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Optimizing the Size of Anaerobic Digesters

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Abstract

Anaerobic digestion of manure from confined feeding operations (CFOs) to produce biogas and in turn electric power in farm or feedlot based units as well as centralized plants is evaluated for two settings in Alberta, Canada: a mixed farming area, Red Deer County, and an area of concentrated beef cattle feedlots, Lethbridge County. Centralized plants transport manure to the plant and digestate back to the source CFO, an added cost relative to farm or feedlot based plants, but gain from the economy of scale in plant capital and operating cost. A centralized plant drawing manure from 61 sources in the mixed farming area, at a manure yield of 34 dry tonne year^{-1} ha^{-1} could produce 6.5 net MW of power at a cost of \$218 MWh^{-1}. No individual CFO in the mixed farming area, including a 7,500 head beef cattle feedlot, can produce power at a lower cost with a farm or feedlot based unit. A centralized plant drawing manure from 560,000 beef cattle in Lethbridge County, at a manure yield of 280 dry tonne year^{-1} ha^{-1}, can produce power at a cost of \$138 MWh^{-1}. In Lethbridge County, An individual feedlot larger than 40,000 head of beef cattle could produce power at a lower cost than the centralized plant. Commercial processes to recover concentrated nutrients and a dischargeable water stream from digestate are not available. However, we analyze the theoretical impact of digestate processing based on a capital cost of 2/3 of the AD plant itself. Digestate processing shifts the balance in favor of centralized processing, and a feedlot would need to be larger than 250,000 head to produce power at a lower cost than a centralized plant. Power from biogas has a high cost relative to current power prices and to the cost of power from other large scale renewable sources. Power from biogas would need to be justified by other factors than energy value alone, such as phosphate, pathogen or odor control.

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ABSTRACT

Anaerobic digestion of manure from confined feeding operations (CFOs) to produce biogas and in turn electric power in farm or feedlot based units as well as centralized plants is evaluated for two settings in Alberta, Canada: a mixed farming area, Red Deer County, and an area of concentrated beef cattle feedlots, Lethbridge County. Centralized plants transport manure to the plant and digestate back to the source CFO, an added cost relative to farm or feedlot based plants, but gain from the economy of scale in plant capital and operating cost. A centralized plant drawing manure from 61 sources in the mixed farming area, at a manure yield of 34 dry tonne $year^{-1}$ ha^{-1} could produce 6.5 net MW of power at a cost of \$218 MWh^{-1}. No individual CFO in the mixed farming area, including a 7,500 head beef cattle feedlot, can produce power at a lower cost with a farm or feedlot based unit. A centralized plant drawing manure from 560,000 beef cattle in Lethbridge County, at a manure yield of 280 dry tonne $year^{-1}$ ha^{-1}, can produce power at a cost of \$138 MWh^{-1}. In Lethbridge County, An individual feedlot larger than 40,000 head of beef cattle could produce power at a lower cost than the centralized plant. Commercial processes to recover concentrated nutrients and a dischargeable water stream from digestate are not available. However, we analyze the theoretical impact of digestate processing based on a capital cost of 2/3 of the AD plant itself. Digestate processing shifts the balance in favor of centralized processing, and a feedlot would need to be larger than 250,000 head to produce power at a lower cost than a centralized plant. Power from biogas has a high cost relative to current power prices and to the cost of power from other large scale renewable sources. Power from biogas would need to be justified by other factors than energy value alone, such as phosphate, pathogen or odor control.

Keywords: Centralized anaerobic digestion, Biogas plant, Optimum size, Manure transport, Digestate processing, Power cost

INTRODUCTION

Animal manure from confined feeding operations (CFOs) is typically land spread as near as possible to the source CFO, to minimize cost (Fleming et al., 1998). Land spreading of manure has up to four problems with it: the loss of a potential green energy source (biogas from anaerobic digestion (AD) of manure), the risk of contamination of ground and surface waters with pathogens such as *E. coli*, buildup of excess phosphate levels in soil, and odor emissions from land spreading.

AD of manure in a thermophilic or mesophilic digester yields a medium heating content biogas that typically ranges 55 to 80% methane, with the balance being CO_2 and traces of other gases (Mathony et al., 1999; Li, 2005). Biogas can be combusted as is or after cleanup of trace amounts of H_2S, for example in an internal combustion engine to generate electrical power, or can be cleaned to pipeline grade natural gas through removal of CO_2 and other trace gases and compression (QuestAir Technologies, 2004; Environmental Power Corporation, 2005).

Digestate, the slurry left after AD processing of manure, has low odor and contains virtually all of the nutrients in the original manure in a dilute liquid. It is almost pathogen free from properly designed AD plants. Today no commercially available nutrient recovery scheme exists for digestate processing other than simple segregation of solids through centrifugation or filtration. Either whole digestate or the liquid fraction of it is still land spread. If solids are separated, they typically contain as much as 60% of the phosphate in the manure. However, they are typically recovered at a moisture level of 70% and thus still have a low nutrient content, and hence long distance transport of it is not economic (Moller et al., 2000 and 2002). Hence AD of manure from CFOs has the potential today to recover energy from manure while reducing both pathogen and odors. Processing of digestate to recover all nutrients or to remove all phosphate is an area of active research (see, for example, Burns and Moody (2002), Gungor and Karthikeyan (2005), and Uludag-Demirer et al. (2005)) and if a commercial technology emerges, AD would also address the problem of excess phosphate in some soil areas. However, as a source of renewable (non-fossil) energy AD must compete with other alternatives, such as combustion of straw/stover and wood, production of ethanol from straw/stover, and non-biomass options such as wind and solar energy. Hence, the cost of recovering energy from manure is critical.

