A broad assessment of manure to power technology and investigation of a potential wind-biogas synergy

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Abstract *The purpose of this paper is to present a broad assessment of animal manure to power technologies, and to investigate the possibility that manure to power could be coupled with a wind generator on-farm to produce more dispatchable power than with either technology alone. Flexible engineering and economic models are developed to determine the amount of energy available from manure; to characterize operation of anaerobic digesters; and to model a farm-level generating system which includes a wind turbine, digester, and methane storage.*

Maximum electrical generating capacity from manure in the U.S. is approximately 5.4 GW, with 2.7 GW coming from manure handled as solids (incineration or gasification), and 2.7 GW from anaerobic digestion of liquid manure. The cost of electricity from anaerobic digestion is approximately $ 0.06 / kWh for a farm with 700 dairy cows. Methane emissions from agriculture account for 7% of anthropogenic methane emissions in the U.S. Therefore, greenhouse gas reductions from anaerobic digestion, due to avoided methane emissions from manure storage, are substantial on a per kWh basis.

A model of a digester system coupled with wind generation is presented, and a case study is carried out for a representative hog farm in NW Iowa. Compared to the stand-alone digester system, the coupled system provides 65% more baseload power in summer, and 170% more during spring. The cost of this electricity is approximately $0.075 / kWh. This cost is comparable to a stand-alone digester system operated as a peaking unit operated 12 hours per day.

Introduction

Animal manure to power (AM to P) technologies can provide renewable energy and alleviate some of the environmental problems associated with manure from large animal operations. A major driver for AM to P installations in the United States is currently odor mitigation. Manure has always been smelly, but as farm size has increased (Figure 1), so has the concentration of manure. In addition, many large farms have adopted liquid-based manure handling systems, which increase the potential for severe odor problems.

The EPA reports that agriculture is the leading source of pollution in domestic waterways, with nutrients and pathogens the primary pollutants in lakes and rivers, respectively [1]. To address this issue, the EPA has passed a rule that requires operators of Concentrated Animal Feeding Operations to obtain permits to spread manure on land[1] [9]. This reality has, along with the odor menace, put a spotlight on manure from animal operations.

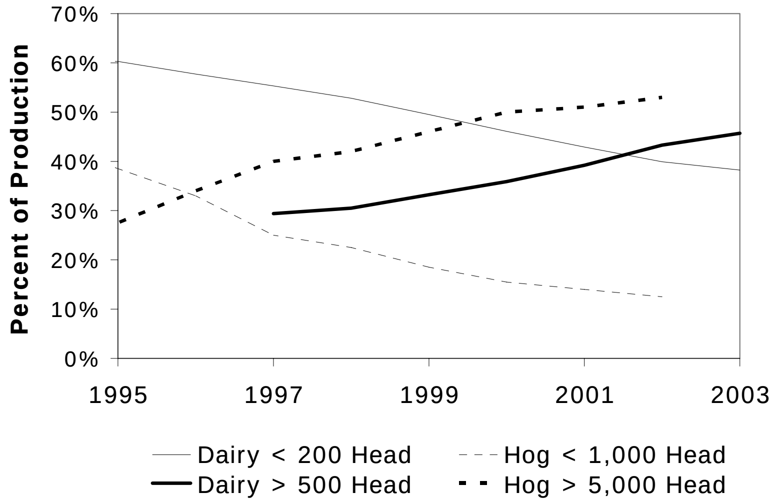

Figure 1. Hog and dairy production in U.S. on smaller and larger farms. More than half of hogs are grown on farms with more than 5,000 animals, and about 45% of milk is produced on farms with more than 500 cows [12].

Finally, concerns regarding greenhouse gas (GHG) emissions have stimulated interest in manure to power technologies. Not only is energy from manure very low-carbon,[2] but farming operations often store liquid animal waste in lagoons and tanks. During storage, bacteria break down some of the organic matter and release methane, a gas with 23 times the global warming potential of carbon dioxide [3].

The bottom line is that large animal operations produce vast volumes of manure, and large amounts of nutrients. Table 1 shows that a dairy farm with 700 milking cows (typical of a large dairy) produces more manure, by volume, and more nitrogen and phosphorous than a town of 15,000 people.

[1] A concentrated feeding operation (CAFO) is roughly defined as an animal operation with over 1,000 Animal Units (AU). An animal unit corresponds to 1,000 pounds of live animal weight – about the weight of a mature beef cow. See appendix 1 for more information on CAFOs.
[2] Energy required to "harvest" manure is minimal. It's already there, whether it is utilized for power generation or not.

Table 1. Manure production parameters for a representative 1,000 AU farm [5].

	humans	dairy cow	beef cow	swine	layer (chicken)	broiler (chicken)	turkey
animal weight	145	1400	750	125	4	2	20
# animals	6,900	700	1,300	8,000	250,000	500,000	50,000
volume (gal/day)	4,100	9,700	6,100	7,500	7,000	9,400	5,600
VS (lb / day)	1,900	8,500	5,400	5,400	10,800	15,000	9,100
COD (lb / day)	3,000	8,900	5,600	6,100	13,700	19,000	9,300
N	200	450	300	420	830	1,100	740
P	20	70	90	160	310	340	280

This paper provides a broad assessment of animal waste to power technologies, and an investigation of the possibility that manure to power could be coupled with wind generation to increase the amount of dispatchable renewable power from the farm. In section 1 I discuss the power potential and relative impact of electricity generation in the U.S. from animal manure. I then give a brief overview of incineration and gasification of manure before providing a more in-depth review of anaerobic digestion in section 3, including a discussion of the value of manure to power (positive and negative). Section 4 contains an analysis of the renewable energy synergy, and I will end with consideration of the regulatory and institutional influences on manure to power technologies.

1 Energy and power from manure

In order to use manure to produce power, it must be collected. Clearly, not all livestock live in confinement – around 40% of milk is produced on farms with fewer than 200 cows (Figure 1). On these types of operations, cows likely spend a substantial fraction of time (particularly in non-winter months) at pasture. That said, in order to get a handle on the potential for power generation using manure, I have calculated the energy and electric power generation potentials that could be attained if manure from all dairy cows, hogs, beef cattle on feed (referred to beef cattle from here on), chickens and turkeys is collected and utilized for power production (Table 2).

Energy and power potential calculations are based on manure production [5, 6], animal populations [12], energy yields, and conversion efficiencies. (See appendix 2 for energy yield and conversion parameters used to determine energy potential.) In 2002, net electricity generation in the U.S. was 3.85 trillion kWh[3] [8]. At 5,400 MW[4] of capacity, electricity from animal manure could account for about 1% of present electricity generation. Figure 2 shows potential electricity generation from manure and the corresponding fraction of retail electric sales on a state level.

[3] 1 kWh = the energy required supply 1 kW of power demand for 1 hour (e.g. to operate ten 100-watt light bulbs for 1 hour).
[4] 1 MW = 1,000 kW; 1 kW = power required to operate ten 100-watt light bulbs.

