BIOMASS AND BIOENERGY 54 (2013) 36–45

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Economic analysis of small-scale agricultural digesters in the United States

Katherine H. Klavon [a], Stephanie A. Lansing [a,*], Walter Mulbry [b], Andrew R. Moss [a], Gary Felton [a]

[a] Department of Environmental Science and Technology, Renewable Energy Research Center, University of Maryland, 1445 Ag Engineering Building, College Park, MD 20742, USA

[b] USDA/ARS Environmental Management and Byproducts Laboratory, Beltsville, MD 20705, USA

ARTICLE INFO

Article history:
Received 5 February 2012
Received in revised form
8 March 2013
Accepted 10 March 2013
Available online

Keywords:
Anaerobic digestion
Small-scale
Manure
Biogas
Economic analysis

ABSTRACT

Anaerobic digestion (AD) is an economically viable manure treatment option for large dairies (>500 cows) in the U.S. However, roughly 90% of U.S. dairies have less than 200 cows, making this technology economically inaccessible to the vast majority of U.S. dairies. While there have been case studies of individual small dairies with anaerobic digesters, there are no comparative studies using cost data from these systems. The objectives of this study were to (1) determine the economic viability of small-scale U.S. digesters using cost data from nine existing 100 to 250-cow dairies and seven theoretical systems and (2) reevaluate the minimum size dairy farm needed for economically feasible AD in the U.S. Cash flow analysis results showed that total capital costs, capital costs per cow, and net costs per cow generally decreased with increasing herd size in existing systems. Among existing revenue streams, use of digested solids for bedding generated the highest revenue ($100 cow^{-1} year^{-1}), followed by biogas use for heating and/or electrical generation ($47 to $70 cow^{-1} year^{-1}) and CO_2 credits ($7 cow^{-1} year^{-1}). No system had a positive cash flow under the assumed conditions (8% discount rate, 20-year term). However, six of the 16 systems had positive cash flows when 50% cost sharing was included in the analysis. Our results suggest that, with cost sharing, economically viable AD systems are possible on 250-cow dairies. Additional revenue streams, such as tipping fees for food waste, may reduce the minimum size to 100-cow dairies.

1. Introduction

Anaerobic digestion is a microbial-mediated process in which methanogenic microorganisms utilize organic matter, carbon dioxide, and hydrogen to produce methane, resulting in the creation of renewable energy and decreases in greenhouse gas emissions, organic pollutants, pathogens, and odor [1,2–8]. Agricultural digesters utilizing this process were first widely constructed in the United States during the 1970s [1,9]. Unfortunately, poor economic viability and technical flaws led to a 60% failure rate of these systems [10]. Through improved designs, the world is currently seeing a revitalization of anaerobic digestion technology with over 30 million manure-based digesters operating globally [11,12].

In the United States, the U.S. Environmental Protection Agency (USEPA) estimated that large-scale dairy operations (>500 cows) have the potential to produce 7 TWh y^{-1} of renewable energy [13], while small-scale dairy operations

* Corresponding author. Tel.: +1 301 405 1197; fax: +1 301 314 9023.
E-mail address: slansing@umd.edu (S.A. Lansing).
0961-9534/$ – see front matter
http://dx.doi.org/10.1016/j.biombioe.2013.03.009

(<500 cows) have the potential to produce an additional 3 TWh y^{-1} (0.78 MWh y^{-1} per cow) [14, 15].

The number of digesters operating on large-scale livestock operations in the U.S. has increased from approximately 100 facilities in 2005 to 171 facilities in July 2011 [16,17]. However, the USEPA does not recommend these systems for facilities with less than 500 cows, as the average capital investment cost of 1.5 million (US$) per system (2010 US$), is not feasible for smaller operations [13,16,18], while other studies have shown that 200–400 cows are needed for anaerobic digestion systems to be economically viable [19,20]. In 2007, 89% of U.S. dairy farms had less than 200 cows, making digestion technology economically inaccessible to the majority of U.S. dairy farms [15].

There are a number of factors, in addition to high capital costs, influencing the economic viability of small-scale anaerobic digesters. One of these factors is the ability to create sufficient revenue from the digester. While electricity generation can be economically successful at large-scale operations [21,22], success is less likely for small-scale operations, which can be affected more acutely by the price of electricity and are less likely to have the capital to purchase and maintain an electric generator [9,19,23–26]. In lieu of electricity production, the direct use of biogas can be economically feasible when on-farm heating requirements are high enough to utilize the produced biogas throughout the year [10,27]. Additionally, carbon credits, tipping fees (for adding off-farm food waste to the digester), and reuse of the solids separated from the digester effluent (as dairy herd bedding or sold as soil amendments) have been shown to increase the economical viability of digesters [9,10,25,28–32].

In addition to increasing revenue opportunities, the use of an anaerobic digester to reduce odors is an important reason for digester installation [3,19,28,29]. While hard to quantify, and often not included in economic assessments, costs of odor control could be considered the price of staying in business as residential areas continue to encroach on once-rural U.S. farms [29].

Additional factors affecting the economic viability of digesters include financing and access to data. The main challenge to financing anaerobic digesters in the U.S. is the lack of information regarding initial capital investment, predicted biogas production, expected lifetime, future electricity prices, operating costs, and non-market benefits [25,32]. The AgSTAR Program, an outreach program of the U.S. Environmental Protection Agency (USEPA), U.S. Department of Agriculture (USDA), and U.S. Department of Energy (USDOE) released a protocol for quantifying and reporting digestion performance, but it is expected to take years to collect a comprehensive database [33].