AD of manure can be implemented at a variety of scales, from individual farm based units to large centralized plants. Denmark in particular has focused on centralized digesters, with transport of manure from the CFO and digestate back to it. The ultimate responsibility for disposition of the digestate remains with the source CFO (H-Gregersen, 1999). Scale issues are critical in all biomass projects and have a critical impact on the cost of produced energy. That cost can be thought of as having three distinct elements. The first is the harvesting cost of biomass, e.g. the cost of acquiring the material and bringing the material from the field to the edge of a road, which are typically independent of scale: a larger plant requires the acquisition of more feedstock, but the unit cost of the feedstock is often unchanged as the draw area increases. The second cost element is the transportation cost of biomass, i.e. the total cost of moving the material from the field to the processing plant, which has a scale dependency because larger plant sizes require biomass to be moved over longer distances. When biomass is relatively evenly distributed over an area, e.g. manure in a large area of mixed farming, the transportation distance increases with the square root of the plant size, since a doubling of the area from which biomass is drawn increases the average driving distance by the square root of 2. The third cost element is the processing cost of biomass, i.e. the cost of turning the biomass into power, ethanol, heat, or some other useful end-product. Biomass processing is typically capital intensive and shows the same economies of scale as other processing plants, such as coal or gas fired power plants or chemical processing plants. Typically scale factors for processing plants are in the range of 0.6 to 0.8 (Park, 1984), where scale factor relates the unit cost of capital from one size to another, i.e.

$$\mathrm{Cost}_{\mathrm{size2}} = \mathrm{Cost}_{\mathrm{size1}} \times \left(\frac{\mathrm{Size}_2}{\mathrm{Size}_1}\right)^{\mathrm{scale\ factor}}$$

In the absence of other constraints, such as a limitation on use of produced energy or heat, biomass utilization based on transported feedstock has an optimum size, which arises from competition between two of the three major cost elements in the overall cost of processing biomass: transportation costs increase with increasing plant size, while capital and operating costs per unit output decrease (Overend, 1982; Nguyen and Prince, 1996; Jenkins, 1997; Larson and

Marrison, 1997; Dornburg and Faaij, 2001, Kumar et al., 2003). Most biomass projects have a similar cost pattern as a function of scale: there is a steep rise in cost at small plant sizes, and a relatively flat profile of cost at large plant sizes, with an optimum at a given plant size.

The objectives of this study are to develop an economic model of power production from anaerobic digestion (AD) of manure for two regions of Canada for which detailed data on manure availability is accessible. The two regions are the western portion of Red Deer County, Alberta, a mixed farming region with some urban and industrial development, and an area between Lethbridge and Calgary, Alberta, that contains many large feedlots associated with finishing beef cattle. Red Deer County would be typical of many mixed farming agricultural regions in Canada. The Lethbridge to Calgary corridor that includes six counties that have a concentration of feedlots is known as “feedlot alley” and it and the surrounding areas are the highest concentration of animal manure in Canada. At any point in time there are more than one million beef cattle in feedlots (CANFAX, 2006). A comparable area in the US is in north Texas and in the vicinity of Dodge City, KS (Dhuyvetter et al., 1998; Ward and Schroeder, 2004), where an estimated five million beef cattle are in feedlots.

The model is based on a consistent scope for all cases of anaerobic digestion in well mixed digesters, with production of electrical power from the biogas. Yields and costs are based on thermophilic AD, although the choice of thermophilic vs.

mesophilic well mixed AD does not create a significant difference. While the produced energy is electrical power, the results of this study on the impact of scale on cost can conceptually be extended to the production of pipeline grade natural gas from AD. The results will help to draw conclusions about the cost of energy from AD of manure, the impact of scale and manure density (yield of manure per unit area) on cost, and whether farm or feedlot based plants are more economic than centralized digesters.

A previous study by Garrison and Richard (2005) evaluated scale issues in anaerobic digestion in a county in Iowa, USA, using the AgSTAR Farmware v2.0 program available from the United States Environmental Protection Agency (US EPA, 1997) to develop estimates for 24 scenarios. They calculated minimum sizes of AD plants that would achieve profitable operation of farm based units producing electrical power or combined heat and power, for example 5,000 hogs in a finishing operating, 20,000 in a farrow-to-finishing operation, and 150 to 350 dairy cattle. This study is discussed further below.

MODEL DEVELOPMENT

The model was developed as a spreadsheet with the potential to easily modify critical parameters. All costs in the model are in 2005 US dollars, and a conversion rate of $1.2 Canadian to $1 US was used where needed.

No cost was assumed for acquiring manure, since an equivalent amount of nutrient in digestate is returned to the source CFO. The model assumes that the CFO is responsible for the construction of all equipment at the farm or feedlot to load solid manure (e.g. a front-end loader in a feedlot), impound liquid manure (e.g. tanks at a dairy) and to receive liquid whole digestate.

The feedstock supply in this model for Red Deer County is based on a survey of the different sources of manure by size, type and location within the county (RDC, 2005), and includes dairies, cow/calf operations, beef cattle feedlots, hog and poultry operations. Most of the CFOs are located in the western half of the county, and quantities and locations were identified for every source. The gross yield of manure in the mixed farming areas, i.e. the manure divided by the total area from which manure is drawn, is 34 dry tonne $year^{-1}$ ha^{-1}. 40% of manure is in the form of liquid and would be shipped in a tanker truck; the remaining 60% would arrive as a solid with a moisture content of 75%. Red Deer County had identified 7 major areas that were thought to produce enough feedstock to potentially support a stand alone typical biogas plant.