Table 2. Power production potential from anaerobic digestion and incineration of animal manure in the U.S.

	anaerobic digestion			incineration/gasification			combined	
	% manure digested	energy (Btu / year)	power (MW)	% manure incinerated	energy (Btu / year)	power (MW)	energy (Btu / year)	power (MW)
dairy cow	100%	1.5E+14	1,500	0%	-	-	1.5E+14	1,500
hog	100%	9.8E+13	990	0%	-	-	9.8E+13	990
beef cattle	0%	-	-	100%	2.4E+14	2,400	2.4E+14	2,400
layer (chicken)	70%	1.5E+13	220	30%	1.1E+13	110	2.6E+13	330
broiler (chicken)	0%	-	-	100%	7.8E+13	780	7.8E+13	780
turkey	0%	-	-	100%	4.1E+13	410	4.1E+13	410
total (non-human)		2.7E+14	2,700		3.7E+14	3,700	**6.3E+14**	**6,400**
human	50%	3.2E+13	600	50%	9.0E+13	903		

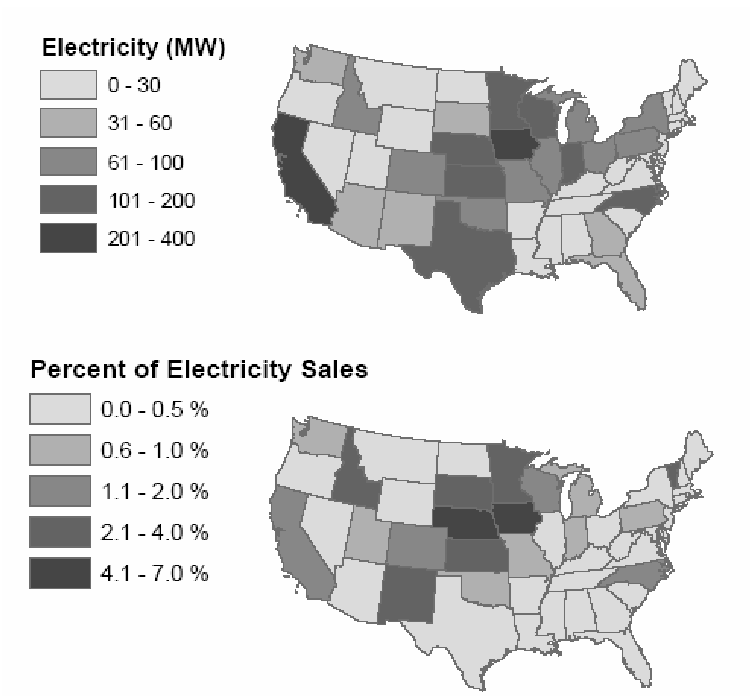

Figure 2. Estimate of manure to power potential and impact.

2 Incineration and gasification

Animal manure that is sufficiently dry can be incinerated to power a steam-turbine generator. Most broiler chickens and turkeys are raised in poultry sheds, where manure accumulates, along with bedding such as wood shavings, in a pack on the floor. The pack is removed periodically, and is applied to land, if appropriate. Broiler litter has moisture content between 15 and 30%; ash content between 10 and 30%, and a higher heating value (HHV) around 4,500 Btu/lb (HHV of bituminous coal is 14,000 Btu/lb) [79, 83, 84, 85, 88]. Four poultry litter fueled power plants operate in the U.K. with capacities between 10 and 65 MW [81]. A 50 MW plant which will utilize turkey litter is currently under construction in Minnesota.

Alternatively, manure may be gasified to produce a combustible gas with a HHV of around 100 Btu / ft^3 [86]. The gas can then be utilized in a reciprocating engine to produce electricity [80].

The USDA estimates that 60% of all manure nitrogen, and 70% of manure phosphorous cannot be spread (at agronomic rates) on land owned by the farm operator because of potential nutrient overload. Poultry litter makes up 64% and 52% of this “excess” nitrogen and phosphorous, respectively [13]. Indeed, contractors are often hired to clean poultry houses and truck away manure, but depending on the concentration of animal operations in the area, the manure may have to be transported considerable distances. In cases where there is limited land locally on which to spread manure, incineration or gasification could provide a cost-effective waste management solution. Phosphorous present in the original litter is concentrated in ash. This can be transported at a much lower cost than the original material.

Although Table 2 indicates that beef cattle manure from feedlots is the largest potential source of manure based power, feedlot manure fuel is less than ideal. The reason is that dirt is incorporated into the manure, and ash levels can reach 50%. However, use of fly ash from coal fired power plants as a base surface can stabilize feedlot surfaces, particularly in wet weather. The result is a lower-ash fuel better suited to utilization for power generation. This practice could make energy production from feedlot manure more feasible [67].

3 Anaerobic digestion

Anaerobic digestion (AD) is practiced on about 50 farms in the U.S. The majority of these use the methane produced during digestion to generate electricity, with a total installed capacity of around 7 MW [35, 36, 40, 41]. In Germany, there are over 2,000 farm-based digesters operating, with installed capacity around 300 MW. This high adoption of AD technology is driven by a feed-in tariff for electricity generated with biomass feedstocks – currently € 0.011 / kWh, with a bonus of € 0.06 / kWh for energy crop utilization [48].[5]

In this section, we will briefly discuss: the AD process; provide a more in-depth analysis of cost and operational issues associated with AD of animal manure, including the prospect for cost reductions; and discuss benefits and drawbacks of AD.

[5] In addition, over 1.5 million biogas plants have been installed in India [16]. These systems are typically family-sized, unheated and the gas is used for cooking and lighting.

3.1 The anaerobic digestion process

During anaerobic digestion (AD), organic matter is converted to methane (CH_4) and carbon dioxide. AD occurs naturally in bogs, sediments, and in the digestive tract of ruminant animals. AD for energy recovery takes place in a sealed container (referred to as the reactor vessel). I review the published data from laboratory studies and data available from field studies to develop standard gas production values for this paper.

The process is carried out by a consortium of bacteria and can be described in three basic steps. First, complex organic material (e.g. proteins and carbohydrates) is broken down into simpler compounds (including sugars and amino acids) through enzyme-mediated hydrolysis and fermentation. Next, these breakdown products are converted to hydrogen gas and organic acids by "acetogenic" bacteria. Finally, "methanogenic" bacteria convert the hydrogen and organic acids into methane and carbon dioxide – a mixture often referred to as biogas. The two major methane-forming pathways are

$$CH_3COOH \rightarrow CH_4 + CO_2, \text{ and} \qquad (1)$$
$$4H_2 + CO_2 \rightarrow CH_4 + 2H_2O. \qquad (2)$$

The conversion of acetic acid to methane (eq. 1) accounts for the majority of methane production. Since the methanogenic bacteria have slow growth rates, a small fraction of the original energy is used to synthesize new cells and most of the energy present in the original organic matter is converted to methane. This slow growth rate, however, means that the material being digested (digestate) must be detained in the reactor for an extended period of time, necessitating large (expensive) reactor vessels. The reaction is only slightly exothermic, so heat usually has to be added to keep the digester up to temperature. Anaerobic activity takes place in a wide range of temperatures, but optimal temperatures are either in the mesophilic range (around 100°F) or in the thermophilic range (140°F) [14, 17].

Methanogenic bacteria are quite sensitive to changes in the digester environment. They cannot function at pH below 6.2 [17]. Inhibition of the digestion process has been reported at ammonia concentrations between 1 and 3 g N / L; however the threshold is sensitive to pH and temperature [67, 69-72]. Bacteria can acclimate to high ammonia concentrations without strong inhibition if ammonia concentrations are increased gradually [68]. Organic acid concentration can increase due to ammonia inhibition of the methanogenic bacteria [69], or from an increase in the organic matter loading rate[6] [17]. Either way, acid-build up can lead to digester failure [17, 69]. This acidification may be buffered by alkaline digester substrate. In addition, the build-up of acids from ammonia inhibition will shift ammonia to the ammonium ion (NH_4^+, which is not believed to be a potent inhibitor), tending to stabilize the digestion process [72].

[6] Since hydrolytic and fermentative bacteria grow faster than the methanogens, there may disequilibrium between the different stages of digestion, leading to build-up of the fermentation products.

Methane production via AD is usually characterized by volatile solids (VS) destruction.[7] The percentage of VS destroyed during digestion varies with digester design and with the makeup of the substrate, as does the volumetric methane yield per mass of VS destroyed. During lab-scale anaerobic digestion of swine manure, VS reduction has varied between 43% and 85%, with methane yields between 8.2 and 12.2 ft^3 / lb. VS destroyed [18, 19, 24, 27, 28, 30, 31]. Since cattle manure has already undergone AD in the animal's rumen, VS destruction tends to be lower, between 30% and 45%, with methane yields of between 7 and 12 ft^3 / lb. VS destroyed [20-25, 29, 30]. The methane content of the biogas can vary between 50 and 80%, but methane concentrations of 60-70% are typical [18-31]. The biogas also contains hydrogen sulfide, at concentrations between 1,000 and 5,000 ppm[8] (higher for hog manure).

