An Engineering-Economic Model for Analyzing Dairy Plug-Flow Anaerobic Digesters: Cost Structures and Policy Implications

C. R. Faulhaber, D. R. Raman, R. T. Burns

Abstract. *Treating animal wastes through anaerobic digestion (AD) yields methane-rich biogas that can be used for power generation or heating, and a nutrient-rich digestate that can be land-applied as fertilizer. Furthermore, AD reduces odors from stored and land-applied manures. Despite these benefits, AD deployment rates in the U.S. are only 5% for dairy farms identified as suitable for AD by the U.S. Environmental Protection Agency. The objective of this study was to analyze the economic and technical limitations of farm-scale anaerobic digesters using a simple model permitting insight into the fundamental constraints on the technology. A model was developed to determine the cost of methane produced via AD based on operation size. Dairy plug-flow systems were modeled because of their well-documented economic performance, and model validation used data from AgSTAR's FarmWare program. The analysis shows that farm size is critical to make digestion-derived methane cost-competitive with natural gas. At low herd sizes (<400 animals), carbon credits and odor reductions alone appear insufficient to overcome the low commercial energy rates in the U.S. However, moderate reductions in digester cost and interest rate, coupled with moderate increases in amortization period and/or natural gas prices, could make AD more competitive with commercial energy in the U.S. even at relatively small herd sizes (approx. 400 animals).*

Keywords. *Anaerobic digestion, Economics, Economy of scale, Renewable energy, Scale factor.*

Anaerobic digestion (AD) is a biological process that converts a portion of the organic material in a waste stream to biogas and produces digestate that can be land-applied as fertilizer (USDA-NRCS, 2007; Tafrup, 1995). The biogas is composed of methane, carbon dioxide, and small amounts of other compounds such as hydrogen sulfide (Rasi et al., 2007). Anaerobic digestion of animal manure has multiple benefits, including renewable energy production, reductions in greenhouse gas (GHG) emissions, odor control, and reductions in manure pathogenicity (Yiridoe et al., 2009). Despite these benefits, AD deployment rates are low for U.S. farms (USDA-NRCS, 2007).

Farm-scale AD was first adopted in the U.S. during the oil crisis in the 1970s (USDA, 2008). Despite technological advancements during the 1980s and 1990s, a 1998 study reported failure rates approaching 50% in manure-fed AD systems (NREL, 1998). In the past decade, policy changes and developments in AD technology have yielded only mild improvements in deployment rates. Kramer (2004) surveyed 23 digesters from 2002 to 2004 and found that five of the digesters that were operational in 2002 had ceased to operate by 2004. In 2006, AgSTAR reported a doubling in the number of digesters operating in the U.S. between 2004 and 2006 (AgSTAR, 2006). However, according to data reported by AgSTAR in 2009, AD deployment rates are far below 1% based on the total number of animal facilities, approximately 2% based upon the number of facilities that the U.S. Environmental Protection Agency (EPA) has identified as being suitable for AD, and approximately 5% for suitable dairies (AgSTAR, 2010).

In December 2009, the U.S. Secretary of Agriculture announced an agreement with U.S. dairy producers to reduce GHG emissions from dairy operations by 25% before 2020; anaerobic digestion was cited as the primary method for meeting this goal (USDA, 2009). Such an increase in deployment will require us to understand and develop methods for overcoming current barriers to AD deployment at dairies.

The University of Florida and the University of California, Davis, both have spreadsheet models available online to evaluate the economic feasibility of AD (Florida Dairy Extension, 2010; California Biomass Collaborative, 2010). However, these models require the user to provide capital and operating costs, meaning that the models are not suitable for production of total costs based simply on operation size. AgSTAR has also developed a model to help farmers determine the economic viability of AD. The model requires several site-specific parameters that are critical to the prediction of costs at one location, but they also mask the larger economic realities of AD. To uncover these realities, a simple model that incorporates fewer site-specific inputs and that provides a first-level approximation accounting for odor and GHG benefits is needed. The goals of our work included creating such a model, which we call the Simplified Framework for

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Analyzing AD (S-FAAD), validating the model, identifying critical constraints, and making recommendations for improving AD deployment.

