which requires the state board to “adopt a statewide greenhouse gas emissions limit equivalent to the statewide greenhouse gas emissions levels in 1990 to be achieved by 2020” (California State Assembly 2006). The state’s cap-and-trade program is the primary mechanism used to achieve this reduction. Supply and demand models of the carbon offset market forecast trading at around \$10 to \$15/MT (Borenstein et al. 2014).

Aside from actual markets for trading carbon credits, in 2010 the Obama administration issued Executive Order 12866, which proposed a new “social cost of carbon.” The U.S. Government (2013) used three integrated assessment models that included changes in net agricultural productivity, human health, property damages from increased flood risk, and the value of ecosystem services due to climate change, among other parameters, to estimate an average SCC. The latest calculations estimate the SCC at \$37/MT, up from the \$24/MT SCC in 2010.

Data

The sampling population for this study consisted of commercial dairy operations and breeding and market hog operations in the United States. All participants were classified as animal feeding operations (AFOs) and/or anaerobic digestion system owners or operators by the United States Environmental Protection Agency (USEPA) and the United States Department of Agriculture (USDA) National Agricultural Statistics Service (NASS). Survey participants were also considered dairy operations, hog operations, or anaerobic digester owners/operators by their own policies, and were over the age of 18. The survey population was split into four samples: 1) dairy and hog animal feeding operations (AFOs) with operational anaerobic digestions systems, 2) dairy and hog AFOs with decommissioned (or shutdown) anaerobic digestion systems, 3) dairy and hog AFOs that do not have anaerobic digestion systems, and 4) third-party operators of anaerobic digestion systems that process manure generated at dairy and hog operations.

The USEPA AgSTAR program provides a list of all operational and decommissioned digesters in the United States on their website. According to the AgSTAR program, there are currently 238 operational digesters (on 193 dairy, 31 hog operations, and 14 other) and 45 decommissioned digesters (31 dairy, 7 hog operations, and 7 other) in the United States (USEPA 2014b). Of the 238 operational digesters, 203 were located on dairy and hog farms, while 21 were owned or operated by a third-party that processes dairy or swine manure. Of the 42 decommissioned digesters, 33 are located on dairy and hog farms, while 5 are owned or operated by a third party that processes dairy and hog manure. The owners and/or operators of these digesters were selected as subjects for this study. Random samples of dairy and swine AFOs with no anaerobic digestion system were pulled from the NASS Estimation Program for dairy and swine. However, if these states did not have a single hog or dairy farm that operated an anaerobic digester, they were excluded. Figure II-1 shows the states that were included in this study. Each of these states was in the NASS Estimation Program for the commodities of interest *and* contained at least one anaerobic digester. For data analysis, the states were aggregated into regions from the USDA NASS Agricultural Resource Management Survey (ARMS).

Data were collected from a 2013 – 2014 nationwide survey of dairy and swine producers. The survey instrument was split into five sections. The survey started by asking a set of introductory questions, which allowed the survey to funnel respondents to the proper set of questions. Animal feeding operation owners/operators that currently use anaerobic digestion technology on their farms, animal feeding operation owners/operators that once used anaerobic digestion technology on their farms (but it has been shutdown), and third-party anaerobic digester operators were asked to answer all five sections of the survey. The sections of the survey used for this study included: 1) Introductory Questions, 2) Policy Implications, and 3) Demographics.

Online and paper versions of the survey instrument were created. The online version was developed using Qualtrics Survey Software. Prior to survey launch, a pretest with two anaerobic digester operators (one agricultural/professional engineer and one environmental health and safety manager for a hog farm) and one USDA NASS official indicated slight modifications to the survey instrument. On December 20, 2013, a postcard, which included a link to the online survey and information about the study, was mailed to all subjects in the sample. On January 21, 2014, a survey packet was mailed to those who did not respond to the online survey announcement. The survey packet included the paper version of the questionnaire, a postage paid return envelope, and a letter reemphasizing the importance of the research and the rights of study participants. The paper survey also included a link to the online survey and contained the same questions in the same order as the online survey. The paper survey was split into three different versions to reduce confusion and make the survey easier for respondents to complete. One survey was created for farms with an anaerobic digester or a decommissioned digester. One survey was created for farms without a digester, and one survey was created for third-party digester operators.

Only one electronic version of the survey was needed because the online survey software directs respondents to the proper questions (based on their responses). A final reminder postcard was mailed on February 12, 2014. The postcard again included a link to the online survey and a reminder of the paper survey received in the last mailing. Mailing addresses of subjects were provided by the United States Department of Agriculture (USDA) National Agricultural Statistics Service (NASS), and each subject was given a 4-digit sequencing, or identification, number so that the researchers could keep track of the subjects that responded to the survey and those that did not. Sequencing numbers were printed on the upper right corner of the address label, which was placed on the postcard or survey packet envelope. Before starting the survey, respondents were asked to provide their sequencing number so that they could be removed from the survey mailing list. Survey responses were collected from December through May 2014.

Since the populations of farms with operational or shutdown digesters was small, the goal was to survey the entire population. However, some operations were on a "do not contact" list with USDA NASS. Therefore, the samples of operations with digesters were slightly smaller than the actual populations. Of the surveys mailed to current and previous digester operators, only one was returned as out-of-scope due to retirement, death, sale, or restructuring, and three were not complete. The resulting response rate for digester operators was almost 30%. Although no surveys were returned from swine operations with shutdown digesters, six completed responses were obtained from dairy farms, so the response rate for all shutdown digesters was a little over 16%. Since only six viable surveys were returned from operations with shutdown digesters, these responses were grouped together with the operational digester responses. This aggregated group represents farms with experience operating anaerobic digesters.

Animal feeding operations that do not have anaerobic digesters were randomly selected for participation in the study by USDA NASS. Digesters are typically on large operations, so the sample of dairy operations with no digester was restricted to dairy operations with 100 head or greater and hog operations with 1,000 head or greater. The Oklahoma NASS office sorted the sampling population by size and selected a systematic random sample. The sample of operations with no digester covered the full range of farm size that was similar to the sample of operations that operated digesters. According to the 2012 Census of Agriculture, 14,415 dairy farms operate with a herd size of 100 or more milk cows, and there are 10,401 swine operations with 1,000 or more hogs and pigs in the

U.S. (USDA 2012). After excluding operations with anaerobic digesters, the populations were 14,191 dairy farms and 10,363 swine operations.

According to USDA NASS representatives, most agricultural surveys of this nature can anticipate a response rate of about 10% to 20%. In order to net the desired response rate from operations that do not operate digesters, a sample size of 2,500 was set. Of the 2,500 surveys distributed for farms with no digester, 62 were returned as undeliverable or out-of-scope (i.e. the respondent was retired, deceased, no longer raising livestock, etc.). The resulting overall sample size for operations with no digester is shown in table II-1, with a response rate of just over 10%.

Procedure

Contingent valuation was used to determine dairy and swine producers' willingness to accept an anaerobic digester. While other nonmarket valuation strategies were considered, we had to take into account that agricultural producers are already one of the most-surveyed people groups. When conducting surveys, especially of the agricultural industry, one must consider the tradeoff between novelty and response rate. Therefore, it was important to select and implement a method that generated the desired information without discouraging responses. By the time dairy and hog producers with anaerobic digesters came to the contingent valuations questions, they would have already answered 45 questions. With contingent valuation, as opposed to other methods such as conjoint choice analysis or best-worst scaling, respondents would only have to answer three more questions. The contingent valuation questions along with the farmer demographic and farm characteristic questions were deemed sufficient to accomplish the objectives of this study.

Since the first contingent valuation studies of the 1960s and 1970s (Davis 1963; Randall, Ives, and Eastman 1974), contingent valuation (CV) has become a popular "survey-based method to elicit values placed on goods, services, and amenities" (Boyle 2003). Initially, the CV method was subject to considerable skepticism due to its hypothetical nature (Adamowicz 2004). However, the use of CV in court cases following the Exxon Valdez oil spill and the publication of two books on CV in the same decade (Cummings, Brookshire, and Schulze 1986; Carson and Mitchell 1989) resulted in numerous studies that helped improve the acceptance and validity of the method while also providing a better understanding of its limitations. Many of these studies were in environment and natural resource economics, agricultural economics, consumer and behavioral economics, and marketing.

Contingent valuation has been widely used to determine *consumer* willingness-to-pay for agricultural products, but it has also been useful in eliciting producer utility under certain economic, political, and/or technological scenarios. Most previous studies sought to determine how policy incentives and/or farm characteristics influence a producer's decision to adopt a new technology or conservation practice. For example, Poe et al. (2001) used contingent valuation to predict participation in Comprehensive Nutrient Management Plans (CNMPs) on New York dairy farms. Cooper and Keim (1996) used contingent valuation to develop a bivariate probit model with sample selection and a double hurdle model to predict farmer adoption of water quality protection practices as a function of Water Quality Incentive Program (WQIP) payment levels.

More recent studies used contingent valuation to determine willingness to pay for or accept agricultural technologies such as precision agriculture, biotechnology crops, disease prevention in livestock, best management practices (BMPs), and greenhouse gas (GHG) reduction mechanisms (e.g. Taneja et al. 2014; Holt 2013; Thompson 2012). To our knowledge, this is the first study to use a discrete choice non-market valuation method to estimate producer willingness-to-accept an *anaerobic digester* under different policy conditions. It is also one of if not the only study to obtain and analyze data on perceptions of anaerobic digestion from dairy and hog producers on a nation-wide scale. Finally, this study is unique in that it presents results from a survey given to producers who currently or previously operate anaerobic digesters *and* to producers who do not utilize anaerobic digestion systems for manure management on their farms.

Previous research on the economic feasibility of anaerobic digestion systems has shown that, when considering anaerobic digestion as a waste management strategy, agricultural producers are primarily concerned with the price they will receive for the renewable electricity they produce (if they plan to use the methane generated from the system for electricity production) and whether or not they will receive external funding (from the government and/or other sources) to help cover the capital costs of the system (e.g. Bishop and Shumway 2009; DeVuyst et al. 2011; Lazarus and Rudstrom 2007; Stokes, Rajagopalan, and Stefanou 2008; Wang et al. 2010). Because of this, two contingent valuation questions were constructed to elicit the price of electricity and the percent of the capital costs covered by government grants that would result in an average hog or dairy producer adopting an anaerobic digester.

In addition to the economic benefits of selling electricity and receiving government grants, one of the primary social and environmental benefits of anaerobic digesters is their ability to capture and combust methane. Farmers typically find it difficult to experience any real *economi*c benefit from emissions reduction. However, the Obama Administration's development of the "Social Cost of Carbon" and the implementation of GHG trading markets in states like California and Michigan have renewed interest in the possibility of trading carbon credits. The third set of contingent valuation questions sought to determine the price of carbon at which the average producer in this study would be willing to accept an anaerobic digestion system. Table II-2 shows the policy variables of interest and the values that were included in the contingent valuation questions. The value ranges were chosen to cover what was perceived to be the likely ranges of WTA. Carbon credit prices are typically reported in $/megaton. However, since carbon trading is not common in the United States, carbon credit prices provided in the contingent valuation framework were given in $/animal unit/year so that producers would have a better idea of the economic impact associated with this scenario.

Using the contingent valuation method, producers were asked one question for each policy scenario. Three different contingent valuation questions were asked because it was assumed that a producer's utility could differ depending on the policy scenario that he or she faces. Producers could be concerned about the sources of income instead of just accepting that income will increase in all three scenarios. A dichotomous choice response format was selected for this contingent valuation study. For each question, producers were asked to answer 'Yes' or 'No'. Table II-3 shows an example of contingent valuation questions. The underlined values for each question could be any of the values included in table II-2 and were randomly assigned with equal probability to the surveys.

Along with the contingent valuation questions, producers were asked to share information on their personal demographics and farm characteristics. These explanatory variables, along with their sample mean and standard deviations are shown in Table II-4. On average, farmers with operational or decommissioned digesters were younger, had slightly higher farm incomes, and received more college degrees than farmers who did not have digesters. For both sample groups, respondents were primarily in the Midwest and Atlantic regions of the United States (see figure II-1 for reference).

Respondents were asked to report farm size, or capacity, in terms of number of animals. For farms that operated anaerobic digesters, some of the dairy farms included only dairy cows, while other operations had dairy cows and replacement heifers. All of the hog farms with digesters were wean-to-finish operations, so no sows, nursery pigs (farrow-to-wean), or boars were included. Four diversified livestock operations managed herds of dairy cows, dairy heifers, and wean-to-finish pigs. All dairy farms without digesters managed dairy cow herds, while some also raised replacement heifers and calves. Of the swine farms with no digester, most were market hog operations, and five were breeding operations with sows and farrow-to-wean pigs,

Farm size was assumed to remain constant throughout the year (i.e. continuous replacement and no seasonal fluctuations). Reported capacities in number of animals were converted to animal units (AU). An animal unit represents 1,000 pounds of live animal weight and serves as a common unit for combining different species of livestock. Several states provide regulations and standards for calculating animal units, and their definition of an animal unit is similar to the definition used in the study. For example, the Livestock Management Facilities Act in Illinois states that an animal unit refers to the one-time capacity of a facility. In the survey instrument, producers reported farm size in terms of capacity.

Animal unit conversions are based on the average mature animal weight of each livestock category. The conversion factor for milk cows was 1.4. The animal unit conversion for dairy heifers was 1.1, and the conversion factor for market or breeding hogs weighing more than 55 pounds was 0.4. Equations for calculating milk cow, dairy heifer, market hog, and breeding hog animal units were specified as

$$\text{Milk cow AU} = \text{milk cow digester population} \times 1.4,$$

$$\text{Dairy heifer AU} = \text{dairy heifer digester population} \times 1.1, \text{and}$$

$$\text{Market or breeding hog AU} = \text{swine over 55 pounds } \times 0.4.$$

Producers who have never operated anaerobic digesters were asked the following question: “Now let’s say your farm is considering implementing an anaerobic digestion system. What are the main factors that would influence your decision to implement an anaerobic digester on your farm? *Please rank the following 9 items; 1=most important and 9=least important*.” Producers who are currently or have operated anaerobic digesters were asked, “What were the main factors that influenced your decision to implement an anaerobic digestion system? ...” Three of the items that the producers were asked to rank were “Environmental stewardship and ecological sustainability”, “Reduce greenhouse gas (GHG) emissions”, and “Reduce odor.” The ranks of these three items were aggregated to generate the variable for relative importance of environmental benefits associated with an anaerobic digester. Table II-4 shows that the average ranked importance of digester environmental benefits was smaller for producers who have operated anaerobic digesters than for producers who have not. This infers that environmental benefits were slightly more important to producers who have utilized anaerobic digesters for manure management and supports the theory that environmental effects could influence a producer's utility and technology adoption decisions (Bishop, Shumway, and Wandschneider 2010).

The probit models were estimated separately for each of the three contingent valuation questions. The probit model was specified as

$$\text{(II-3)} \qquad \text{Prob}\big(Y_{ij} = 1\big) = \Phi\big(V_{ij}\big)$$

$$\text{s.t.}\, V_{ij} = \beta_{0j} + \beta_{1j}P_{ij} + \beta_{2j}T_{ij} + \beta_{3j}N_{ij} + \beta_{4j}A_{ij} + \beta_{5j}I_{ij} + \beta_{6j}E_{ij} + \beta_{7j}ENV_{ij} + \beta_{8j}ATL_{ij} + \beta_{9j}MW_{ij} + \beta_{10j}W_{ij}$$

where V_{ij} is the i^{th} owner/operator's indirect utility for adopting or not adopting an anaerobic digestion system, given the j^{th} contingent valuation scenario, Y_{ij} is a dichotomous choice dependent variable that equals 1 if the producer replied 'yes' to the anaerobic digester contingent valuation scenario and 0 otherwise, Φ is the standard normal cumulative distribution function (cdf), P_{ij} is the price or percent embedded in the three contingent valuation questions (table II-2), T_{ij} is an indicator variable for dairy farms, N_{ij} is the natural log of the size of the operation in animal units, A_{ij} is the producer's age in years, I_i is the natural log of income generated by the farming operation, E_{ij} represents the education level obtained and equals 1 of the respondent achieved a college Bachelor's degree or higher and 0 otherwise, ENV_{ij} represents the relative importance of the environmental benefits associated with the digester, and ATL_{ij},

MW_{ij}, and W_{ij} are indicator variables for the respondent's region (the indicator variable for the ARMS Southern region was dropped)

Probit models were estimated with the QLIM (qualitative and limited dependent variable model) procedure in SAS 9.3. Following model specification and estimation, average willingness-to-accept (WTA) values and marginal effects were calculated for each contingent valuation scenario and parameter estimate, respectively. Marginal effects for the probit model are calculated as

(II-4)
$$\begin{aligned} m_P &= \frac{\delta E[Y|P]}{\delta P} \\ &= \phi\big(\hat{\beta}_0 + \hat{\beta}_1\bar{P} + \hat{\beta}_2\bar{T} + \hat{\beta}_3\bar{N} + \hat{\beta}_{4j}\bar{A} + \hat{\beta}_{5j}\bar{I} + \hat{\beta}_6\bar{E} + \hat{\beta}_7\overline{ENV} \\ &\quad + \hat{\beta}_8\overline{ATL} + \hat{\beta}_9\overline{MW} + \hat{\beta}_{10}\bar{W}\big)\hat{\beta}_1 \end{aligned}$$

where m_P is the marginal effect on the variable for price (or percent grant), which is used here as an example, ϕ is the standard normal probability density function (pdf) for the probit regression equation specified in (II-3), calculated at the sample means. Marginal effects of farm size, age, farm income, and ranked importance of digester environmental benefits were calculated in equations similar to (II-4). For independent variables that are discrete, marginal effects were calculated as

(II-5)
$$m_T = \{\text{Prob}(Y = 1)|(T = 1) - \text{Prob}(Y = 1)|(T = 0)\}$$

where m_T is the marginal effect on the indicator variable for farm type, which is used here as an example and $\text{Prob}(Y = 1)$ is the probability that a producer will adopt a digester (given the type of farm they operate in this example). Equation (II-5) was also used to calculate the marginal effect the producer having a bachelor's degree and living in his or her specified region.

Willingness-to-accept was calculated as

$$\text{(II-6)} \qquad \overline{WTA_J} = -\bar{P}_j = -\frac{\hat{\beta}_{0j} + \hat{\beta}_{2j}\bar{T}_j + \hat{\beta}_{3j}\bar{N}_j + \hat{\beta}_{4j}\bar{A}_j + \hat{\beta}_{5j}\bar{I}_j + \hat{\beta}_{6j}\bar{E}_j + \hat{\beta}_{7j}ENV_{ij} + \hat{\beta}_{8j}\overline{ATL}_j + \hat{\beta}_{9j}\overline{MW}_j + \hat{\beta}_{10j}\bar{W}_j}{\hat{\beta}_{1j}}$$

where $\overline{WTA_J}$ is the average policy payment the sample of producers is willingness-to-accept to implement an anaerobic digester on a swine or dairy farm. Average WTA is calculated by setting (II-3) equal to zero and inserting sample means for the explanatory variables. We can then solve for the average policy payment variable, the negative of which is equal to the average WTA.

After producers answered “No” to questions about whether their farm currently or previously operated an anaerobic digester, they were asked, “If no, have you ever *considered* implementing an anaerobic digester on your farm?” If they have considered implementing an anaerobic digester for manure management, they may have more knowledge about the system. It could also be important to distinguish between variables that influence the likelihood that a producer will *consider* anaerobic digestion for manure management and parameters or characteristics that effect whether or not a producer will adopt a digester.

Therefore, a bivariate probit model with sample selection can be specified as

$$\text{(II-7)} \qquad Prob(w_{ij} = 1) = \Phi(W_{ij})$$

$$W_{ij} = \gamma_{0j} + \gamma_{1j}PEER_{ij} + \gamma_{2j}ENV_{ij} + \gamma_{3j}T_{ij} + \gamma_{4j}N_{ij} + \gamma_{5j}A_{ij} + \gamma_{6j}E_{ij}$$

$$\text{(II-8)} \qquad Prob(z_{ij} = 1) = \Phi(Z_{ij})$$

$$Z_{ij} = \beta_{0j} + \beta_{1j}P_{ij} + \beta_{2j}T_{ij} + \beta_{3j}N_{ij} + \beta_{4j}A_{ij} + \beta_{5j}E_{ij} + \beta_{6j}ENV_{ij} + \beta_{7j}ATL_{ij} + \beta_{8j}MW_{ij}, \qquad \text{if } w_{ij} = 1$$

where W_{ij} is the i^{th} owner/operator's indirect utility for considering the adopting of an anaerobic digestion system, given the j^{th} contingent valuation scenario, w_{ij} is a dichotomous choice dependent variable and equals 1 if the non-adopting producer has ever *considered* an anaerobic digester and 0 otherwise, $PEER_{ij}$ is the natural log of the number of "neighbors" with operational digesters in the state where the producer resides and is used to estimate peer group influence, Z_{ij} is the indirect utility of adopting or not adopting an anaerobic digestion system for of the i^{th} owner/operator who has considered anaerobic digestion for manure management, z_{ij} is a dichotomous choice dependent variable that is only observed when $w_{ij} = 1$ and equals 1 if the producer replied 'yes' to the anaerobic digester contingent valuation scenario and 0 otherwise, and all other variables are as defined above. Variable means and standard deviations are provided in table II-5.