There have been a few studies that characterize VS destruction and methane production during AD on commercial animal operations. These indicate that in digesters processing swine manure, VS are reduced by about 65% [33, 42, 44], and that methane yield is 8.2 ft^3 / lb VS destroyed [34]. In addition, the concentrations of fixed solids[9] (FS) are reduced in digester effluent [33, 42, 44]. This is an indication that solids are accumulating in the digesters, reducing effective volume (more discussion of solids accumulation provided in section 3.3). Digesters processing dairy manure reduce VS by about 30%, with methane yields of 12.3 ft^3 / lb VS destroyed [34, 39, 43]. The VS destruction rates and methane yield from hog manure are in line with the values from the literature discussed above. VS reduction and methane yield from dairy manure digesters fall at the lower and upper end, respectively, of the values in the literature. The methane yield will be comparable whether one assumes 30% VS reduction and yields of 12 ft^3 / lb VS destroyed, or a 35% VS reduction and 10 ft^3 / lb VS destroyed. As such, for this paper I use the values obtained in the field trials: 30% VS destruction and methane yields of 12 ft^3 / lb VS destroyed.

3.2 Capital cost of anaerobic digestion systems

I have broken down the costs of digester systems into three major components: the digester, the combined heat and power (CHP) unit, and everything else. The digester includes the reactor vessel, heat exchanger (to keep digester to temperature), necessary manure pumps or preheating/mixing tanks, and gas and water piping. The CHP unit is just that (including safety and control equipment); everything else includes engineering, start-up, the engine room, and any necessary energy distribution on the farm.
Figure 3 shows capital costs of digester power plants in the U.S. There are clear economies of scale up to 100 kWe[10]. The cost of the digester comprises about half of the capital cost, and the CHP unit about a third (Figure 4).

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[7] Volatile solids represent the fraction of solid matter that will volatize at 550 ± 50°C [17].
[8] Hydrogen sulfide gas is poisonous – exposure to concentrations of 500 ppm can cause death within 30 minutes. However, most digesters are well-ventilated (outside), and any gas leak will be diluted immediately. Manure gas is more dangerous in manure pits, where the dense gas does not dilute. 16 deaths were reported from manure pit gas suffocation between 1980 and 1985, and there was an incident in 1989 where 5 people died after successively entering the manure pit [15].
[9] Solids which do not volatize at 550° C
[10] kWe = electric power output in kilowatts. Used to avoid confusion with heat output of the CHP unit.

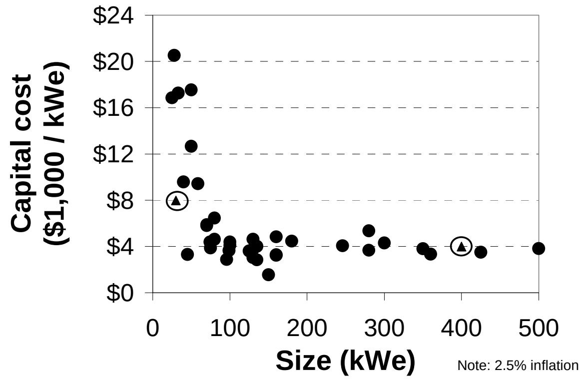

Figure 3. Capital costs of anaerobic digesters in U.S. (dots) and Germany (triangle in circle). Includes only equipment necessary for digestion and biogas utilization (does not include solid separation or composting equipment) [32, 36, 37, 38, 40, 41, 42, 43, 45,47, 51].

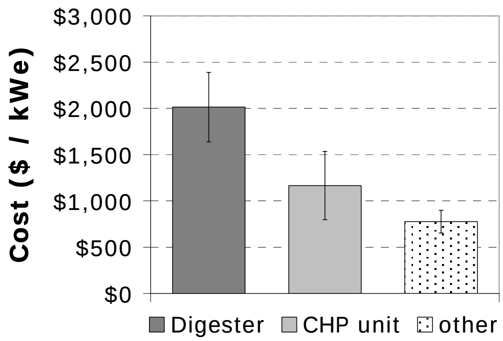

Figure 4. Digester cost breakdown [37, 42, 43, 45, 47] for a 100 kWe, $4,000 /kWe digester system. "Other" includes engineering, start-up, engine building, and power distribution on-farm. Error bars represent one standard deviation from five data sources.

As mentioned above, there are over 2,000 operating farm-based biogas plants in Germany. Many are smaller than 100 kWe (as small as 15 kWe) , and costs for small systems are below costs for similar-sized systems in the U.S. (Figure 3). If farm-based biogas systems become more common, and more designers and suppliers get into the business, it is possible that capital costs will decrease as economies of scale and design efficiencies take effect. [11] Gas engines that run on biogas from landfills are common, but these systems are not designed for CHP.

Another option to reduce the cost of the digester vessel (half the investment of the system) would be to separate urine and feces when excreted and only digest the feces portion of the manure stream[12], or to slightly dewater diluted manure slurry before

[11] This seems to be the case with small digesters in Germany. Large systems there (> 100 kW) may be comparatively more expensive because systems are designed with long retention times – as high as 60 days, with 45 days being fairly common. These systems are built to co-digest crops such as corn silage and grass [50]. Since these substrates have not already undergone some degradation in an animal's gut, they require longer retention times in the digester.

[12] While this may not seem very feasible, experiments are being carried out at North Carolina State University on a belt manure handling system, where urine runs off the belt, while feces remain on the belt [7].

digestion. These options would reduce the necessary volume, and thus cost, of the digester vessel. Figure 5 shows the impact that vessel and CHP cost reductions would have on the overall system cost.

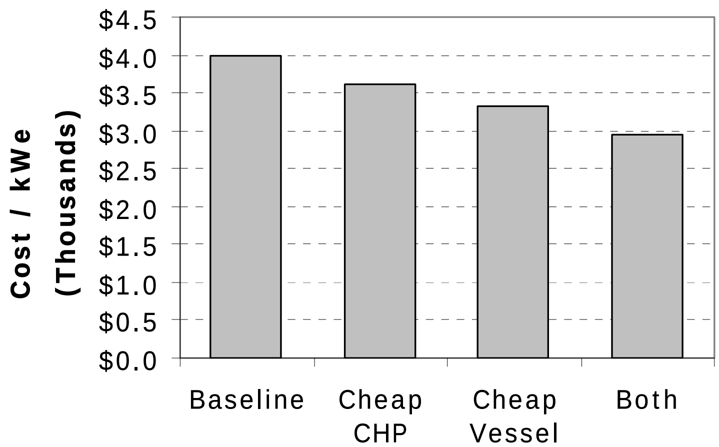

Figure 5. Capital costs of digester plants: baseline, and with possible cost reductions. "Cheap CHP" corresponds to a 33% decrease from baseline CHP cost. "Cheap vessel" is reduced by 38%, compared to the baseline vessel cost. The vessel cost reduction corresponds to the urine portion of excreted manure (if only feces are digested, volume to be treated is reduced by 38%).

Operation costs would likely increase for a higher-solids digestion unit. The manure separating technology and dewatering will add costs. However, without ammonia nitrogen from urine, the digestion process may proceed faster (see section 3.1), further reducing the necessary vessel volume, which would partially offset the higher operation cost. We will explore the implications of various operations costs, and reduced capital costs in section 3.3.

Finally, modular digesters, designed for higher-solids manure streams typical on smaller farms, are emerging in Europe (see appendix 2). While these digesters are not very cost-effective currently [50], the possibility of cost reduction through standardized off-site construction may enable more economic digestion on smaller farms, and because the systems can be delivered and removed on a flat-bed truck (i.e. repossessed), might make low-cost financing easier to secure.

3.3 Digester operation and cost of energy

Most digesters in the U.S. and Germany are operated at around 100°F, while in Denmark and the Netherlands, most digesters operate at 140°F. As mentioned above, high-temperature digesters require a smaller reactor because organic degradation occurs faster at high temperatures. However, thermophilic digesters also require more careful monitoring because fermentation products can quickly build up and upset digester operation if organic loading rates are not managed properly.