Precise confined feeding operation locations were not available for the Lethbridge to Calgary beef cattle feedlot corridor but cattle numbers are so high in some counties that reasonable transportation numbers can be approximated by assuming the feedlots are dispersed evenly across each county and using the center of the county as the average transportation distance for shipment outside the counties. Transportation costs are hence less precise for feedlot alley than for Red Deer County, but within the accuracy of the overall study.

Transport of manure and digestate is by truck; for a detailed analysis of manure transport cost by both truck and pipeline see Ghafoori et al. (2005). Transportation costs are derived from an analysis of current trucking rates in Alberta (AAFRD, 2004; Taylor, 2005), and are consistent with literature values for solid manure but significantly lower for liquid manure (Araji and Stodick, 1990; Brenneman, 1995; Ribaudo et al., 2003; Aillery et al., 2005). The two critical parameters for truck transport are the distance fixed cost of trucking (DFC, in \$ $tonne^{-1}$), which is independent of distance traveled and includes the cost of loading and unloading the truck, and the distance variable cost (DVC, in \$ $tonne^{-1}$ km^{-1}), which is directly dependent on time of travel, which at an constant average speed (assumed at 80 km hr^{-1} in this study) is in turn directly dependent on distance traveled. In this study values of DFC are \$5.0 and \$3.5 for solid and liquid manure. DVC is \$0.09 for both liquid and solid manure.

For centralized digesters, the power cost includes the DFC and DVC of moving manure plus digestate. For farm and feedlot based digesters processing solid manure, the power cost includes the DFC of loading manure, since processing manure at the farm level would require an incremental truck trip: manure to digester, and digestate to field, as opposed to a possible single move of manure to field. DVC is zero for a farm based digester because haul distances are negligible. For farm based digesters processing liquid manure, e.g. hog barns and some dairy operations, the power cost includes no incremental DFC since manure is assumed to flow or be pumped to the digester without being loaded on a truck.

The processing technology is thermophilic anaerobic digestion followed by minor gas cleanup (moisture control and some sulfur removal in a packed column) and combustion of the gas. For all cases up to 25 MW the basis of power generation is an internal combustion engine electrical generation module with a generation efficiency of 37-43% (Harrison, 2005; GE Energy, 2006); above 25 MW we assume combined cycle (gas turbine and heat recovery steam generator with a generation efficiency of 55% (Shilling, 2004). Operating labor is included in the cost for all centralized AD plants and large feedlot based plants (animals in excess of 7,500), but is not included in the cost of farm-based units and feedlots of 7,500 or less; the farmer or feedlot operator is assumed to operate the plant “for free”. Identical factors are used, however, to calculate capital recovery charges, based on a 12% pre-tax return on equity, and plant maintenance, based on 3% of capital cost per year.

Values for the capital cost of AD plants reported in the literature for actual plants and from studies, as well as data from vendor quotations and budgetary estimates, show a high degree of scatter (Hashimoto et al., 1979; Mathony et al., 1999; H-Gregersen, 1999; Nielsen and H-Gregersen, 2002; Row and Neable, 2005; Tofani, 2006). All costs were adjusted to 2005 US dollars, and adjusted to a consistent scope (e.g. data for Danish plants that did not include power generation was adjusted to include this cost, using data from a European manufacturer (Harrison, 2005; GE Energy, 2006)). Figure 1 shows the capital cost data as a function of plant size and lines of best fit to individual data sets. While the data show a high degree of variance, the value of the scale factor is consistent between data sets. Based on Fig. 1 a scale factor of 0.6 is used in this study, a value that is also consistent with chemical process plants and with prior studies of AD (Hashimoto and Chen, 1981; Park, 1984; Lusk, 1998). Capital cost estimates include the cost of equipment to connect to an electrical power grid, but do not include any one time or ongoing administrative charges for the connection. Note that the highest data in Fig. 1 are from actual plants in Denmark (H-Gregersen, 1999), and that data from studies and budgetary estimates are lower than the one consistent set from actual plants. The values in this study are based on a capital cost of 80% of the best fit curve for Danish plant data. We deliberately have not included estimates based on the AgSTAR Farmware model in Fig. 1 because of concerns about the validity and accuracy of the currently available version of the model (Farmware v3.0 is being released in 2006). The Farmware v2.0 ignores the impact of scale for some components: for example, the cost for the internal combustion engine and generator is fixed at $1,050 per kW with heat recovery and $600 per kW without heat recovery regardless of generator size. In effect this is a scale factor of one, a value in conflict with the cost of actual commercial units (Harrison, 2005; GE Energy, 2006). Mixers, a major cost element, are similarly estimated with a scale factor of one. In addition, Farmware gives overall estimates that are so significantly lower than budgetary quotes from vendors and actual Danish costs that we suspect the validity. For example, a plant producing 11,000 m^3 biogas day^{-1} has an estimated capital cost of $9.1 M from best fit of Danish data, $7.7 M and $5.7 M from two recent budgetary quotes to Red Deer County, and $3.1 M from Farmware program. Resolution of discrepancies between the AgSTAR model and other estimates of AD capital costs is an opportunity for future study.