For the first stage of the bivariate probit model with sample selection, the variable $PEER_{ij}$ is assumed to affect whether or not a producer will consider implementing an anaerobic digester on his or her farm. In order to adopt a digester, a producer must first consider whether or not a digester will be beneficial. The larger the population of operational digesters (or number of neighbors) in a state, the more likely other producers are to have seen, heard about, or read something about the technology. This "tendency for an individual's behavior to be influenced by exposure to the behavior of his or her peers" is called the neighborhood effect (Baerenklau 2005, pg 1). If producers are more familiar with the technology, they may be more likely to consider how it could be used on their farms.

Results and Discussion

Probit Models

While the magnitudes of the parameter estimates for the probit models in table II-6 are not directly interpretable, the signs of the coefficients are meaningful. All but one of the parameter estimates for price or percent government grant were positive. The positive sign on the coefficients for percent capital cost covered by government grant indicates that an increase in the percentage grant funding will increase the probability that more producers will implement digesters. In the probit model for producers who operate anaerobic digesters, the coefficient for the price of carbon credits was negative but was not significant.

The positive and significant coefficient for percent government grant corresponds with previous literature that points to high capital costs as the reason anaerobic digesters are often economically infeasible and not more readily adopted (Lazarus and Rudstrom 2007; Kruger et al. 2008; Stokes, Rajagopalan, and Stefanou 2008; Bishop and Shumway 2009; Wang et al. 2010; DeVuyst et al. 2011). Producers who have experience with anaerobic digesters may understand the challenges of the high capital costs associated with the technology. They may also have more experience with policies that help cover capital costs and therefore find them more realistic than policies that encourage electricity generation or carbon trading.

The parameter estimate for percent government grants to cover digester capital costs was also positive and significant for non-adopters (table II-6). As the percentage of the digester capital cost covered by government grants increases, the likelihood of adopting a digester also increases. Government grants could be important because, on average, the number one reason non-adopters do not want an anaerobic digester on their farm is because the costs often exceed the benefits (figure II-6). Of the producers who responded to the question on the "most important thing that would have to be done to encourage more adoption of anaerobic digesters", 33% of swine producers and 36% of dairy producers listed lower cost of construction and/or that the systems must be more profitable (figure II-7). However, the same sample of producers ranked 'not enough government support' second to last as a reason for not wanting a digester (figure II-6), and about 6% stated that digesters should be economically feasible without government subsidies (figure II-7).

Anaerobic digester adopters and non-adopters agree that system profitability is difficult because capital costs of these systems are very high. However, producers who have operated anaerobic digestion systems seem more likely to support government intervention to help reduce costs. There is evidence to suggest that, while producers who have not operated anaerobic digesters agree that costs are too high, they would prefer lower costs are achieved without government support. This lends support to the theory that the source of income matters for some producers.

Unlike producers who have operated anaerobic digesters, the parameter estimate for carbon credit price was positive and significant for non-adopters (table II-6). As the price of carbon per animal per year increases, non-adopters are more likely to implement an anaerobic digester. In figure II-5, the overall average rank for 'government subsidies for reducing GHG emissions and carbon trading' was higher for producers who do not have an anaerobic digester than for producers who do. Since non-adopters may be less inclined to accept government support, additional market options, such as carbon trading, may be more appealing.

At the end of each survey, producers were asked, “In your opinion, what is the one most important thing that would have to be done to encourage more wide-spread adoption of anaerobic digestion systems?” The results from this question are summarized in figure II-4. The producers who currently operate anaerobic digesters had three main criteria: lower cost of construction, improved or continued support through government grants, and higher prices for co-products, especially electricity. Respondents mentioned that electricity prices should range anywhere from $0.09/kWh to $0.20/kWh in order for digesters to be profitable. Some of the ‘Other’ answers included cost-sharing programs and reducing regulations and paperwork associated with anaerobic digester design, construction, and electricity contracts.

About 58% of respondents mentioned lower construction costs or increased government support through grants (which are typically tied to capital costs), and the parameter estimate for percent government grant was significant for both sample groups. Producers were also asked to rank the main factors that influenced their decision to implement an anaerobic digestion system. Two of the top three reasons producers implemented anaerobic digesters were to sell co-products and because they received government payments, grants, or tax credits for renewable energy. While the parameter estimate of electricity price was not significant, it was positive, and additional results show that producers who operate anaerobic digesters think that the price of electricity is important for the economic feasibility and future adoption of anaerobic digestion systems.

Figure II-5 also provides some more insight into results for the probit model for producer willingness to accept a digester based on the price of carbon credits. Recall that the coefficient estimate for price of carbon credit was statistically insignificant and negative. The two lowest ranked reasons for producers implementing a digester were so that they could receive government payments, grants, tax credits, or carbon credit trading for reducing GHG emisions and so that they can reduce greenhouse gas emissions. Producers who have operated anaerobic digesters seem to either not care as much about reducing carbon emissions and/or understand that carbon trading in the U.S. is not readily available or universally profitable at this time.

Most of the estimates for the dairy farm indicator variable were negative. Farm type was only significant in the non-adopter probit model for carbon credit price and in the probit model for government grants with anaerobic digester adopters. The negative sign attached to the variable for dairy farm indicates that swine producers may be more likely to adopt an anaerobic digester or think that other producers will adopt an anaerobic digester when carbon credits or government grants are considered.

Parameter estimates for farm size were positive and significant in probit models for government grants with producers who have operated anaerobic digesters and for all probit models for producers who have never operated anaerobic digesters. (table II-6). This suggests that as farm size increases, the likelihood of a producer adopting an anaerobic digester also increases. Producers who do not currently operate anaerobic digesters were asked to rank the main reasons they would not want an anaerobic digestion system on their farm. On average, the second most important reason for not wanting to adopt a digester was that the producer believed his or her operation was too small (figure II-6).

At the end of the survey, producers who do not operate anaerobic digesters were asked, “In your opinion, what is the one most important thing that would have to be done to encourage more wide-spread adoption of anaerobic digestion systems?” The results from this question are summarized in figure II-7. A variety of suggestions were offered by producers who do not operate anaerobic digesters. Several respondents mentioned that one of the most important things that would have to be done to encourage more wide-spread adoption of anaerobic digestion systems is to design systems for small farms that work well and are economically feasible. Overall, some producers seemed worried that their farms were too small for an anaerobic digester.

It was hypothesized that younger producers are more likely to adopt anaerobic digesters. Probit models for eliciting the likelihood that those producers with no digester will adopt an anaerobic digester based on electricity price and government grants included a negative and significant parameter estimate for the age variable. As producers draw closer to retirement, their utility for introducing new technology, such as an anaerobic digester, may decrease, especially if the payback period on the new technology exceeds the number of years they plan to continue farming.

The null hypothesis that farm income has no effect on the likelihood of anaerobic digester adoption could not be rejected because none of the parameter estimates for farm income were significant. All but one of the estimates for the education variable were negative. Under the carbon credit scenario, the estimate for education producers with no digester was negative and significant, which suggests that producers with less than a bachelor’s degree were more likely to adopt an anaerobic digester

Estimates on the variable for ranked relative importance of environmental benefits associated with an anaerobic digester were negative for all models. These estimates were significant for one of the probit models for producers who operate anaerobic digesters and for all of the probit models for producers who do not operate anaerobic digesters. Since lower rank equals higher importance, the negative sign on the parameter estimate for environmental benefits infers that producers who do not currently operate a digester and who gave a higher importance to the environmental factor associated with anaerobic digesters are more likely to adopt the technology. These results support the theory that environmental effects contribute to the heterogeneity of producers' motives for adopting anaerobic digesters (Bishop, Shumway, Wandschneider 2010). Producers' decisions could be based on differences in beliefs, such as environmental beliefs, rather than just differences in profit. However, only the government grant probit models of farms with digesters had importance of environmental benefits as a significant variable. Therefore, under scenarios of co-product marketing, producers who already operate digesters may consider expected profits as more important for influencing other producers to adopt.

Under scenarios for selling electricity and carbon credits, producers who operate digesters in the Atlantic, Midwest, and Western regions are more likely to think other producers will adopt digesters than their counterparts in the South region. This could be partially due to the number and type of renewable energy policies available in each of these regions. The U.S. Department of Energy maintains a Database of State Incentives for Renewables & Efficiency (DSIRE), which lists 14 different financial incentives and regulatory policies that promote renewable energy. Some of the incentives and regulations are listed at the state and/or local level. Figure II-3 summarizes the concentration of these policies in each state.

Data from DSIRE was aggregated to create figure II-3. A state received a point for having a state-wide policy and another point for policies on the local level. Only policies dealing with renewable electricity production, GHG emission offsets, and grants were considered. As shown in figure II-3, these policies are more prevalent in the upper Atlantic, Midwest, and West regions. Producers who currently operate anaerobic digesters are likely aware of the available renewable energy incentives in their states. Producers residing in states with a higher saturation of renewable energy incentives and regulations could be more likely to think that other producers will adopt anaerobic digesters.

Marginal Effects

Since the magnitudes of the parameter estimates in each probit model were not directly interpretable, marginal effects were also calculated for each variable and are provided in table II-7. For the producers who have operated anaerobic digesters, the marginal effect for the percentage of the capital costs covered by government grants was 0.0005, which means that a 1% increase in grant funding will result in a 0.05% (0.0005 × 100) increase in the probability that more agricultural producers will implement anaerobic digesters. For the same sample and probit model, a 1 AU increase in farm size is equal to a 0.5% increase in the likelihood that other producers will adopt digesters. The marginal effect for the Atlantic region indicator variable was 0.999 in the probit model for the effect of electricity prices on agricultural producers’ willingness to accept a digester. For this scenario, a producer living in the Atlantic region is 99% more likely to think that other producers will implement digesters than a producer living in the South region (table II-7). The remaining marginal effects provide similar information.

Table II-7 provides the marginal effects for producers who have never operated anaerobic digesters. The marginal effect for the price of carbon credits is 0.015, so a $1/animal/year increase in the price of carbon will result in a 1.5% increase in the likelihood that a producer will implement a digester. According to the probit model for the effect of electricity prices on digester adoption, a producer who has a college Bachelor's degree is 4.4% less likely to implement an anaerobic digester than a producer who has not achieved a higher level of education. The signs differ for marginal effects of age in the probit models for both sample groups and for all scenarios. A one-year increase in the age of a producer with no digester will make him or her about 0.7% less likely to implement an anaerobic digester in the sell electricity and government grant scenarios.

Willingness-to-Accept (WTA)

Average willingness-to-accept (WTA) values were calculated for each probit model within each sample group, and these results are included in table II-8. The average willingness-to-adopt for producers who have operated a digester was $0.18/kWh. Producers with no anaerobic digester required an electricity price of $0.51/kWh in order to adopt. In the survey, producers were asked how much they currently pay for electricity on their farms, and the means for both samples are included in table II-8. For comparison, producers in this study pay, on average, about $0.092 - $0.096/kWh.

The WTA values for carbon credit price were both outside the range of values used in the contingent valuation questions. We cannot extrapolate outside this range, and the negative value for producers who have operated anaerobic digesters is unexpected.

However, estimating a WTA value outside of the range provided in the contingent valuation (CV) framework does tell us that it is highly unlikely that producers will implement anaerobic digesters on their farms based on carbon credits. Table II-8 lists the current market price of carbon credits on the European Climate Exchange (ECX) and the Social Cost of Carbon (SCC), both converted from \$/MT to \$/animal/year (based on the amount of carbon produced per animal per year). Both of the values are below the WTA value estimated for producers who have not operated anaerobic digesters. The WTA value is close to the SCC, but the SCC is used for regulatory cost-benefit analysis and is not a market price.

Average WTA values for a digester based on the percent of the capital cost covered by government grants vary between sample groups. Producers who have operated anaerobic digesters suggested that other agricultural producers would be willing-to-accept a digester if they could receive government grants to cover 22% of the capital cost (table II-8). However, the average producer that has never operated an anaerobic digester would require that 62% of the digester's capital costs be covered by government grants. One reason for this may be that producers who have experience with anaerobic digesters feel more obligated to answer yes in a survey about anaerobic digestion—a problem known as "yea-saying" (Blamey, Bennett, and Morrison 1999).

According to survey responses, producers who have operated anaerobic digesters and received government grants were awarded funds that covered almost 50% of the capital cost (table II-8). The WTA estimate for producers who have not operated anaerobic digesters exceeded the average value obtained for digesters included in this study, and this phenomenon may have occurred for a couple of reasons. First, although some producers believe that digesters should be economically feasible without government assistance, they are still very concerned about the capital costs of the system (figures 6 and 7). Second, producers who have never operated digesters may have limited knowledge about the technology and the associated costs. As shown in figure II-7, 32% of swine producers and 11% of dairy producers listed *education* as the one most important thing for encouraging future adoption. Without having a complete understanding of the costs and benefits associated with anaerobic digesters, producers who have never operated them could be more likely to reject a CV question on adoption unless the majority of the costs are covered by government grants.

The fact that the three CV questions generate varying WTA results could be due to several reasons. First, this could provide additional evidence that the source of income matters to producers. While some producers would desire government grants, others would prefer that the digester is economically feasible without assistance from the government. Economic feasibility could be achieved by reducing construction costs, selling electricity at retail price, or selling carbon credits. While policies may be necessary to set up markets for renewable electricity and carbon credits, the social, psychic, and/or transaction costs associated with these policies may differ from those associated with government grants.

Second, these results could also indicate that the application of contingent valuation (CV) methodology to anaerobic digester technology adoption can be difficult when producers have limited knowledge of the technology and associated costs. The capital costs of anaerobic digesters are significant, and these CV questions only deal with potential revenues. Therefore, producers who have never operated or considered operating an anaerobic digester may not have enough information to properly decide whether or not they would adopt one under different policy and co-product marketing scenarios.

Bivariate Probit Model with Sample Selection

Results from the estimation of the bivariate probit models with sample selection are provided in table II-9. In the first-stage models, where producers were asked whether or not they had ever considered implementing an anaerobic digester, variables for peer influence, farm type, and farm size were positive and significant. Dairy farms and farms with more animal units are more likely to consider adopting anaerobic digestion systems. The variable for environmental stewardship rank was also significant and was negative, which is expected because farmers who place a higher value on the environmental benefits of anaerobic digesters should be more likely to consider adopting them. The lower the rank given to the environmental benefits of anaerobic digestion, the more likely a producer is to consider adopting an anaerobic digester.

As hypothesized, as the number of operational anaerobic digesters in a state (or number of neighbors) increases, the more likely a producer is to consider implementing an anaerobic digester. This corresponds with previous research on neighborhood effects and technology adoption (Baerenklau 2005). These results indicate that the neighborhood effect *is* important, at least for encouraging producers to consider an anaerobic digester for manure management. Overall, peer group influence, farm characteristics, and producers' beliefs seemed to be more important in determining whether or not they had considered anaerobic digestion than their demographics (i.e. age, education), which were not significant.

The second-stage model included only producers who *have* considered adopting an anaerobic digester. Once the producers responded that they have considered adopting an anaerobic digester, they were asked if they would implement a digester based on a set of contingent valuation scenarios. When considering electricity sales, the variable for price was significant. Recall that, in the probit model that included all producers who do not operate anaerobic digesters, the variable for electricity price was not significant. This seems to indicate that, once producers have crossed the hurdle of considering adoption, they are primarily interested in the price they could receive for the electricity that they produce when actually deciding whether or not to adopt. The variable for ranked relative importance of environmental benefits was positive and insignificant in the scenario involving selling electricity. Producers who have considered adopting an anaerobic digester and who would deem the price of electricity as an important factor for adoption are likely to rank the digester's market benefits as more important than nonmarket, environmental benefits.

All variables for farm type were negative, indicating that hog producers who have considered anaerobic digestion may be more likely to actually adopt an anaerobic digester. This could be because most hog farms already use lagoons for manure management. These lagoons could be covered with an impermeable membrane to capture and collect methane that could be used to produce electricity or generate carbon credits. While some dairy farms also use lagoons, the composition of dairy manure allows for more diverse methods of manure management, such as compost and storage. After considering anaerobic digestion, younger farmers and those with less education were more likely to adopt a digester.

After sample selection for those who have considered adoption, no farmers from the Southern region remained in the sample. Therefore, the indicator variable for the Western region was dropped in the anaerobic digester adoption equation. It was expected that producers in the Atlantic and Midwest regions would be more likely to adopt anaerobic digesters after considering them because of neighborhood effects and the larger number of incentives for renewables in these regions (see figures 2 and 3). However, no regional indicator variables were significant, so no such conclusions could be drawn.

Conclusions

This study used two types of probit models to determine how government policies and farm and producer characteristics influence the adoption of anaerobic digesters on dairy and swine operations. Producers seemed primarily concerned with the capital costs associated with anaerobic digester implementation. Results for producers who have operated anaerobic digesters and producers who have never operated anaerobic digesters indicate the percent capital cost that is covered by government grants is important and positively related to the likelihood of adoption.

When looking at the roles of farm characteristics and producer demographics in anaerobic digester adoption, farm characteristics seemed to dominate. Farm size, type, and location were consistently influential in the adoption decision. Larger farms were more likely to consider adoption and adopt anaerobic digesters, and producers commonly cited that their farm was too small for an anaerobic digester. Dairy producers were more likely to *consider* adopting an anaerobic digester and this is possibly because more information is available on the application of anaerobic digesters on dairy farms.

However, hog producers tended to be more likely to adopt, especially if they had already considered anaerobic digestion for manure management, which could be due to their operations being more easily adaptable to anaerobic digestion technology.

As the number of in-state neighbors with anaerobic digesters increased, so did the likelihood that producers with no digester would consider adoption. In two CV scenarios, regional indicator variables for producers with digesters were also positive and significant. The location of a farm may be an important consideration for anaerobic digester adoption for several reasons. Climate is an important factor for digester operation and productivity. Also, the location of a farm affects the availability of renewable energy policies and the amount of exposure to operational anaerobic digesters that a producer could receive. Overall, younger farmers with less than a college Bachelor’s degree are more likely to adopt anaerobic digesters.

While not apparent in the probit models, the bivariate probit model with sample selection revealed that neighborhood effects, environmental considerations, and farm characteristics are associated with whether or not a producer will consider adopting an anaerobic digester for manure management on his or her farm. However, as shown in the electricity marketing scenario, after considering anaerobic digestion, producers are more concerned with the price they will receive for the electricity they generate. Motivations and influences such as neighborhood effects and environmental beliefs may be enough for producers to *consider* anaerobic digestion, but may not be enough to encourage a producer to inevitably adopt a digester for manure management. Once a producer has considered anaerobic digestion, the decision to adopt could be more heavily tied to profit maximization, as the producer learns more about the costs and benefits associated with the system.

Results of this study could have implications in renewable energy policy formulation. Along with the variables described above, the decision to adopt a digester seemed to be influenced by the type of policy that was presented in the CV question. Most renewable energy policies are designed to increase income to a level that encourages adoption (USEPA 2014c). However, producers may attach different psychic, social, and/or transaction costs to different types of policies. If the source of income matters to producers, some policies may be more effective at encouraging adoption than others. Results of this study indicate that government grants to cover a portion of the capital costs may be most effective. Examining anaerobic digester design regulations and standards to determine if changes could be made to reduce capital costs could also be beneficial. Future analysis on the demand for anaerobic digesters may want to include additional information or methodologies that allow the respondent to have a better understanding of the benefits, costs, and logistics associated with anaerobic digesters.

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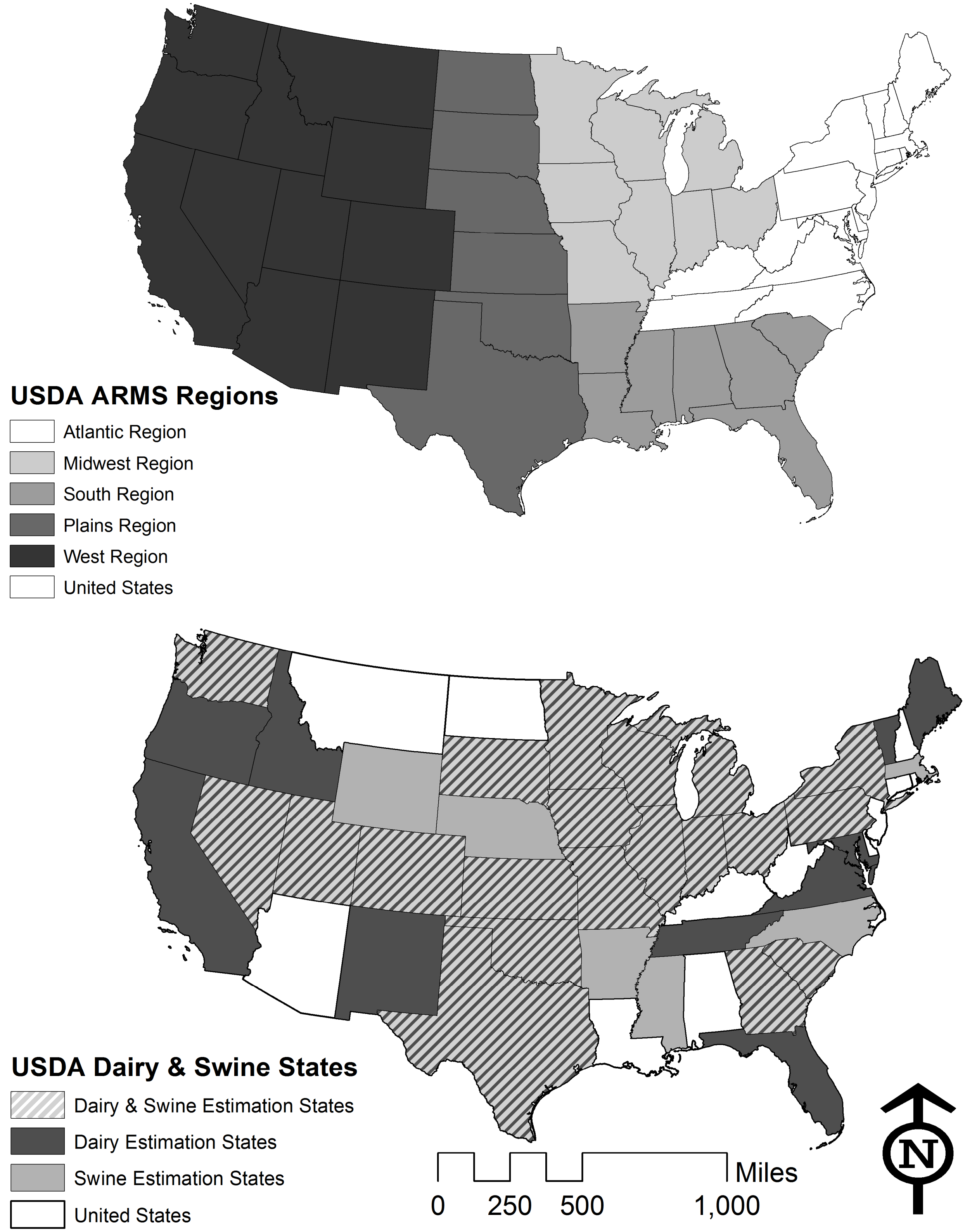


Figure II-1. Schematic of states included in this study and their respective regions.