To produce electricity, the biogas is usually utilized in a CHP reciprocating engine, although microturbines are also in use. Heat from the CHP unit is used to keep the digester at the proper temperature. Using heat transfer coefficients from [17], I have calculated the fraction of heat available from the CHP unit after digester heat requirements are satisfied (Figure 6).

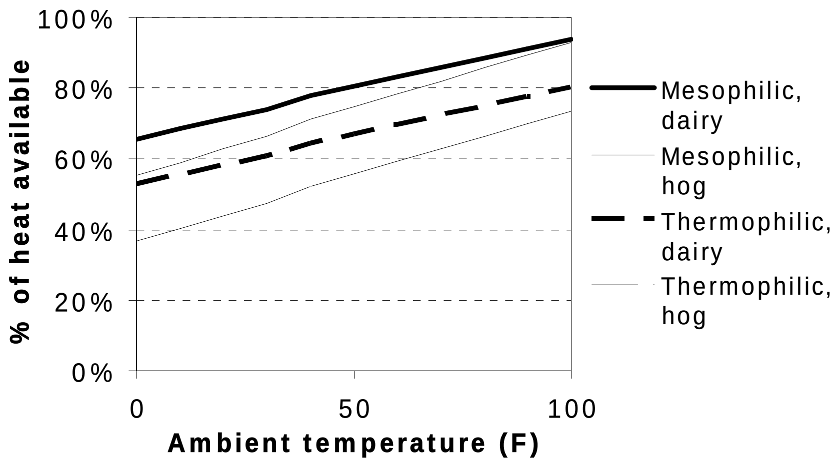

Figure 6. Fraction of heat available from CHP unit, after digester heating requirement is satisfied. (This digester produces ~32,000 ft^3 CH_4 / day, and electrical output is approximately 100 kWe). Note that hog manure tends to be more dilute than dairy slurry, so a larger volume of material must be heated.

Operation and maintenance costs (O&M) on digesters can include engine maintenance (oil changes) and overhauls, manure pump replacement, scrubbing hydrogen sulfide from digester gas and drying gas, and it may include periodic removal of accumulated solids from the digester. Cost of energy is not only sensitive to capital and operations costs, but also to capacity factor, payback periods, and discount rates. I will use the following parameters as baselines in the engineering-economic analyses, (unless where otherwise noted):

Capacity factor (CF):	0.9
Payback period:	12 years
Discount rate (DR):	0.1
Capital cost:	$4,000 / kWe
Size:	100 kWe

In addition, I will consider the following three O&M cost regimes:

LoO&M:	Annual fixed cost = 1.5% of capital cost Annual variable cost = $0.01 / kWh
MidO&M:	Annual fixed cost = 3.0 % of capital cost Annual variable cost = $0.02 / kWh

HiO&M: Annual fixed cost = 4.0 % of capital cost
Annual variable cost = $0.025 / kWh

Because farming practices and manure properties differ, and because there are not many systems that have operated for over 10 years, O&M costs in practice are not well quantified. Values such as $0.02 / kWh or a flat 5% of capital have been assumed [41-43], but they may not accurately reflect the total costs associated with keeping a system running. For example, they often ignore costs associated with accumulating solids in the digester. The LoO&M regime would probably not account for this cost; the MidO&M may account for it, and the HiO&M regime would account for this cost. It is also possible, however, that digesters could be designed to more easily accommodate solids removal. Thus, the range of O&M costs will provide a likely range for the cost of energy from digesters.

Figure 7 shows the cost of gas from a digester (does not include CHP unit or any electrical connections). Figure 8 shows the effect of capital cost changes on cost of electricity, under different O&M regimes. Figure 9 explores how changes in payback period and capacity factor (CF) influence the cost of electricity.

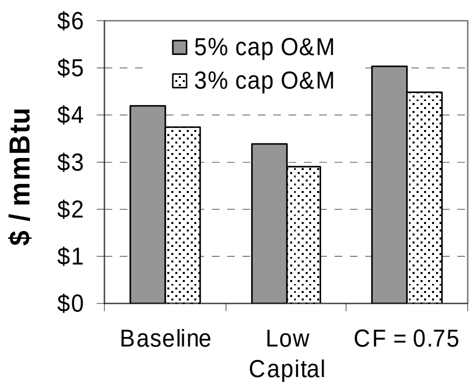

Figure 7. Cost of gas from digester. Darker bars show costs associated with O&M costs at 5% of capital expenditure; lighter bars represent O&M at 3% of capital. Low capital refers to a 38% reduction in digester vessel cost.

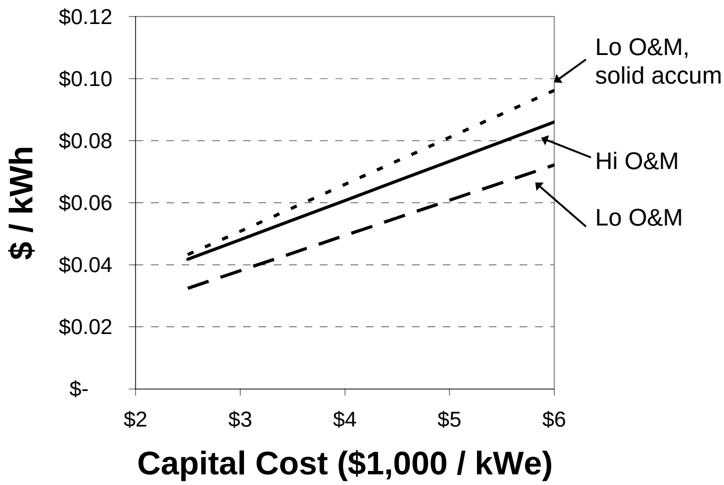

Figure 8. Levelized cost of electricity from digester. For "Lo O&M, solid accum" solids accumulation in the digester causes biogas production to decreases linearly with time; output is decreased by 50% after 12 years – included to illustrate the effect of not considering solids removal in O&M costs.

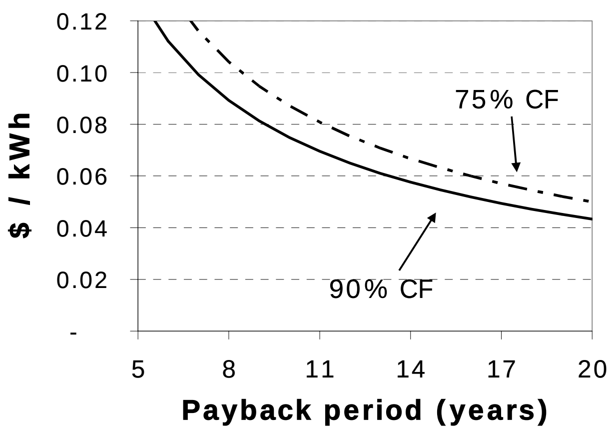

Figure 9. Electricity price from digester for different payback periods and with reduced capacity factor. (10% DR, Mid O&M scenario).

Digesters may also be operated as peaking plants. In this case, electricity is generated during high-demand periods (daytime), and gas is allowed to accumulate during off-peak times. Many digesters in the U.S. have a soft inflatable-type cover under which biogas accumulates (see Appendix 2 for a few images). If the gas pressure within the digester is low enough, the cover could be subject to wind damage. To overcome this potential problem, digesters in Germany are designed with an inflated cover. It is pressurized with an electric air blower and remains taught regardless of digester gas pressure [52]. Since it can accommodate some pressure fluctuations, the digester does not require special equipment to operate in peaker mode. However, costs do increase because of the need for a larger engine-generator set (see appendix 4 for cost curve I have used for cost of CHP units). In addition, IC engines running on dirty gas (containing hydrogen sulfide) may be more subject to wear and corrosion issues if they are shut down frequently. A possible solution to this problem would be to briefly run the unit on propane just before shutdown. Cost of electricity from a peaking unit is shown in Figure 10.