Materials and Methods

The S-FAAD model was implemented in Microsoft Excel, with all computations being done using normal cell formulae. Visual Basic for Applications (VBA) code was written to enable ranges of input variables to be tested, to study the breakdown of costs, and to perform a sensitivity analysis. The S-FAAD model computes a price (\$ m^{-3}) for the biogas produced from AD, taking into account the capital and operating costs of the digester, as well as crediting cost avoidances due to odor and GHG abatement. By assuming a biogas methane fraction (and thus energy density), the cost of energy (as methane) in the biogas (\$ GJ^{-1}) is computed. This is a crucial value because it allows us to compare the cost of AD-generated energy to its commercial competitor: natural gas. The comparison to natural gas may appear unfair, since AD brings multiple other benefits and possibilities, including, but not limited to, (1) GHG reductions, (2) odor reductions, and (3) the possibility to use the biogas in engine generators to produce electricity and heat. Regarding the first two issues, S-FAAD provides explicit dollar credits to the AD system for GHG reductions and for odor reductions. The final concern, i.e., that the economics of AD are improved if conversion to electricity is achieved, is only valid if renewable-energy tax credits or similar incentives are available. If such credits are not available, then conversion to electricity is unlikely to have any economic benefit; otherwise, farms across the U.S. would be purchasing low-cost natural gas and generating their own electricity on-site.

The endpoint of the S-FAAD model is computation of a value we term the methane cost ratio (MCR). The MCR is a dimensionless number that is found by dividing the biogas energy cost (\$ GJ^{-1}) by the commercial price of natural gas (\$ GJ^{-1}). We posit that the MCR is a key indicator of AD deployment: if the MCR is above 1.0, then commercial energy is cheaper than digestion-derived energy, making digester deployment and long-term operation unlikely. Conversely, if the MCR is below 1.0, then digester-derived energy is cost-competitive with commercial sources, making long-term operation of digesters more likely. To obtain the MCR, several operating parameters and costs are considered, as shown in figure 1.

Figure 1 summarizes the data flow in S-FAAD. The operation size and assumptions for digester operation and biogas production rates are used to calculate the cost for producing methane via AD. This value is then compared to the market natural gas prices to determine the MCR. The S-FAAD model can be broken down further into operating parameters and annual expenses and revenue sources.

Operating Parameters and Assumptions

The principal assumptions for dairy manure and biogas production include the hydraulic retention time (HRT), influent strength, fraction of manure biodegraded, methane concentration, daily biogas production per cow, and the energy density of manure solids. The S-FAAD model assumes a 20-day HRT, which falls into the typical range for plug-flow digesters (Wilkie, 2005). Influent strength was assumed as 0.11 kg L^{-1} (total solids), which is based on a typical range of 0.11 to 0.14 kg L^{-1} for scrape collection systems for plug-flow digesters (USDA-NRCS, 2007). Manure solids were assumed to have the energy density of cellulose: 17 MJ kg^{-1} (GCEP, 2005). The fraction biodegraded was assumed to be 26% (Martin et al., 2003; Cornell University, 2008), and a biogas production rate of 1.9 m^3 cow^{-1} d^{-1} was assumed (USDA-NRCS, 2007), as was a biogas volumetric methane concentration of 60% (Ghafoori and Flynn, 2007). Determining herd size is complicated by whether different data sources consider only lactating animals or total herd numbers. We assume the numbers to represent the average annual herd size from which manure is collected. These key operating assumptions were used to calculate the annual biogas produc–

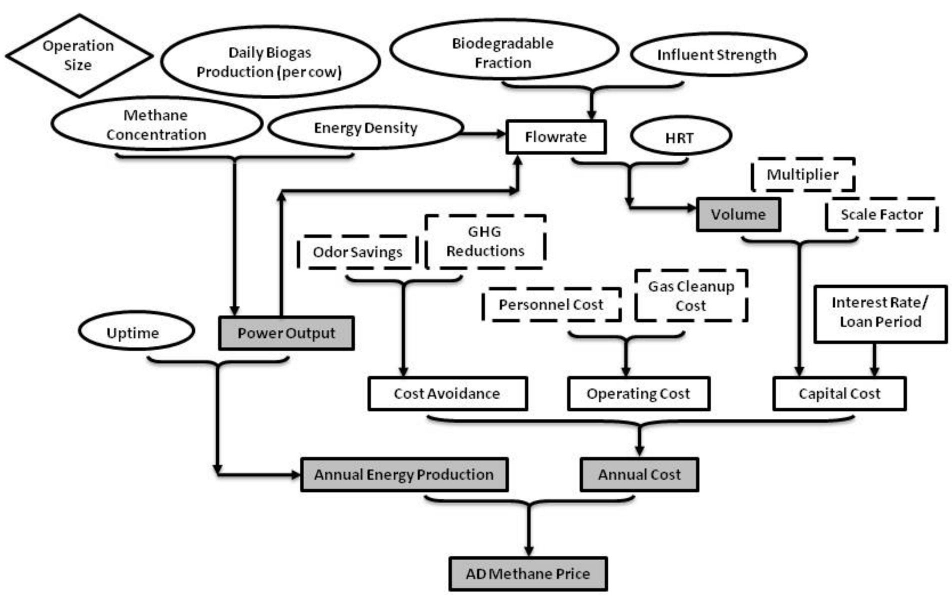

Figure 1. S-FAAD flowchart. Diamonds represent user inputs, ovals represent assumed values, rectangles represent computed values, dotted rectangles represent computed values based on user-selectable assumptions not shown, and shaded rectangles indicate primary outputs.

tion, the power output based on the methane concentration and energy content of methane, the biodegradable loading requirement for the digester, the volumetric flowrate into the digester, and the required digester volume. The model ignores energy losses due to digester heating and is thus most appropriate for warm U.S. climates and optimistic for colder climates.

