SMALL-SCALE ANAEROBIC DIGESTION IN THE UNITED STATES: DESIGN OPTIONS AND FINANCIAL VIABILITY

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INTRODUCTION

Anaerobic digesters were first widely constructed in the United States during the 1970's energy crisis. Within the anaerobic environment inside a digester, methanogenic microorganisms, utilize organic matter, carbon dioxide, and hydrogen to produce methane, resulting in the creation of renewable energy with decreases in greenhouse gas emissions, organic pollutants, pathogens, and odor (Martin, 2004). Unfortunately, poor economic viability and technical flaws led to a 60% failure rate of these systems (Bishop and Shumway, 2009). Through improved designs, the world is currently seeing a revitalization of anaerobic digestion technology with over 30 million manure-based digesters operating globally (Chen et al., 2010; Rao et al., 2010).

The United States Environmental Protection Agency (USEPA) estimated that large-scale U.S. dairy operations (>500 cows) could produce 6.8 million MWh of renewable energy annually (AgSTAR, 2010). Derived from data in Vanhorn et al. (1994) and the US National Agricultural Statistics Service (2009), it was determined that small-scale dairy operations (<500 cows) have the potential of producing an additional 3.4 million MWh annually (780 kWh/cow).

In recent years, the number of digesters on large-scale livestock operations in the U.S. has increased from approximately 100 facilities in 2005 to 171 facilities in July 2011 (AgSTAR, 2010). With an average capital investment of 1.5 million U.S. dollars, the USEPA does not recommend biogas recovery systems for facilities with less than 500 cows. Other studies have shown at least 200-400 cows are needed for anaerobic digestion systems to be economically viable (Metha, 2002; Moser, 2011). In the United States in 2007, 89% of dairy farms had less than 200 cows, making digestion technology economically inaccessible to the majority of U.S. dairy farms (US National Agricultural Statistics Service, 2009).

Traditional sources of revenue from anaerobic digestion are the creation of biogas and the sale of electricity. While revenue from electricity sales has been successfully achieved at large-scale operations (Nelson and Lamb, 2002; Wright and Inglis, 2003), it is connected to economies of scale and thus not often profitable for small-scale systems, which are more dependent on the price of electricity (Lazarus and Rudstrom, 2007; Ghafoori and Flynn, 2007; Giesy et al., 2009). Small dairies that produce electricity at a profit credit their success to receiving additional off-farm waste, having a favorable buyer for their electricity, and dedicating substantial time to the project development stage (Millen, 2008). When electrical generation was not economically viable, the direct use of biogas was found to be economically feasible when the on-farm heating requirements were high enough to regularly utilize the produced biogas (Barcmort et al., 2008; Bishop and Shumway, 2009).

Perhaps the greatest economic issue facing small-scale digestion is uncertainty of both traditional and non-market factors. Gloy and Dressler (2010) cited the main challenges facing anaerobic digestion financing are the lack of information regarding the initial capital investment, predicted biogas production, expected lifetime, future electricity prices and operating costs. Stokes et al. (2008) highlighted the lack of quantified data on non-market benefits as a major obstacle to widespread anaerobic digestion implementation. The AgSTAR Program, an outreach program supported by the U.S. Environmental Protection Agency (USEPA), U.S. Department of Agriculture (USDA) and U.S. Department of Energy (USDOE) to encourage the use of anaerobic digesters in the U.S., has begun to address the lack of standardized digestion performance data by releasing the report, "*Protocol for Quantifying and Reporting the Performance of Anaerobic Digestion Systems for Livestock Manures"*, but is expected to take years to collect a comprehensive database.

The Minnesota Project, evaluated six anaerobic digester designs for small dairies, 100-300 cows, ranging in cost from $105,000 - $230,000 (2010 US$) (Goodrich, 2005). The largest reduction in capital investment was achieved through the elimination of electricity generation capabilities. The Minnesota Project subsequently constructed a small-scale up-flow digester for 160 milking cows at a cost of $460,000 (US) (Lazarus, 2009. The system, while an excellent first step, has run into problems common at most dairies: engine failure and complications with manure handling.

Objectives

Of the 30 million-plus digesters operating around the world, the majority are low-cost and concentrated in the tropics where the ambient temperature is at or near the optimal digestion temperature of 35°C. In this study, low-cost digestion models from the developing world were modified to transfer this technology to small and medium scale dairy farmers in temperate climates with abundant waste resources.