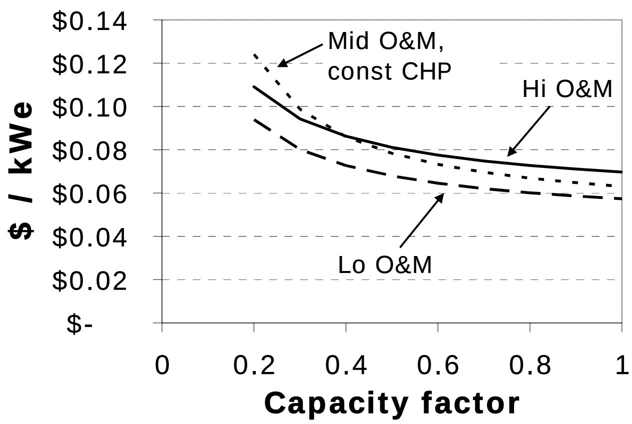

Figure 10. Cost of electricity: peaker analysis. "const CHP" refers to a constant marginal price for the CHP unit (while this is not likely to be the case, I have included it, in light of the constant marginal cost for digesters above 100 kWe apparent from Figure 3).

Another operational strategy is to burn the biogas in a diesel dual-fuel engine. 10% diesel (by energy) is injected along with the biogas to more efficiently produce electricity. Figure 10 shows the benefit (on a per kWh basis) of using a dual-fuel approach. Diesel engines are likely cheaper than gas engines, so I have included a benefit calculation with a 10% discount on the dual-fuel engine, compared to the baseline biogas engine.

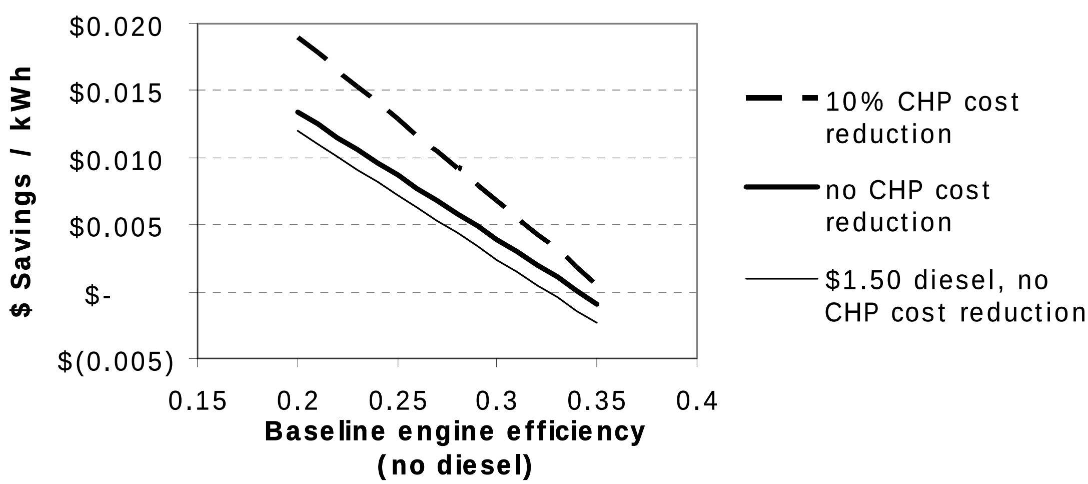

Figure 11. Dollar savings per kWh generated using diesel dual-fuel approach. Baseline diesel cost is $ 1 / gallon.

Finally, the rate at which future digester operational costs are discounted influences the final cost of electricity. For the base case in the Mid O&M regime, the cost of electricity is 6.5 ¢ / kWh (10 % discounting). At a discount rate of 20 %, electricity cost is 5.7 ¢ / kWh.

3.4 Other benefits and costs associated with anaerobic digestion

Odor mitigation

Odor is a major concern for owners of concentrated animal feeding operations. Many states currently have right-to-farm laws, which limit individuals' ability to file nuisance lawsuits against farms. However, in one 2002 case, plaintiffs were awarded $1 million in damages, and a judge imposed $32 million in punitive damages on a hog operation. This case has been subsequently settled outside of courts [58] and the punitive damages have been dropped, but odor from large animal operations will likely continue to be a major issue. Figure 12 shows the value of an avoided lawsuit as a function of the probability that a $500,000 fine will be imposed sometime in the next 15 years.

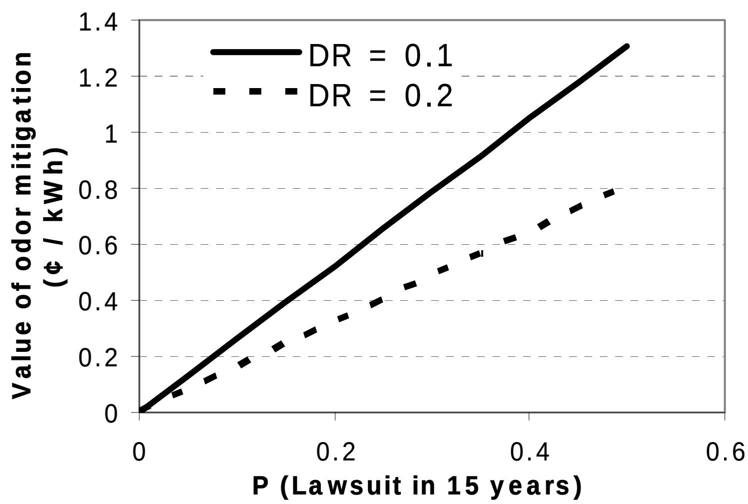

Figure 12. Value of avoided odor lawsuit. The lawsuit is equally probable in any year.

Alternatively, researchers at Iowa State University have found that the presence of a large hog operation within one mile of a home reduces its value by about 10% [53]. Lastly, odor mitigation with AD might enable a farm operation to stay in business – a value that is difficult to quantify.

Greenhouse gases

In 2002, methane emissions from agricultural manure management totaled 39 Tg of CO_2 equivalents. These emissions represent about 7% of total CH_4 emissions from anthropogenic activities in the U.S., or about 0.6% of total greenhouse gas emissions (CO_2 eq.) [4]. Harvesting CH_4 from manure with anaerobic digesters can significantly reduce methane emissions to the atmosphere. If all hog and dairy manure is digested and there is no fugitive methane emission from the digester, avoided GHG emissions would be around 1,100 g CO_2 eq per kWh (Table 3).

Table 3. Methane emissions from manure management, and reductions possible with AD [4, 8].

	Unit	Dairy Farms	Hog Farms	All poultry
manure management				
CH4 emissions	Tg CO2, equiv	15	18	3
anaerobic digestion				
manure digested	%	100%	100%	70%
CH4 production	Tg CO2, equiv	62	40	9
electricity production	kWh	1.3E+10	8.6E+09	1.9E+09
emissions from manure management avoided, due to CH4 capture and use	g CO2 / kWh	1,142	2,047	1,342
fugitive CH4 emissions	%	10%	10%	10%
CH4 avoided	g CO2 / kWh	684	1,589	885
U.S electricity industry avg = 613 g CO2 / kWh				

Since methane emissions emanate mostly from large operations that store liquid manure in pits or tanks, the actual values for avoided GHGs from AD are likely higher than values shown in Table 3. On the other hand, it is possible that anaerobic activity in manure continues after the slurry leaves the digester. If manure storage (post-digestion) is not covered, fugitive methane emissions are possible, lowering avoided GHGs from AD.

Nutrients

Anaerobic digestion does not reduce concentrations of nitrogen or phosphorous in manure. The process likely increases concentrations of ammonia nitrogen in digested manure [18, 23, 43]. While ammonia is a more valuable fertilizer in the sense that it is more easily utilized by plants, it can also volatize during manure storage and application, depending on farming practices and meteorological conditions. Ammonia can cause air quality and/or eutrophication issues elsewhere [55]. Covered manure storage and injection of manure slurry directly onto growing crops can increase the value of digested manure, and reduce possibility of adverse environmental impacts from ammonia. However these practices are relatively costly compared to uncovered lagoon storage and spray slurry application.