Annual Expenses and Revenue

To determine the economic viability of AD, S-FAAD computes the capital costs, operating costs, carbon tax credits, and odor abatement savings.

Capital Cost

The total capital cost for the digester (C_{TC}) is determined from the digester volume (V_D) using a standard scaling equation (eq. 1) (Brown, 2003):

$$C_{GC} = M \times V_D^{SF} \tag{1}$$

where *SF* is a scaling factor, and *M* is a multiplier. Although tabulated values of *SF* and *M* are available for many unit operations (e.g., Brown, 2003), we are unaware of such figures being available for anaerobic digesters. However, AgSTAR (2009) compiled tables containing the total capital costs for plug-flow digesters built between 2005 and 2008 and then used the data to find the following equation relating the total capital cost to operation size (S_{op}):

$$C_{TC} = 617 \times S_{op} + 566{,}000 \tag{2}$$

AgSTAR's equation includes the digester cost as well as costs for electrical generating equipment, system installation, and engineering. Because S-FAAD assumes that biogas is not used to generate electricity, a 36% correction (reduction) was applied based on data presented by the USDA (USDA, 2008). Costs were corrected to 2010 U.S. dollars, and a power equation was fit to the resulting data across operation sizes from 500 to 3000 animals (AgSTAR, 2009). The resulting scale factor and multiplier were 0.59 and \$13,575 (\$ cow^{-1}) respectively, with $r^2 = 0.988$. It is interesting to note that plug-flow digester capital costs appear to follow a "six-tenths" rule (i.e., the scale factor is 0.6), as is often seen in process equipment (Brown, 2003). Because S-FAAD also incorporates the influent strength, HRT, per-capita biogas production rates, and the methane concentration in the biogas, to compute the digester volume, we wanted an equation relating digester cost to digester volume. To do this, the base case assumptions were used to develop a constant relating operation size to volume, as shown in equation 3:

$$V = S_{op}\left\{\beta\,\frac{(HRT)(PCB)(f_{\mathrm{CH4}})}{(ED)(f_{BD})(TS)}\right\} \tag{3}$$

where β is a lumped unit conversion (numerical value is 0.0377), S_{op} is the operation size (average number of animals from which manure is collected), *HRT* is the hydraulic retention time (d), *PCB* is the per-capita biogas production (m^3 cow^{-1} d^{-1}), f_{CH4} is the volume fraction of methane in the biogas, *ED* is the energy density of the biodegradable solids in the slurry (MJ kg^{-1}), f_{BD} is the biodegradable fraction of the total solids in the slurry, and *TS* is the concentration of total solids in the digester influent (kg L^{-1}). Under our baseline assumptions of HRT = 20 d, PCB = 1.9 m^3 cow^{-1} d^{-1}, f_{CH4} = 60%, ED = 17 MJ kg^{-1}, f_{BD} = 26%, and TS = 0.11 kg L^{-1}, the ratio of reactor volume to herd size is 1.77 m^3 cow^{-1}. This ratio allowed us to convert a predicted reactor volume into equivalent "base case" herd size and to then employ equation 1 to calculate the total capital cost.

Operating Costs

The operating costs considered in S-FAAD include personnel costs and gas cleanup costs. Peters et al. (2003) provide typical labor requirements for continuous-flow reactors. Using this value, the labor requirement is approximately 4 h d^{-1}, or 50% of a full-time employee (FTE). The annual cost for one FTE is assumed to be \$40,000. As the size of the digester and pumps increase, the operator time required is not expected to change significantly; thus, in S-FAAD, the labor requirement is treated as independent of digester size.

There are several levels of biogas cleaning, with the simplest typically involving moisture and hydrogen sulfide removal, and sophisticated cases removing carbon dioxide to create pipeline-quality natural gas. Gas cleanup costs that range from \$0.03 to \$0.14 per cubic meter of biogas are cited by USDA-NRCS (2007) based on updated costs from Walsh et al. (1988). Minimal gas cleanup (hydrogen sulfide removal only), with a cost of \$0.03 m^{-3} biogas, was used for the baseline calculations, but the impact of higher gas cleanup costs was also explored.