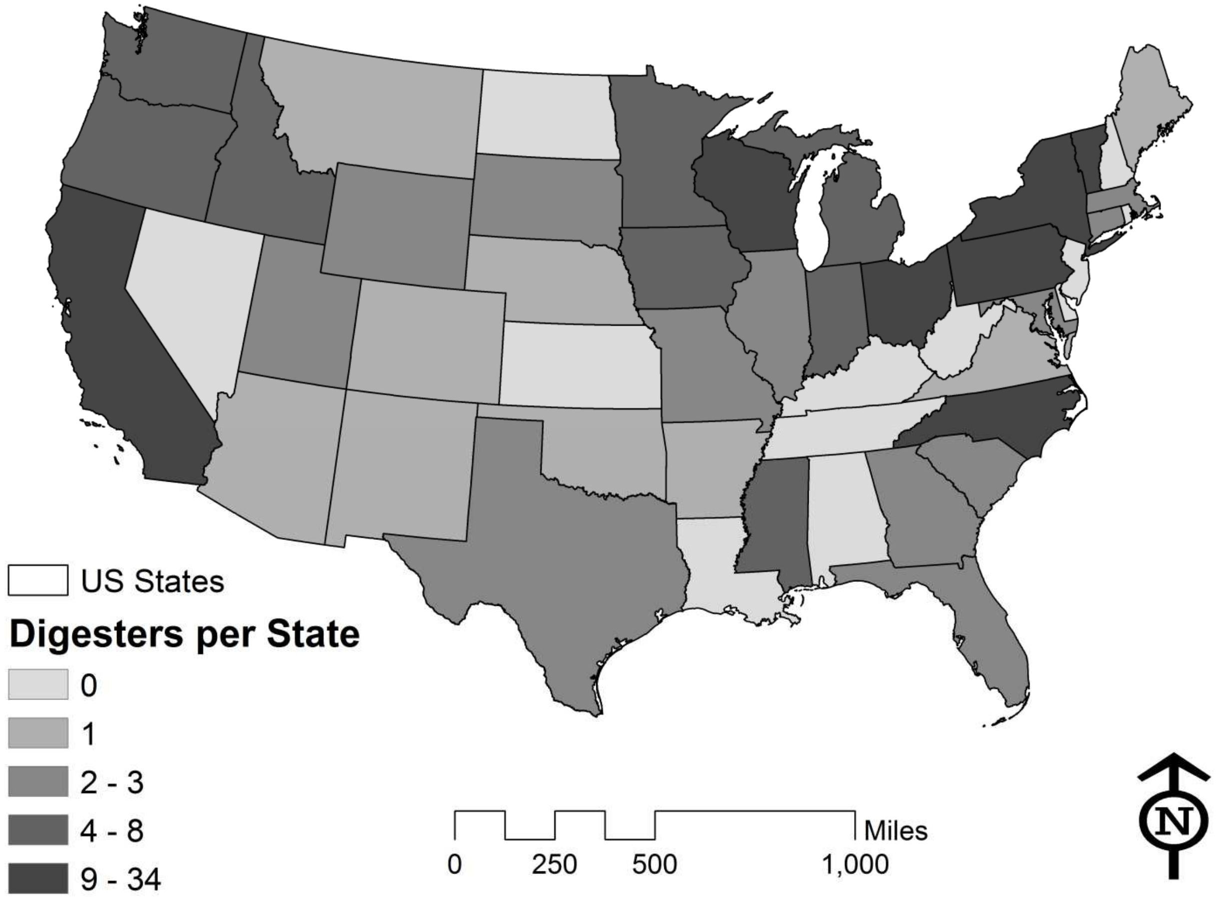


Figure II-2. Number of digesters (on dairy or hog farms) in each state

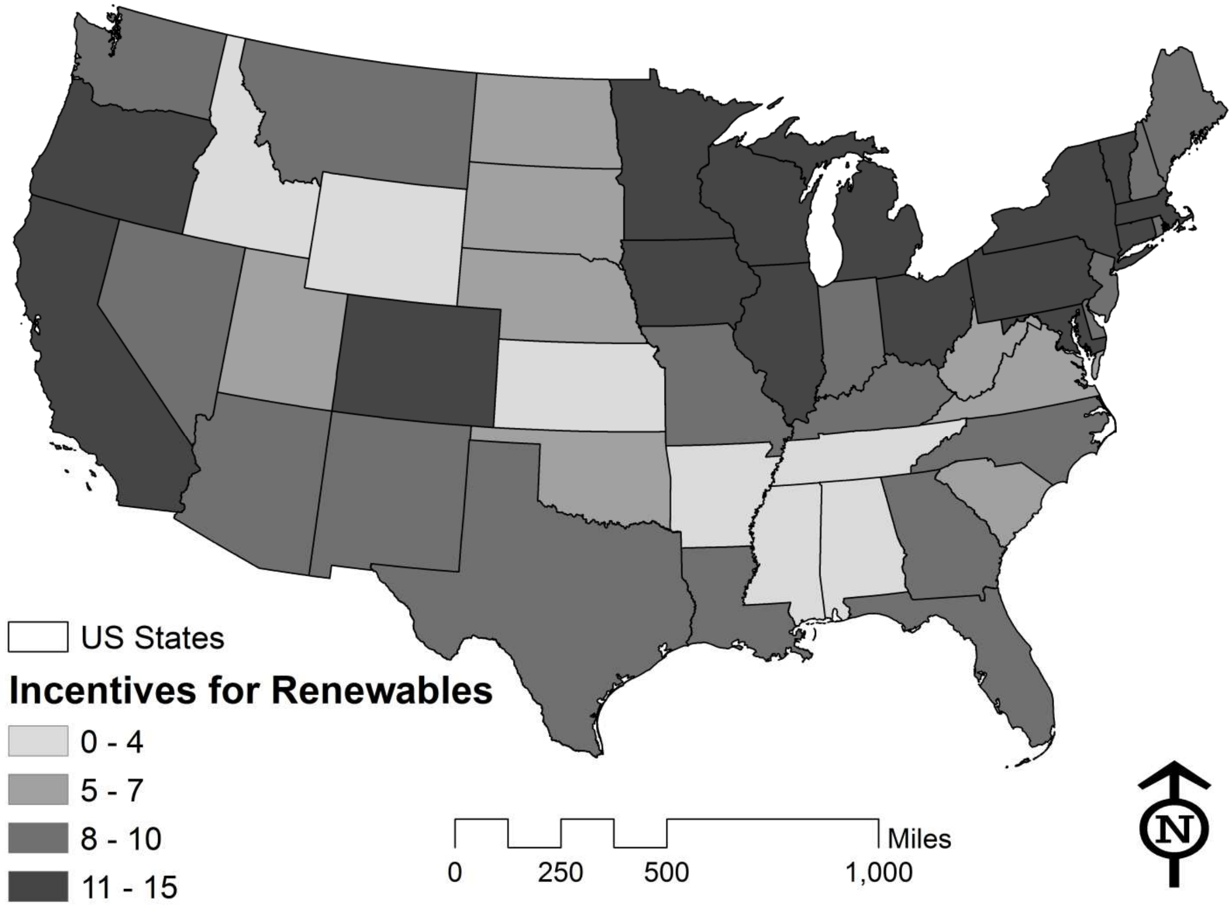


Figure II-3. Number of financial incentives and regulatory policies that promote renewable energy in each U.S. state (USDOE 2014)

Table II-1. Sampling Statistics

Statistics Sample group	Farm Type Dairy	 Swine	 Total
Population			
Digester	193	31	224
Shutdown digester	31	7	38
No digester	14,191	10,363	24,816
Sample Size			
Digester	152	29	181
Shutdown digester	30	7	37
No digester	1,250	1,250	2,500
Adjusted Sample Size			
Digester	151	29	180
Shutdown digester	30	7	37
No digester[a]	-	-	2,438
Responses			
Digester	47	8	55
Shutdown digester	7	0	7
No digester	172	114	286
Completed responses			
Digester	45	8	53
Shutdown digester	6	0	6
No digester	155	103	258
Response rate			
Digester	29.8%	27.6%	29.4%
Shutdown digester	20.0%	0.0%	16.2%
No digester	12.4%	8.2%	10.6%
Sampling error[b]			
Digester	12.8%	30.3%	11.8%
Shutdown digester	36.5%	-	37.2%
No digester	7.8%	9.6%	6.1%

[a] Out-of-scope responses did not provide sequencing numbers

[b] Computed at 95% confidence level

Table II-2. Contingent Valuation Question Attributes and Levels

Policy Item to be Valued	Value
Price per kWh	$0.05/kWh
	$0.20/kWh
	$0.35/kWh
Price of carbon credit	$0.10/AU/yr
	$5/AU/yr
	$10/AU/yr
Percent capital cost covered by government grants	20%
	50%
	80%

Table II-3. Example Set of Contingent Valuation Questions

No.	Contingent Valuation Question
1	Holding everything else constant, would you implement an anaerobic digester on your farm if you could sell the surplus electricity generated for <u>$0.05</u> per kWh? ☐ Yes ☐ No
2	Assuming no other incentives, would you implement an anaerobic digester on your farm if you could sell carbon credits for <u>$10.00</u> per animal unit per year? ☐ Yes ☐ No
3	Holding everything else constant and neglecting the other incentives, would you implement an anaerobic digester on your farm if you could receive government grants to cover <u>50%</u> of the capital cost? ☐ Yes ☐ No

Table II-4. Characteristic Variables of Survey Respondents Used in Probit Models

		Digester		No Digester	
Variable	Definition	*n*	Mean[a]	*n*	Mean[a]
Farm Size	Animal units	56	2,859 (2,385)	274	1,089 (1,598)
Cows	Farm size in number of dairy cows	56	1,696 (2,009)	165	552 (986)
Heifers	Farm size in number of dairy heifers	36	919 (793)	26	262 (333)
Calves	Farm size in number of dairy calves	0	--	6	119 (111)
Sows	Farm size in number of sows	0	--	5	459 (516)
Farrow-to-wean	Farm size in number of pigs	0	--	66	2,447 (4,595)
Wean-to-finish	Farm size in number of pigs	7	7,049 (3,812)	98	3,059 (3,739)
Dairy	1 if dairy; 0 if swine	56	0.820 (0.388)	274	0.565 (0.497)
Age	Age in years	53	46.6 (11.3)	270	51.0 (9.6)
Farm Income	Natural log of annual farm income	53	157.78 (93.82)	258	153.28 (97.11)
Education	1 if Bachelor's degree; 0 otherwise	56	0.468 (0.504)	268	0.294 (0.457)
Environment	Ranked importance of digester environmental benefits	53	13.57 (4.60)	258	15.84 (5.37)
West	1 if West/Plains region, 0 otherwise	56	0.080 (0.274)	274	0.087 (0.282)
Midwest	1 if Midwest region, 0 otherwise	56	0.280 (0.454)	274	0.610 (0.489)
South	1 if South region, 0 otherwise	56	0.040 (0.198)	274	0.017 (0.131)
Atlantic	1 if Atlantic region, 0 otherwise	56	0.580 (0.499)	274	0.199 (0.400)

[a]Standard deviation in parenthesis.

Table II-5. Characteristic Variables of Survey Respondents Used in Bivariate Probit Models

Variable	Definition	Mean	Standard Deviation
Neighbors	Number operational digesters in state	12.85	11.87
Environment	Ranked importance of environmental benefits	4.53	2.57
Dairy	1 if dairy; 0 if swine	0.565	0.497
Farm size	Number of animal units	1,089	1,598
Age	Age in years	51.0	9.6
Education	1 if Bachelor's degree; 0 otherwise	0.294	0.457

Table II-6. Probit Estimates for Dairy and Hog Producers

	Estimate					
	Sell Electricity, $n = 51$ $/kWh		Carbon Credits, $n = 48$ $/animal/year		Grants, $n = 50$ % capital cost	
Parameter	Digester	No Digester	Digester	No Digester	Digester	No Digester
Intercept	-2.130	-0.345	-0.811	-0.388	-3.796	-1.290
Price/Percent	0.897	0.118	-0.025	0.045^{*}	0.111^{**}	0.017^{***}
Farm type	-0.626	0.034	-0.338	-0.475^{**}	-6.309^{*}	-0.227
Farm size	-0.037	0.308^{***}	-0.458^{*}	0.216^{**}	1.243^{*}	0.206^{**}
Age	0.018	-0.017^{*}	-0.009	0.008	0.059	-0.017^{*}
Farm income	-0.306	-0.015	0.075	-0.034	0.656	0.042
Education	-0.292	-0.111	-0.613	-0.389^{*}	0.027	-0.118
Environment	-0.072	-0.042^{**}	-0.073	-0.052^{***}	-0.679^{*}	-0.028^{*}
Atlantic	7.507^{***}	0.041	5.104^{***}	-0.615	-5.755^{*}	-0.057
Midwest	6.140^{***}	0.116	5.624^{***}	-0.584	-3.727	-0.051
West	7.762^{***}	-0.576	4.893^{***}	-0.777^{*}	6.357	-0.238

Note: Each equation includes a binary choice dependent variable, which equals 1 for 'Yes' and 0 for 'No' when producers were asked if they would implement an anaerobic digester based on electricity price, carbon credit price, and percent capital cost covered by government grants (see table II-3 for reference).

***Significant at the $\alpha = 0.01$ level

**Significant at the $\alpha = 0.05$ level

*Significant at the $\alpha = 0.1$ level

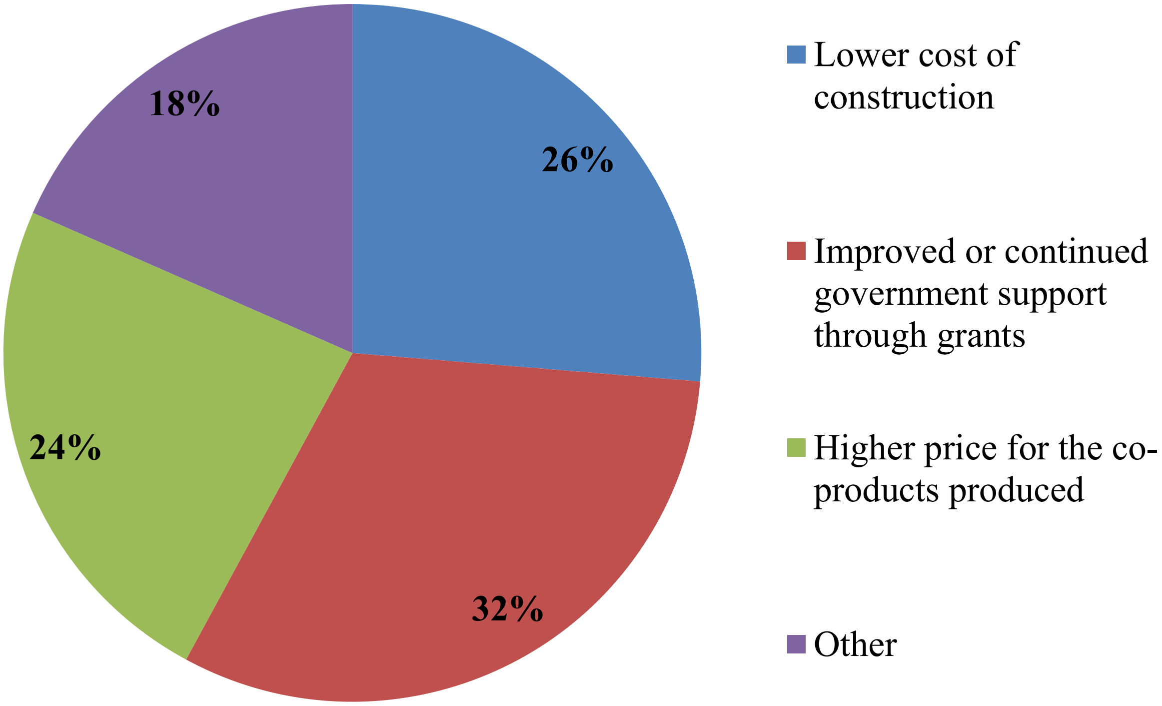


Figure II-4. The one most important thing that would have to be done to encourage more wide-spread adoption of anaerobic digestion systems, according to producers who have used them

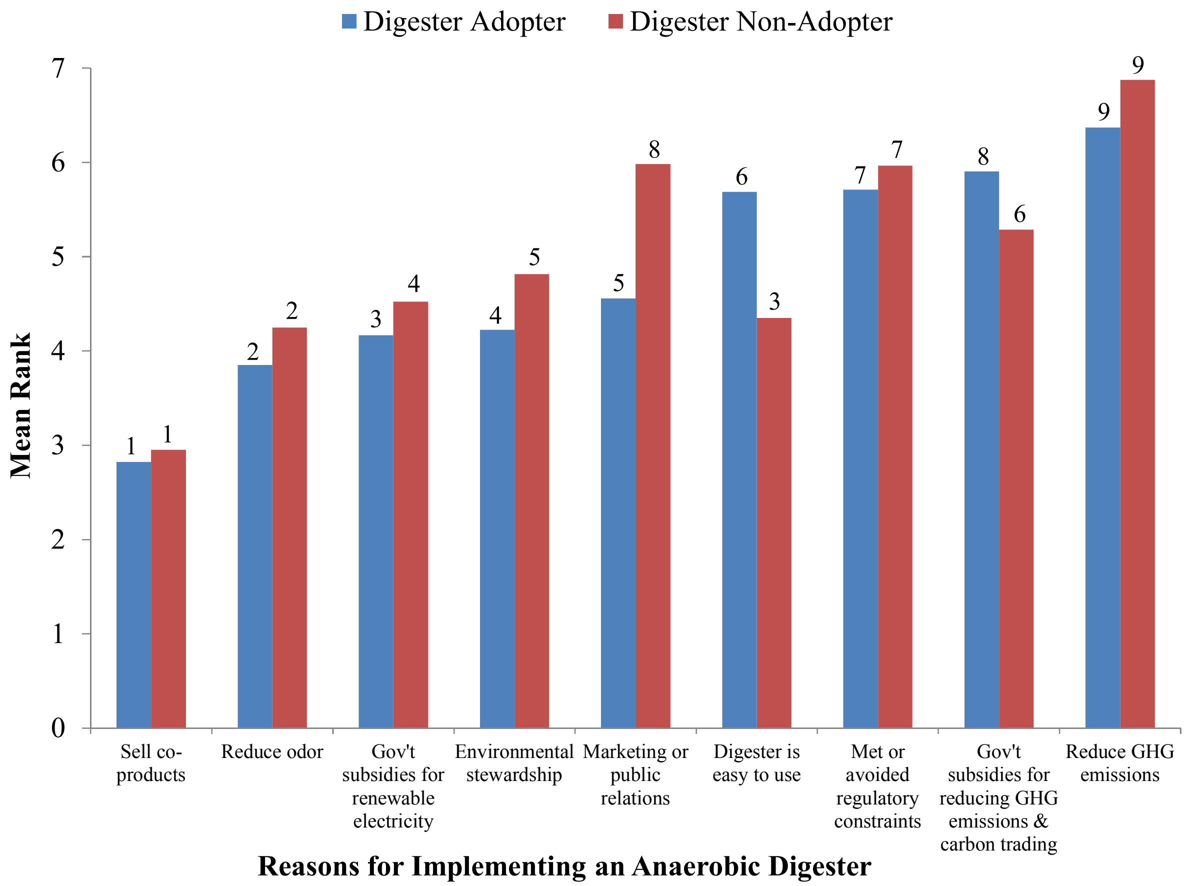


Figure II-5. Mean rankings for factors that would influence a producer's decision to implement an anaerobic digester on his or her farm