1.1. *Objectives*

In the U.S., small-operations dominate the dairy sector but are not encouraged to build anaerobic digestion systems due to the high capital investment. The objective of this study was to determine the economic viability of small-scale U.S. digesters and to determine how new and existing systems could be designed or altered to improve economic sustainability in the agricultural market. Cost data from nine existing and seven theoretical systems were used to quantify the potential revenue streams needed to make the digesters cost effective and to reevaluate the minimum size dairy farm needed for economically feasible anaerobic digestion in the U.S.

2. Methods

2.1. *Small-scale digestion system descriptions*

The evaluation contained economic data from nine existing and seven theoretical U.S. digesters for dairy farms with 250 cows or less. The digester types included upright, plug-flow, covered lagoon, fixed-film, and upflow blanket reactor. Existing systems' cost data were compiled from published studies and interviews of providers and farmers, while theoretical digesters' cost data were derived from published reports [34–46]. The digestion systems used in the economic analysis are listed in Table 1.

Four of the existing systems were installed as part of a research or outreach program. D1, an upright mixed digester, received separated manure with the undigested solids being composted and field applied. D2, a plug-flow digester, received un-separated manure with solids potentially reused as bedding material [34,35]. D3, an upflow-tank reactor or induced blanket reactor, received un-separated manure with the digested solids being recycled as bedding material [36]. The system was designed to primarily use biogas in a generator but had a backup boiler in the event of generator failure [36]. D7, a fixed-film digester constructed with a biofilter, received separated manure with solids being reused as bedding or field applied [38,39].

The remaining four existing systems were installed on private dairies. D4, a horizontal plug-flow digester, received un-separated manure and included U-shaped tank with a modified plastic greenhouse cover to capture biogas [40]. D5, a fixed-film digester, used corrugated plastic drainage tiles as the fixed media and received separated liquid manure [41]. The removed solids were composted with heat from the digester's boilers and used as bedding [41]. D6, a covered lagoon system utilizing a two-tank manure activation system, included a small seeding tank and a main treatment lagoon with a flexible cover [42]. No solid separation equipment was included in this system [42]. D8, an upright mixed digester, received un-separated manure and was designed as two insulated glass-lined steel tanks with silo roofs to collect biogas [43]. The digester used biogas directly in a boiler to heat the digester and produce steam for the farm, or in a generator to produce emergency electricity. This digester was analyzed under both scenarios: boiler used, $D8_a$, or generator used, $D8_b$ [43].

Five of the theoretical systems were from a report by the Minnesota Project highlighting different digester designs that could be applied to small-scale dairy farms [44]. T1, a covered pond, was designed as a lined basin with an insulated cover in which the solids could be removed before digestion and composted or removed when digestion pond was emptied. T2, a conventional plug-flow digester, was designed for high solids (12%) with an elongated tank, flexible cover, and a solid separator post-digestion. T3, an upright unmixed digester,

Table 1 – Small-scale digester systems in the United States used in this study, 2011.

ID	Name	Digester type	Digester site	Years of operation	# of Cows	Additional items included	Bedding reused	Biogas use
D1	Digester 1	Upright mixed	USDA, MD	1994–Present	220	Collection, separator, boiler	No	Boiler
D2	Digester 2	Plug-flow	Northeast IA CC Farm, IA	2002–2003	120	Gen-set	Yes	Electrical generation
D3	Digester 3	Upflow-tank	Jer-Lindy Farm, MN	2008–Present	160	Collection, building, boiler, gen-set	Yes	Electrical generation
D4	Digester 4	Plug-flow	Freund Dairy, CT	1997–Present	250	Boiler	Yes	Boiler
D5	Digester 5	Fixed-film	JJ Farber Dairy, NY	1997–2006	100	Boiler	Yes	Boiler
D6	Digester 6	Covered lagoon	Spring Valley Dairy, NY	2003–Unknown	236	Gen-set, manure storage	No	Electrical generation
D7	Digester 7	Fixed-film	Williston Cattle Co., VT	2004–2008	250	Extra research ports, boiler	Yes	Boiler
$D8_a$	Digester 8_a	Upright mixed	WA State Dairy Farm, WA	1976–1979	200	Boiler	No	Boiler
$D8_b$	Digester 8_b	Upright mixed	WA State Dairy Farm, WA	1976–1979	200	Gen-set	No	Electrical generation
T1	Theoretical 1	Covered lagoon	Designed, not constructed	–	100	Collection, boiler	Yes	Boiler
T2	Theoretical 2	Plug-flow	Designed, not constructed	–	100	Collection, boiler	Yes	Boiler
T3	Theoretical 3	Upright unmixed	Designed, not constructed	–	100	Separator, composter, boiler	Yes	Boiler
T4	Theoretical 4	Upright mixed	Designed, not constructed	–	100	Separator, boiler	Yes	Boiler
T5	Theoretical 5	"Low-cost" plug-flow	Designed, not constructed	–	100	Collection, boiler	No	Boiler
$T6_a$	Theoretical 6_a	Taiwanese-model plug-flow	Designed, not constructed	–	100	Collection, boiler	Yes	Boiler
$T6_b$	Theoretical 6_b	Taiwanese-model plug-flow	Designed, not constructed	–	100	Collection, gen-set,	Yes	Electrical generation
MP1	Manure pit 1	Earthen manure pit	Theoretical	–	150	Pit, pumps, pipes	No	n/a
MP2	Manure pit 2	Lagoon (no cover)	Theoretical	–	250	Lagoon, solid separator, composting pad, pumps, pipes	Yes	n/a

was designed for separated manure with the solids separated and composted prior to digestion. T4, an upright mixed digester, was designed for un-separated manure and thus had a larger tank volume than T3. T5, a low-cost plug-flow system, was designed using a plastic liner inside a steel culvert.