[Figure 1 here]

Fig. 1. The estimated cost of biogas plants generating electric power (■ Hashimoto et al. (1979); ✹ Mathony et al. (1999); ◆ H-Gregersen (1999); □ Nielsen and H-Gregersen (2002); ▲ Row and Neable (2005); △ Tofani (2006))

The model is designed to allow for revenue from the sale of power, heat, by-product fertilizer, subsidies, and carbon credits. In this study we exclude revenue from heat, since there are few sinks in rural settings in North America for low quality waste heat, and for fertilizer, since no payment is assumed to the source CFO and presumably this would only be the case if the manure nutrient value was returned. Revenue from the sale of carbon credits is not included in this study; for an analysis, see Ghafoori et al. (2006a and 2006b).

RESULTS

Red Deer County: Mixed Farming Region

61 manure sources were identified for the western half of Red Deer County. Two sets of cases were developed to process all of this manure: centralized digesters (ranging from seven to one) and a digester at each farm or feedlot. The location of each centralized digester was based on minimizing the aggregate transportation cost. Nine different scenarios for centralized digesters were evaluated, one with seven digesters, two with six, one with five, one with four, one with three, one with two, and one with just one centralized digester. In each case the total gross power production was 8.1 MW gross, and 6.5 MW net after a parasitic (inside the AD plant) power consumption of 20%. The nine scenarios involved 14 different AD plant sizes.

Figure 2 shows the cost of power as a function of plant size for the 14 different plants that were used in the various scenarios. Overall power cost as a function of size shows the pattern typical of all biomass plants processing externally sourced feedstock: a very high increase in output cost at small capacities. The inflections in the unit transport costs reflect the precision of location of CFOs in Red Deer County. For each plant a precise transportation cost is calculated based on actual distances from CFO's to proposed centralized digester locations. The minor inflections in unit processing cost reflect increasing efficiency of power generation as the generator size increases; for an internal combustion powered generator it increases from 37% to 43% (Harrison, 2005; GE Energy, 2006).

[Figure 2 here]

Fig. 2. Estimated power cost at individual centralized plants in Red Deer County.

It is evident that at 6.5 MW of net output, at which all identified manure sources are being processed in a single centralized digester, the optimum size has still not been reached. Manure could be drawn from outside the county with an expected further drop in the overall cost of power. However, the incremental reduction in power cost from incremental manure is low, i.e. the curve of overall power cost vs. size becomes quite flat above 4 MW. Manure and digestate transport cost is 30 to 60% of total power cost, with digestate transportation being the larger component because of the increase in volume of digestate vs. solid manure, about 2.5 times. It is also evident that the distance fixed cost of loading and unloading manure is high compared to the distance variable cost of actually trucking the manure over roads. More time is spent in loading manure and digestate than in transporting it to or from the digester. It is evident from Fig. 2 that if a commercial process were available to recover all nutrients from digestate as solid fertilizer, leaving a water stream that could be discharged to a watercourse, then significant savings, on the order of $60 per MWh, could be realized in power cost. Digestate processing can be expected to have a comparable economy of scale, 0.6, to anaerobic digestion of manure and other chemical processing (Park, 1984).

Plants were then combined in scenarios in which all manure in the county was processed. Figure 3 shows the weighted average cost of power for each of the nine scenarios, ranging from $278 per MWh for seven distributed small centralized digesters, to $218 per MWh for one centralized digester, the most economic alternative. Note that the cost of power, even from the most economic alternative for the county, is high compared to typical wholesale power price levels in North America; $30 to $100 per MWh are typical average monthly power price figures in deregulated power markets (RBC Capital Markets, 2006).

[Figure 3 here]

Fig. 3. Estimated average biogas power cost in Red Deer County.

The cost of generating power at the farm or feedlot was next calculated for each of the 61 CFOs, and results are shown in Fig. 4. 40 sources are small and would produce power of less than 50 net kW, at an average cost of about $710 per MWh. The largest source, a beef cattle feedlot of 7500 head, would produce between 650 and 700 kW at a cost of $227 per MWh. It is evident from Fig. 4

that no CFO in Red Deer County can produce power from AD of manure at a lower cost than a single centralized plant.

[Figure 4 here]

Fig. 4. Farm-based power cost as a function of capacity vs. centralized processing in Red Deer County (number of manure sources at each capacity is identified at the top of bar charts).

Centralized digestion has three advantages in addition to the cost factors included in this model. First, it would centralize a large quantity of digestate and enable the future processing of this digestate as technology emerges to do so. This kind of processing would be chemical and physical processing and would likely only be economic at a larger scale, i.e. it would not be economic to apply in small farm based units. A second advantage of centralized digestion is that it gives the option of producing pipeline quality gas as an alternative to power (QuestAir Technologies, 2004; Environmental Power Corporation, 2005). Producing pipeline quality gas would require gas cleaning (removal of CO_2 and H_2S), an easy chemical process. It would also require compression, a step that also has a significant economy of scale. A third advantage of centralized digestion is that it enables the option, if combined with CO_2 removal, of sequestering the CO_2, for example in a depleted natural gas formation. The use of a renewable energy source such as manure gives a single carbon credit for displacing fossil fuel; sequestration of carbon from a renewable energy source would give a second carbon credit for a net removal of carbon from the atmosphere. Again, the steps involved in sequestration, including compression and pipelining of the gas, would likely be economic at larger scale.