Maintenance Costs

The maintenance cost was calculated based on the reactor cost. According to Peters et al. (2003), maintenance costs run between 2% and 11% of the fixed capital investment cost each year depending on the process. Based on this, a value of 5% was selected.

Carbon Credit Savings

Anaerobic digestion reduces GHG emissions in two ways: by reducing direct GHG emissions from a non-AD waste management method, and by avoiding fossil carbon burning through the use of digestion-generated methane instead of natural gas. The 2008 U.S. EPA greenhouse gas inventory (USEPA, 2009) was used to calculate GHG emissions reductions for using AD instead of a liquid slurry storage structure, with 99% methane collection efficiency and 98% methane destruction efficiency assumed. The emissions offset by using AD methane instead of natural gas were then calculated from the CO_2 emissions resulting from combustion. Note, however, that GHG emissions associated with digester construction as well as other indirect emissions were ignored in this analysis. To convert these GHG reductions into economic values, a carbon credit approach was used. Metcalf (2009) suggests valuing carbon credits in the U.S. at \$15 to \$20 Mg^{-1} CO_2. A value of \$20 Mg^{-1} CO_2 equivalent was used as a baseline value in S-FAAD.

Odor Abatement Savings

To put an economic value on the odor reductions caused by AD, we credited the AD operation with the net increase in property values that would occur due to a reduction in odor emission. This required an estimate of the area (acres of property) adversely affected by odor prior to AD installation, and an estimate of the property devaluation that occurs due to odors. Odor setback distances (PAAQL, 2006) were used to determine the impact area, and data from a hedonic study were used to estimate reductions in property values (Herriges et al., 2005). The Herriges et al. (2005) work evaluated the impact of hog operations on property values in five counties in Iowa using a hedonic price model. No similar data were found for dairy manure odors; therefore, S-FAAD uses property devaluations based on the hog operation study. Reductions in property values varied with facility size, distance, and wind direction, but averaged 2% (Herriges et al., 2005). The setback distance used was based on guidelines developed by Purdue University's Agricultural Air Quality Laboratory (PAAQL, 2006). A simplified equation was obtained from average values assumed in the PAAQL model:

$$D \cong \frac{S_{op}}{1420} \tag{4}$$

where D is the offset distance (km), and S_{op} is the operation size (number of cows). This equation assumes that no odor abatement technology is used. When AD is utilized for odor abatement, the impact distance is reduced by applying a correction factor of 0.88 (PAAQL, 2006). We assumed a property rental rate of \$14,000 ha^{-1} year^{-1} and computed a cost benefit for AD based on a reduction in impacted area.

Sensitivity Analysis

To understand how the assumed values impacted the calculated MCR, a sensitivity analysis was completed. Sensitivity coefficients, that is, percent changes in output per percent change in inputs, were computed about the baseline value (Hamby, 1994).

Results and Discussion

Model Validation

To validate the model, FarmWare 3.4 was used as the standard, and a baseline scenario was developed to compare S-FAAD to FarmWare 3.4. The simulations in FarmWare 3.4 assumed that the dairy farm is located in Iowa, cattle are confined in a freestall scraped barn, the method used for manure management prior to AD is a storage tank containing manure and milking center wastewater, and propane is the replacement fuel (natural gas is not available). Data points were collected for 200, 400, 600, 800, and 1000 cow operations, with all costs in 2010 U.S. dollars (fig. 2).

As showed in figure 2, the capital costs reported by FarmWare 3.4 and S-FAAD are very similar. For dairy farms with more than 600 cows, the capital cost reported by S-FAAD is almost the same (within 3%) as the value reported by FarmWare 3.4. For farms with 200 or 400 cows, the percent difference between S-FAAD and FarmWare 3.4 increases slightly. Based on the operation size ranges discussed in AgSTAR (2009), which range from 500 to 3000 dairy cows, it is reasonable that the difference in the values reported by FarmWare 3.4 and S-FAAD would increase outside of the range originally surveyed by AgSTAR. Despite these differences for smaller farm sizes, figure 2 demonstrates that S-FAAD provides a reasonable estimate for the capital cost of AD using fewer site-specific parameters and inputs.

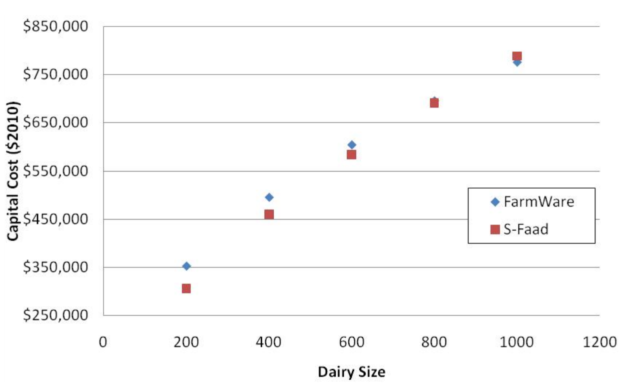

Figure 2. Capital cost comparison.