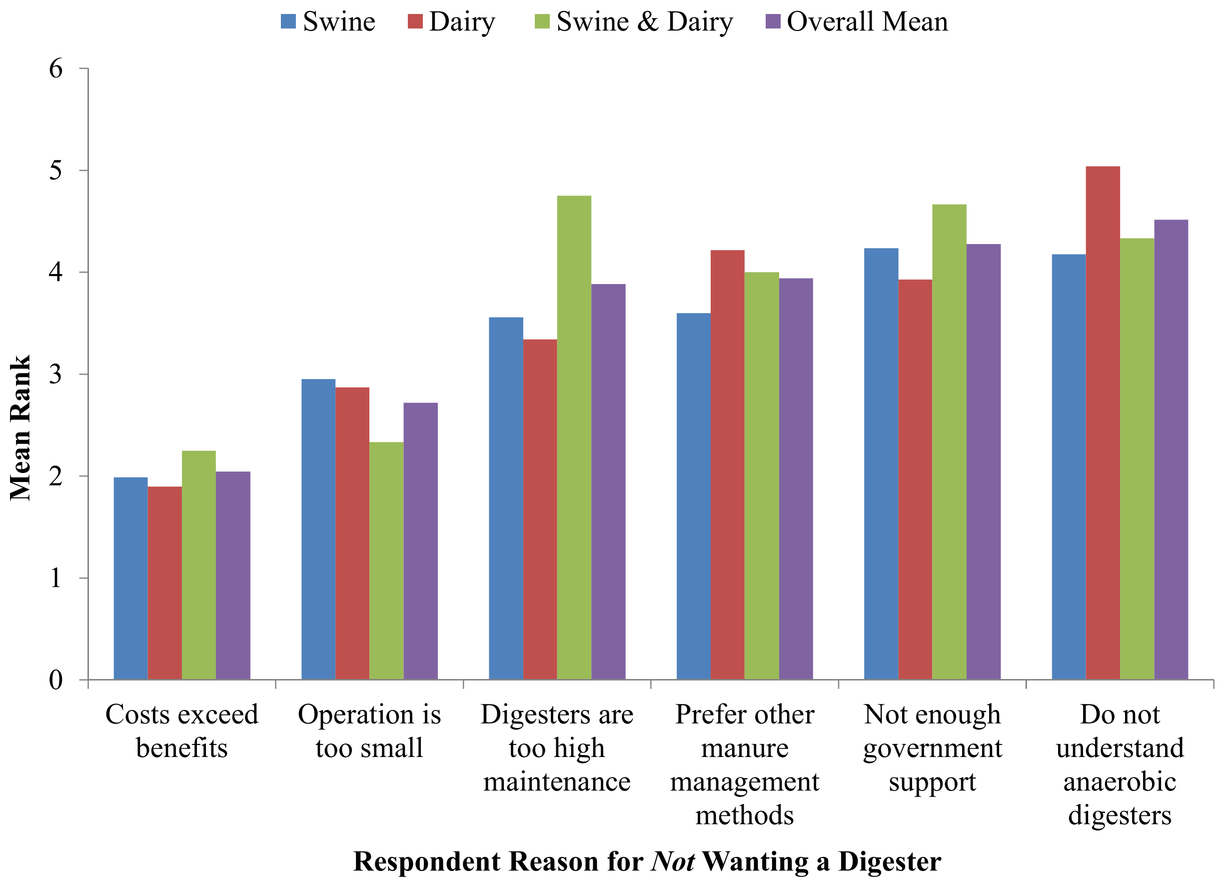
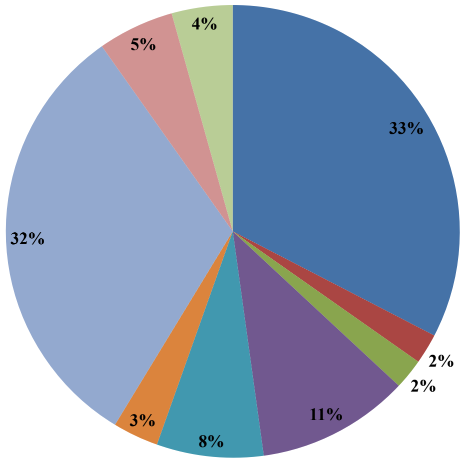
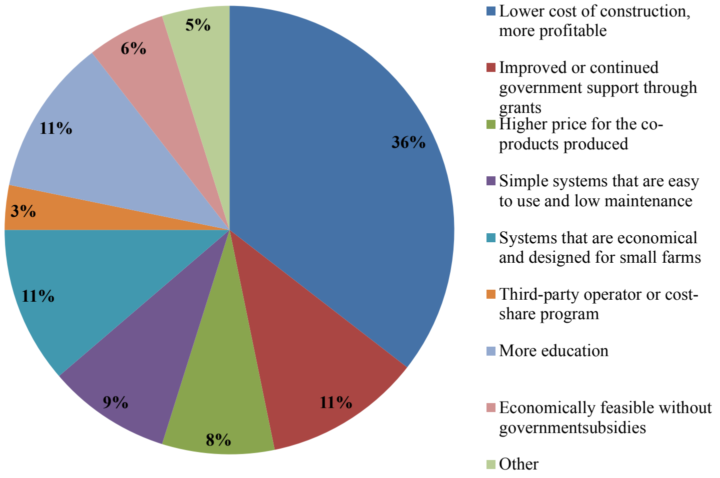


Figure II-6. Non-adopter mean rankings for reasons they would not want an anaerobic digestion system



Swine Operations



Dairy Operations

Figure II-7. The one most important thing that would have to be done to encourage more wide-spread adoption of anaerobic digestion systems, according to producers who have *not* used them

Table II-7. Marginal Effects of Co-product Prices, Government Grants, Farm Characteristics, and Farmer Demographics and Beliefs on the Probability of Adopting an Anaerobic Digester

	Estimate					
	Sell Electricity, $n = 51$ $/kWh		Carbon Credits, $n = 48$ $/animal/year		Grants, $n = 50$ % capital cost	
Parameter	Digester	No Digester	Digester	No Digester	Digester	No Digester
Price or percent	0.358	0.047	-0.009	0.015	0.0005	0.007
Farm type	-0.239	0.014	-0.123	-0.165	-0.029	-0.089
Farm size (AU)	-0.015	0.122	-0.158	0.072	0.005	0.081
Age	0.007	-0.007	-0.003	0.001	0.0002	-0.007
Farm income	-0.122	-0.006	0.026	-0.002	0.003	0.016
Education	-0.116	-0.044	-0.206	-0.127	0.0001	-0.046
Environment	-0.029	-0.017	-0.025	-0.004	-0.003	-0.011
Atlantic region	0.999	0.016	0.939	-0.187	-0.255	-0.022
Midwest region	0.954	0.046	0.982	-0.204	-0.360	-0.020
Western region	0.695	-0.218	0.815	-0.220	0.005	-0.091

***Significant at the $\alpha = 0.01$ level

**Significant at the $\alpha = 0.05$ level

*Significant at the $\alpha = 0.1$ level

Table II-8. Producer Willingness-to-accept (WTA) a Digester with Reference Values

	WTA Sell Electricity	Electricity Costs[a]	WTA Carbon Credits	ECX[b]	SCC[c]	WTA Grants	Grants[a]
Group	$/kWh		$/animal/year			% capital cost	
Digester	0.18	0.092	-17	2.72	17.5	22	49.6
No digester	0.51	0.096	18			62	N/A

[a] Mean values, as reported by survey respondents

[b] European Climate Exchange (ECX 2014)

[c] Social cost of carbon, for regulatory analysis under Executive Order 12866, $r = 3\%$ (U.S. Government 2013)

Table II-9. Bivariate Probit with Sample Selection Estimates for Non-adopters

	Estimate		
Parameter	Sell Electricity, $/kWh	Carbon Credits, $/animal/year	Government Grants, % capital cost
Dependent Variable: Consider Anaerobic Digester[a],			
	$n = 182$	$n = 197$	$n = 196$
Intercept	-3.671***	-2.778***	-3.655***
Neighbors	0.224**	0.196*	0.192**
Environment	-0.050***	-0.039**	-0.028*
Farm type	0.485**	0.405*	0.482**
Farm Size (AU)	0.447***	0.331***	0.409***
Age	0.008	0.002	-0.005
Education	0.099	0.244	0.193
Rho[b]	0.001	-0.351	-0.555
Dependent Variable: Adopt Anaerobic Digester[c]			
	$n = 66$	$n = 70$	$n = 68$
Intercept	0.614	1.248	4.377*
Price or percent	0.996**	0.010	0.014*
Farm type	-0.046	-0.330**	-1.068***
Farm size (AU)	0.051	0.005	-0.219
Age	-0.009	-0.005	-0.034*
Education	-0.242*	-0.236*	-0.550*
Environment	0.003	-0.006	-0.008
Atlantic region	0.164	-0.268	-0.153
Midwest region	-0.051	-0.151	-0.229

Note: For this model, it is assumed that we observe whether a producer will adopt an anaerobic digester only after they have *considered* implementing an anaerobic digester on his or her farm.

[a] Binary dependent variable, which equals 1 if the producer answered ‘Yes’ and 0 if the producer answered ‘No’ to the question: “Have you ever *considered* implementing an anaerobic digester on your farm?”

[b] Rho $= \rho = \text{corr}(\mu_{ij}, \varepsilon_{ij})$, and for these models Rho is insignificant. Therefore, selection bias is not present in the estimation of the anaerobic digester adoption equations.

[c] Binary dependent variable which equals 1 for ‘Yes’ and 0 for ‘No’ when producers were asked if they would implement an anaerobic digester based on electricity price, carbon credit price, and percent capital cost covered by government grants (see table II-3).

***Significant at the $\alpha = 0.01$ level

**Significant at the $\alpha = 0.05$ level

*Significant at the $\alpha = 0.1$ level

CHAPTER III

ANAEROBIC DIGESTER PRODUCTION AND COST FUNCTIONS

Abstract

The economic feasibility of anaerobic digesters on animal feeding operations has been investigated by case studies that utilize enterprise budget analyses. This study uses econometric methods to estimate production and cost functions for anaerobic digesters and then determines net present value (NPV) using the estimated functions. Production, fixed cost, and variable cost functions were estimated using a Cobb-Douglas functional form. Economies of size were evident for plug flow and complete mix anaerobic digesters, where were more economically feasible on dairy farms than on swine operations. In the absence of government grants, positive net returns were only predicted for very large swine farms with animal populations in the 98th percentile.

Introduction

As animal production facilities become larger and more concentrated, the risk of environmental and social externalities increase (Centner 2003). Environmental degradation from nutrient pollution consistently ranks as one of the top water quality issues in the U.S. (Carpenter 1998). In addition to water quality impairments, the livestock industry in the U.S. is often blamed for atmospheric environmental problems, including the discharge of methane into the atmosphere (Zaks et al. 2011). Methane is a potent greenhouse gas that could contribute to global warming (Lashof and Ahuja 1990). While livestock are not a net source of carbon dioxide, enteric fermentation and manure management account for almost 35% of methane emissions from anthropogenic activities in the United States (USEPA 2014b). The production of livestock also requires large amounts of human and fossil fuel energy, with the agricultural sector accounting for approximately 19% of the energy use in the U.S. (Canning 2010; Pimentel 1973; Pimentel and Pimentel 1996; Pimentel 2008).

Despite the environmental and resource concerns identified for confined animal agriculture, anaerobic digestion could be a viable solution to multiple problems. With anaerobic digestion, solids and biosolids are stabilized by decomposing organic matter in the absence of molecular oxygen (Tchobanoglous et al. 2014). To alleviate greenhouse gas emissions, anaerobic digestion systems capture and combust methane. Anaerobic digesters also have the potential to produce value-added co-products on the back end that could include soil amendments, livestock bedding, and liquid that can be used as fertilizer (Zaks et al. 2011; Bishop and Shumway 2009). However, despite the potential environmental and economic benefits, anaerobic digestion systems are not yet common in the United States. Currently only 238 of the almost 20,000 (~1%) confined animal feeding operations in the United States have anaerobic digestion systems (USEPA 2012a; USEPA 2014a).

The potential environmental benefits of these systems are only one side of a very complex *economic* issue. The economics, and more specifically the capital costs, of these systems are often blamed for their limited adoption (Lazarus and Rudstrom 2007; Kruger et al. 2008; Stokes, Rajagopalan, and Stefanou 2008; Bishop and Shumway 2009; Wang 2010; DeVuyst et al. 2011). Most literature on the economic feasibility of anaerobic digestion systems has used site-specific case studies. Bishop and Shumway (2009) and Kruger et al. (2008) describe financial analyses of anaerobic digesters on two dairy farms in the Pacific Northwest. Both found that reduced capital costs from government grants, additional revenue streams from co-products like electricity, fiber, nutrients, and co-digestion of food waste are important for obtaining sufficient return on investment.

Lazarus and Rudstrom (2007) studied the economic feasibility of an anaerobic digestion system on a Minnesota dairy farm. They used a ten-year capital budgeting analysis and found that the profitability of the digester was primarily due to favorable pricing by the local electrical utility and financial assistance from various government agencies. Wang (2010) aggregated cost and returns data from six dairy farms in the state of Vermont to study the economics of converting manure to electricity and also found that economic returns for digesters primarily depend on electricity premium price, government grants and/or subsidies, and selling value-added co-products. Stokes, Rajagopalan, and Stefanou (2008) used capital budgeting and a real option framework to determine why producers in Pennsylvania adopt methane digesters. They determined that the initial investment of a digester is so great that “significant grant funding is required to induce methane digester investment since the option to delay the investment has value” (Stokes, Rajagopalan, and Stefanou 2008, p. 675).

Finally, DeVuyst et al. (2011) examined the economic feasibility of co-locating a beef cattle feedlot and anaerobic digester with an existing corn ethanol plant. The idea was to create a closed-loop system, where byproduct from the ethanol plant was used as forage for the beef cattle, manure from the beef cattle was used as input into the anaerobic digester, and excess heat and energy produced by the anaerobic digester was utilized by the ethanol plant. Investment in an anaerobic digester at the cattle feedlot was not recommended due to high capital costs and required loan services that could not be supported by projected revenues.

It is certainly important to examine the economic feasibility of anaerobic digesters on a case-by-case basis, but it is also imperative to understand economies of size and scale for this technology at a regional or national level. Most previous studies examined anaerobic digesters that were already established and operational. However, agriculturalists and policy makers currently do not have enough empirical evidence to know the specifics on what works best for successful implementation of anaerobic digesters. For example, what sizes of CAFOs (number of animals) are typically the most profitable? Therefore, the purpose of this study is to use data from a nation-wide survey of anaerobic digester operators to provide information that will help researchers, policy makers, and CAFO owners/operators more easily identify operating and design parameters that make anaerobic digestion more profitable. The products and co-products from anaerobic digestion vary depending on the inputs, economics of the system, and/or the desires of the owner/operator. However, *all* anaerobic digestion systems produce methane. Therefore, the objective of this study is to develop a production function, a fixed cost function, and a variable cost function for methane production in an anaerobic digester to be used in a producer's expected net present value maximization problem. The secondary objective is to determine the levels of inputs that make the digester the most economically feasible. Econometric methods, including regression and misspecification testing, are used to estimate production and cost functions.

Theory

The expected net present value maximizing decision maker's problem for an anaerobic digester on a dairy or swine operation of fixed size is

$$\max_{n} E(NPV_i) = \sum_{i=0}^{n} \sum_{t=1}^{T} \left[\frac{p_{it} y_{it} - AVC_{it} y_{it}}{(1 + r_t)^t} \right] - AFC_i y_i \tag{III-1}$$

$$\begin{gathered} \text{s.t. } E(NPV_i) \geq 0 \\ y_{it} = f(\boldsymbol{x_{it}}; \boldsymbol{\beta}, \boldsymbol{\gamma}) \\ AFC_{it} = f(\boldsymbol{x_{it}}; \boldsymbol{r}, \boldsymbol{\psi}) \\ AVC_{it} = f(\boldsymbol{x_{ti}}; \boldsymbol{\omega}, \boldsymbol{\varphi}) \end{gathered}$$

where n is a choice variable for the outputs that the producer wishes to produce, where, $i = 0$ is no production, $i = 1$ is recovered methane, $i = 2, \dots n$ are any additional value-added co-products, $E(NPV_i)$ is the expected present value of the anaerobic digester investment, r_t is the discount rate for the t^{th} year, where $t = 1, \dots, T$ and $T = 25$ years, and $r = 10\%$, p_{it} is the price of each co-product in \$/unit, y_{it} is a methane production function for anaerobic digestion systems, which estimates methane production in MBtu/year and is also used to estimate the production of additional co-products, AFC_i represents the average fixed cost function for producing methane and other digester co-products in \$/MBtu/year, AVC_{it} is the average variable cost function for methane production in an anaerobic digester in \$/MBtu/year^2, and $\boldsymbol{x_{it}}$ is a vector of digester design parameters, inputs, and farm characteristics.

As described by Heady and Dillon (1961), the physical parameters are often the most important and limiting when trying to develop efficient estimates for agricultural production functions. The economic feasibility of any production process depends not only on prices but also on the science, technology, and physical possibilities of the system (Heady and Dillon 1961; Dicks and Doll 1983). Therefore, it is important to understand the fundamentals of how methane is created through anaerobic digestion.

During anaerobic digestion, organic matter is broken down in a process that includes four chemical and biochemical reactions: hydrolysis, fermentation (or acidogenesis), acetogenesis, and methanogenesis (Tchobanoglous et al. 2014). Hydrolysis is considered the most important, or rate-limiting, step in the anaerobic digestion process (Mata-Alvarez 2000). During hydrolysis, dissolved, insoluble particles are broken down into fermentable sugars by enzymes (Poulsen 1983). Fermentation is the process by which sugars are converted to alcohol by bacteria and possibly small populations of protozoa, fungi, and yeasts (Poulsen 1983; Tchobanoglous et al. 2014). During acetogenesis, fermentation products are oxidized into substrates appropriate for methanogenesis, which is the bacterial conversion of oxidized organic compounds into methane and carbon dioxide (Tchobanoglous et al. 2014). When designing an anaerobic digestion system, there are several factors that affect these chemical and biochemical reactions.

The temperature of the system affects the rate of bacterial growth and waste degradation, effluent odor reduction, the quantity of moisture in the biogas, the concentration of ammonia and hydrogen sulfide gas dissolved in solution, and the quantity of gas produced (Burke 2001). The chemical and biochemical processes responsible for breaking down organic waste particles and forming methane are extremely sensitive to variations in temperature. Therefore, maintaining a stable temperature in the anaerobic digester can be even more important than selecting a design operating temperature (Tchobanoglous et al. 2014). The range of standard operating temperatures for methane production in plug flow and complete mix digesters is very small (95-104°F) (NRCS 2009).

Loading rate refers to the solids concentration of material entering the digester per unit of time. Loading rates that are either too high (concentrated) or too low (diluted) can result in non-optimal digester performance. NRCS (2009) standards recommend total solids concentrations between 11% and 14% for plug flow digesters and less than 11% for complete mix digesters. Retention time is defined as the time that the liquids and solids are held in the digester (usually in days). The reactions that take place inside the digester (hydrolysis, fermentation, acetogenesis, and methanogenesis) are directly related to hydrolic retention time (HRT) and solids retention time (SRT) (Tchobanoglous et al. 2014). Retention time must be set above the minimum time required for each reaction. Otherwise, bacteria will not grow fast enough for the digestion process to continue at an optimal rate (Dicks and Doll 1983; Tchobanoglous et al. 2014).The minimum retention time for plug flow digesters is 20 days, and the minimum retention time for complete mix digesters is 17 days (NRCS 2009).

Other physical parameters that could influence methane production include quantity of manure, digester volume, type of digester, and the composition of inputs. Unlike those described in the previous paragraph, these parameters do not have published guidelines for optimal methane production, and little is known as to as to how they affect profitability of anaerobic digesters. Just as nitrogen and/or phosphorus fertilizer is a primary input in a crop production system, the primary input for methane production in an anaerobic digester is manure. The quantity and composition of the manure excreted by livestock will determine the digester's design parameters, such as volume, type, retention time, and loading rate (Tchobanoglous et al. 2014). For example, a 1,375-lb lactating dairy cow producing 100 lb milk/day will excrete 2.6 ft^3 manure/day with a total solids content of 13% (USDA 2008). Multiplying the amount of manure excreted per cow by the number of cows at the dairy and the required retention time for manure (in days) will approximate the volume of the digester.

While all anaerobic digesters perform the same, basic functions, there are several types that are used when handling manure. The type of digester selected can vary depending on manure or waste stream composition, material handling techniques, budget, and personal preference. While there are several types of digesters, they are typically split into three categories: passive systems, low rate systems, and high rate systems (Hamilton 2013). For passive systems, methane recovery is added to existing manure management or treatment infrastructure. In low rate systems, manure is the primary source of methane-forming microorganisms. High rate systems differ in that methane-forming microorganisms are added to and contained in the digester to increase methane production efficiency (Hamilton 2013). The most common anaerobic digesters are covered lagoons (passive systems), complete mix digesters, and plug flow digesters (both low rate systems).

For methane production, inputs other than manure could increase or decrease manure produced in an anaerobic digester. Food processing wastes that have similar characteristics as livestock manure, in terms of moisture, total solids, and volatile solids content and chemical/biological oxygen demand, can improve the methane output of an anaerobic digester (Scott and Ma 2004). Food wastes have twice the methane yield per pound of volatile solids when compared to manure (Goldstein 2012). However, since most anaerobic digesters in the U.S. are designed to treat animal wastes, the addition of food or other organic wastes that do not have similar physical, biological, and chemical compositions could disrupt the system, so careful consideration must be taken when adding food waste to an anaerobic digester. Livestock producers may also be interested in how the size of their operation (or the number of animals contributing manure to the digester) and the species of livestock that they produce could affect digester productivity and profitability.