The goals of the research were to make anaerobic digestion of manure more readily available, cost effective, and manageable to small dairy farmers in the United States. Specifically, the research objectives were to (1) perform an economic assessment of constructed pilot-scale research digesters, (2) perform an economic assessment on a 100-cow scale-up of the research digester design, (3) create a small-scale digester database and perform a cost analyses of these systems, (4) reevaluate the minimum size dairy farm needed for an economically feasible anaerobic digester in the U.S.

METHODS

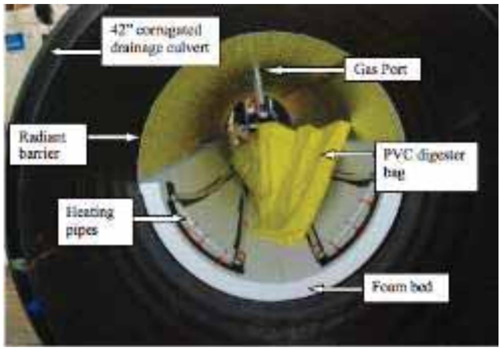
Research site

The University of Maryland (UMD) research digesters were constructed using a modified Taiwanese digester design developed by Raul Botero and T. R. Preston for tropical climates. The traditional Taiwanese digester includes a plug-flow reactor constructed of a tubular polyethylene bag and PVC piping (Lansing et al., 2008). Modifications to this design were necessitated by the sensitivity of methanogens to the lower temperatures inherent in the temperate climate of the U.S.

There are nine plug-flow UMD research digesters located at the United States Department of Agriculture (USDA) dairy facility in Beltsville, Maryland. Each digester is 4.36 meters in length with a diameter of 0.91 meters and a total capacity of 700 gallons (2.65 m^3) per digester. The digesters are fed 25 gallons (0.09 m^3) of manure daily with a combined treatment volume of 225 (0.85 m^3) gallons per day with a 21-day retention time.

The UMD research digesters were constructed of a PVC-based flexible material, laid in insulative foam beds surrounded by radiant barriers, and enclosed within 1.07 meter drainage culverts to both protect and maintain the desired shape of the digesters as shown in Figure 1.

Figure 1: The inside of the UMD modified Taiwanese-model plug-flow digester



Manure is pumped into a stainless steel heating kettle and warmed to 35°C before draining into the digesters. Preheating of manure influent is a technique that has shown promise in past experiments but has not been tested as a modification to the Taiwanese design. Once the manure reaches 35°C, it is released into the digester. The culverts are partially buried for added insulation and protected from the elements by a windshield structure.

The UMD research digesters are augmented with recirculation capabilities, allowing the effluent from the digesters to be reintroduced into the system through the heating kettle. Recirculation has been shown to aid in the distribution of the microorganisms and aid in keeping warm material circulating through the system. These modifications represent a departure from the original plug-flow, unheated Taiwanese-model digestion system in an effort to create a design that is compatible with a temperate climate.

The USDA's dairy facility uses a manure scraper system to remove the waste from its 120-cow facility. The manure is separated using a solid separator. The solids are composted, while the liquid portion is treated by a mixed digester system installed in 1994 for $263,000 (1994 US$). The digester effluent is stored in a lagoon and spray applied to the fields as fertilizer. The influent to the UMD research digesters is pumped from two locations. Six of the UMD research digesters receive un-separated manure pumped from the manure storage pit located before solid separation, and three UMD research digesters receive liquid manure pumped from a manure storage pit located after solid separation. The effluent from the nine research digesters is pumped back into the storage lagoon. These influent and effluent connections were used as the boundary line for the economic analysis of the research digesters; thus, neither the solids separator nor the lagoon storage is included in the economic assessment.

The UMD research system was conceptually scaled up to supply a 100-cow dairy (referenced as UMD digester.) The scale up was performed on a component by component basis to most accurately represent real costs.

Smaller-scale anaerobic digestion systems

The UMD digester was evaluated against literature values obtained from existing and theoretical digesters for farms of 250 or less cows. The digester types include complete-mixed, plug-flow, covered lagoons, fixed film, and up-flow. The cost data were compiled from published studies and conversations with providers and farmers for actual systems. Projected costs for the theoretical systems were determined by extrapolating costs of existing components from other systems. The digestion systems used in the economic analysis are listed in Table 1. The UMD digester was evaluated under two scenarios: the first scenario was calculated without an electric generation system, and the second scenario included an electric generation system and payback from the utility.