Baseline Results

Using the baseline assumptions of 7% interest rate, 20-year amortization period, 90% uptime, \$20 Mg^{-1} carbon value, and \$0.03 m^{-3} gas cleanup cost, and a natural gas energy cost of \$5.29 GJ^{-1} (based on a 2010 average), the MCR ranged from 1.4 for the 1000-head facility, to nearly 4.1 for the 200-head facility. The 1.4 value suggests that energy from AD would cost 140% of pipeline natural gas, making AD not economically viable. Breakeven (i.e., MCR of 1.0) occurs around 1700 head under the baseline assumptions, which appears to be a reasonable value since the median herd size at dairies using AD is 1300 (AgSTAR 2010).

Impact of Interest Rate, Amortization Period, Uptime, Carbon Value, and Gas Cleanup Costs on MCR

The MCR was highly sensitive to interest rates, as shown in figure 3. AD becomes economically viable for farm sizes greater than 1000 animals as the interest rate approaches 1%, but interest rates alone are not sufficient for an 800-cow dairy to become economically feasible.

The amortization period, which in S-FAAD is a surrogate for system life expectancy, is also a key driver of MCR, as shown in figure 4. While the amortization period alone does not provide an economically viable solution for any of the sizes evaluated, it is important to note that as the amortization period decreases, the MCR goes up significantly. This simply drives home the importance of well-designed and long-lived systems on overall process economics.

Well-designed systems should not only last a long time, they should also be operational for a large fraction of the year. Figure 5 illustrates the enormous impact of uptime on the economic viability of AD systems. A 30% drop in the MCR results in a 50% increase in the MCR for operation sizes of 200 animals. Multiple challenges to high uptime have been cited by farms running digesters, including equipment reliability, foam and crust formation in the digester, and proper temperature control (Cornell University, 2008).

The base case used a literature-suggested value for carbon credits in the U.S. of \$20 Mg^{-1} CO_2 (Metcalf, 2009). However, carbon credit prices have not exceeded \$3.50 Mg^{-1} on the Chicago Climate Exchange (2010). Figure 6 shows how important carbon values are to viable AD, in light of the relatively low commercial energy prices in the U.S. With carbon values near actual market values, and with all other inputs at base case levels, none of the scenarios tested is economically viable. The best case system is the 1000-head system, with an MCR around 1.4.

As discussed in previous sections, the gas cleanup costs vary significantly based on the type of conditioning required. As shown in figure 7, if gas cleanup only involves hydrogen

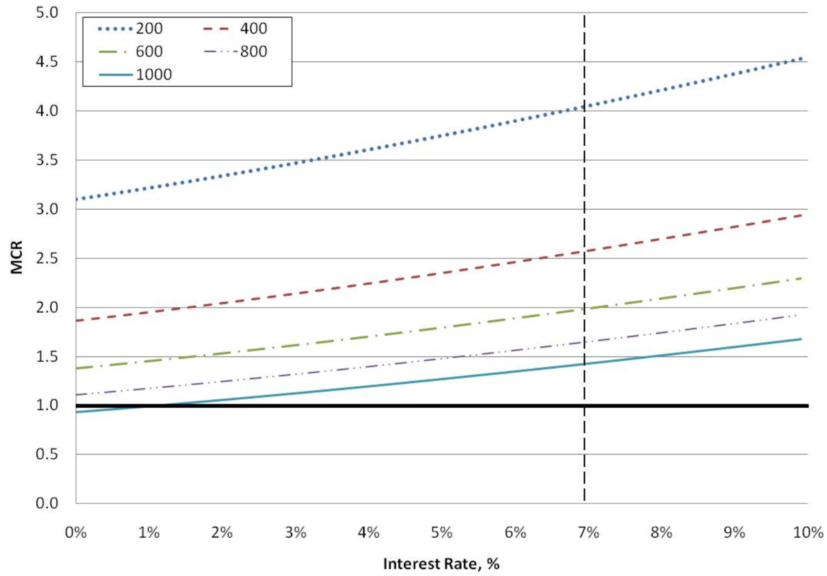

Figure 3. Impact of interest rate on MCR for herd sizes ranging from 200 to 1000 animals. The vertical dotted line illustrates the baseline value for interest rate, and the solid black line illustrates the breakeven point.