When considering anaerobic digestion for manure management livestock producers are primarily concerned with how much the system costs and whether or not their farm is large enough (in terms of number of animals or animal units) to generate the revenues required to overcome the large capital costs of the system. Figure III-1 shows the results from a survey question given to producers who do not currently operate anaerobic digesters. The producers were asked to rank the reasons they would not want an anaerobic digester on their farm. On average, the two most important reasons for producers not wanting an anaerobic digester were 1) that the costs of the digester exceed the benefits and 2) that they believed their operation is too small to support an anaerobic digester.

While the economic feasibility of anaerobic digesters on dairy farms has been researched, little academic information is available on anaerobic digester economies of size, especially on swine farms. Leuer, Hyde, and Richard (2008) tested three different dairy farm sizes and determined that methane digesters are only profitable for farms with 1,000 or more cows that produce animal bedding as a co-product. Gloy (2011) discussed how the substantial economies of size associated with anaerobic digesters on dairy farms could contribute to the distributional impacts of policies that create markets for carbon dioxide offset trading. Although previous studies have estimated economies of size and observed positive relationships among livestock numbers and methane production, more information is needed to determine how varying digester design and input parameters affect digester scale economies.

Data

Data for this study were collected from a 2013 – 2014 nationwide survey of dairy and swine producers. The survey started by asking a set of introductory questions, which allowed the survey to funnel respondents to the proper set of questions. Animal feeding operation owners/operators that currently use anaerobic digestion technology on their farms, animal feeding operation owners/operators that once used anaerobic digestion technology on their farms (but it has been shut down), and third-party anaerobic digester operators were asked to answer three sections of the survey: 1) Introductory Questions, 2) Physical Parameters and Digester Design, and 3) Economic Considerations.

The survey population for this study consisted of operational and decommissioned digesters that process (or processed) dairy and/or swine manure in the United States. The USEPA AgSTAR program provides a list of all operational and decommissioned digesters in the United States on their website. According to the AgSTAR program, there are currently 238 operational digesters (193 dairy, 31 hog operations, and 14 other) and 45 decommissioned digesters (31 dairy, 7 hog operations, and 7 other) in the United States (USEPA 2014a). Of the 238 operational digesters, 203 were located on dairy and hog farms, while 21 were owned or operated by a third-party that processes dairy or swine manure. Of the 42 decommissioned digesters, 33 are located on dairy and hog farms, while 5 are owned or operated by a third party that processes dairy and hog manure. The owners and/or operators of these digesters were selected as subjects for this study.

Online and paper versions of the survey instrument were created. The online version was developed using Qualtrics Survey Software. Prior to survey launch, a pretest with two anaerobic digester operators (one agricultural/professional engineer and one environmental health and safety manager for a hog farm) and one USDA NASS official indicated only slight modifications to the survey instrument. On December 20, 2013, a postcard, which included a link to the online survey and information about the study, was mailed to all subjects in the sample. On January 21, 2014, a survey packet was mailed to those who did not respond to the online survey announcement. The survey packet included the paper version of the questionnaire, a postage paid return envelope, and a letter reemphasizing the importance of the research and the rights of study participants.

The paper survey also included a link to the online survey and contained the same questions in the same order as the online survey.

A final reminder postcard was mailed on February 12, 2014. The postcard again included a link to the online survey and a reminder of the paper survey received in the last mailing. Mailing addresses of subjects were provided by the United States Department of Agriculture (USDA) National Agricultural Statistics Service (NASS), and each subject was given a 4-digit sequencing, or identification, number so that the researchers could keep track of the subjects that responded to the survey and those that did not. Sequencing numbers were printed on the upper right corner of the address label, which was placed on the postcard or survey packet envelope. Before starting the survey, respondents were asked to provide their sequencing number so that they could be removed from the survey mailing list. Survey responses were collected from December through May 2014.

Since the populations of farms with operational and shutdown digesters were small, the goal was to survey the entire population. However, some operations were on a "do not contact" list with USDA NASS. Therefore, the samples were slightly smaller than the actual populations, as shown in table III-1. Of the surveys mailed to current and previous digester operators, only one was returned as out-of-scope due to retirement, death, sale, or restructuring, and three were not complete. The resulting response rate for digester operators was almost 30%. Although no surveys were returned from swine operations with shutdown digesters, six completed responses were obtained from dairy farms, so the response rate for all shutdown digesters was a little over 16%. Since only six viable surveys were returned from operations with shutdown digesters, these responses were grouped together with the operational digester responses. Surveys for decommissioned digesters contained the same physical and economic data as surveys for operational digesters. When developing production and cost functions, it was important to capture information from digesters that have not worked with those that have been successful. For the combined sample, the overall response rate was 27.2%, and the sampling error was 11.3% (table III-1).

Table III-2 lists summary statistics for variables included in the “Physical Parameters and Digester Design” section of the survey. Respondents were asked to report farm size, or capacity, in terms of number of animals and then to specify the number of animals that contribute manure to the anaerobic digester, which will henceforth be referred to as the “digester population.” Some of the dairy farms included only dairy cows, while other operations had dairy cows and heifers. All of the hog farms included in the analysis were wean-to-finish operations, so no sows, nursery pigs (farrow-to-wean), or boars were included. Four diversified livestock operations managed herds of dairy cows, dairy heifers, and wean-to-finish pigs. On average, digester population was smaller than farm size. While all of the dairy farms used dairy cow manure in the digester, less than half also incorporated manure from heifers. One dairy farm accepted swine manure from an outside source (table III-2).

Digester population for each farm was assumed to remain constant throughout the year (i.e. continuous replacement and no seasonal fluctuations). Reported digester populations in number of animals were converted to animal units (AU). An animal unit represents 1,000 pounds of live animal weight and serves as a common unit for combining different species of livestock. Several states provide regulations and standards for calculating animal units, and their definition of an animal unit is similar to the definition used in the study. For example, the Livestock Management Facilities Act in Illinois states that an animal unit refers to the one-time capacity of a facility. In the survey instrument, producers reported that the number of animals feeding the digester remains constant throughout the year, and the number given is a one-time “snapshot” of the number of animals feeding the digester.

Animal unit conversions are based on the average mature animal weight of each livestock category. The conversion factor for milk cow digester populations was 1.4. The animal unit conversion for dairy heifers was 1.1, and the conversion factor for market hogs weighing more than 55 pounds was 0.4. Equations for calculating milk cow, dairy heifer, and market hog animal units were specified as

$$\text{Milk cow AU} = \text{milk cow digester population} \times 1.4,$$

$$\text{Dairy heifer AU} = \text{dairy heifer digester population} \times 1.1, \text{and}$$

$$\text{Market hog AU} = \text{swine over 55 pounds } \times 0.4.$$

Almost half of the digesters are plug flow systems, which could include vertical plug flow, horizontal plug flow, or mixed plug flow systems. The next largest group included complete mix anaerobic digestion systems. A little over 8% of respondents reported that they operated a covered lagoon system, and the remaining digesters were induced blanket reactors, anaerobic sequencing batch reactors, or other types of systems. On average, digesters were in operation for 6.5 years, primarily constructed with concrete, located above ground, and had an internal heater or mechanism for controlling temperature. For most digesters, manure was the primary material entering the digester, but some digesters also processed food production/processing waste, crop residue, and/or byproducts from other manufacturing processes (e.g. glycerol from ethanol production). Approximately half of the survey participants were located in the USDA Agricultural Resource Management Survey (ARMS) Atlantic Region, followed by 25% in the Midwest Region. The remaining 20% were located in the West, Plains, or South region or did not answer the survey question about state of residence. Figure III-1 provides a reference map for USDA ARMS regions.

Table III-3 summarizes data collected in the “Economic Considerations” section of the survey. The mean capital investment for the operational and shutdown digesters was almost $2 million. Digester capital costs were primarily covered by personal (or business) savings, capital, or loans and government grants. A few respondents reported other payments options, such as third-party financing and additional local or environmental grants. For farms that employed an anaerobic digester operator, the operator worked about 25 hours per week, and the average annual costs associated with the operation, labor, maintenance, and repairs of the anaerobic digestion system were $50,400 per year. Aside from electricity generation, most of the methane produced by farms in this study was used for boiler or furnace fuel (heat) or flared. Two respondents reported using some methane for compressed natural gas (CNG) vehicle fuel. The mean revenue for these activities totaled $11,750 per year. For operations that used methane for electricity production, the average annual revenue and cost savings from electricity generation was $376,979.

In addition to methane and electricity, some survey participants produced additional digester co-products. Over 70% of the farms surveyed reported animal bedding as a co-product. The heat from the digestion process combined with solids separation allows anaerobic digester operators on dairy farms to produce pathogen-free fibers that can be used for animal bedding and/or soil amendments (Bishop and Shumway 2009; Lazarus and Rudstrom 2007). The production of fertilizer was listed as a revenue stream by 45% of producers surveyed, and 18% of survey respondents produced compost soil amendments. Other co-products included carbon offsets and other value-added products.

Procedure

Because design parameters can vary significantly by type of digester, separate production functions were estimated for plug flow and complete mix digesters. Over 80% of the digesters were either plug flow or complete mix digesters. Similarly, almost 80% of the operational digesters in the United States are plug flow or complete mix anaerobic digestion systems. Insufficient data was collected to determine production functions for other digester types, such as covered lagoons and fixed film digesters.

The functional form used to estimate production functions can affect the conclusions. Tchobanoglous et al. (2014) uses a linear functional form. However, the Tchobanoglous equation uses inputs such as chemical oxygen demand of the digester influent and effluent and net mass of cell tissue produced per day. Data for these parameters were not provided here. Other literature that has modeled the physical aspects of methane production in an anaerobic digester use the Freundlich equation that was initially developed by soil scientists to model phosphorus and colloidal adsorption in soils (Freundlich 1910; Sibbesen 1981; Pandey 2010). In economics, the Freundlich equation would resemble a Cobb-Douglas type production function.

Figure III-3 shows that variables for digester population and non-manure inputs (as a percentage of total inputs entering the digester) could follow a Cobb-Douglas functional form. Figure III-3 also illustrates how some design parameters like temperature do not provide a good fit for a Cobb-Douglas functional form. Table III-2 shows that almost 90% of all digesters included in this study have some sort of temperature control mechanism. In fact, 100% of the plug flow and complete mix digesters keep their systems running within the range specified by NRCS (2009), as shown in Figure III-3. Since variables like temperature, loading rate, and retention time should not vary outside the specified ranges and do not appear to be a good fit, production and cost functions were specified without including these variables.

A Cobb-Douglas production function for methane produced from a plug flow anaerobic digester was specified as

$$\ln y_{1j} = \beta_0 + \beta_1 \ln A_j + \beta_2 \ln I_j + \gamma_1 F_j + \gamma_2 G_j + \gamma_3 C_j + \gamma_3 S_j + \varepsilon_j \tag{III-2}$$

where y_{1j} is the amount of methane produced in the j^{th} digester in MBtu/year, where $j = 1, \dots, n$, A_j is the population feeding the digester in animal units (AU), I_j is the percentage of non-manure inputs, such as food waste, entering the digester, F_j is an indicator variable for farm type, which equals 1 for dairy farms and 0 otherwise, G_j is an indicator variable for whether or not the digester is above ground, C_j is an indicator variable for whether or not the digester was primarily constructed with concrete, S_j is an indicator variable for whether or not steel was the primary construction material, and $\varepsilon_j \sim N(\mu, \sigma_\varepsilon^2)$ is the random error term. Equation (III-2) was also specified for a complete mix anaerobic digester.

The data used to estimate equation (III-2) are cross-sectional, and the sample of farms includes many small farms (in terms of animal units) and few large farms. The sizes of the digesters on these farms (in terms of volume in ft^3) vary in a similar fashion. Many of the digesters have been (or were) operational for 10 years or less while only a few of the digesters have operated for more than 10 years. Because of the varying sizes of farms, digesters, and operating years, heteroskedasticity was expected. Maximum likelihood estimation (MLE) assuming exponential heteroskedasticity was used instead of ordinary least squares. Joint and individual misspecification testing, using methods described by McGuirk, Driscoll, and Alwang (1993), of the mean and variance equations for normality, stability, functional form, dependence, and heteroskedasticity showed that the Cobb-Douglas production function for methane in (III-2) was correctly specified.

While separate production functions were specified for plug flow and complete mix digesters, fixed and variable cost functions were estimated for *all* plug flow and complete mix digesters included in this study. Digester design parameters that influence the production of methane differ depending on digester type, but the parameters that influence the fixed and variable costs of a digester do not vary among different digesters. Although the fixed and variable cost functions remain constant among digester types, separate cost functions were specified for digesters that produce only methane and digesters that produce methane and other co-products. The two added co-products were electricity and animal bedding. Electricity production requires an electricity generator, which increases fixed and variable costs. Likewise, recycling processed manure solids into animal bedding requires a solids separator and possibly additional equipment.

Total fixed cost appeared to have a positive linear relationship with input variables. Due to economies of size, average fixed cost, as shown in table III-3, decreases with size. Figure III-4 contains two scatter plots that show a type of power relationship between average fixed cost and the input variables for digester population in animal units (AU) and digester volume in ft^3. These plots suggest that the fixed cost function may be more appropriately specified as a Cobb-Douglas type function than a linear function. This approach is supported by other economic studies that have used Cobb-Douglas functions to specify cost equations (Binswanger 1974; Brown, Caves, and Christensen 1979).

A Cobb-Douglas average fixed cost function for methane produced from an anaerobic digester was specified as

$$\ln AFC_{1j} = \alpha + r_1 \ln A_j + r_2 \ln V_j + \psi_1 F_j + \psi_2 G_j + \psi_3 C_j + \psi_4 S_j + \mu_i \tag{III-3}$$

where AFC_{1j} is the average fixed (or capital) cost of producing methane in the j^{th} digester in \$/MBtu, V_j is the volume of the digester in ft^3, r_1 is a parameter to be estimated and represents the cost per animal unit of constructing the digester in \$/AU, r_2 is a parameter to be estimated and represents the cost per unit volume of constructing the digester in \$/ft^3, and $\mu_i \sim N(\mu, \sigma_v^2)$ is the random error term.

Variables such as hydraulic retention time (H) are directly related to the design size, or volume, of the digester and are therefore included in the intercept term, α. Using methods described by McGuirk, Driscoll, and Alwang (1993), the null hypothesis that the Cobb-Douglas cost function for methane in (III-3) was specified correctly could not be rejected. A fixed cost function for anaerobic digestion systems that produces methane and other co-products was specified as

(III-4) $$\ln AFC_{ij} = \alpha + r_1 \ln A_j + r_2 \ln V_j + \psi_1 F_j + \psi_2 G_j + \psi_3 C_j + \psi_4 S_j + \psi_6 E_j + \psi_7 B_j + \mu_j$$

where E_i is an indicator variable for electricity generation and B_i is an indicator variable for whether or not animal bedding is a co-product.

A variable cost function for the methane digesters included in this study was also estimated. Figure III-5 shows that the variable cost function also may be more appropriately specified as a Cobb-Douglas function than a linear function. A Cobb-Douglas variable cost function for methane produced from an anaerobic digester was specified as

(III-5) $$\ln AVC_{1j} = b + \omega_1 \ln A_j + \omega_2 \ln I_j + \varphi_1 F_j + \varphi_2 G_j + \varphi_3 C_j + \varphi_4 S_j + \nu_j$$

where AVC_{1j} is the average variable (or operating) cost of producing methane in the j^{th} digester in \$/MBtu/year^2, ω_1 is a parameter to be estimated and represents the cost per animal unit of operating the digester in \$/AU, ω_2 is a parameter to be estimated and represents the variable cost of processing manure with other inputs in \$/year, and $\nu_j \sim N(\mu, \sigma_\nu^2)$ is the random error term. Joint and individual misspecification of the mean and variance equations indicated that Cobb-Douglas variable cost function for methane in (III-5) was specified correctly. A variable cost function for an anaerobic digester that produces methane and other co-products was specified as

(III-6) $$\ln AVC_{ij} = b + \omega_1 \ln A_j + \omega_2 \ln I_j + \varphi_1 F_j + \varphi_2 G_j + \varphi_3 C_j + \varphi_4 S_j + \varphi_4 E_j + \varphi_5 B_j + \nu_j$$

where all variables and parameters are as described previously.

Plugging (III-2), (III-3), and (III-5) into (III-1) and transforming the log-linear equations, the expected NPV maximization problem for a digester that produces only methane can be written as

$$(\text{III-7})\quad \max_{n} E(NPV_1)$$

$$= \sum_{t=0}^{T} \left[\frac{1}{(1+r_t)^t}\right] \left[p_1 e^{\left(\beta_0+\beta_1 \ln A+\beta_2 \ln I++\gamma_1 F+\gamma_2 G+\gamma_3 C+\gamma_3 S+\sigma^2/_2\right)}\right.$$

$$\left. - e^{\left(b+\omega_1 \ln A+\omega_3 \ln I+\varphi_1 F+\varphi_2 G+\varphi_3 C+\varphi_3 S+\sigma^2/_2\right)} e^{\left(\beta_0+\beta_1 \ln A+\beta_2 \ln I++\gamma_1 F+\gamma_2 G+\gamma_3 C+\gamma_3 S+\sigma^2/_2\right)}\right]$$

$$- e^{\left(\alpha+r_A \ln A+r_V \ln V+\psi_1 F+\psi_2 G+\psi_3 C+\psi_4 S+\sigma^2/_2\right)} e^{\left(\beta_0+\beta_1 \ln A+\beta_2 \ln I++\gamma_1 F+\gamma_2 G+\gamma_3 C+\gamma_3 S+\sigma^2/_2\right)}$$

where all variables are the same as described in equations (III-2), (III-3), and (III-5). Net present values, as shown in (III-7) were calculated for several different farm sizes. This was done for digesters that produce only methane, for digesters that produce both methane and co-products, and for digesters that produce methane and co-products and receive government grants.

Production of co-products was estimated by attaching a conversion factor to the methane production function. In most cases, the methane produced by the anaerobic digester is injected into an internal combustion engine to produce electricity. The conversion coefficient calculation for electricity is a straight-forward unit conversion, which includes the ratio of 1 British thermal unit (Btu) to 0.293 watt-hours (Wh). The conversion coefficient for animal bedding is less straight forward, but is still intuitive because both methane and animal bedding are generated from organic solids in the digester. Conversion coefficients are included in table III-5, and a more in-depth explanation of the conversion coefficient calculations is available in Appendix A. In the survey producers were asked to specify the end use of the methane produced in their anaerobic digesters. This information was provided as a percent of each use. To prevent double counting of methane revenues, averages for each end use were included in the present value calculations. Within the survey sample, producers reported that, on average, government grants covered almost 50% of the capital costs associated with their digesters. While the primary objective of this study was to determine the economic feasibility of digesters *without* government grants, they are added at the end to see how they affect anaerobic digester economies of size. For the scenario with government grants, the expected net present value maximizing decision maker's problem for a plug flow or complete mix anaerobic digester is

(III-8)
$$\max_{n} E(NPV_i) = \sum_{i=0}^{n}\sum_{t=1}^{T}\left[\frac{p_{it}y_{it} - AVC_{it}y_{it}}{(1+r_t)^t}\right] - (1-\Gamma)AFC_i y_i$$

where Γ is the percentage of the fixed costs that are covered by government grants.

A discount rate of 10% was used to calculate expected net present value. The price of methane ($p_1 = \$4.12/\text{MBtu}$) was obtained from the Henry Hub natural gas futures for November 2014. In the survey, producers who produce electricity with their anaerobic digester were asked for the price they receive for selling electricity "back on the grid." The average price received by producers with plug flow digesters was $\$0.073/\text{kWh}$, and the average price of electricity generated by complete mix digesters was $\$0.066/\text{kWh}$. Several university extension publications estimate the cost of animal bedding between \$50/ton and $\$100/\text{ton}$ (e.g. Tranel, Bentley, and Lager 2013; Vanderwerff et al. 2013). For this study, \$50/ton animal bedding is used as a conservative estimate.

Results

Table III-6 shows estimates of the Cobb-Douglas production function specified in (III-2). All variables except 'below ground' were significant at the 90% confidence level in the production function for plug flow digesters. In the production function for complete mix digesters, digester population and dairy farms were the only significant variables. The parameter estimates for digester population, or the number of animals feeding the digester, are close to and greater than 1, indicating constant to increasing economies of size. The estimate for the non-manure input materials was negative and significant in the production function for plug flow digesters, which reflects the relationship shown in figure III-3. Higher levels of non-manure inputs could impede methane production, but the effect is small.

Parameter estimates for the dairy farm indicator variable were positive and significant, which suggests that plug flow and complete mix digesters that process dairy manure produce more methane than digesters located on swine farms. Estimates for concrete were also positive in both equations and larger than the estimates for steel. Digesters constructed from primarily concrete could be more insulated and provide a more controlled environment, which could help them be more productive. It was expected that the same would be true for digesters constructed below or partially below ground, but estimates for that variable were not significant.

Table III-7 includes estimates of the fixed cost function. For all digesters, coefficients for digester population and digester volume had a negative sign. The negative sign on these estimates corresponds to the scatter plots with trend lines shown in figure III-4. The parameter estimate for digester population is also less than one. As herd size increases, fixed costs per AU decrease at a decreasing rate. Although the estimate for digester volume is only significant for complete mix digesters, it is negative and less than one. Anaerobic digesters are more cost-effective for dairy farms, as indicated by the negative sign on the estimate for the dairy indicator variable. Digesters that are built below ground have lower fixed costs than digesters that are above ground. The result that digesters built below ground are less expensive is unexpected, considering that they should incur additional excavation costs.