Cash-flow analysis

In order to evaluate the economic viability of the proposed modified plug-flow system, a cash-flow approach was used, as recommended by the USEPA-AgSTAR *Protocol for Quantifying and Reporting the Performance of Anaerobic Digestion Systems for Livestock Manures*. The cash-flow approach tabulates and compares all annual costs and revenues. Required assumptions described by the AgSTAR Protocol are as follows: (1) initial capital for the system is considered to be a combination of internal capital and borrowed capital, (2) the interest rate on borrowed capital is assumed to be equal to the rate of return on internal capital, (3) no cost-sharing assistance is included in the analysis, (4) payments for the total capital costs occur as a uniform series of annual payments over the useful life of the system, and (5) the useful life of the system is assumed to be 20 years and the replacement of system components with shorter lifetimes is accounted for in annual operation and maintenance costs. The discount rate on borrowed capital is assumed to equal the average effective interest rate (7.8%) on non-real-estate farm loans. All costs were converted to 2010 U.S. dollars using the Engineering News Record (ENR) Construction Cost Index. See Klavon (2011) for a detailed method of the cash-flow analysis.

Table 1. Database of small-scale digester systems in the United States, 2011

Name	Digester Type	Digester Site	# of cows	Items Included
UMD 1	Taiwanese-model Plug Flow	UMD Research Digesters, MD	100	digester, collection, excavation, gen-set
UMD 2	Taiwanese-model Plug Flow	UMD Research Digesters, MD	100	digester, collection, excavation
Theoretical 1	Covered Lagoon	Designed, not constructed	100	digester, collection, boiler
Theoretical 2	Plug Flow	Designed, not constructed	100	digester, collection, boiler
Theoretical 3	Upright	Designed, not constructed	100	digester, separator, composter, boiler
Theoretical 4	Upright Mixed	Designed, not constructed	100	digester, separator, boiler
Theoretical 5	“Low-cost” Plug Flow	Designed, not constructed	100	digester, collection, boiler
Theoretical 6	Upright Mixed	WA State Dairy Farm, WA	200	digester, gen-set
Digester 1	Upright	USDA Beltsville, MD	220	digester, collection, separator, boiler
Digester 2	Plug Flow	Northeast IA CC Farm, IA	120	digester, gen-set
Digester 3	Upflow-tank	Jer-Lindy Farm, MN	160	digester, collection, building, labor, excavation, boiler, gen-set
Digester 4	Plug Flow	Freund Dairy, CT	250	digester, boiler
Digester 5	Fixed-Film	JJ Farber Dairy, NY	100	digester, boiler
Digester 6	Covered Lagoon	Spring Valley Dairy, NY	236	digester, gen-set, manure storage
Digester 7	Fixed-Film	Williston Cattle Co., VT	250	digester, extra research ports, boiler
Digester 8	Upright Mixed	WA State Dairy Farm, WA	200	digester, boiler
Manure Pit 1	Earthen Manure Pit	Typical, MD	150	Pit, pumps, pipes
Manure Pit 2	Lagoon (no cover)	Typical, MD	250	Lagoon, solid separator, concrete pad, pumps, pipes

RESULTS

Capital costs

The most expensive components of the UMD research digesters were the digester bags, culverts, and conveyance system (piping and pumps), resulting in a total system capital cost of $83,970 (2010 US$), not including labor. Utilizing the same design but scaled up for a 100-cow facility, the capital cost of the UMD system for a 100-cow farm with electrical generation (UMD1) was calculated to be $284,150 (2010 US$) with the co-generator accounting for 36% of the total capital cost. The capital cost of the UMD system without electrical generation (UMD2) totaled $184,150 (2010 US$).

Cash-flow analysis

The cash-flow analysis found two systems had a positive cash-flow without cost sharing when all possible revenue sources were included, Theoretical 6 and Digester 8 (Tables 2, 3). Bedding reuse accounted for the greatest percentage of annual revenue. When carbon credits and bedding reuse were excluded as annual benefits, no smaller-scale digestion system had a positive cash-flow.