"Feedlot Alley": Concentrated Feedlots Area

Data for the Lethbridge to Calgary corridor is available on a county wide basis, although the size and location of some individual feedlots are known to the authors. Of the more than one million beef cattle in feedlots in the corridor, about 560,000 are in Lethbridge County itself (CANFAX, 2006). Lethbridge County has an area approximately the same as the western half of Red Deer County but with much higher manure gross yield (280 dry tonne $year^{-1}$ ha^{-1}). Various combinations of centralized AD plants were analyzed, ranging from 60,000 head, from the county with the least amount of beef cattle, to 1,130,000 head, all of the beef cattle in the corridor. These, the bars in Fig. 5 (lower axis) are compared to the cost of a plant operated at a feedlot level (upper axis).

[Figure 5 here]

Fig. 5. Feedlot-based power cost vs. centralized processing in concentrated feedlot areas in the absence of digestate processing.

The lowest cost power from a centralized plant, $138 per MWh, is realized from a centralized plant operating in Lethbridge County (560,000 head), or Lethbridge County plus one large feedlot located in an adjacent county (640,000 head). A single centralized digester serving all of feedlot alley has a significantly higher cost of power, about $245 per MWh, because the incremental capital efficiency does not offset the higher transportation cost. Similarly, smaller centralized digesters have a higher power cost because the reduced transportation cost does not offset the loss in capital efficiency. Figure 5 also illustrates that in the absence of digestate processing a feedlot with more than about 40,000 head of cattle can process its own manure more economically than the most cost effective centralized digester. Canada's feedlot alley has individual feedlots up to 60,000 animals. The cost reduction for feedlot processing at 60,000 animals is not large, about $15 per MWh, and a feedlot might choose to pass on the burden of constructing and operating an AD plant to a centralized complex even at 60,000 head. Individual feedlots in the US can be as large as 150,000 head (Simplot Company, 2006), and the penalty for centralized AD with digestate return becomes more significant at this size.

The capital and operating costs of digestate processing are not known because no process has been commercially applied past simple separation of solids and a liquid fraction. However, we have approximately modeled digestate processing by assuming that the capital cost would be 2/3 of the cost of the AD plant excluding power generation (Li, 2005). We further assume that the products of digestate processing are dischargeable water and solid or highly concentrated liquid ammonia fertilizers with a negligible cost of transport relative to digestate. Note that if the basis of digestate processing is reverse osmosis a concentrated stream of potassium rich water would still require land spreading or mixing in irrigation water; this stream would be low in volume compared to the full digestate stream. Figure 6 shows the impact of these assumptions. Digestate processing increases the capital cost and decreases the transportation cost because digestate is not returned to the source CFO.

[Figure 6 here]

Fig. 6. Feedlot-based power cost vs. centralized processing in concentrated feedlot areas with subsequent digestate processing.

From Fig. 6 it is clear that the transportation saving is higher than the capital recovery cost, and power cost for the most cost effective centralized plant drops to $86 per MWh. Further the increased capital intensity means that an individual feedlot can not produce power for less than a centralized plant until it exceeds 250,000 head. We know of no single feedlot of this size in North America, and hence if digestate processing has the cost assumed in this study then centralized AD plants will be the most economic choice in areas of intense feedlot CFOs. We note that the assumptions on digestate processing are very preliminary, and the model does not provide for the purchase of manure from the source CFO or the sale of concentrated fertilizers. This level of detail is not warranted until a better definition of the technology and capital and operating cost of digestate processing is defined. The key observation is that digestate processing will significantly reduce the cost of the production of biogas from manure, and will favor large centralized AD plants.

DISCUSSION

Anaerobic digestion of animal manure does not make low cost power. In a mixed farming area, the cost of power from biogas from AD of manure is over $200 per MWh, which is very high compared to average current power prices in North America. Even in an area of concentrated feedlots giving a very high density of manure per hectare the cost of power is over $130 per MWh. This is high not only in relation to current power prices, but also relative to alternative sources of power from biomass. For example, Kumar et al. (2003) estimated a cost of $60 to $70 per MWh for large scale straw fired power plants in western Canada. In addition, this research clearly shows that farm and small feedlot based AD treatment of manure is uneconomic compared to centralized processing.

There are several implications for AD processing of manure. First, AD of manure will be hard to justify solely as a renewable energy project, because there are abundant biomass resources for less expensive alternatives. Hence, the incentive for AD processing of manure needs to be broadened to include one of the other problems with land spreading of manure: pathogen control, odor control, and phosphate control. Combining the production of biogas with the one or more of these three issues may create sufficient justification for AD of manure.

At a commercial scale, digestate processing today is limited to simple segregation of solids. This captures more than half of the phosphate in the digestate, but the remaining liquid fraction of digestate is a low-concentration slurry that still must be land spread. Phosphate control would be far more effective with total recovery of phosphate from digestate, e.g. through precipitation of residual phosphate from the liquid fraction of digestate. Ideally, processing of digestate would also recover nitrogen and potassium in concentrated form, allowing the water to be discharged from the AD plant. This degree of digestate processing would significantly reduce the cost of AD treatment of manure. In the two most economic cases in this study, the centralized plants in Red Deer and Lethbridge counties, the cost of digestate return is 25% and 40% of the total cost of power, respectively.

Digestate processing to produce solid fertilizers would require changes in modeling the cost of either power or pipeline grade natural gas from AD of manure, because the CFO that is the source of the manure might want a payment for the manure if the concentrated fertilizers from the AD plant were marketed rather than being returned to the source CFO. Manure is rich in phosphate, and marketing the phosphate component of recovered nutrients to areas deficient in phosphate would be a key part of addressing the problem of excess phosphate levels in soils.