Table III-8 includes empirical estimates for the variable cost function, where the intercept and estimates for digester population, dairy farms, below ground, and animal bedding show significance in one or both equations. As with average fixed costs, estimates for digester population and non-manure inputs had a negative sign. Digesters that are located on dairy farms and that are built below ground experience lower variable costs. For the variable cost equation, the negative sign on the estimate for the below ground indicator variable is expected because these digesters are not as exposed to the elements and should be able to more easily maintain steady operating conditions (such as temperature).

Estimated production and cost functions were used to calculate net present values for digester populations of various sizes. The digester populations used for these calculations were the minimum, first quartile, median, third quartile, and maximum values from the survey sample (200, 750, 2000, 5000, and 17,080 AU). As shown in figures 6 and 7, present values for digesters that produce only methane were negative for all digesters and became more negative for swine operations as digester population increased toward the maximum value in the sample. Net present values (NPVs) for complete mix digesters on dairy farms that produce only methane appeared to reach a minimum around 5,000 AU and then began to increase. These results are not surprising, since most studies on the economics of anaerobic digestion systems conclude that methane production alone is not economically feasible (Lazarus and Rudstrom 2007;

Kruger 2008; Stokes, Rajagopalan, and Stefanou 2008; Bishop and Shumway 2009; Wang 2010; DeVuyst et al. 2011).

Figures 6 and 7 also show the effects of digester population and influent composition on present values of plug flow and complete mix anaerobic digesters on dairy and swine farms. For plug flow digesters on swine farms, influent composition had little effect on the present value of the system. This effect was greater for complete mix digesters and changed as digester population increased. For both types of animal species and digesters that produce only manure, the addition of other organic wastes was economically beneficial. For very large operations that produce methane *and* other co-products (figures 8 and 9), it becomes more economically beneficial to digest 100% manure. While the effect on NPV is small, complete mix digesters on small swine operations (< 5,000 AU) could benefit more from the addition of other organic wastes. While these non-manure inputs help increase digester output, accepting organic wastes from outside sources (e.g. restaurants or food processing plants) could also generate additional revenues via tipping fees (Bishop and Shumway 2009; Lazarus and Rudstrom 2007).

Figures III-8 and III-9 and table III-9 provide a more detailed look at how digester population affects NPV. At around 900 AU, the NPV (with 6% discount rate) of complete mix digesters on dairy farms becomes positive, and the same occurs for plug flow digesters at around 900 AU. On swine farms, a positive NPV is achieved at 5,300 AU for plug flow digesters and at 6,300 AU for complete mix systems. Increasing the rate of return to 10% increases the digester population required to achieve a positive NPV. Especially on swine farms, complete mix digesters seem to be more expensive but are also more productive. Complete mix digesters experience greater economies of size and are able to reach positive returns more rapidly, despite starting out as more negative than their plug flow counterparts. These results suggest that plug flow digesters could be better for small farms, while complete mix digesters are more economically feasible for large dairy and swine operations.

According to the 2012 Census of Agriculture, 40% of the milk cow inventory in the United States was on operations with 1,000 - 3,500+ AU, and 3,500+ was the largest category provided by the census[7]. The average digester population reported for this study was around 3,000 AU. This is slightly lower than the average *farm size* that was reported by respondents[8], indicating that for most farms, every animal does not contribute manure to the anaerobic digester. Digester population was used because it provides the precise number of animal units contributing manure to the anaerobic digestion system. In figure III-9, the average digester population for this study is near the minimum present value for anaerobic digesters on swine farms. Since the NPV-maximizing digester population for swine farms was outside the range of what is available on most dairy and swine animal feeding operations, government grants were added to the expected net present value maximizing decision maker's problem.

Figures 10 and 11 show how government grants influence the present value of plug flow and complete mix anaerobic digestion systems on dairy and swine farms. Survey respondents indicated that government grants are awarded to cover a percentage of the capital costs associated with the anaerobic digestion system. On average, operations with plug flow digesters received government grants that covered 43% of

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[7] The 2012 Census of Agriculture reports milk cow inventory in number of milk cows per operation, but this data was converted to animal units for the purposes of this study.

[8] Some farms also reported digester populations that were either equal to or greater than farm size.

digester fixed costs, and operations with complete mix digesters received grants for 53% of digester costs. These average values were used to generate results included in figures 10 and 11, along with grants that cover 25% and 75% of digester costs. At the average values of 43% and 53% grants and a 6% rate of return, swine operations could experience positive NPVs with 3,700 AU with a plug flow digester or 3,300 AU with a complete mix digester. If government grants totaled 25%, 5,800 AU for plug flow systems and 6,900 AU for complete mix systems would be required for positive NPVs. At government grants totaling 75% of the capital costs, positive present values could be achieved with approximately 1,000 AU. On dairy farms, a digester population of 1,000 AU or less was required to reach a positive NPV with government grants.

Conclusions

The objectives of this study were to develop production and cost functions for methane digesters and to determine NPV-maximizing levels of relevant inputs. Production, fixed cost, and variable cost functions used Cobb-Douglas functional forms. As expected, size does matter. Digester population was significant for methane production and for digester fixed and variable costs. Digester population exhibited increasing returns to scale for methane production. As the animal population feeding the digester increases, fixed and variable costs decrease at decreasing rates.

Co-products such as electricity and animal bedding were important, since the production of methane resulted in negative present values. However, in the absence of government grants, positive NPVs cannot be achieved for small or average-sized swine farms. Expected net present value could increase with the addition of other co-products or revenue sources. Within the survey sample, 27 respondents reported the production of solid and/or liquid fertilizer, and 10 indicated that they produce compost soil amendments or potting soil as a result of their anaerobic digester. Results indicate that, for smaller digester populations, more methane is produced when manure is not the only digester input, and producers could receive additional benefits from charging tipping fees for processing organic waste from outside sources (Bishop and Shumway 2009; Lazarus and Rudstrom 2007). Future studies could determine the effects of adding additional co-products to the NPV maximization problem.

Currently, digesters are more productive and cost-effective on dairy farms. Results from this study indicate that complete mix and plug flow systems are not as economically feasible for swine operations as they are for dairy operations. One reason for this could be because only 14% of the operations included in the estimation of production and cost functions were swine operations. Also, swine manure has higher water content than dairy manure, so swine operations could benefit more from passive systems, such as covered lagoons. Passive systems may not produce methane at as high a rate as plug flow or complete mix systems, but they are less expensive. While passive systems may be better for swine operations, they are unlikely to yield better results for dairy operations. The higher rate of methane production with dairy manure in plug flow and complete mix systems is more likely to offset the higher costs associated with these systems.

Digesters tend to cost less when they are constructed below ground and when steel is the primary construction material (as opposed to concrete or other materials). This could be because most of the digesters in the study were actually “partially below ground”, but were classified as below ground for the indicator variable. Digester construction material presents an interesting trade off. While digesters constructed with primarily concrete are more productive, they are also more expensive than digesters constructed from steel or plastic. Since approximately 87% of the digesters included in this study were constructed with concrete, these results could present an opportunity for reducing the costs of digester construction and increasing economic feasibility for smaller animal feeding operations. However, more research is needed to determine if digester design parameters could be manipulated in order to reduce costs, while also maintain proper human and environmental safety standards.

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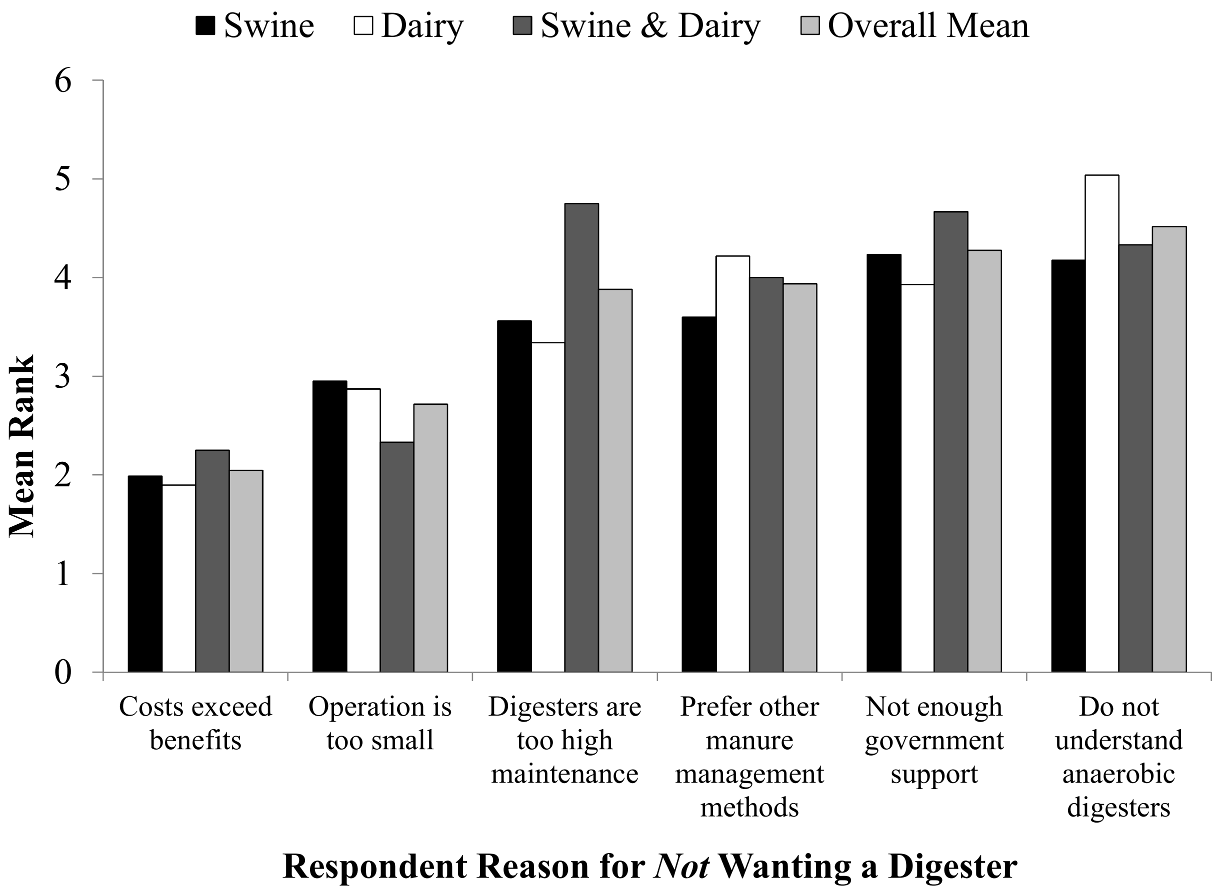


Figure III-1. Non-adopter mean rankings for reasons they would not want an anaerobic digestion system

Table III-1. Sampling Statistics

Statistics Sample group	Farm Type Dairy	 Swine	 Total
Population			
Digester	193	31	224
Shutdown digester	31	7	38
Total	224	38	262
Sample Size			
Digester	152	29	181
Shutdown digester	30	7	37
Total	182	36	218
Adjusted Sample Size			
Digester	151	29	180
Shutdown digester	30	7	37
Total	181	36	217
Responses			
Digester	47	8	55
Shutdown digester	7	0	7
Total	54	8	62
Completed responses			
Digester	45	8	53
Shutdown digester	6	0	6
Total	51	8	59
Response rate			
Digester	29.8%	27.6%	29.4%
Shutdown digester	20.0%	0.0%	16.2%
Total	28.2%	22.2%	27.2%
Sampling error[a]	12.1%	31.2%	11.3%

[a] Computed at 95% confidence level

Table III-2. Summary Statistics for Digester Physical Parameters

Variable	Description	n	Mean	Standard Deviation
AU	Farm size (AU)	60	2,842	2,744
COWS	Dairy farm size (number of cows)	56	1,696	2,009
HEIFERS	Dairy farm size (number of heifers)	36	919	793
HOGS	Hog farm size (number of market hogs)	7	7,049	3,812
DIGAU	Population feeding digester (AU)	60	2,341	2,683
DIGCOWS	Number of dairy cows feeding digester	56	1,591	1,948
DIGHEIFERS	Number of dairy heifers feeding digester	15	832	808
DIGHOGS	Number of market hogs feeding digester	8	5,243	2,895
CL	Covered lagoon	60	0.083	0.279
CM	Complete mix system	60	0.367	0.486
PF	Plug flow system	60	0.467	0.503
IBR	Induced blanket reactor	60	0.017	0.129
ASBR	Anaerobic sequencing batch reactor	60	0.033	0.181
DIGOTHER	Other type of digester	60	0.017	0.129
YRSOP	Years digester is/was operational	58	6.55	5.97
GROUND	Digester built below ground	60	0.833	0.376
CONCRETE	Digester constructed with concrete	60	0.817	0.390
STEEL	Digester constructed with steel	60	0.317	0.469
PLASTIC	Digester constructed with plastic	60	0.233	0.427
CONSOTHER	Digester constructed with other material	60	0.117	0.324
VOL	Volume of digester in ft^3	45	288,775	645,067
TCONTROL	Digester has temperature control mechanism	58	0.897	0.307
TEMP	Operating temperature in °F	57	98.1	7.86
TS	Total solids content in %	52	7.6	4.1
LRT	Loading rate (lb VS/ft^3/day)	31	8,831	5,638
HRT	Hydraulic retention time (days)	55	25	13
SRT	Solids retention time in days	55	36	59
TP	Percent phosphorus removed	34	8.7	20.2
MANURE	Percent influent that is manure	56	90.6	14.6
FOOD	Percent influent that is food waste	33	18.5	21.8
CROPRES	Percent influent that is crop residue	3	0.7	0.6
BYPRODUCT	Percent influent that is other byproduct	4	4.3	4.3
ATL	Atlantic USDA ARMS region	60	0.55	0.50
MW	Midwest USDA ARMS region	60	0.25	0.44
W	West or Plains USDA ARMS region	60	0.08	0.28
S	South USDA ARMS region	60	0.02	0.13

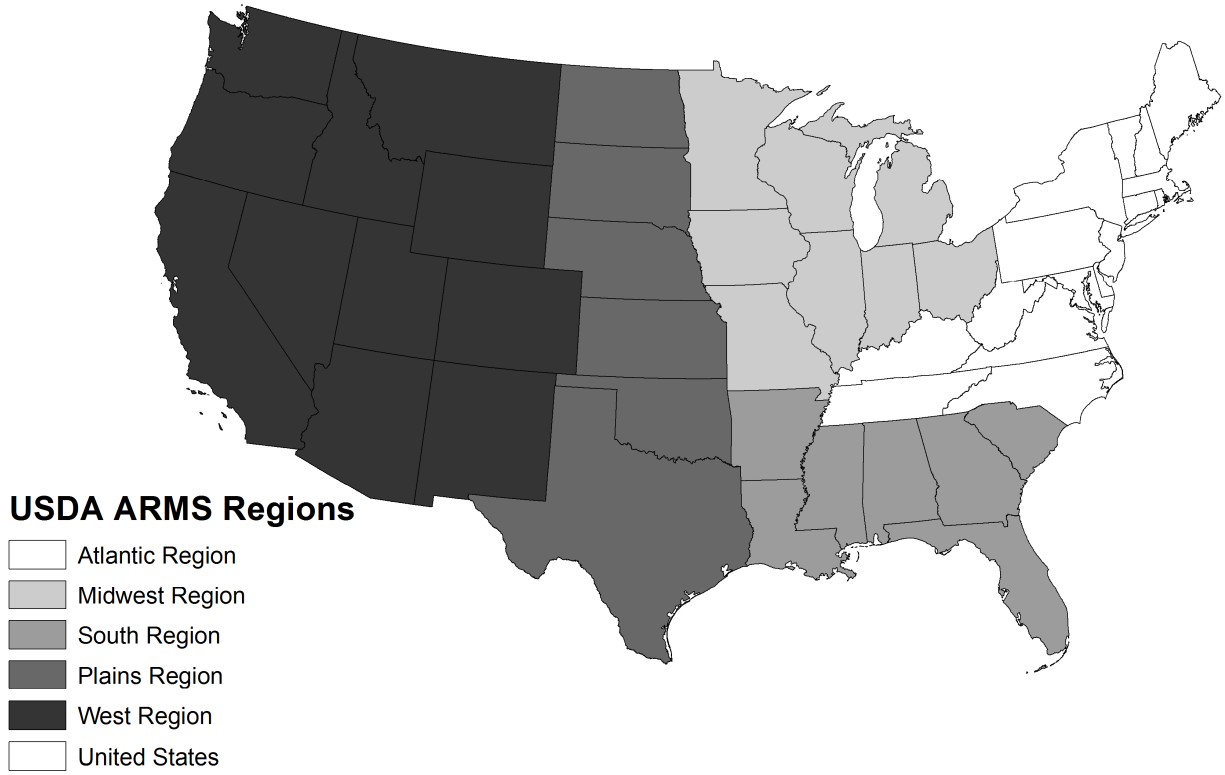


Figure III-2. Map of USDA ARMS Regions.

Table III-3. Summary Statistics for Digester Economic Parameters

Variable	Description	*n*	Mean	Standard Deviation
COST	Total capital cost of system ($)	55	1,972,727	1,525,761
AVG COST	Average capital cost of system ($/MBtu)	55	151.24	178.39
PERSONAL	Capital cost paid by operator	50	0.56	0.27
GRANT	Capital cost paid by government grants	50	0.47	0.27
OTHER	Percent of capital cost paid by other sources	7	0.39	0.38
LABOR	Operator labor (hours/week)	55	24.6	14.4
VAR COST	Variable cost of system ($/year)	50	50,400	39,896
AVG VAR COST	Average variable cost ($/MBtu/year^2)	50	3.74	7.83
FLARE	Methane is flared	25	0.20	0.31
BOILER	Methane that is used for furnace fuel	12	0.50	0.46
GENSET	Methane used for electricity generation	45	0.94	0.10
CNG	Methane used as CNG	2	0.58	0.59
METHANE	Revenue from methane production ($/year)	50	11,750	11,805
INSTALLCAP	Installed electricity capacity (kW)	53	447	402
SELL	Electricity is sold "back on the grid"	52	0.865	0.345
OFF-FARM	Electricity used off-farm	53	0.489	0.341
WHOLESALEP	Wholesale price paid of electricity	44	0.070	0.035
RETAILP	Retail price of electricity	51	0.092	0.038
ELECTRICITY	Revenue from electricity ($/year)	41	376,979	320,131
NPK	NPK fertilizer is co-product	60	0.450	0.502
COMPOST	Compost soil amendment is co-product	60	0.183	0.390
BEDDING	Animal bedding is co-product	60	0.650	0.481
CO-OTHER	System includes other co-product	60	0.167	0.376
CO-PRODUCTS	Revenue from co-products ($/year)	47	70,957	45,715
ADINCOME	Income attributed to digester	53	0.175	0.076

Table III-4. Characteristic Variables Used in Production and Cost Functions for Each Type of Digester

	Plug Flow Digesters $n = 28$		Complete Mix Digesters $n = 22$	
Variable	Mean	Standard Deviation	Mean	Standard Deviation
Methane produced (MBtu/yr)	41,328	50,732	26,087	21,614
Avg. fixed cost ($/MBtu/yr)	154.00	228.65	150.56	127.93
Avg. variable cost ($/MBtu/yr^2)	4.28	9.84	1.96	1.06
Farm size (AU)	3,768	3,444	2,514	2,030
Dairy farm size (cows)	1,709	2,522	1,144	973
Dairy farm size (heifers)	1,035	979	796	510
Hog farm size (pigs)	4,300	200	11,750	3,182
Digester population (AU)	2,891	3,447	1,775	1,474
Digester cows (head)	1,636	2,500	1,104	935
Digester heifers (head)	840	1,072	756	500
Digester pigs (head)	3,700	1,400	6,167	3819
Digester volume (ft^3)	148,003	172,620	313,493	463,678
Dairy (% dairy farms)	0.86	0.36	0.86	0.35
Digester input (% non-manure)	0.14	0.25	0.10	0.12
Below ground (%)	0.89	0.31	0.73	0.46
Concrete (%)	0.96	0.19	0.77	0.43
Steel (%)	0.29	0.46	0.45	0.51
Electricity generation (%)	0.86	0.36	0.95	0.21
Animal bedding (%)	0.71	0.46	0.73	0.46