DISCUSSION

Cash-flow analysis for smaller-scale digesters in the U.S.

The UMD system did not perform well with or without electrical generation capabilities due to high initial capital costs and insufficient revenue. The system may perform better when actual operation and maintenance data are available as the system was designed to utilized less biogas for internal heating and expensive automotive capabilities that could decrease the time required for digester operation.

Of the two systems with a positive cash-flow, Digester 8 did not have electrical generation and Theoretical 6 had electrical generation capabilities. Both systems had lower initial capital costs, which was the largest factor in determining their cost effectiveness. Digester 8, a complete mixed digester with a boiler system, was installed in 1976 for $164,520 (2010 US$) (Coppinger et al., 1980). Given the age of the system, it is possible that the cost to build the same system today would be higher than is accounted for in this analysis, as the construction cost index is used for general construction costs and is not an exact inflation rate for all the materials used in construction of the digester. Theoretical 6, which is Digester 8 with added electrical generation capabilities, could have a similar inflation error as Digester 8.

Given the limited ability of traditional manure management systems to generate revenue, neither manure pit systems had a positive cash-flow. It is assumed that this cost is already being absorbed by the farm before the installation of the digester. If the cost of the manure pit were added to the cost of the digester, none of the digester systems would generate a positive cash-flow.

Table 2. Capital costs and cash flow analysis for the small-scale digestion systems. Parentheses represent a negative number, numbers are 2010 US$, rounded to $10

System	Capital Costs	Capital Cost/Cow	Annual Operating Cost	Annual Income	Annual Net Cost	Annual Cost/Cow
UMD 1	$284,150	$2,840	($14,210)	$15,370	($27,780)	($280)
UMD 2	$184,150	$1,840	($5,520)	$15,960	($8,320)	($80)
Theoretical 1	$217,480	$2,170	($6,520)	$15,960	($12,710)	($130)
Theoretical 2	$192,650	$1,930	($5,780)	$15,960	($9,440)	($90)
Theoretical 3	$189,110	$1,890	($5,670)	$15,960	($8,970)	($90)
Theoretical 4	$163,110	$1,630	($4,890)	$15,960	($5,540)	($60)
Theoretical 5	$124,100	$1,240	($3,720)	$15,960	($400)	$0
Theoretical 6	$176,450	$880	($8,820)	$30,750	$3,960	$20
Digester 1	$427,990	$1,950	($12,840)	$35,110	($21,320)	($100)
Digester 2	$266,930	$2,220	($13,350)	$18,450	($22,090)	($180)
Digester 3	$487,160	$3,040	($13,390)	$28,790	($34,220)	($210)
Digester 4	$349,890	$1,400	($10,500)	$39,900	($6,240)	($20)
Digester 5	$176,140	$1,760	($31,550)	$17,090	($32,400)	($320)
Digester 6	$188,830	$800	($10,550)	$22,680	($7,100)	($30)
Digester 7	$371,070	$1,480	($11,130)	$39,900	($9,020)	($40)
Digester 8	$164,520	$820	($4,940)	$31,920	$10,220	$50
Manure Pit 1	$150,000	$1,000	($15,000)	$0	($30,280)	($200)
Manure Pit 2	$600,000	$2,400	($25,000)	$33,800	($52,310)	($210)

Impact of revenue generation on the cash-flow analysis

Given the industrial market price of natural gas in 2010-2011, $5.10/cf, and the price of electricity, $0.09/kWh, it was more cost effective to use the biogas directly than it was to convert it into electricity, even without taking into account the higher capital cost and operating cost of an electrical generation system. This gave all systems utilizing boilers a higher annual income per cow than those utilizing electrical generation. Other studies have also concluded the direct use of biogas in lieu of electrical production was economically feasible when the on farm heating requirements were high enough to regularly utilize all of the produced biogas (Bracmort et al., 2008; Bishop and Shumway, 2009). Past studies have also demonstrated that increasing the price of electricity expanded the economic feasibility of anaerobic digesters to smaller farms (60 – 650) (Metha, 2002; Bishop and Shumway, 2009; Giesy et al., 2009).

Bedding reuse was one of the highest income sources generated from digester use, ranging from $10,000 - $25,000 (2010 US$) annually. This finding is congruent with other studies, which found bedding recycling for on-farm use or for off-farm sale to be an important income source for farms with solid separator capabilities. For existing digestion systems where the cost of the solid separator was not included in the capital costs, it was assumed the separator already existed on the farm.