Pathogens

The EPA reports that pathogens from agriculture are a leading source of pollution in rivers [1]. However, it is difficult to definitively determine the source of pathogens involved in water-bourn pathogen outbreaks [59]. As such, it is difficult to determine how human health would be affected by reduced pathogen levels in manure spread on land.

Pathogen concentration reduction in digesters proceeds faster and further toward complete inactivation at elevated temperatures [60-62]. In the European Union, substrates from off-farm to be digested on-farm must be treated at 70°C for 1 hour before digestion to prevent the spread of disease [63].

Animal welfare

An analysis of animal manure to power would be incomplete without a discussion of the animals being raised. In order to produce power from manure, it must be collected. On most large hog operations, hogs live in barns on slatted floors over manure pits. On older operations, the pits below the hogs serve as manure storage. On many newer operations, the pits are flushed weekly to a storage lagoon. On large dairies, cows often live in open-stall sheds where they can walk freely and lie down in bedded stalls. Manure is collected either with mechanical scrapers, or the barns are flushed with water. As discussed above, manure from beef cattle, broiler chicken and turkey operations is allowed to collect and is removed infrequently (see appendix 5 for a few images of concentrated animal feeding operations).

A potentially disturbing aspect of manure to power systems is that the technology could enable and even encourage CAFOs. The cost of animal welfare as it relates to energy production is outside the scope of this paper. However, one point of view is that a comfortable animal is the most productive. It is the author's belief that there are costs associated with industrial animal agriculture that are not seen by operators. Some of these may be related to animal welfare. However, some may also relate to human health. For example, animals are often administered sub-therapeutic doses of antibiotics to promote growth on confined animal operations. This practice may put humans at risk by promoting growth of antibiotic-resistant bacteria [64-66]. CAFOs are a large part of our food production chain and the problems associated with their operation have to be addressed.

In this section, I have looked at the quantifiable and the (to date) non-quantifiable cost of AM to P using available data. From the above, using mid to conservative assumptions AM to P can produce reasonably cost effective power. We now consider the possibility that a synergy between wind and biogas could increase the value of power from AM to P.

4 Renewable energy synergy: Digester and gas storage coupled with wind generation

Renewable energy sources such as solar and wind are intermittent. This lowers the value of power generated from such sources. A digester system including gas storage, coupled with an on-farm wind turbine could provide more dispatchable power than a digester or wind turbine alone. In this section, I investigate the potential and cost of this wind + biogas synergy.

The basic idea of the model is that when the wind is blowing, electricity is generated with the wind turbine and digester gas is stored. When the wind is not blowing, biogas from the digester and gas storage is utilized to produce electricity. For a given time period, the model determines the maximum baseload capacity possible given wind speeds [75], biogas production, and storage volume.

In the case presented here, the farm is a 7,500 head hog operation in NW Iowa (wind power class 4, see appendix 6), and the digester has a baseline (no synergy) capacity of 100 kWe. The wind data are taken near ground level, where wind speeds are lower than at turbine hub height. I have scaled the wind data to achieve the 0.3 capacity factor appropriate for a wind power class 4 location [75].

Marginal cost curves for CHP unit and gas storage are shown in appendix 4. Payback period is 12 years and discounting on O&M is 10%. O&M costs are as follows:

Digester and gas storage:
- Fixed O&M: 3 % of capital cost
- Variable O&M: $ 0.02 / kWh

Wind turbine:
- Fixed O&M: 2 % of capital cost
- Variable O&M: $ 0.01 / kWh

Table 4 describes the stand-alone costs of the digester and wind turbine.

Table 4. Baseline stand-alone costs of digester and wind (no synergy). All units in thousands (except capacity and cost / kWh).

System	Capacity (kWe)	Digester Cost	CHP Cost	Gas Storage Cost	Wind Turbine Cost	Total Cap. Cost	O&M (PV)	(kWh / year)	cost ($/kWh)
Digester	100	$280	$120	$0	$0	$400	$189	788	$0.062
Wind turbine	1,000	$0	$0	$0	$1,000	$1,000	$315	2,628	$0.042

Figure 13 and Figure 14 show model results for the month of August, 2003. Biogas storage capacity in this case is 500,000 gallons (76,000 ft^3 of gas). The maximum baseload capacity for this period is 176 kWe. Notice that for this run, the amount of gas in storage at the beginning of the period is about 10% of capacity. However, in this case, even if gas storage were at capacity at the start of the period, the “low point” around day 10 would still occur.

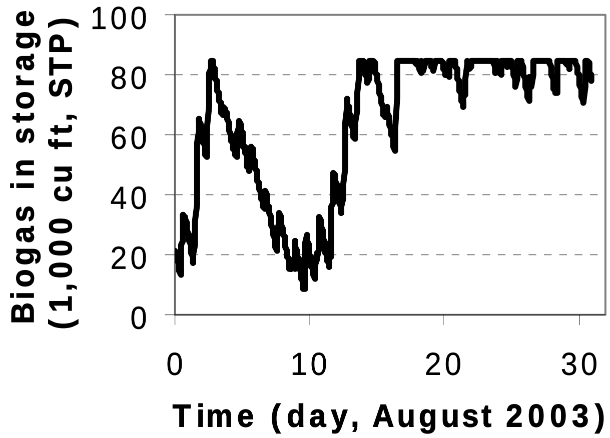

Figure 13. Volume of biogas in storage during August. Baseload output is 176 kWe.

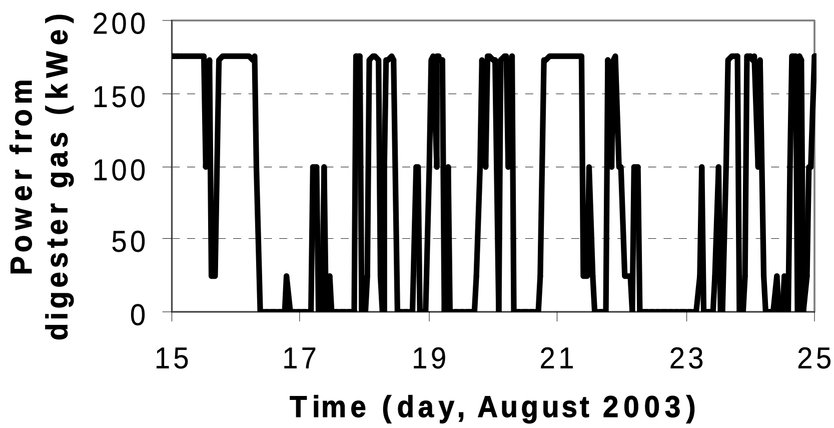

Figure 14. Electric power supplied by digester CHP unit. (Note the time-axis spans 10 days)

The baseload capacity available during the month of August is not very sensitive to gas storage capacity (Figure 15). On the other hand, increasing the storage capacity has a profound effect on the baseload capacity available in March. Note that when gas storage volume is zero, the baseload capacity is above the baseline of 100 kWe. The digester has some integrated gas storage, as with the peaker unit described in section 3.3.