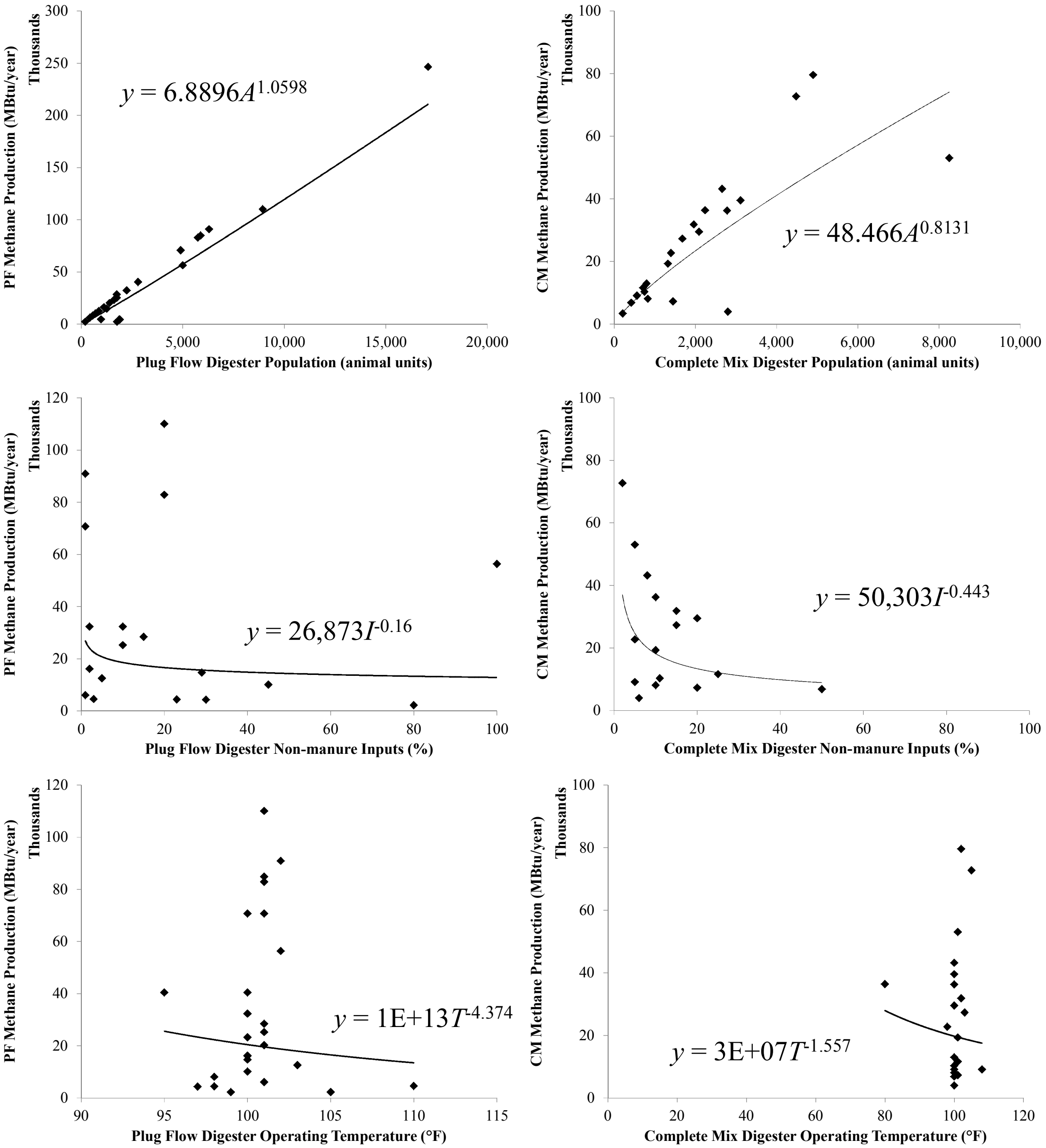


Figure III-3. Economies of size with plug flow (PF) and complete mix (CM) anaerobic manure digesters using methane production

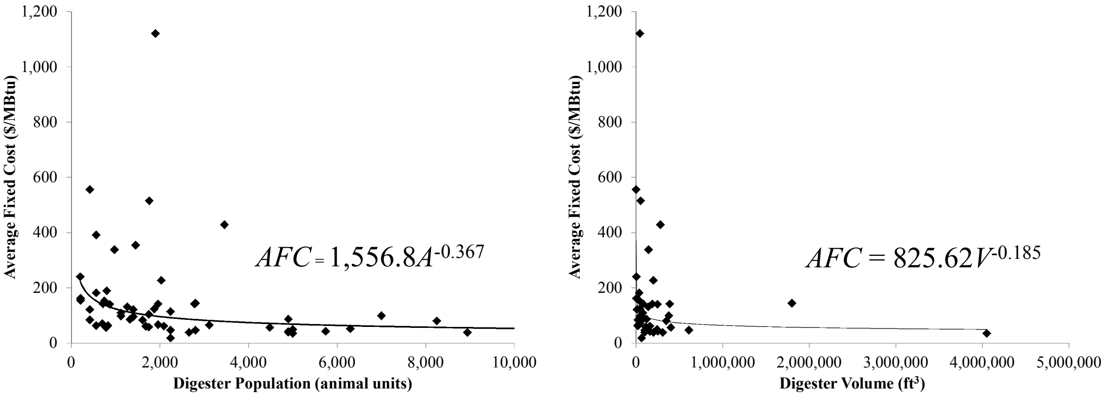


Figure III-4. Economies of size with anaerobic manure digesters using average fixed cost

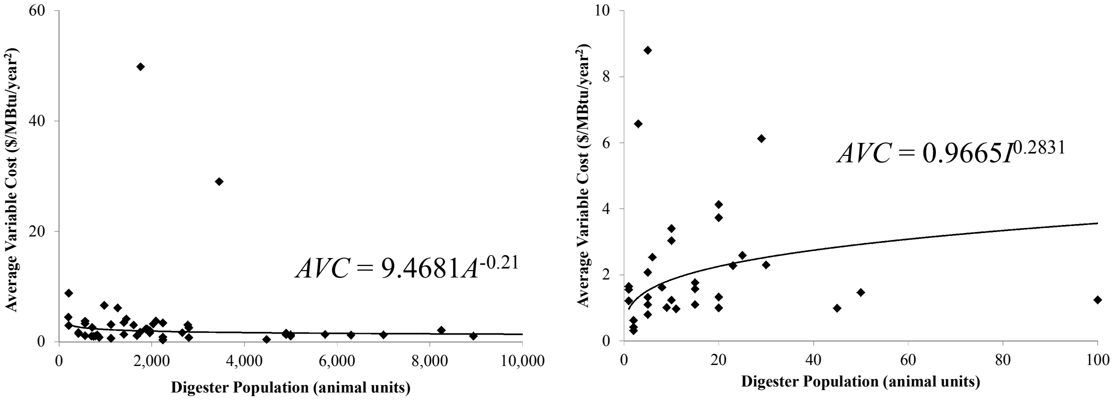


Figure III-5. Economies of size with anaerobic manure digesters using average variable cost

Table III-5. Conversion Factors and Prices for Present Value Estimation

Digester Type	Electricity Conversion Factor[a]	Animal Bedding Conversion Factor[b]	Methane Price, p_1	Electricity Price, p_2	Animal Bedding Price, p_3
Plug Flow	293	0.1836	$4.12/MBtu	$0.073/kWh	$50/ton
Complete Mix				$0.066/kWh	

[a] Yields electricity generation in kilowatt hours (kWh) per year

[b] Animal bedding production in tons total solids (TS) per year

Table III-6. Parameter Estimates for Methane Production Functions

	Plug Flow Digester		Complete Mix Digester	
Variable	Estimate	Standard Error	Estimate	Standard Error
Intercept	0.986^{***}	0.145	0.960	1.050
Digester population	0.979^{***}	0.022	1.048^{***}	0.104
Non-manure inputs	-0.034^{***}	0.010	-0.055	0.071
Dairy farm	1.589^{***}	0.052	1.237^{***}	0.202
Below ground	0.041	0.082	-0.009	0.194
Concrete	0.263^{***}	0.098	0.415^{*}	0.258
Steel	0.073^{*}	0.039	-0.192	0.150
Sigma	0.068^{***}	0.010	0.208^{***}	0.041

Note: Dependent variable is methane produced in MBtu/year.

***Significant at the $\alpha = 0.01$ level

**Significant at the $\alpha = 0.05$ level

*Significant at the $\alpha = 0.1$ level

Table III-7. Parameter Estimates for Digester Fixed Cost Functions

	Methane Only		Methane + Co-Products	
Variable	Estimate	Standard Error	Estimate	Standard Error
Constant term	9.857***	0.916	9.803***	0.871
Digester population	-0.391***	0.128	-0.376***	0.128
Digester volume	-0.139	0.093	-0.164*	0.099
Dairy farm	-1.028***	0.231	-0.954***	0.255
Below ground	-0.552*	0.286	-0.645**	0.295
Concrete	0.492	0.518	0.555	0.498
Steel	-0.007	0.184	-0.067	0.192
Electricity generation			0.353	0.412
Animal bedding			-0.152	0.238
Sigma	0.332**	0.135	0.356***	0.128

Note: Dependent variable is average fixed cost in $/MBtu/year.

***Significant at the $\alpha = 0.01$ level

**Significant at the $\alpha = 0.05$ level

*Significant at the $\alpha = 0.1$ level

Table III-8. Parameter Estimates for Digester Variable Cost Functions

	Methane Only		Methane + Co-Products	
Variable	Estimate	Standard Error	Estimate	Standard Error
Constant term	3.347^{***}	0.774	3.053^{***}	0.813
Digester population	-0.304^{**}	0.126	-0.277^{**}	0.120
Non-manure inputs	-0.034	0.072	-0.062	0.065
Dairy farm	-0.650^{***}	0.215	-0.741^{***}	0.191
Below ground	-0.396	0.316	-0.598^{*}	0.326
Concrete	0.463	0.329	0.357	0.281
Steel	-0.107	0.197	0.080	0.203
Electricity generation			0.079	0.430
Animal bedding			0.435^{*}	0.248
Sigma	0.225^{***}	0.057	0.167^{***}	0.051

Note: Dependent variable is average variable cost in \$/MBtu/year^2.

***Significant at the $\alpha = 0.01$ level

**Significant at the $\alpha = 0.05$ level

*Significant at the $\alpha = 0.1$ level

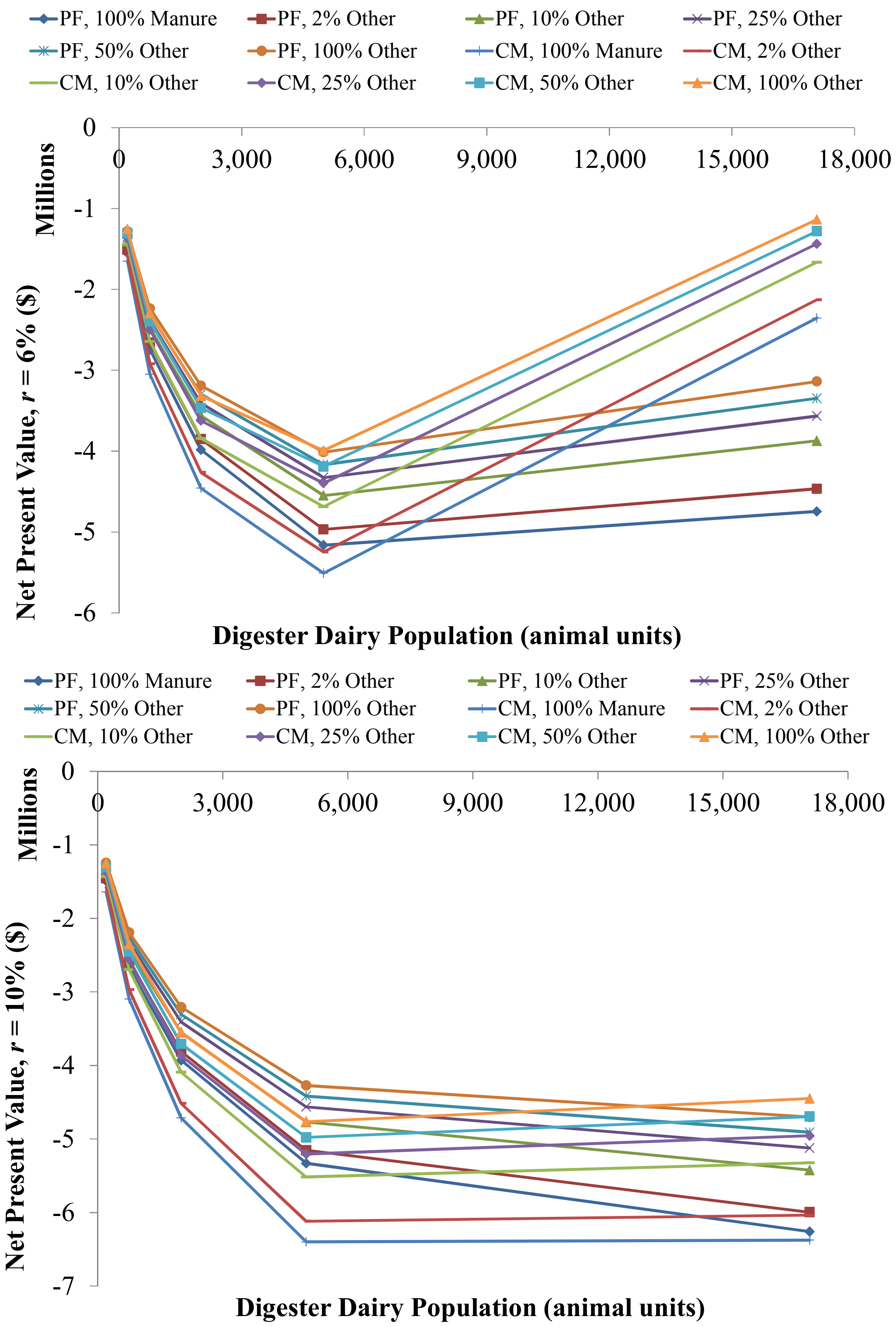


Figure III-6. Net present values, at r = 6% and r = 10%, for concrete, below-ground plug flow (PF) and complete mix (CM) digesters that process varying levels of dairy manure and other organic waste materials and produce only methane

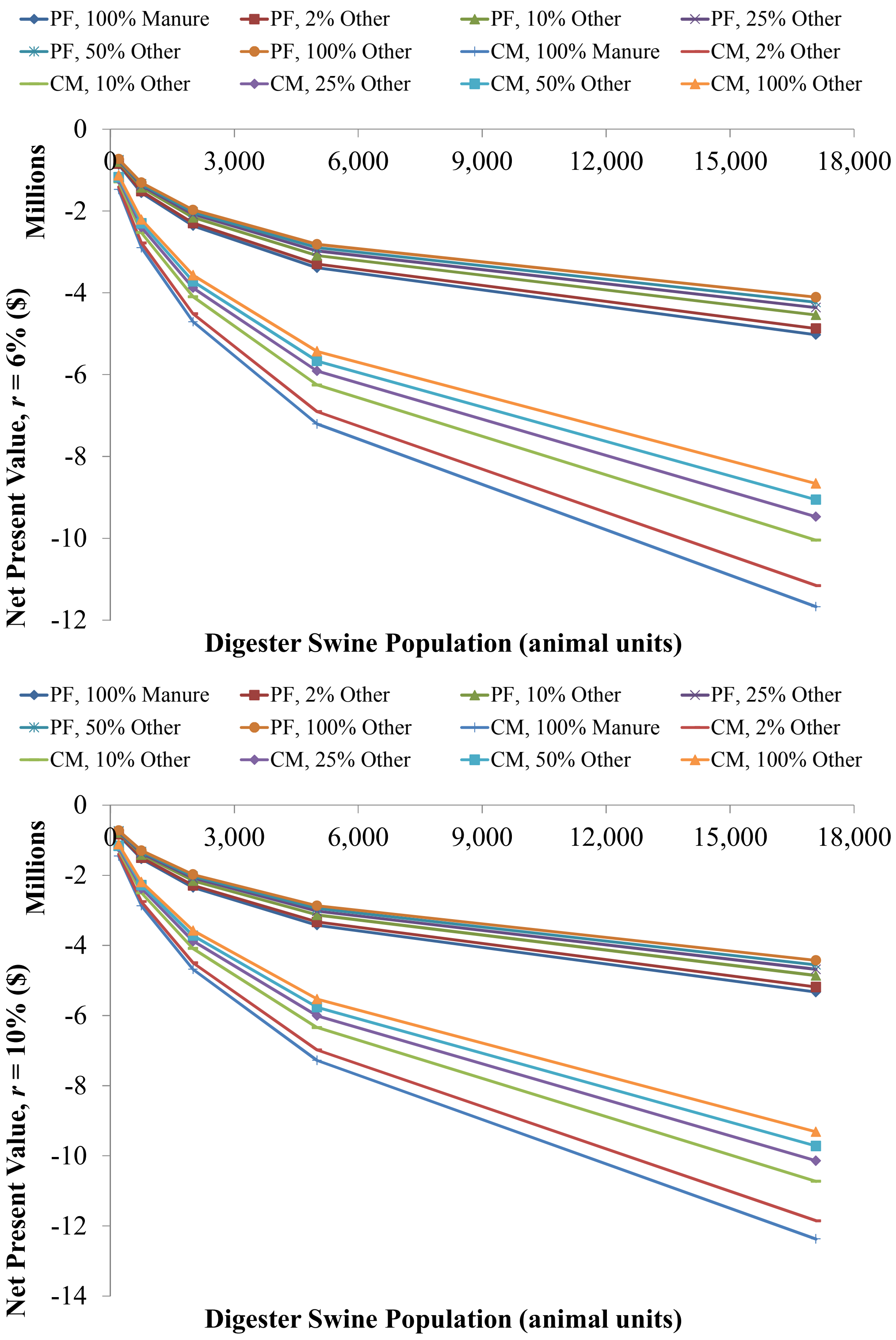


Figure III-7. Net present values, at r = 6% and r = 10%, for concrete, below-ground plug flow (PF) and complete mix (CM) digesters that process varying levels of swine manure and other organic waste materials and produce only methane

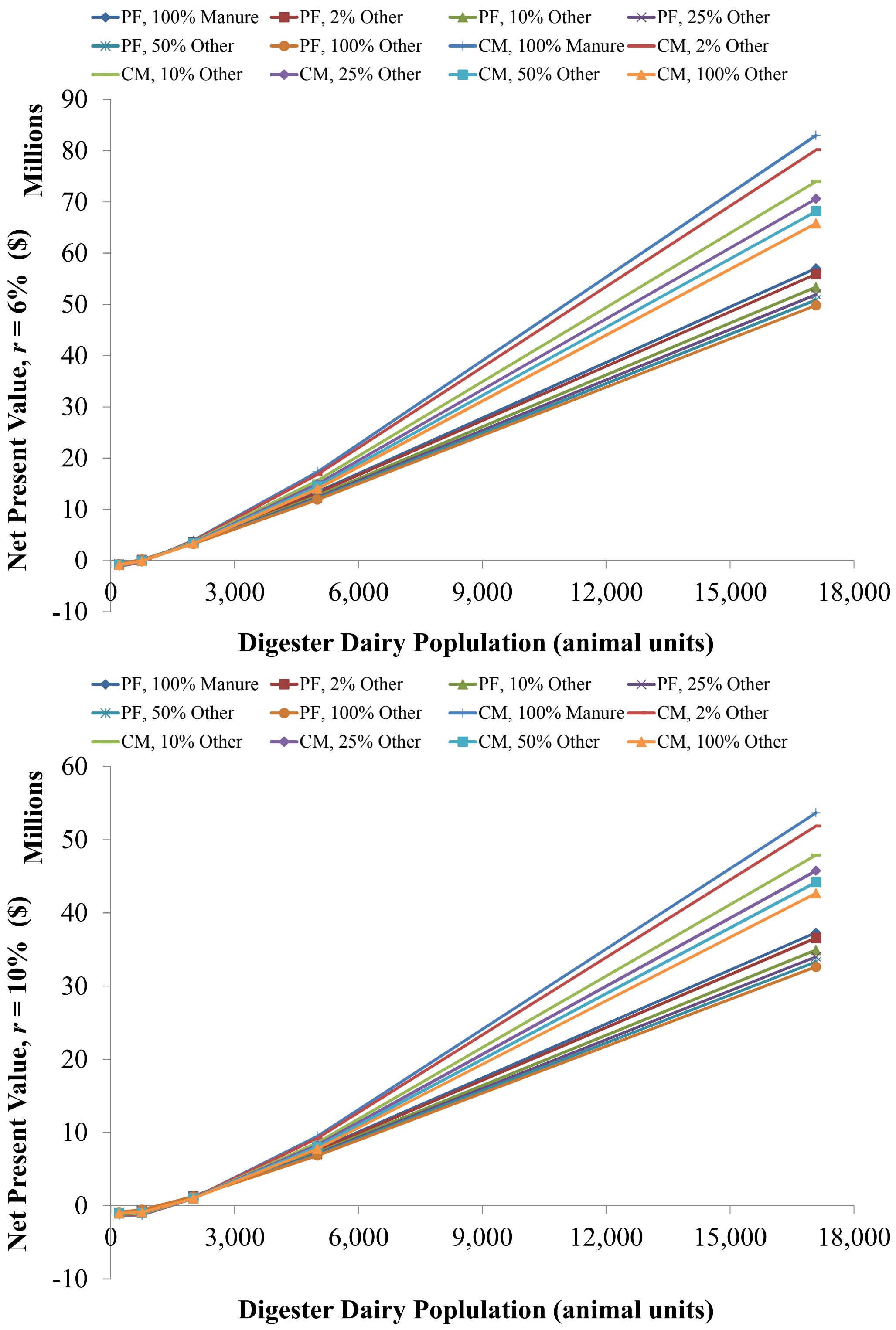
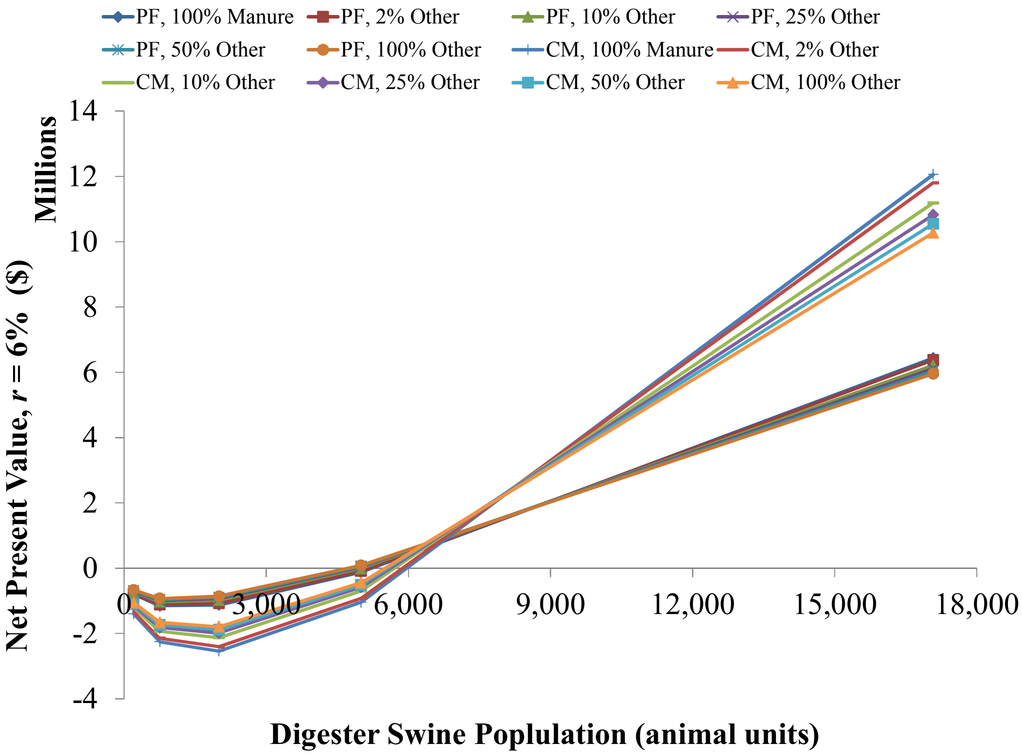