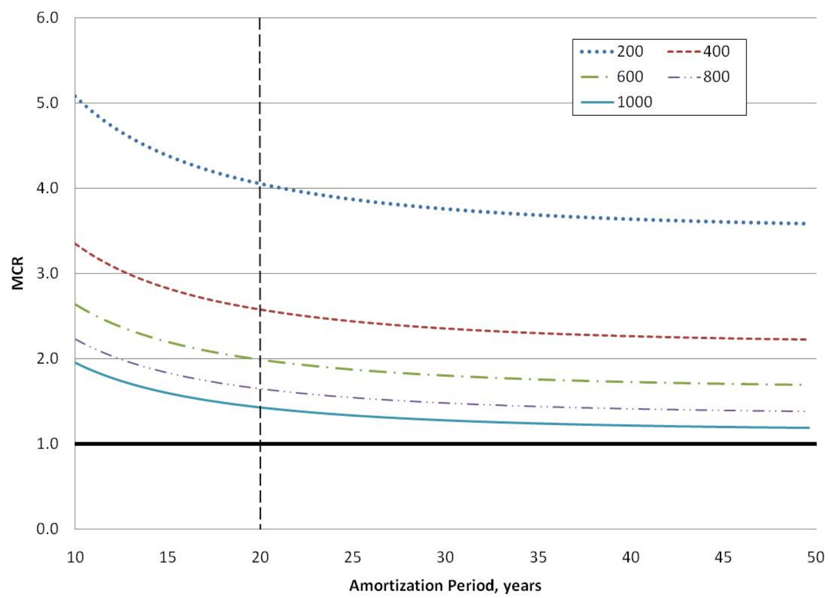

Figure 4. Impact of amortization period on MCR for herd sizes ranging from 200 to 1000 animals. The vertical dotted line illustrates the baseline value for the amortization period, and the solid black line illustrates the breakeven point.

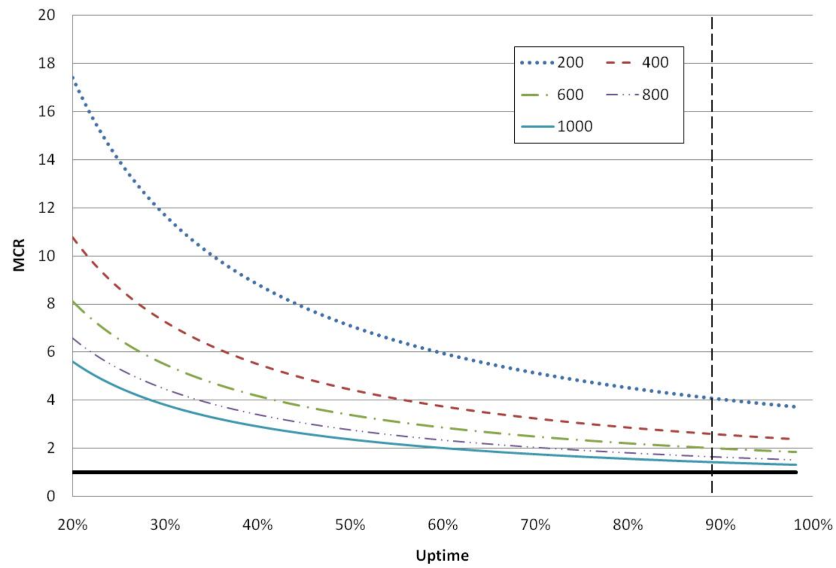

Figure 5. Impact of uptime on MCR for herd sizes ranging from 200 to 1000 animals. The vertical dotted line illustrates the baseline value for the uptime, and the solid black line illustrates the breakeven point.

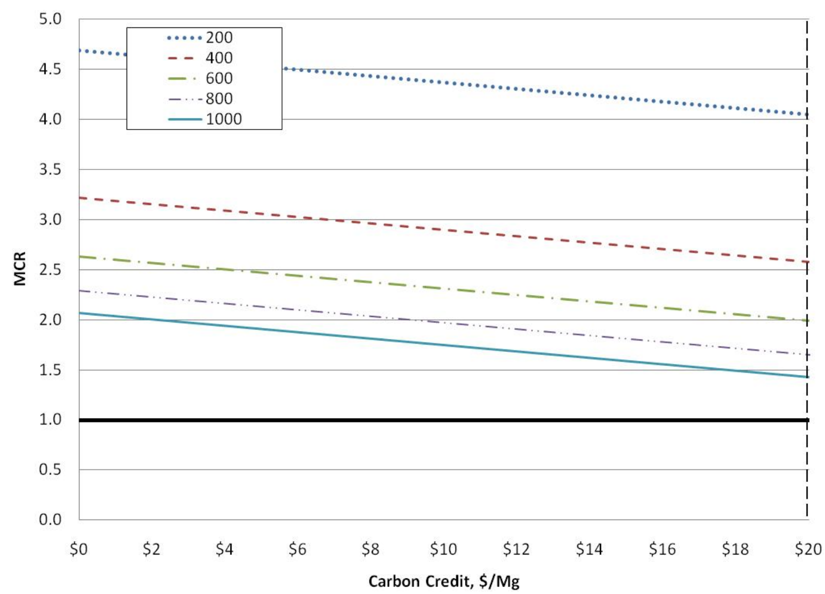

Figure 6. Impact of CO_2 value on MCR for herd sizes ranging from 200 to 1000 animals. The vertical dotted line illustrates the baseline value for the CO_2 credit, and the solid black line illustrates the breakeven point.