T6 was from an analysis conducted by the University of Maryland (UMD) [45]. The UMD conceptual digester design was a modified version of the traditional Taiwanese-model digester and had a PVC-based tubular bag digester inside an insulated and heated culvert. $T6_a$ was calculated without electricity generation, while $T6_b$ included an electric generation system (accounting for 36% of the capital costs).

In addition to data from the 16 digesters, average capital cost data for two types of manure pit systems, an earthen pit without solid separation and a concrete lagoon with solid separation and composting, were collected to demonstrate the costs of traditional manure management systems. The capital costs and operation and maintenance costs of these two systems were calculated based on the records from five farmers (three with earthen pits and two with lagoons and solid separation). It was assumed that the lagoon system with solid separation and composting reused bedding.

2.2. *Cash flow analysis*

The economic viability of each system was evaluated using a cash flow approach and methodology recommended by AgSTAR [33]. The cash flow approach tabulates and compares all annual costs and revenues. The useful life of the system was assumed to be 20 years with replacement cost of system components with shorter lifetimes accounted for in annual operation and maintenance costs. The discount rate on borrowed capital was assumed to be the average effective annual interest rate (8% y^{-1}) of non-real-estate farm loans in 2010 [33,47].

Published operation and maintenance costs were available for four systems (D3–D6). If records were not available on annual operation and maintenance costs, the cost were assumed to be 3% of the total capital costs for boiler-only systems, following the recommendations of AgSTAR [33]. As other studies have found annual operation and maintenance costs for digesters with electrical generation to be 5% of total capital costs, this value was used for electrical generation systems [1,37,46].

Boundary conditions were established to include only components required solely for the digester system. It was assumed that manure storage and spreading systems were already installed on the farm.

2.3. *Annual revenue*

The revenue streams analyzed included biogas production, electrical generation (where appropriate), sale of digester solids for bedding (termed "bedding reuse"), and carbon credit offsets. For systems without generators, it was assumed that all produced biogas not used to heat the digester was utilized on the farm to offset the cost of natural gas that would have been purchased at the average 2010–2011 agricultural consumer rate for natural gas, 0.18 \$ m^{-3} (2010 US\$) [48]. If biogas production data was not provided, it was assumed that one cow produced 2.0 $m^3\,d^{-1}$ of biogas, which is comparable to the 1.9 $m^3\,d^{-1}$ calculated by the Natural Resources Conservation Service (NRCS) [14,46]. It was also assumed that the produced biogas contained 60% methane by volume, one-third of which was used to heat the digester leaving two-thirds for revenue considerations [14,27,46].

For systems with generators, it was assumed that 1.0 kWh was produced from 0.9 m^3 of biogas, offsetting electricity that would have been purchased by the farm at 2010 retail prices, 90 $\$\,MW\,h^{-1}$ (2010 US$) [14,49], which is within the range of 80–140 $\$\,MW\,h^{-1}$ (2010 US$) used in previous economic evaluations of anaerobic digesters in the U.S. [19,24,26]. Additionally, it was assumed that farms had net metering pricing, which allows renewable energy operations to receive retail value for excess electricity produced [50,51]. In the United States, net metering laws have been enacted in 46 States, but laws vary from State to State and do not always include biogas production as an eligible renewable energy source [52].

Revenue values from bedding reuse were calculated based on the assumption that a dairy cow produces approximately 7.65 $m^3\,y^{-1}$ of fiber [53,54] and bedding costs average 13 $\$\,m^{-3}$ (2010 US$) [54,55]. It was assumed that only digestion systems with solid separation equipment could receive revenue from bedding reuse.

Carbon emission reduction calculations were based on the AgSTAR Reporting Protocol-Section 6.0: Reduction in Methane Emissions, with the following correction made to Table 4 of this Protocol [33]. The default value of kg CH_4 emitted was listed in Table 4 as 10^{-6} Btu (0.01 J) [33]. This value was corrected to 10^{-9} Btu (0.01E−3 J), as specified in the IPCC Guidelines for National Greenhouse Gas Inventories [56]. A carbon credit cost of 5.70 $\$\,t^{-1}$ (2010$) CO_2-C equivalent was used, which has been used in other economic assessments and is within the range traded on the Chicago Climate Exchange between 2008 and 2011 [50,57].

All costs and results were converted to and reported in 2010 U.S. dollars using the Engineering News Record (ENR) Construction Cost Index [58–62].

2.4. Sensitivity analysis

A sensitivity analysis was conducted for the annual discount rate (4% and 8%) and lifetime expectancy (10 and 20 years), with an 8% discount rate and 20-year lifetime representing the base-case scenario and a 4% discount rate and 20-year lifetime representing the best-case scenario. In the literature, discount rates range from 4.0 to 14.25% and lifetime expectancies range from 10 to 20 years [9,10,24,26,27,33]. In addition, cost sharing of 50% of capital cost was analyzed under each scenario.