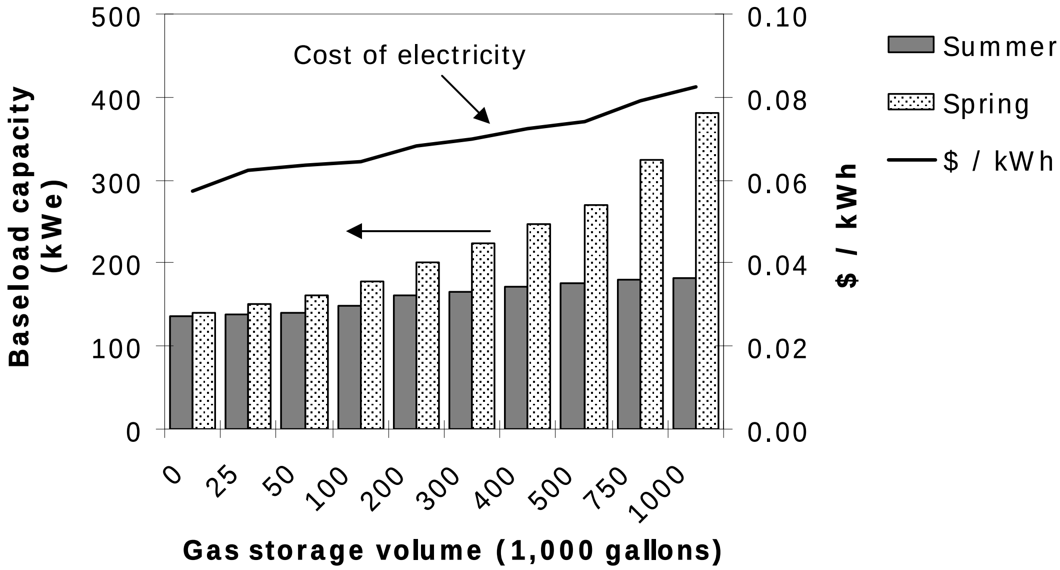

Figure 15. Baseload capacity available from digester + wind system, along with cost of electricity from the coupled system.

This model calculates the amount of baseload power available from an anaerobic digester coupled with a wind turbine and gas storage. It shows the potential of this synergy to provide a substantial increase in baseload capacity. The cost of energy is comparable to the cost of energy from a digester alone operated as a peaking unit. Since all of the energy generated using a peaking unit is (by definition) during times of high demand, the peaker configuration seems to provide the most valuable energy.

5 Institutional and regulatory influences on adoption of manure to power technologies

AgSTAR is a voluntary program sponsored jointly by the U.S. Department of Energy (DOE), Department of Agriculture (USDA) and the Environmental Protection Agency (EPA). Its main goal is to reduce methane emissions from manure management. To accomplish this goal, AgSTAR provides informational assistance to operators interested in biogas technologies [73].

In addition, the National Resource Conservation Service (NRCS) of the USDA has issued conservation practice standards regarding anaerobic digesters [74]. These documents provide assistance to state officials in developing their own conservation practice standards.

There is also financial assistance available for manure to power systems from the federal government. In the American Jobs Creation Act of 2004, the range of energy resources qualified for the production tax credit has been expanded. Open-loop biomass (which includes manure to power systems) is now eligible for the tax credit [11]. In addition, the Rural Business-Cooperative Service of the USDA has proposed a rule to implement grants and loans to farm operators to make investment in small renewable energy systems [10]. This Renewable Energy Systems and Energy Efficiency Improvements Program was established by the 2002 Farm Bill.

A number of states have programs to provide financial assistance (in the form of grants and loans to) to farm operations who wish to install manure to power systems (California and Pennsylvania among them). In addition, many states have adopted legislation related to odor detection levels and hydrogen sulfide concentrations [54].

While these air quality regulations could promote adoption of biogas technology, anaerobic digestion is not the only solution to odor issues, particularly for hog operations. For example, one promising alternative is to house hogs on a deep bed of crop waste (straw, corn byproducts, etc) in an inexpensive hoop structure. This production system avoids anaerobic conditions (and thus odor and methane emissions) and seems to be cost-competitive with more traditional intensive hog production systems.

6 Conclusions

Maximum electrical generating capacity from manure in the U.S. is approximately 6.4 GW, with 3.7 GW coming from manure handled as solids (incineration or gasification), and 2.7from anaerobic digestion of liquid manure. The cost of electricity from anaerobic digestion is approximately $ 0.06 / kWh. Methane emissions from agriculture account for 7% of anthropogenic methane emissions in the U.S. Therefore, greenhouse gas reductions from anaerobic digestion, due to avoided methane emissions from manure storage, are substantial on a per kWh basis.

Compared to the stand-alone digester system, the coupled wind + biogas system provides 65% more baseload power in summer, and 170% more during spring. The cost of this electricity is approximately $0.075 / kWh. This cost is comparable to a stand-alone generator operated as a peaking unit operated 12 hours per day.

Anaerobic digestion will likely play some role in manure management in the future. Odor mitigation will continue to be an important driver, but without high prices for electricity (e.g. Germany) digestion will not be feasible for many farm operations. Alternative manure handling equipment on farms could more efficiently utilize nutrients, but these systems require significant capital investments.

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Appendix 1

The EPA passed regulation in 2002 that requires CAFOs to obtain permits to spread manure on land. The U.S. EPA authorizes individual states to issue permits to CAFOs, and if a state is not authorized, the U.S. EPA is responsible (approx. 5 states are currently not authorized). The nutrient limits are based on nitrogen or phosphorous, and can be issued on a field-to-field basis. It is up to the discretion of the local permitting authority to formally decide application limits [9]. The following table outlines CAFO designations (numbers correspond to number of animals except where noted AU – Animal Unit)

Operation Type	CAFO threshold
any animal operation	>1,000 AU
cattle	>1,000
dairy cattle	>700
hog (>55 lb)	>2,500
hog (<55 lb)	>10,000
chicken (liquid manure handling system)	>30,000
chicken, not layers (not liq. Handling system)	>125,000
layers (not liq. handling system)	>82,000

[2].

Appendix 2

DIGESTION

Parameter	Unit	Dairy Cow	Hog	Beef Cattle	Layer (chicken)	Broiler (chicken)	Turkey	Humans	**Total (non-human)**
animal population	# of animals	9.1E+06	6.0E+07	1.4E+07	3.4E+08	1.1E+09	1.0E+08	2.8E+08	
VS produced	lb / animal / day	15.4	1.1	5.9	0.05	0.03	0.18	0.23	
VS destroyed	%	30%	65%	30%	65%	65%	65%	65%	
methane produced per lb VS	cu ft / lb	11.0	8.2	11	8.2	8.2	8.2	8.2	
methane produced per animal (VS)	cu ft / animal / day	46.2	4.5	17.8	0.3	0.2	1.0	1.2	
Percent of manure digested	%	100%	100%	0%	70%	0%	0%	50%	
energy / animal / day (methane, VS)	Btu / animal / day	46,200	4,531	17,820	256	181	970	1,234	
energy potential in U.S.	Btu / year	1.5E+14	9.8E+13	-	1.5E+13	-	-	3.2E+13	
conversion efficiency	%	30%	30%	30%	30%	30%	30%	30%	
kWh / day / animal (VS, energy)	kWh / animal / day	4.06	0.40	1.57	0.02	0.02	0.09	0.11	
animals to make 1 kW	# animals / kW	6	60	15	1,067	1,507	281	221	
electricity (power) potential in U.S.	MW	**1,540**	**987**	**0**	**221**	**0**	**0**	**633**	**2,748**

INCINERATION/GASIFICATION

Parameter	Unit	Dairy Cow	Hog	Beef Cattle	Layer (chicken)	Broiler (chicken)	Turkey	Human	**Total**
animal production	# of animals / year	-	-	-	3.4E+08	8.6E+09	2.7E+08	-	
animal population (average)	# of animals	9.1E+06	6.0E+07	1.4E+07	3.4E+08	1.1E+09	1.0E+08	2.8E+08	
manure solids produced	lb / animal / day	15.4	1.05	10.50	0.06	0.04	0.24	0.40	
percent of manure incinerated or gasified	%	0%	0%	100%	30%	100%	100%	50%	
energy content of manure	Btu / lb	4,000	4,000	4,000	4,000	4,000	4,000	-	
energy per animal	Btu / animal / day	61,600	4,200	46,667	284	196	1,067	1,760	
energy potential in U.S.	Btu / year	-	-	2.4E+14	1.1E+13	7.8E+13	4.1E+13	9.0E+13	
conversion efficiency	%	30%	30%	30%	30%	30%	30%	30%	
animals to make 1 kW	# animals / kW	-	-	6	960	1396	256	155	
electricity (power) potential in U.S.	MW	**0**	**0**	**2,369**	**105**	**781**	**409**	**903**	**3,665**

Table A-1. Parameters used to estimate power potential from anaerobic digestion and incineration of animal manures in the U.S. Sources are as follows: digestion: animal population and VS production, [5, 6, 12]; VS destruction and methane production from [33, 34, 39, 42, 43, 44] (see section 3.1 for a description of the digestion process); engine efficiencies (electrical) are often reported to be below 30%, however this may be due to underutilization of the engine's capacity [38, 42, 43, 46, 47]. Furthermore, efficiency may be increased with a diesel dual-fuel approach, so I have assumed 30% engine electrical efficiency (~ 11,400 Btu / kWh). For incineration/gasification: animal populations [12]; energy content of manure based on [79, 83, 84, 85, 88].