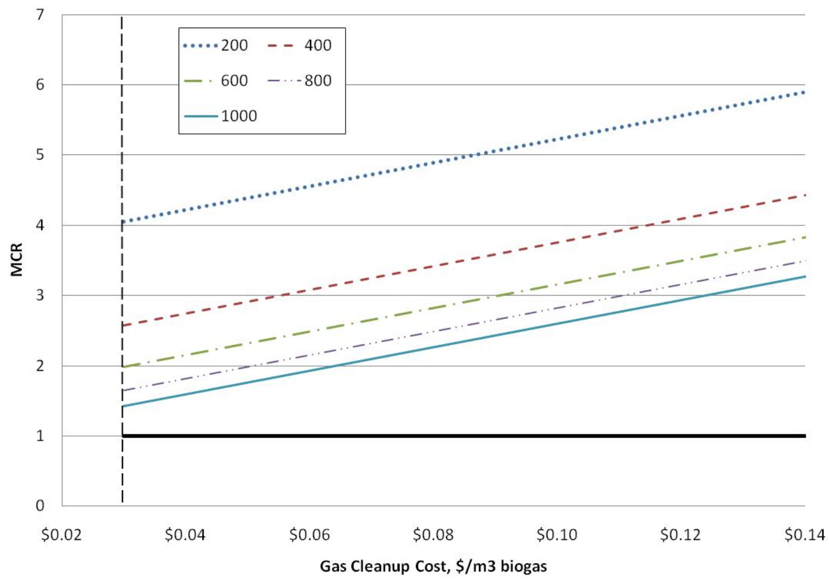

Figure 7. Impact of gas cleanup cost on MCR for herd sizes ranging from 200 to 1000 animals. The vertical dotted line illustrates the baseline value for gas cleanup costs, and the solid black line illustrates the breakeven point.

sulfide removal ($0.03 m^{-3} biogas), then 1000-cow dairies are close to being economically viable; however, as the gas cleanup cost increases, so does the MCR.

Cost Breakdown

To better understand the annual cost for installing and operating a digester, the percent of the total cash flow represented by each expense and cost benefit was determined. Figure 8 illustrates how costs are broken down over the range of operations studied using baseline parameter values.

Figure 8 shows that amortized capital costs dominate the overall cost of AD. As the operation size increases, this term drops slightly, but still remains above 30% for 1000-cow dairies. Based on these results, decreasing amortized capital costs appears to be the most effective way to improve AD deployment rates and decrease the MCR. Decreases in amortized capital costs can be realized in a multitude of ways, including: (1) improved structural design to reduce actual digester construction costs without sacrificing longevity and reliability, (2) improved structural design to increase expected lifetime and thereby lengthen amortization period, (3) provision of low-cost loans or matching funds for digester construction, or (4) improved bioprocess engineering to enable equal degradation at lower retention times (thus decreasing reactor size and cost while maintaining gas production). It is important to emphasize that it is the amortized capital cost, and not simply the capital cost, that must be decreased; digesters made using low-cost materials such as tubular polyethylene bags (Lansing et al., 2008) may require replacement after a few years and can only be compared to other systems on an amortized capital cost basis.

These graphs assume a gas cleanup cost of $0.03 m^{-3} biogas. If CO_2 is removed from the biogas at $0.14 m^{-3}, then the