3. Results

3.1. Capital costs

Capital costs per cow generally decreased with increasing herd size (Fig. 1). However, no other relationships were evident between capital costs and digester design, or the presence or absence of electrical generators. Capital costs of the 16 systems ranged from 120,000 to 490,000$ with capital

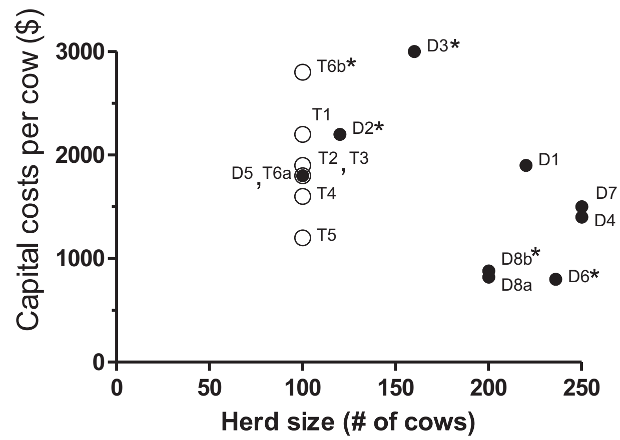

Fig. 1 – Capital costs per cow as a function of farm herd size. Values from existing digester systems are shown as solid circles. Values from theoretical digester systems are shown as open circles. The five systems that include electrical generators are marked with asterisks.

costs per cow generally ranging between 1400$ and 2200$ (Table 2). Costs of the theoretical systems spanned the same cost range as those of existing systems (Fig. 1).

With respect to capital costs of different digester designs, covered lagoon systems were represented by the least expensive system (D6) as well as one of the most expensive systems (T1) in the group. The second least expensive system (D8) was an upright mixed digester constructed in 1976. Systems on larger dairies (>200 cows) with electrical generators (D6, $D8_b$) had comparable net costs per cow to those of systems without generators (D4, D7, $D8_a$). However, systems on smaller dairies (100–160 cows) with electrical generators (D2, D3, $T6_b$) had higher costs per cow than those of comparable dairies without electrical generators (D1, D5, T1–T5, $T6_a$) (Fig. 1).

3.2. Operating costs

Annual operating costs ranged from 25% to 50% of annual capital costs (Table 2). The exception was D5, where the annual operating cost was 30% greater than its annual capital costs and represented 18% of total capital costs. These values came from a case study and included insurance, reporting, and manure spreading costs [41]. If an operating cost of 3% had been used, D5 would still have had a negative cash flow but would have increased from the least economical system to the 5th most economical of the 16 systems. The other three systems where existing data were used (D3, D4 and D6) had annual operating costs of 3%, 6%, and 6% of total capital costs, respectively [37,42].

The majority of the operating costs ranged between 40$ and 60$ per cow and did not appear to be dependent on the size of the herd nor the inclusion of a generator (Table 2). The only types of systems to have operating costs greater than 100$ per cow were plug-flow (D2 and $T6_b$) and fixed-film (D5) systems (Table 2). When operating costs of 5% and 3% were used instead of the published operating costs for D3, D6 and

Table 2 – Cash flow analysis for the small-scale digestion systems. Parentheses represent a negative number (2010 US$).

ID	Capital costs	Capital cost/cow	Annual capital costs[a]	Annual operating cost[b]	Annual operating cost per cow	Annual revenue[c]	Annual net cost[d]	Annual net cost/cow[e]	Potential annual net cost/cow including bedding reuse[f]
D1	($430,000)	($1900)	($44,000)	($13,000)	($59)	$14,000	($43,000)	($200)	($91)
D2[g]	($270,000)	($2200)	($27,000)	($13,000)	($110)	$18,000	($22,000)	($180)	
D3[g]	($490,000)	($3000)	($50,000)	($13,000)	($81)	$25,000	($38,000)	($240)	
D4	($350,000)	($1400)	($36,000)	($22,000)	($88)	$40,000	($18,000)	($72)	
D5	($180,000)	($1800)	($18,000)	($32,000)	($320)	$16,000	($34,000)	($340)	
D6[g]	($190,000)	($800)	($19,000)	($11,000)	($47)	$13,000	($17,000)	($72)	($3)
D7	($370,000)	($1500)	($38,000)	($11,000)	($44)	$40,000	($9000)	($36)	
$D8_a$	($160,000)	($820)	($16,000)	($4900)	($25)	$12,000	($8900)	($45)	$12
$D8_b$[g]	($180,000)	($880)	($18,000)	($8800)	($44)	$11,000	($16,000)	($80)	($25)
T1	($220,000)	($2200)	($22,000)	($6500)	($65)	$16,000	($13,000)	($130)	
T2	($190,000)	($1900)	($19,000)	($5800)	($58)	$16,000	($8800)	($88)	
T3	($190,000)	($1900)	($19,000)	($5700)	($57)	$16,000	($8700)	($87)	
T4	($160,000)	($1600)	($16,000)	($4900)	($49)	$16,000	($4900)	($49)	
T5	($120,000)	($1200)	($12,000)	($3700)	($37)	$6000	($9700)	($97)	($70)
$T6_a$	($180,000)	($1800)	($18,000)	($5500)	($55)	$16,000	($7500)	($75)	
$T6_b$[g]	($280,000)	($2800)	($29,000)	($14,000)	($140)	$15,000	($28,000)	($280)	
MP1	($150,000)	($1000)	($15,000)	($15,000)	($100)	$0	($30,000)	($200)	
MP2	($600,000)	($2400)	($61,000)	($25,000)	($100)	$25,000	($61,000)	($240)	