Data on the capital cost of centralized AD plants is limited; the best source of data is from a number of plants in Denmark (H-Gregersen, 1999). In this study we made two assumptions, to minimize the potential for bias against farm or small-feedlot based plants: capital cost of AD plants is 80% of the best fit of the Danish plant data, and no operating labor cost is incurred for farm or feedlot based units up to the equivalent of 7500 beef cattle. The assumption on operating labor is questionable for all but small CFOs: operation of an AD plant processing the manure from 7500 beef cattle, or even half that number, with no net operating labor cost is an aggressive assumption. Despite the reservations discussed above regarding AgSTAR Farmware, we note that the study of Garrison and Richard (2005) reaches a similar conceptual conclusion to this study: the economic feasibility varies significantly with scale, and AD plants become less economic with reduced throughput.

Pipeline grade natural gas can be produced from biogas by removing H_2S and CO_2 and compressing the gas; at least one plant is proposed in the United States (Environmental Power Corp, 2005). Gas cleanup and compression both have an economy of scale, and the general conclusion of this work, that AD of manure at the size of a farm or small feedlot is less economic than centralized processing, is not likely to be changed by the choice of pipeline grade natural gas as the end product instead of power.

CONCLUSIONS

Key conclusions from this study are:

- In the western half of Red Deer County, a mixed farming area generating 34 dry tonnes $year^{-1}$ ha^{-1}, a 6.5 MW net power plant processing all manure has a lower cost of power production, \$218 MWh^{-1} than any farm or feedlot based plant. The cost of transporting manure to the AD plant and digestate back to the source CFO is less than offset by the economy of scale realized in capital and operating costs.

- In Lethbridge County, which has 560,000 head of beef cattle in feedlots and produces 280 dry tonne $year^{-1}$ ha^{-1} of manure, feedlots greater than 40,000 head could produce power at a lower cost than a centralized plant processing all of the manure in the county, \$138 MWh^{-1}.

- Digestate processing to produce concentrated fertilizers and a dischargeable water stream is not commercially available today. However, based on a preliminary estimate of the capital cost of digestate processing of 2/3 the cost of the AD power plant, digestate processing would reduce the cost of power in Lethbridge County to \$86 MWh^{-1}, and centralized processing would be more cost effective than processing at the feedlot up to a size of 250,000 head of beef cattle.

- The cost of power from manure is high compared to current North American power prices, and compared to the cost of power from other biomass sources such as straw. It is difficult to justify power from manure on an energy basis alone; further justification might come from one or more of phosphate, pathogen or odor control.

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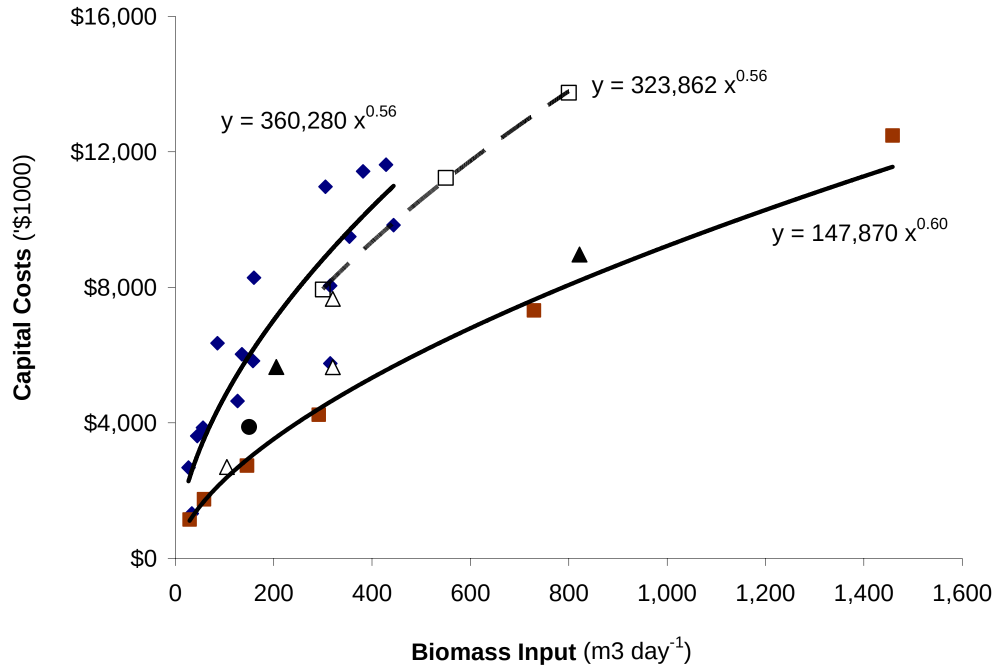

Fig. 1. The estimated cost of biogas plants generating electric power (■ Hashimoto et al. (1979); ✹ Mathony et al. (1999); ◆ H-Gregersen (1999); □ Nielsen and H-Gregersen (2002); ▲ Row and Neable (2005); △ Tofani (2006))