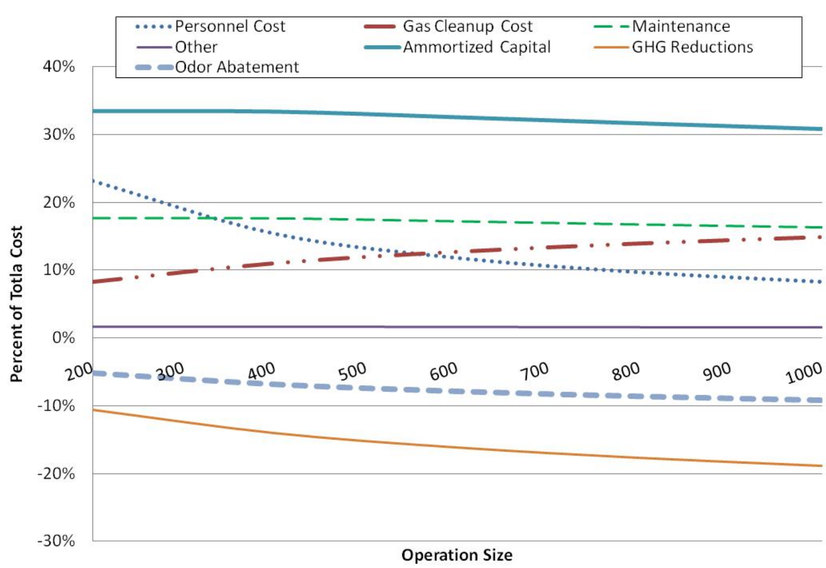

Figure 8. Cost breakdown vs. operation size. Revenue streams are shown on the graph as negative percentages, and annual costs are shown as positive percentages.

gas cleanup cost overtakes the amortized capital cost for all operation sizes.

Another important variable to note is the natural gas price. Natural gas prices fluctuate significantly. In S-FAAD, the natural gas price is the denominator in the MCR and is directly tied to AD economics. If natural gas prices increase to the peak prices realized in 2008, the outlook for AD becomes much brighter; however, as long as natural gas prices remain low, AD struggles to be an economically viable solution, especially on smaller dairies.

Finally, it is worth noting that odor credits range from about 5% to 9% of overall revenue over the scale studied. These values are likely overestimates, insofar as we based the property loss values on hog data and dairies have been found to produce significantly lower odors (e.g., Zhu et al., 2000). Moreover, the odor credit is perhaps the most uncertain of any in the model, and even if property values increase due to AD, there is no existing mechanism by which the dairy would realize any revenue. We justify leaving the term in the analysis because even a rough quantification of this oft-mentioned benefit of AD shows that it is not an economic game changer.

Sensitivity Results

The terms with the highest sensitivity coefficients are shown in figure 9. Sensitivity coefficients indicate the percent change in the MCR resulting from a 1% increase in the variable listed: For example, a 1% increase in the operation size from the base case causes a 0.6% drop in the MCR. The scale factor used in equation 1 had the greatest sensitivity coefficient, as expected. While this value cannot be readily adjusted to improve AD economics, its high sensitivity coefficient illustrates the importance of accurately estimating this term. The multiplier is the second most sensitive variable. Unlike the scale factor, this value could be changed via technological advancements that improve AD digester design. The uptime for a digester heavily impacts AD economics, as shown below; we believe many operational ADs struggle with this. Unsurprisingly, the market natural gas price is also highly sensitive, and market fluctuations in natural gas price can drastically change the economic outlook for AD.

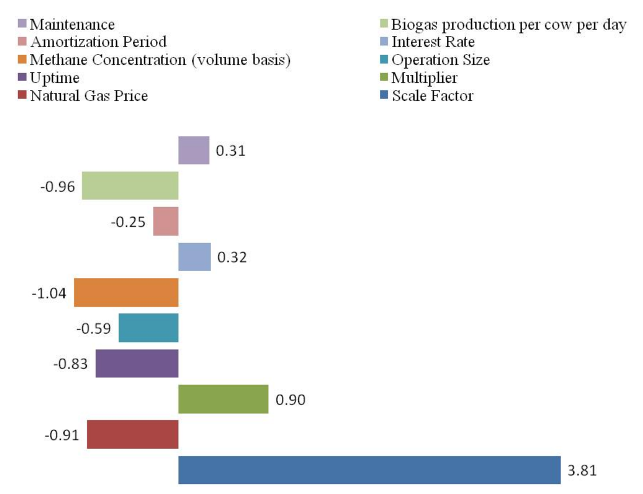

Figure 9. Sensitivity analysis results. Sensitivity coefficients represent the percent change in the MCR with a 1% increase in the variable listed.

Conclusions

The Simplified Framework for Analyzing Anaerobic Digestion (S-FAAD) reported here showed that digester capital costs dominate the overall cost of producing energy using anaerobic digestion. Given the \$20 Mg^{-1} carbon credit prices that have been suggested in the literature, the use of AD to achieve the U.S. Secretary of Agriculture's GHG emissions reduction goals appears economically viable if natural gas prices are sufficiently high. In reality, carbon credit values are not as high as predicted, and gas cleanup costs may not be as low as predicted. Under these more realistic assumptions, S-FAAD showed that the low commercial energy prices in the U.S. mean that without price supports (in the form of carbon credits, low interest loans, or grants), even at 1000-animal herd sizes, biogas from AD cannot compete with pipeline natural gas. Therefore, evaluating policy changes and technological advancements that could lead to increases in digester life and decreases in amortized digester cost and interest rates is recommended.

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