Table 3. Annual revenue for the small-scale digestion systems (2010 US$, rounded to $10)

Name	Biogas	Electrical Generation	Bedding Reuse	CO2 Credits	Total Revenue
UMD 1	$0	$4,700	$10,000	$670	$15,370
UMD 2	$5,270	$0	$10,000	$690	$15,960
Theoretical 1	$5,270	$0	$10,000	$690	$15,960
Theoretical 2	$5,270	$0	$10,000	$690	$15,960
Theoretical 3	$5,270	$0	$10,000	$690	$15,960
Theoretical 4	$5,270	$0	$10,000	$690	$15,960
Theoretical 5	$5,270	$0	$10,000	$690	$15,960
Theoretical 6	$0	$9,400	$20,000	$1,350	$30,750
Digester 1	$11,590	$0	$22,000	$1,520	$35,110
Digester 2	$0	$5,640	$12,000	$810	$18,450
Digester 3	$0	$7,520	$16,000	$1,080	$28,789[a]
Digester 4	$13,170	$0	$25,000	$1,730	$39,900
Digester 5	$5,270	$0	$10,000	$690	$17,089[a]
Digester 6	$0	$11,090	$23,600	$1,590	$22,675[a]
Digester 7	$13,170	$0	$25,000	$1,730	$39,900
Digester 8	$10,540	$0	$20,000	$1,380	$31,920
Manure Pit 1	$0	$0	$15,000	$0	$15,000
Manure Pit 2	$0	$0	$25,000	$0	$25,000

[a] Total revenue amount used in the cash flow analysis is based on case study data adjusted to 2010$ and not the addition of the columns due to actual revenue data available.

Food waste and tipping fees

The negative cash-flow observed in many of the analyzed systems could be offset by the addition of food waste and the accompanying tipping fees. To have a positive cash-flow, UMD2 would need an additional $690 (2010 US$) in monthly tipping fees, while UMD1 would need $2,320 (2010$) in monthly tipping fees. Taking food waste could also increase income beyond the tipping fee by contributing additional volatile solids to the digester, thus increasing biogas production. There is some risk to accepting off-farm food waste, as some wastes are not well-suited for anaerobic digestion and can decrease biogas production.

Additional funding options

This analysis assumed the farmer paid 100% of the investment, but in practice there are multiple cost-sharing opportunities available to U.S. farmers for anaerobic digester projects. Federal sources of funding have been know to cover 50% of the project costs, and various grants, loans, tax exemptions, and production incentives are also available on the State and local level. Giesy et al. (2009) found economic feasibility of digesters to be highly sensitive to cost-sharing opportunities. When cost-sharing opportunities were utilized to pay for 25% of the initial capital cost, three additional systems, Theoretical 5, Digester 4, and Digester 7, had a positive cash-flow. When cost-sharing opportunities were utilized to pay for 50% of the initial capital cost, nine additional systems, including UMD2, had a positive cash-flow.

CONCLUSIONS

This study demonstrates that anaerobic digesters can be cost effective for small-scale systems, although their viability must be analyzed on an individual basis, as 63% of the systems analyzed were more expensive than the AgSTAR recommended capital cost of $1,500/cow. However, with an increase in revenue, such as an increase in the price of electricity or the addition of tipping fees, a greater capital cost could be afforded by the farmer. The most cost effective method to create economically viable small-scale digesters is to lower the capital cost using cheaper materials. With a 44% drop in capital costs, the UMD system without electricity generation would have been cost neutral.

While small-scale anaerobic digestion is economical in some cases, it is farm dependent and a majority of the systems analysis did not have a positive cash-flow. In this analysis, at least half of the existing digesters are now shutdown (4 out of 8), with three cases due to the dairy closing or management changes and not specifically related to a digester failure. The longest running small-scale system has been operational for almost two decades, and there are four small-scale systems under construction, showing some success in the market. Success appears to be dependent on the willingness of farmers to invest time and personal energy into the digester with economics being only one way to gauge the success of a project. With the appearance of multiple private companies attempting to fill the niche of small-scale anaerobic digestion with modular and proprietary designs, this technology could see much greater implementation in the coming years.

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