a Values calculated using an 8% annual discount rate and 20-year lifetime.
b Values calculated using 3–5% of total capital costs or from literature values as described in text.
c Values calculated by summing income from biogas use, bedding reuse, and CO_2 credits as shown in Table 4.
d Values calculated by summing annual capital costs, annual operating costs, and annual revenue.
e Values calculated by dividing the annual net cost by the number of cows utilizing the digester.
f Values calculated by dividing the annual net cost, including potential revenue from bedding reuse, by the number of cows utilizing the digester. The cost of the separator (50,000$ for T5 and 60,000$ for D6, $D8_a$, and $D8_b$) was added to the capital cost in order for bedding reuse to be a potential revenue source.
g Includes electrical generation.

D4, D5, respectfully, D3 has an operating cost of 150$ per cow and D4–D6 had operating cost of 40–53$ per cow (not shown).

3.3. *Cash flow and sensitivity analyses*

A cash flow analysis identified no digestion systems with a positive cash flow using an 8% y^{-1} discount rate and 20-year lifetime (Table 2). In general, systems that utilized biogas directly (D1, D4, D5, D7, $D8_a$, T1–T5, $T6_a$) had lower net costs per cow (with eight out of 11 having annual net costs per cow under 100$) than the five systems (D2, D3, D6, $D8_b$, $T6_b$) with electrical generation. Cost sharing improved cash flow values more than reducing the interest rate (Table 3, Fig. 2). Under the best-case scenario of 4% y^{-1} interest over a 20-year lifetime without cost sharing, only digester D7 had a positive cash flow. However, six of 16 systems (D4, D7, T2–T4, and $T6_a$) had a positive cash flow using 8% y^{-1} interest over a 20-year lifetime with 50% cost sharing.

3.4. *Revenue streams*

Details of the revenue streams from the digestion systems are shown in Table 4. Bedding reuse was the highest revenue source (100$ y^{-1} per cow), roughly twice the revenue from biogas production (Table 4). When costs and revenue from bedding reuse were added to the five systems without solid separation capabilities (D1, D6, $D8_a$, $D8_b$, and T5), two developed a positive cash flow (D6 and $D8_a$) under the base-scenario (8% y^{-1} discount rate, 20-year lifetime) (Table 2, Table 4) and one ($D8_b$) developed a positive cash flow under the best-case scenario (4% y^{-1} discount rate and 20-year lifetime) (not shown). Neither D1 (which already included a separator) nor T5 developed a positive cash flow under any scenario without cost sharing. Thus, the addition of a separator did increase revenue, but not always enough to overcome the initial capital investment. Based on the bedding and economic assumptions of this analysis, the initial capital cost of a separation systems (60,000$ for 250 cow system and 50,000$ for 100 cow system) would be recovered in 3.5 and 15 years, respectively (not shown).

Given the 2010 prices of natural gas (0.18$ m^{-3}) and electricity (90$ MW h^{-1}), it was slightly more cost effective to use biogas directly (53$ y^{-1} per cow) than to convert biogas to electricity (47$ y^{-1} per cow) (Table 4) [48,49]. However, if the digester was heated solely with waste heat from the generator and 100% of the biogas was used for electricity generation, potential revenue from electricity increased (70$ y^{-1} per cow). This increase was insufficient to generate a positive cash flow for any of the digesters using electrical generation (not shown).

The annual electricity generation potential per cow was calculated as 0.8 MWh, which is in the range used in other analyses (0.4–3.9 MWh y^{-1}) [8,63]. If the electricity generation potential was doubled to 1.6 MWh y^{-1}, the systems with electricity generation (D2, D3, D6, $D8_b$, and $T6_b$) would still have a negative cash flow. D6 and $D8_b$ became cost neutral at

Table 3 – Sensitivity analysis of cash flow for the small-scale digestion systems. Parentheses represent a negative number (2010 US$).

ID	4%, 10 (No cost sharing)	4%, 10 (50% Cost sharing)	4%, 20 (No cost sharing)	4%, 20 (50% cost sharing)	8%, 10 (No cost sharing)	8%, 10 (50% Cost sharing)	8%, 20 (No cost sharing)	8%, 20 (50% Cost sharing)
D1	($52,000)	($25,000)	($31,000)	($15,000)	($63,000)	($31,000)	($43,000)	($21,000)
D2	($28,000)	($11,000)	($15,000)	($4800)	($35,000)	($15,000)	($22,000)	($8600)
D3	($48,000)	($18,000)	($24,000)	($5900)	($61,000)	($24,000)	($38,000)	($13,000)
D4	($25,000)	($3600)	($7800)	**$5100**	($34,000)	($8100)	($18,000)	**$180**
D5	($38,000)	($27,000)	($29,000)	($22,000)	($42,000)	($29,000)	($34,000)	($25,000)
D6	($21,000)	($9600)	($12,000)	($4900)	($26,000)	($12,000)	($17,000)	($7600)
D7	($17,000)	**$6100**	**$1700**	**$15,000**	($26,000)	**$1300**	($8800)	**$10,000**
D8a	($13,000)	($3000)	($5000)	**$1000**	($17,000)	($5200)	($9700)	($1300)
D8b	($20,000)	($8700)	($11,000)	($4300)	($24,000)	($11,000)	($16,000)	($6800)
T1	($17,000)	($3900)	($6500)	**$1500**	($23,000)	($6700)	($13,000)	($1600)
T2	($14,000)	($1700)	($4000)	**$3100**	($19,000)	($4200)	($9400)	**$390**
T3	($13,000)	($1400)	($3600)	**$3300**	($18,000)	($3800)	($9000)	**$670**
T4	($9,000)	**$1000**	($910)	**$5100**	($13,000)	($1100)	($5500)	**$2800**
T5	($13,000)	($5400)	($6800)	($2300)	($16,000)	($6900)	($10,000)	($4000)
$T6_a$	($12,000)	($850)	($3100)	**$3700**	($17,000)	($3200)	($8300)	**$1100**
$T6_b$	($34,000)	($17,000)	($20,000)	($9500)	($41,000)	($20,000)	($28,000)	($13,000)