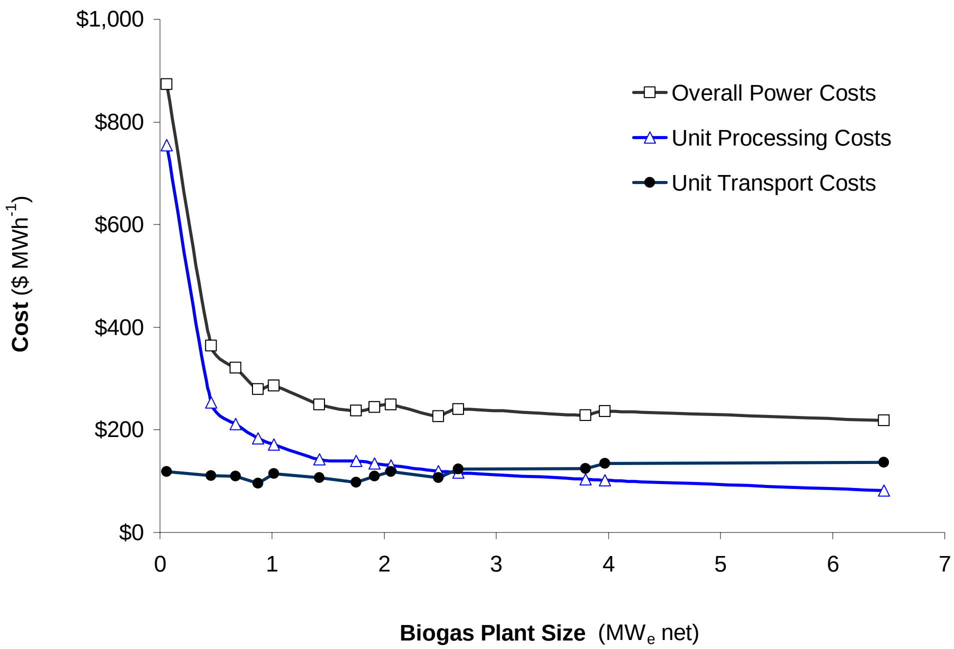

Fig. 2. Estimated power cost at individual centralized plants in Red Deer County.

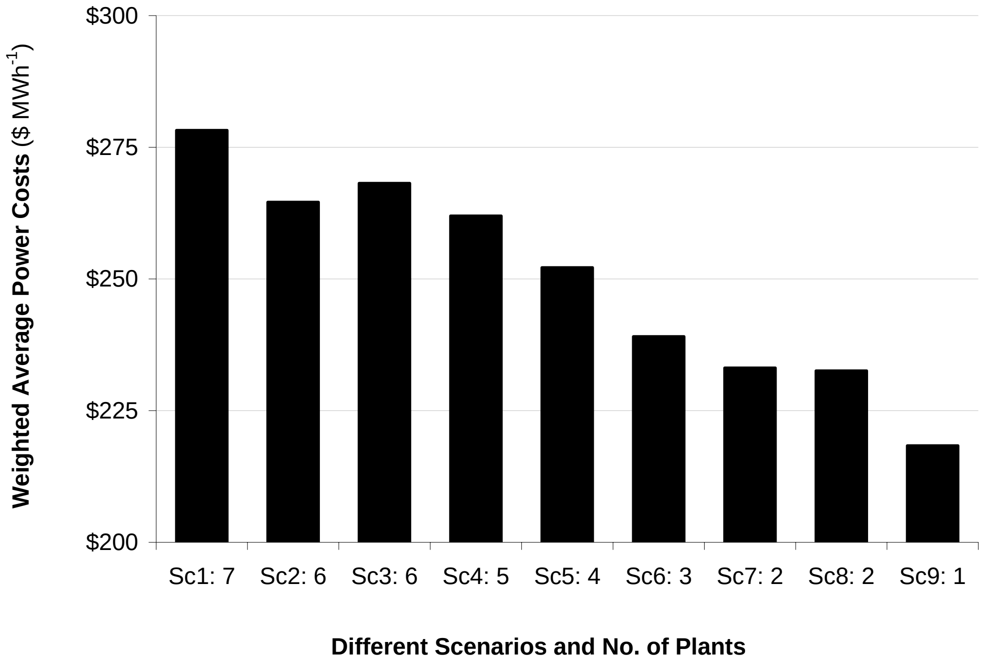

Fig. 3. Estimated average biogas power cost in Red Deer County.