Figure III-8. Net present values, at $r = 6\%$ and $r = 10\%$, for concrete, below-ground plug flow (PF) and complete mix (CM) digesters that process varying levels of dairy manure and other organic waste materials and produce methane, electricity, and animal bedding



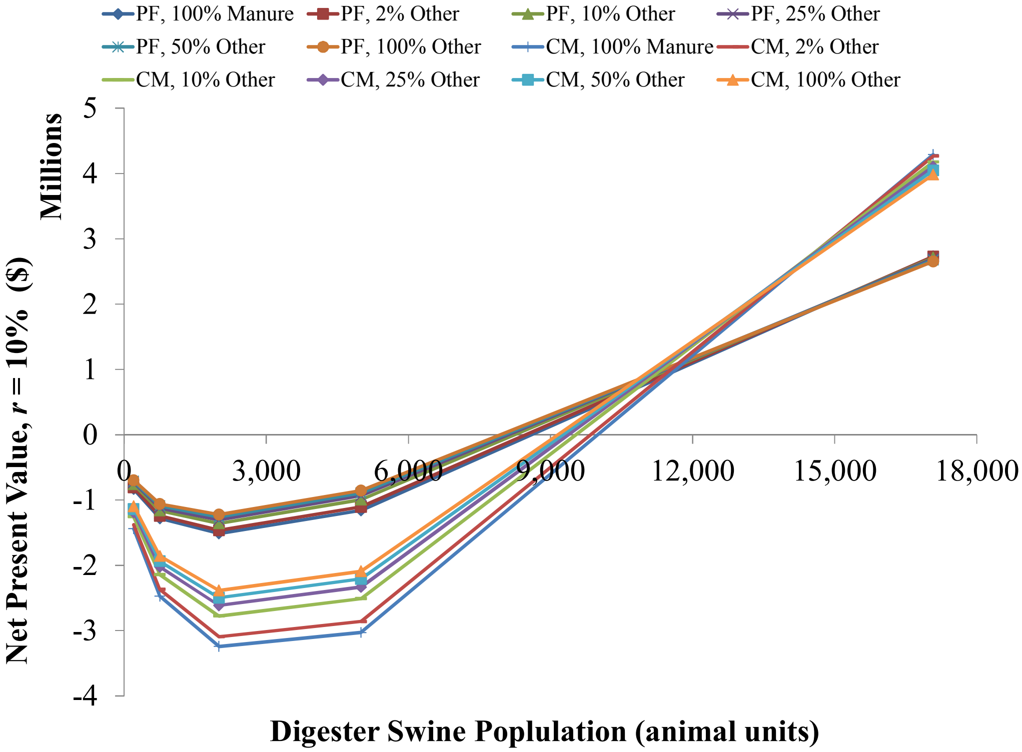


Figure III-9. Net present values, at $r = 6\%$ and $r = 10\%$, for concrete, below-ground plug flow (PF) and complete mix (CM) digesters that process varying levels of swine manure and other organic waste materials and produce methane, electricity, and animal bedding

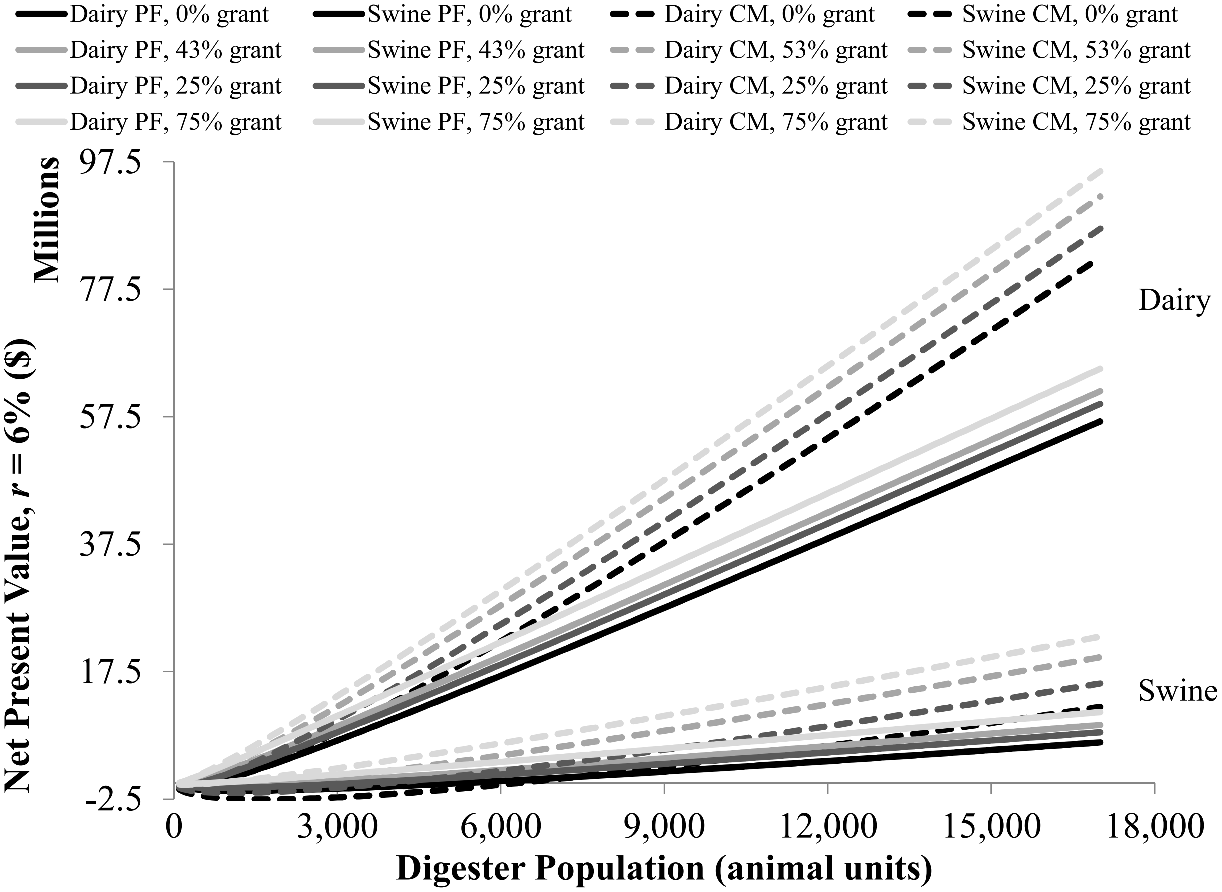


Figure III-10. Net present values, at r = 6%, for concrete, below-ground plug flow (PF) and complete mix (CM) digesters that process dairy or swine manure, produce methane, electricity, and animal bedding, and receive government grants

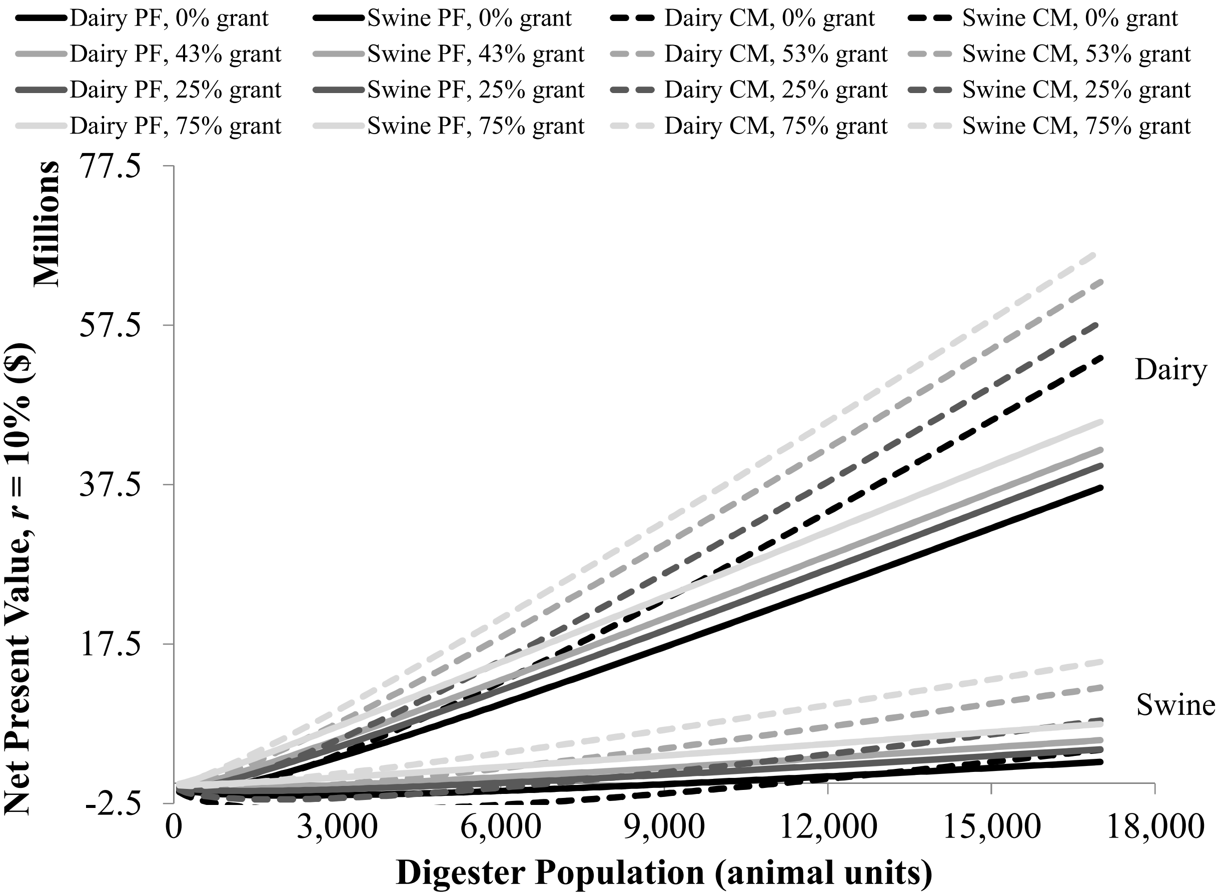


Figure III-11. Net present values at r = 10%, for concrete, below-ground plug flow (PF) and complete mix (CM) digesters that process dairy or swine manure, produce methane, electricity, and animal bedding, and receive government grants

Table III-9. Digester[a] Population (in 1000-lb animal units) at $E(NPV) = 0$

	$r = 6\%$				$r = 10\%$			
	Dairy		Swine		Dairy		Swine	
Percent Government Grant	PF	CM	PF	CM	PF	CM	PF	CM
0%	800	900	5,300	6,300	1,300	1,600	9,400	11,200
25%	500	600	3,400	4,000	800	1,000	5,800	6,900
Mean[b]	300	300	2,200	1,800	500	500	3,700	3,300
75%	100	100	700	800	200	200	1,100	1,300

[a] Digester processes only manure; and methane, electricity, and animal bedding are generated as co-products.

[b] Sample mean: 43% for plug flow (PF) digesters, 53% for complete mix (CF) digesters

Appendix E: Co-product Conversion Coefficients

The purpose of this appendix is to describe the methods used for calculating co-production conversion coefficients. Since, in most cases, the methane produced by the anaerobic digester is injected into an internal combustion engine to produce electricity, the conversion coefficient calculation for electricity is the most straight-forward. The amount of power generated by methane can be calculated using the ratio of 0.293 Watt-hours (W) to one British thermal unit (Btu). The conversion of methane in MBtu/year to electricity in kWh/year was calculated as

(E.1) $$\frac{\text{MBtu}}{\text{yr}} \times \frac{1{,}000{,}000\ \text{Btu}}{1\text{MBtu}} \times \frac{0.293\ \text{Wh}}{1\ \text{Btu}} \times \frac{1\ \text{kw}}{1{,}000\ \text{W}} = 293\ \text{kWh/yr.}$$

Unit conversion from methane in MBtu/year to solids for animal bedding may seem less straight forward, but it can be accomplished because, like methane, animal bedding is produced from the manure solids that are processed in the digester. Manure is comprised of several components. The components most responsible for methane production are the volatile solids (VS). According to USDA (2008), dairy and swine manure contains about 0.1 lb VS per lb of manure. Ultimate methane yield is the maximum amount of methane produced per mass of oxygen demand removed (Hamilton 2013). However, we know from laboratory bench-scale and field experiments that not all the oxygen demand contained in manure is removed during digestion and converted into methane. Specific methane yield is based on laboratory biochemical methane potential (BMP) analyses. Moody et al. (2011) and Hamilton (2013) report specific methane yield values of 0.13 L CH_4/g VS for swine manure and 0.24 L CH_4/g VS for dairy manure. However, these swine manure samples represented the low extremes for swine manure because they appeared to be partially digested due to age and weathering. Specific methane yield for swine and dairy manure are similar and typically between 0.2 and 0.3 L CH_4/g VS. A specific methane yield of 0.25 L CH_4/g VS was used in this study for swine and dairy manure. Hamilton (2013 p. 4) warns that BMP analysis "indicates the potential of substrates to produce methane under perfect laboratory conditions." Therefore, in order to estimate the methane yield from anaerobic digesters, we need to multiply the specific methane yield by a conversion factor ranging between 0.6 and 0.9 (Tchobanoglous et al. 2014). For this study, conversion efficiency of 0.8 was used for the complete mix and plug flow and covered lagoon systems. The conversion of methane in MBtu/year to animal bedding in ton TS/year for dairy and swine manure was calculated as

$$\text{(E.2)}\quad \frac{\text{MBtu}}{\text{yr}} \times \frac{1{,}000{,}000\ \text{Btu}}{1\text{MBtu}} \times \frac{1\ \text{ft}^3\ \text{CH}_4}{1{,}000\ \text{Btu}} \times \frac{28.3168\ \text{L}}{1\ \text{ft}^3} \times \frac{1\ \text{g VS}}{(0.8)(0.25\ \text{L CH}_4)} \times \frac{1\ \text{g TS}}{0.85\ \text{g VS}} \times \frac{1\ \text{lb}}{453.592\ \text{g}} \times \frac{1\ \text{ton}}{2{,}000\ \text{lb}} = 0.1836 \text{ton TS/yr.}$$

References

Hamilton, D.W. 2013. *Anaerobic Digestion of Animal Manures: Methane Production Potential of Waste Materials, BAE 1762*. Stillwater, OK: Oklahoma Cooperative Extension Service.

Moody, L.B., R. T. Burns, G. Bishop, S. T. Sell, R. Spajic. 2011. "Using biochemical methane potential assays to aid in co-substrate selection for co-digestion." *AppliedEngineering in Agriculture* 27(3): 433-439.

Appendix F: Breakeven Herd Sizes

Animal units are widely used as a measure of farm size. However, breakeven farm sizes from table III-9 were converted to herd sizes in terms of number of head to provide a clearer picture of the number of dairy cows, dairy heifers, or swine that would be required for an anaerobic digester to breakeven. As a reminder, the anaerobic digester used in the breakeven analysis processes only manure and produces methane, electricity, and animal bedding as co-products.

In this study, the average dairy farm with an anaerobic digester had 1,696 dairy cows and 919 dairy heifers. While not included in the estimation of digester production and cost functions, dairy farms without anaerobic digesters were also surveyed. For reference, the average size of dairy farms without anaerobic digesters was 552 dairy cows and 262 dairy heifers. According to the USDA NASS 2012 Census of Agriculture, 64,098 dairy farms operated with a combined inventory of 9.3 million dairy cows, which yields an average farm size of 145 dairy cows. This is well below the average size of farms included in this study. While the USDA number is presented here for context, we must keep in mind that this is the average of *all* dairy farms in the United States, even those that obtain less than 25% of their income from farming. Also, the dairy farms surveyed in this study had to have herd populations of 100 or more cows.

As indicated by production and cost function results, anaerobic digesters are more economically feasible on larger operations due to economies of size. This conclusion is reflected in the results of table F.1. Larger dairy farms do not require as much government assistance as smaller dairy farms in order for the anaerobic digester to break even. Breakeven values were calculated with two different rates of return (6% and 10%) and assuming a technology lifespan of 25 years. According to these results, the average dairy farm (included in this study, with 552 dairy cows) that does not already have an anaerobic digester could adopt a digester and breakeven with only 25% of the capital costs covered by government grants. If the same dairy farm required a 10% rate of return, it would need government grants to cover between 40 and 50% of the digester costs, depending on the type of digester adopted. On a nation-wide scale, the average dairy farm would need government grants to cover around 75% of the digester costs in order to breakeven.

All dairy farms surveyed in this study operated with dairy cows and replacement heifers or only dairy cows. No farms were exclusively replacement heifer operations. However, for convenience, breakeven digester populations were converted to dairy cow and replacement heifer herds separately. The Census of Agriculture also reported the production of 1,079,045 replacement heifers on 2,716 operations, which means that in 2012, the average dairy replacement operation had almost 400 heifers. According to the results in table F.1, a farm of this size would need the government to cover *at least* 40% of the capital costs associated with the anaerobic digester, depending on the type of digester and rate of return required.

According to the Census of Agriculture, the average size of all swine operations in the U.S. in 2012 was 1,044 head. This average is based on a year-end national inventory of 66,026,785 hogs on 63,246 farms of varying sizes, characteristics, and operational structures. Of the farms with digesters that responded to the survey, the average number of wean-to-finish pigs (or pigs that weigh 55 pounds or more) was 7,049. Again, while not included in the estimation of production and cost functions, the average size of wean-to-finish hog farms without anaerobic digesters was 3,059.

Breakeven digester populations for swine operations are included in table F.2. These results show that even hog farms that currently operate anaerobic digesters required government grant payments at or above the sample mean (43% for plug flow digesters and 53% for complete mix digesters). Swine farms that have never operated anaerobic digesters would need government grants to cover at least 75% of the capital costs in order to break even.

These results underscore the need for improved anaerobic digestion technologies that are more economical for small farms. It is also recognized that many farms will require a new technology to breakeven in less than 25 years. These results support earlier conclusions that government subsidies are required for digester economic feasibility. With resources made possible by the 2014 Farm Bill, the USDA announced in early 2015 that it is making $280 million available to eligible applicants through the Rural Energy for America Program (REAP). Through this program, applicants could receive grants for up to 25% of total project costs and loan guarantees for up to 75 percent of total project costs for renewable energy systems (including anaerobic digesters) and energy efficiency improvements. While this study does not include any analysis on loan guarantees, results do indicate that government grants for up to 25% of total project costs are not enough to 1) make anaerobic digesters economically feasible on small farms and swine operations (although covered lagoons could be an exception; see Chapter 1) and 2) encourage producers to adopt an anaerobic digester (Chapter 2).

Table F.1. Dairy Cow and Heifer Digester Populations at $E(NPV) = 0$

	$r = 6\%$				$r = 10\%$			
	Cow		Heifer		Cow		Heifer	
Percent Government Grant	PF	CM	PF	CM	PF	CM	PF	CM
0%	571	643	727	818	929	1,143	1,182	1,455
25%	357	429	455	545	571	714	727	909
Mean[a]	214	214	273	273	357	357	455	455
75%	71	71	91	91	143	143	182	182

[a] Sample mean: 43% for plug flow (PF) digesters, 53% for complete mix (CF) digesters

Table F.2. Digester Populations at $E(NPV) = 0$ for Swine[a] Operations

	$r = 6\%$		$r = 10\%$	
Percent Government Grant	PF	CM	PF	CM
0%	13,250	15,750	23,500	28,000
25%	8,500	10,000	14,500	17,250
Mean[b]	5,500	4,500	9,250	8,250
75%	1,750	2,000	2,750	3,250

[a] Numbers are based on swine that weigh 55 pounds or more

[b] Sample mean: 43% for plug flow (PF) digesters, 53% for complete mix (CF) digesters

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