Boldface signifies a positive value.

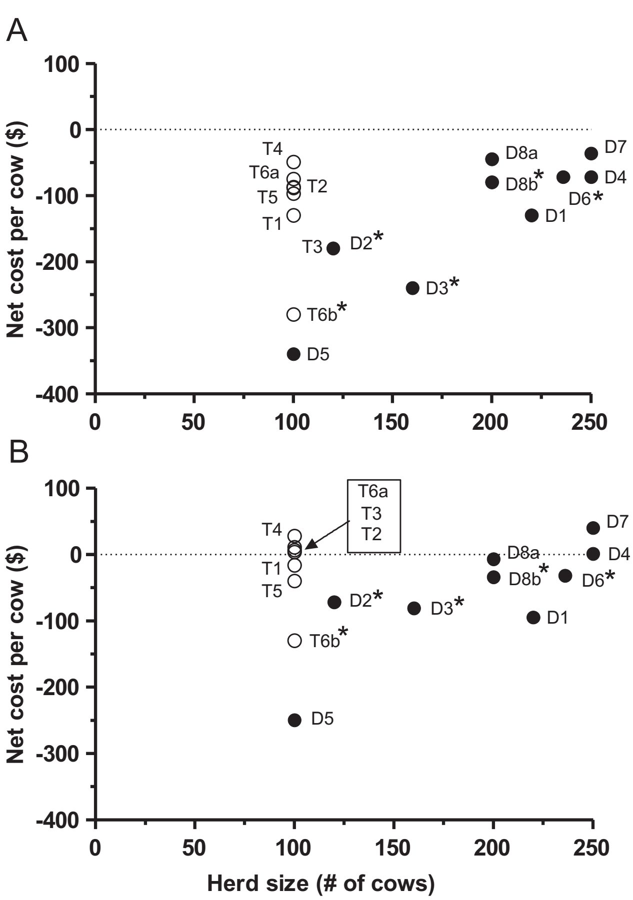

Fig. 2 – Annual net costs per cow as a function of farm herd size. A, values were calculated without cost sharing of capital costs. B, values were calculated using 50% cost sharing of capital costs. Values from existing digester systems are shown as solid circles. Values from theoretical digester systems are shown as open circles. The five systems that include electrical generators are marked with asterisks.

2.0 and 2.2 MWh y^{-1}, respectively. If electrical generation was removed from systems utilizing generators (D2, D3, D6, $D8_b$, and $T6_b$) their respective annual costs decreased but not enough to become cost effective (not shown).

Revenue from carbon credits was the lowest revenue source generated from the digesters (7$ y^{-1} per cow) (Table 4). The digesters in this study had carbon emission reductions ranging from 121,000–303,000 kg CO_2-C annually, for 100–250 cows, respectively. When the trading cost of carbon is low, such as 0.05$ t^{-1} CO_2-C traded on the Chicago Climate Exchange in 2010, the annual revenue for each system ranged from 6 to 15$ (not shown) [57]. If the highest rate for CO_2 reduction was used, 7.40$ t^{-1} CO_2-C (US$) traded in June 2008, the annual revenue was 2240$ for a 250-cow digestion system (not shown).

4. Discussion

4.1. *Impacts of size, design, and revenue on cash flow*

Cash flow analysis results showed that total capital costs, capital costs per cow, and net costs per cow generally decreased with increasing herd size in existing systems. Of the 16 systems analyzed, only one (D7) had a positive cash flow under the best-case scenario without cost sharing. The D7 system was on a larger farm (250 cows), had average capital costs per cow (1500$ y^{-1}), and garnered revenue from direct biogas use, bedding reuse, and CO_2 credits. Of the three least cost-effective systems, two had electric generation (D3 and $T6_b$) and one (D5) did not have electric generation. D3 and $T6_b$ had the highest initial capital costs (roughly $3000 cow^{-1}), and therefore needed to generate greater annual revenues to create positive cash flows.

While those systems with the highest capital costs were not cost effective, the systems with low capital costs were not necessarily cost effective either. The three systems with lowest capital costs (D6, $D8_a$, and $D8_b$) did not perform positively under any scenario until bedding reuse was added as a

Table 4 – Annual revenue for the small-scale digestion systems (2010 US$).