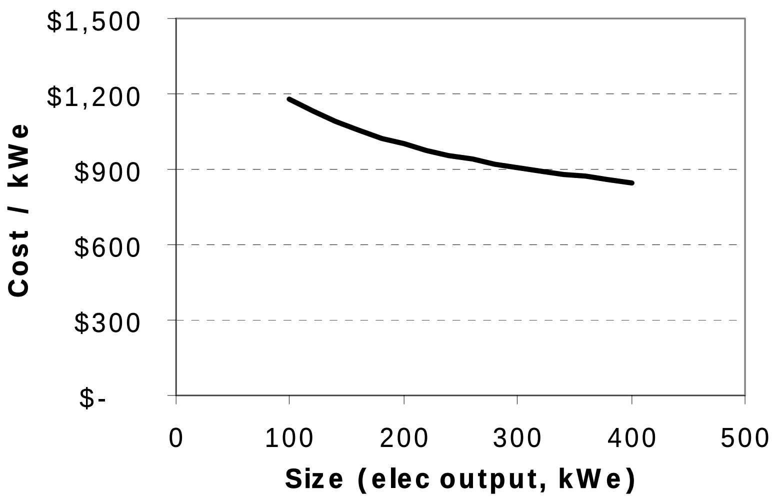
Appendix 3

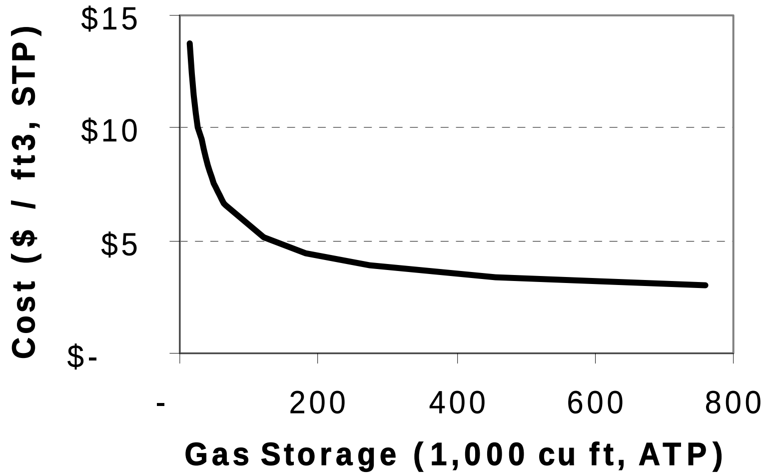
< http://www.schmack-biogas.com/english/frame_referenzen.htm>

<http://www.evur.tu-berlin.de/Meetings/2003%20Beijing/program.htm>

From Top: A 40 kWe digester in Germany (cement) [90] < http://www.schmack-biogas.com/english/frame_referenzen.htm>**; a high-solids modular digester in Germany [49]** <http://www.evur.tu-berlin.de/Meetings/2003%20Beijing/program.htm>**; a plug flow digester in New York, U.S. [89].**

Appendix 4





Cost curves for internal-combustion CHP units (top) and low-pressure gas storage. Costs for CHP units 100 kWe from [37, 42, 43, 45, 47]; shape of the curve is assumed. Cost of gas storage comes from [78]

Appendix 5

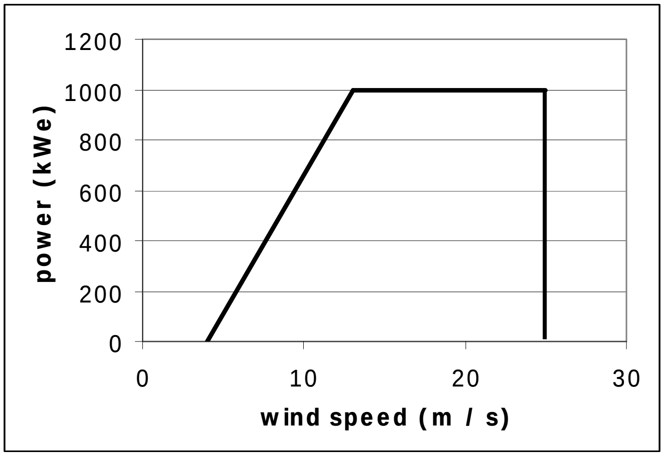
Beef cattle feedlot [79]:
<http://www.osti.gov/energycitations/servlets/purl/792063-s92sR5/native/792063.pdf?zone=ecd>

Beef Cattle feedlot [91]:
< http://faculty.eas.ualberta.ca/jdwilson/feedlot.jpg>

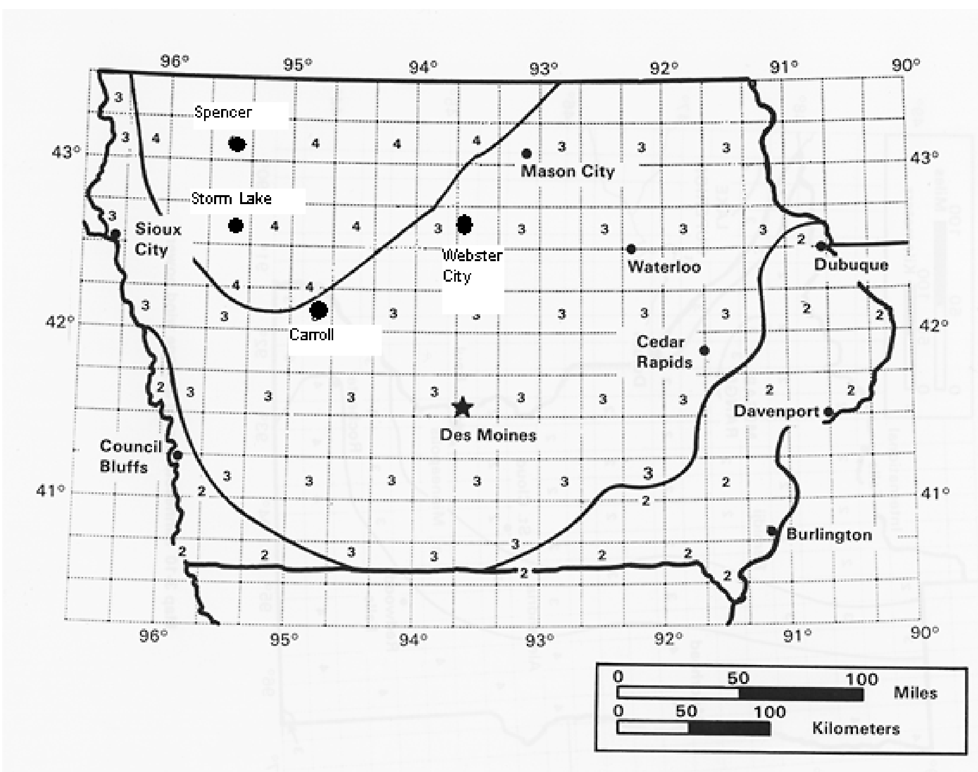
Broiler chicken house [79]:
<http://www.osti.gov/energycitations/servlets/purl/792063-s92sR5/native/792063.pdf?zone=ecd>

From top: beef cattle feedlot [79]; beef cattle feedlot [91]; dairy freestall barn [89]; broiler chicken house [79].

Appendix 6



Power curve used for wind power calculation.



Wind category map: Iowa. Wind data for synergy model comes from Spencer, IA: NW corner of the state [77].