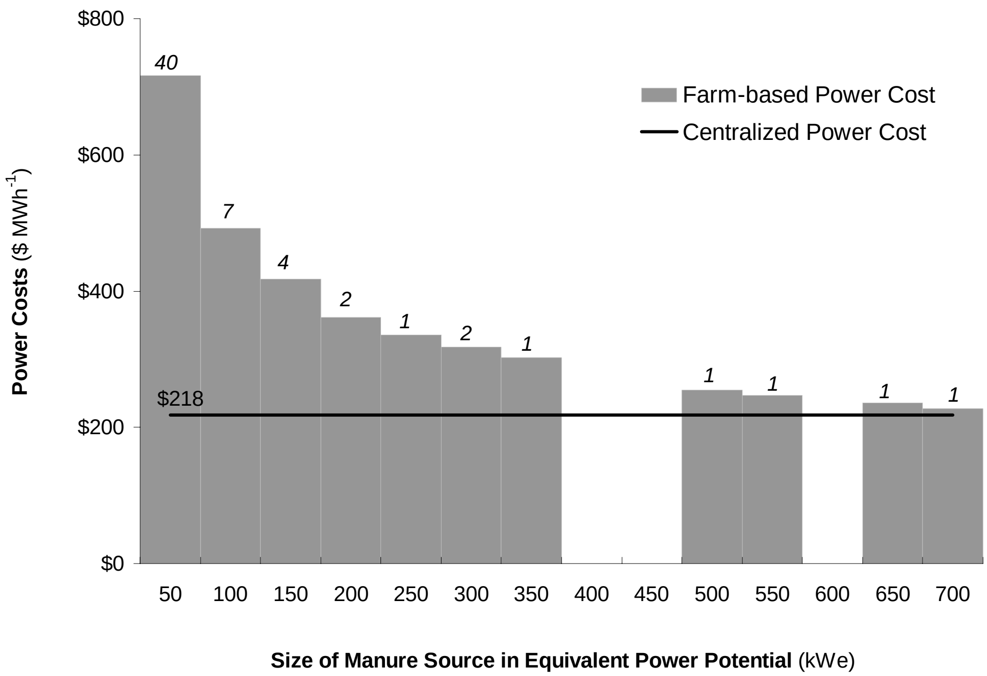

Fig. 4. Farm-based power cost as a function of capacity vs. centralized processing in Red Deer County (number of manure sources at each capacity is identified at the top of bar charts).

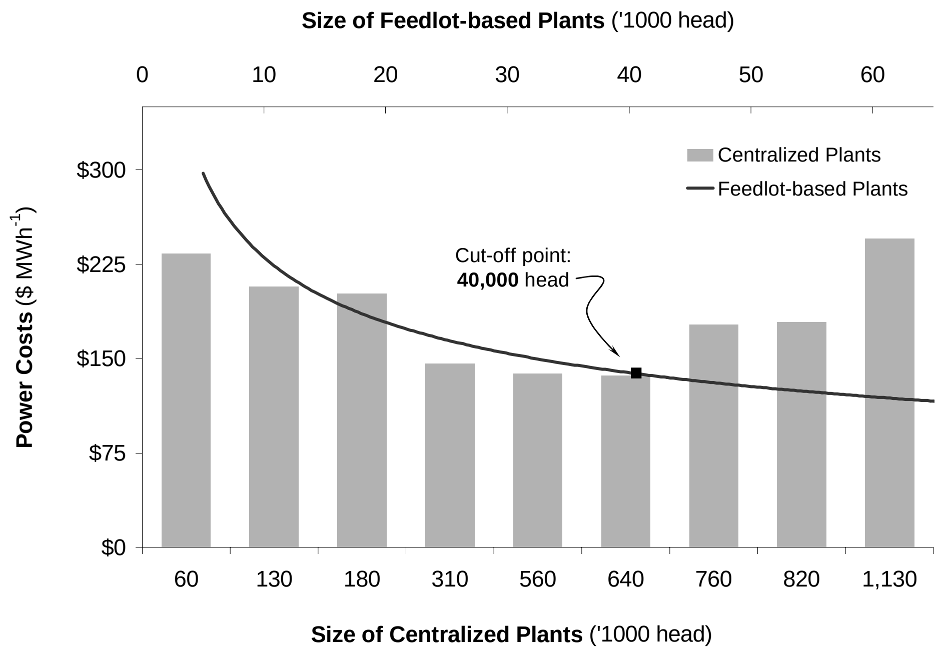

Fig. 5. Feedlot-based power cost vs. centralized processing in concentrated feedlot areas in the absence of digestate processing.

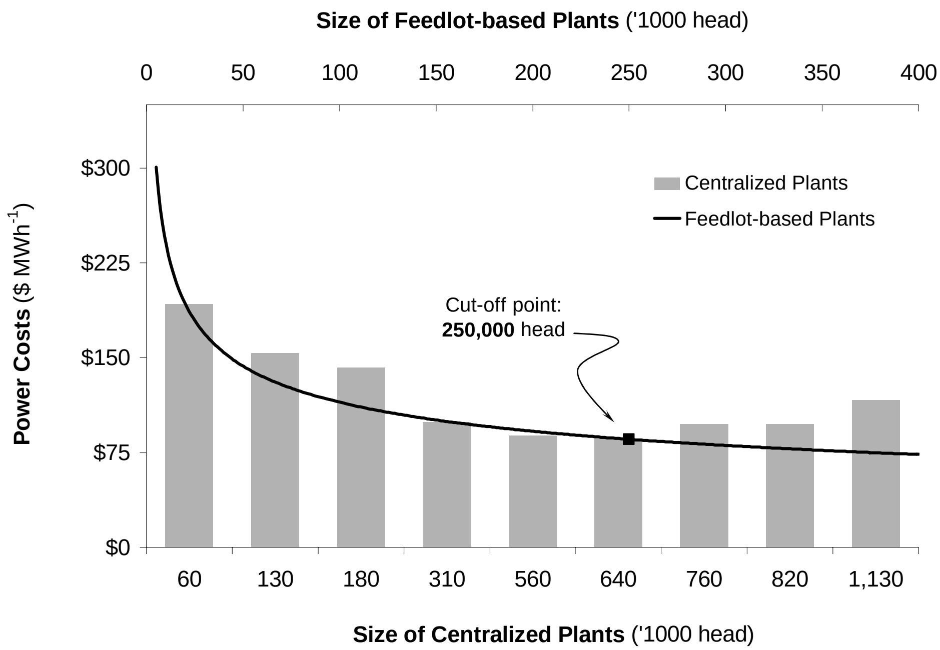

Fig. 6. Feedlot-based power cost vs. centralized processing in concentrated feedlot areas with subsequent digestate processing.