ID	Biogas[a]	Electrical generation[b]	Bedding reuse[c]	CO_2 credits[d]	Total revenue[e]	Total revenue per cow[f]	Potential total revenue including bedding reuse[g]	Total potential revenue per cow[h]
D1	$12,000	$0	$0	$1500	$14,000	$64	$36,000	$160
D2	$0	$5600	$12,000	$810	$18,000	$150		
D3	$0	$7500	$16,000	$1100	$25,000	$160		
D4	$13,000	$0	$25,000	$1700	$40,000	$160		
D5	$5300	$0	$10,000	$690	$16,000	$160		
D6	$0	$11,000	$0	$1600	$13,000	$55	$37,000	$160
D7	$13,000	$0	$25,000	$1700	$40,000	$160		
D8a	$11,000	$0	$0	$1400	$12,000	$60	$32,000	$160
D8b	$0	$9400	$0	$1300	$11,000	$55	$31,000	$160
T1	$5300	$0	$10,000	$690	$16,000	$160		
T2	$5300	$0	$10,000	$690	$16,000	$160		
T3	$5300	$0	$10,000	$690	$16,000	$160		
T4	$5300	$0	$10,000	$690	$16,000	$160		
T5	$5300	$0	$0	$690	$6000	$60	$16,000	$160
$T6_a$	$5300	$0	$10,000	$690	$16,000	$160		
$T6_b$	$0	$4700	$10,000	$670	$15,000	$150		
MP1	$0	$0	$0	$0	$0	$0		
MP2	$0	$0	$25,000	$0	$25,000	$100		

a Values calculated assuming an annual per cow biogas production of 730 m^3, a methane content of 60% by volume, with two-thirds of the biogas available after digester heating, and a price of 0.18 US$ m^{-3} equal to (53 $ y^{-1} per cow) (2010 US$).
b Values calculated assuming an annual per cow energy production of 0.78 MWh and electricity price of 90 US$ MW h^{-1} equal to (47 $ y^{-1} per cow) (2010 US$).
c Values calculated assuming one dairy cow produces 7.65 m^{-3} of fiber per year and bedding costs average 13 US$ m^{-3} equal to (100 $ y^{-1} per cow) (2010 US$).
d Values calculated assuming an annual CO_2 reduction of 1181 kg per cow and 5.70 US$ t^{-1} CO_2-C equivalent equal to (7 $ y^{-1} per cow) (2010 US$).
e Values calculated by summing revenue sources.
f Values calculated by dividing total revenue by the number of cows.
g These digestion systems do not currently reuse bedding. The potential income were bedding reuse instituted was calculated assuming one dairy cow produces 7.65 m^{-3} of fiber per year and bedding costs average 13 US$ m^{-3} equal to (100 $ y^{-1} per cow) (2010 US$).
h Values calculated by dividing total potential revenue by the number of cows.

revenue source. In addition, D8 was built in 1976. While all costs were adjusted using the construction cost index, it is possible that the cost to build the same system today would be higher than the extrapolated cost, as the construction cost index does not reflect an exact inflation rate for all materials used in the construction of a digester.

Among existing revenue streams, use of digested solids for bedding generated the highest revenue ($100 cow^{-1} $year^{-1}$), followed by biogas use for heating and/or electrical generation ($47 to $70 cow^{-1} $year^{-1}$) and CO_2 credits ($7 cow^{-1} $year^{-1}$). When utilized, bedding reuse accounted for approximately 60% of income. This result is consistent with previous studies that have found bedding recycling for on-farm use or for off-farm sale to be an important revenue source for farms with solid separation capabilities [10,29,30,53]. The estimated revenue for D4 (40,000$) was 24,000$ higher than estimated in a previous study due to greater savings calculated for bedding reuse and biogas use in the previous study [40]. It should be noted that cost of the separation system used in this analysis (60,000$ for 250 cow system and 50,000$ for 100 cow system) is an average cost. Economic analyses have shown the cost of separators can range from 17,000 to 54,000$, and the cost of separators plus the building and related separator equipment can range from 46,000 to 71,000$ [29,37,41,44].

4.2. *Sensitivity of revenue assumptions and cost sharing*

Changes in revenue with respect to biogas use assumptions had minimal affect on the cost effectiveness of the systems. In addition, improving energy production efficiency by using waste heat to heat the digesters or by increasing the generation potential did not change the cost effectiveness of any system. Farmers and experts interviewed in this study observed that farm-scale systems often perform at lower efficiencies than originally predicted. Thus, the more conservative generation potential value used for this economic analysis is likely more accurate for estimating actual field results.

The economic value of the greenhouse gas reductions attributed to digester installation does not greatly increase revenue for a small-scale dairy. This is in agreement with a previous study that predicted even with a trading value of 26$ t^{-1} CO_2-C, carbon trading would only be cost effective for 3% of small-scale (<250 cows) farms [64]. Additional costs not accounted for in this assessment were annual carbon audits. Farmers receiving carbon emission offsets will incur an additional cost associated with initial and annual inspections and verification of their operations, ranging in cost from 3000 to 5000$ for the initial verification and 700 to 1000$ for annual carbon audits [65], making carbon credit price neutral or cost prohibitive for smaller operations.

As expected, the inclusion of cost sharing had a positive impact on the cash flow of the systems. There are multiple cost-sharing opportunities available to U.S. farmers for anaerobic digesters. Various U.S. federal, state, and local sources of grants, loans, tax exemptions, and production incentives typically cover up to 50% of the project costs [50,66]. Giesy et al. [24] found that the economic feasibility of digesters was highly sensitive to cost-sharing opportunities. Increased use of cost sharing will likely accelerate the adoption of small-scale digesters.

4.3. *Food waste and tipping fees*

The negative cash flow observed in many systems could be offset by the addition of food waste into the digester and the accompanying tipping fees. For example, to have a positive cash flow, T4 would need an additional 410$ in monthly tipping fees. Seven systems (D7, $D8_a$, T2–T5, $T6_a$) would have a positive cash flow with the additional revenue from monthly tipping fees of less than 1000$, which, at 0.02$ per gallon, is equivalent to approximately 210 tons (50,000 gallons) of food waste or eight truck loads. Although accepting food waste could also increase biogas production and biogas revenue by contributing additional volatile solids to the digester, operating costs would increase with additional land application costs [10,67].

4.4. *Additional potential revenue sources*

For the 16 systems studied, the additional monthly revenue needed for the systems to have a positive cash flow ranged from 2300 to 740$ in systems without solid separation and from 3200 to 410$ in systems with solid separation. In addition to the traditional revenue sources discussed above, there are potential future revenue sources from innovative uses of biogas and digester by-products and additional savings calculated from the use of anaerobic digesters that were not included in this analysis.

It should be noted that the revenue values calculated in this analysis were less than those calculated in previous studies [37,41,42,44] due to the assumptions made in this analysis and exclusion of revenue from non-traditional sources. For example, odor was considered a revenue source by The Minnesota Project report, in which T1–T5 designs were proposed, at an annual price of 18,000$ for a 100-cow system [44]. Due to the exclusion of odor and other differing assumptions, the revenues calculated in The Minnesota Project Report for T1–T5 were 50% greater than the revenues calculated in this study. State renewable energy credits can also be a source of revenue and were included in a cost analysis of D3 at an estimated annual value of 2000$ [37]. Savings due to the reductions in spreading costs due to the exclusion of rainwater from a lagoon with covered digester were used in a previous cost analysis of D6, estimated at an annual saving rate of 4000$ [42]. In all, the estimated revenue for D6 was 10,000$ lower in this study compared to the previous study due to the exclusion of saving from rainwater reduction in the lagoon and greater savings from electricity and heat use [42].

Additional future revenue may come from innovative uses of the biogas effluent and digested fibers separated from the digestate. The use of compressed biogas as a substitute transportation fuel for gasoline and diesel is being investigated globally as governments aim to increase renewable energy use [68,69]. Biogas powered fuel cells are another technology being investigated [70]. Apple and Microsoft are both planning on powering future data centers with fuel cells run on biogas [71]. A potential revenue source from digestion by-products stems from the recovery of struvite (magnesium ammonium phosphate) from digester effluent for use as a commercial fertilizer. Struvite is being successfully recovered in Europe and Asia and on a pilot-scale basis in the U.S. [72,73]. Digested fiber has found use in the production of biodegradable plant pots and as a nursery media component to replace peat, coir and bark [74].

4.5. *Minimum herd size needed for economically viable digestion in the U.S.*

Our results suggest that anaerobic digestion can be economically viable under specific conditions for farms with herd sizes as low as 100 cows. However, these systems will be an additional expense to the farm as the capital and operating costs cannot be overcome by the revenue produced from small herds. Ten of the 16 systems had a net cost per cow of less than 100$ per year, which could be considered a necessary business expense when odor control is required for continued operation.

The annual cost of 100$ per cow could be overcome in multiple scenarios. The use of 50% cost sharing makes six of the 16 systems cost effective without any additional revenue sources. Conversely, additional revenue of 100$ per cow, or 10,000$ per year for a 100-cow farm, from co-digestion of off-farm food waste or innovative uses of the biogas or digestate can make a digester cost effective without the need for additional cost sharing. The monthly tipping fees from off-farm waste of 1000$ would make seven systems become cost effective.

AgSTAR bases its minimum herd size (500 cows) on an estimated capital cost of 1500$ per cow for an aerobic digestion system [18]. Using the AgSTAR method for estimating capital costs for three types of digesters (plug-flow, complete mixed, and covered lagoon), only the complete mixed system, with average estimated costs of 1500$ for 100–250 cows, corresponded with the capital costs found in this analysis [18]. The AgSTAR plug-flow digester estimate (2200$) was greater than the 1800$ per cow averaged among the systems in this analysis and the AgSTAR covered lagoon estimate (3100$) was roughly double the 1500$ average among the systems analyzed.

5. Conclusions

Our results suggest that, with cost sharing, economically viable AD systems are possible on 250-cow dairies. Although no system had a positive cash flow under the assumed conditions (8% discount rate, 20-year term), six of the 16 systems had positive cash flows when 50% cost sharing was included in the analysis. Additional revenue streams, such as tipping fees for food waste, or additional cost sharing will be necessary to have economically viable AD systems on 100-cow dairies.

Acknowledgements

This work was supported by funding from the Maryland Water Resources Research Center (Grant# 06HQGR0090) and University of Maryland Agriculture Experiment Stations. We would like to thank Jon Leith, Mike Kemp, and Brad Green at the USDA Beltsville Agricultural Research Center for their support and assistance. We also wish to thank Gary Seibel and the ENST Project Development Center, as well as student assistants Faaiz Ajaz, Scott Allen, Grant Hughes-Baldwin, Ashley Belle, Anisha Gupta, Kayoko Iwata, Caiti Jackson, PJ Klavon, Sol Lisboa Kotlik, Akua Nkrumah, Ryan Novak, Owen Williams, and Freddy Witarsa.

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