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Optimizing the Logistics of Anaerobic Digestion of Manure

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Abstract

Electrical power production from the combustion of biogas from anaerobic digestion (AD) of manure is a means of recovering energy from animal waste. We evaluate the lowest cost method of moving material to and from centralized AD plants serving multiple confined feeding operations. Two areas are modeled, Lethbridge County, Alberta, Canada, an area of concentrated beef cattle feedlots, and Red Deer County, Alberta, a mixed-farming area with hog, dairy, chicken and beef cattle farms, and feedlots. We evaluate two types of AD plant: ones that return digestate to the source confined feeding operation for land spreading (current technology), and ones that process digestate to produce solid fertilizer and a dischargeable water stream (technology under development). We evaluate manure and digestate trucking, trucking of manure with return of digestate by pipelines, and pipelining of manure plus digestate. We compare the overall cost of power from these scenarios to farm or feedlot-based AD units. For a centralized AD plant with digestate return for land spreading the most economical transport option for manure plus digestate is by truck for the mixed-farming area and by pipelines for the concentrated feedlot area. For a centralized AD plant with digestate processing, the most economical transport option is trucking of manure for both cases.

However, for the concentrated feedlot area, pipeline transport of manure is close in cost to trucking, and the impact of truck congestion would likely lead to selection of pipeline transport. For the mixed-farming area, centralized AD is more economical than for any individual farm or feedlot unit. For the concentrated feedlot area, a centralized AD plant is less economical than a feedlot-based AD unit more than 55,000 head (digestate return) and 300,000 head (digestate processing). The study demonstrates the viability of centralized AD plants vs farm-based units in most farming environments, and that careful analysis of the cost of pipeline vs truck transport of manure and digestate is required on a case-by-case basis.

Index Entries: Anaerobic digestion; biogas plant; digestate processing; manure; manure pipeline; optimum size; trucking.

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Introduction

There are three reasons to process manure to biogas (a mixture of methane, carbon dioxide, and trace gases) through anaerobic digestion (AD). The first reason is to recover useable energy that contributes no net carbon to the atmosphere *(1,2)*. Biogas from small AD plants is typically used for heat or combined heat and power, with power being produced from an internal combustion engine-driven generator. Typical generator efficiencies based on lower heating value are 37–43% *(3,4)*. The amount of heat recovered depends on the available heat sink; European AD plants often feed biogas to a combined heat and power plant that utilizes waste heat in a district heating system *(5)*. Larger amounts of biogas can be processed in a combined cycle power plant with thermal efficiencies of 55% or higher *(6)*. As an alternative, biogas can be scrubbed to remove H_2S and CO_2 and compressed to produce a pipeline quality natural gas *(7,8)*. If the CO_2 is recovered and sequestered a double-carbon credit can be claimed, one for displacing fossil fuel for power generation and one for carbon capture *(9)*.

A second reason to use AD for biogas is to reduce the risk from pathogens, for example, *Escherichia coli*, from land spreading, the most common manure disposal step today. Thermophilic or mesophilic AD with a sanitization step destroys all or virtually all pathogens *(10–12)*. Note that current AD technology does not eliminate the need for land spreading, but rather changes what is spread from raw manure to digestate (the material left after biogas production) or its liquid component.

A third and prospective benefit from AD processing of manure is the potential to recover nutrients from digestate, leaving a disposable water stream. As discussed below in the results of the study this has the potential to significantly reduce transport costs associated with centralized AD plants. In addition, it has the potential to alleviate serious nutrient imbalance problems, reducing the risk to human health from excess phosphate in drinking water *(13–15)*, by producing a concentrated fertilizer that can be economically moved to areas that need the nutrients. Full digestate processing is an area of intense research, but the only commercially available and fully demonstrated treatment of digestate today is solid–liquid separation, which can remove half or more of phosphate into a transportable solid fraction *(16,17)*.

AD has a strong economy of scale. Both analysis of actual capital cost data from Danish plants and theoretical studies show a scale factor of about 0.6 *(18)*, where scale factor is the exponent in the relationship:

$$\text{Cost}_{\text{plant2}} = \text{Cost}_{\text{plant1}} \times (\text{Capacity}_{\text{plant2}}/\text{Capacity}_{\text{plant1}})^{\text{scale factor}}$$

In biomass processing plants that transport biomass from external sources, there is a tradeoff in two cost factors. As plant capacity increases, biomass must be moved to the plant from longer distances, increasing the transportation cost. As plant capacity increases, the economy of scale that arises from the scale factor reduces the cost of capital recovery and operating costs per unit of output. Competition between these two cost factors leads to an optimum size of processing for biomass processing *(19–24)*. As biomass availability per overall unit area surrounding a plant (which we call gross yield to distinguish from species-specific yields of biomass) increases, optimum plant size increases.

In previous work we used two locations in the province of Alberta, Canada, to model the economics of AD of manure in centralized plants vs plants based at the confined feeding operation (CFO) *(18)*. Lethbridge County is an area of intense processing of beef cattle and is unique in Canada; typical feedlots contain 25,000 to 100,000 head, and the overall county contains an average of 570,000 beef cattle *(25)*. Average gross yield of manure is 280 dry t/km^2/yr (for clarity, gross manure yield is the yield per total area in the county). Manure as recovered has an estimated moisture content of 70% *(26)*. A similar area in North America is the large meat processing industry supported by feedlots in the area of eastern Colorado, western Kansas, western Oklahoma, and North Texas *(27,28)*.

The western half of Red Deer County is a mixed-farming area, typical of many such areas in North America, in which grain and forage farms are mixed with beef cattle (cow calf and small feedlot), dairy, hog, and poultry operations. A detailed analysis of virtually all manure sources in the county was completed in 2005 *(29)*. The manure gross yield is 34 dry t/km^2/yr. Forty percent 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 estimated moisture content of 70%.

Pipeline transport of manure and digestate is an alternative to truck transport *(30,31)*. Pipelining of biomass has a significant economy of scale, with a scale factor less than 0.5 *(30–32)*, whereas truck transport has no economy of scale: more material simply requires more truck trips, with no or very minor variation in unit cost of transport. Hence at large scale, pipeline transport will become more economical than truck transport. As all pipelined manure initially is moved by truck, either from farm or individual feedlot pens, the fixed cost of loading a truck, about $4–5/t, is always incurred. (All costs in this study are reported in 2005 US dollars; where required a conversion factor of 1$ USD = 1.2$ Cdn was used.)

Transshipment from truck to pipeline incurs some additional costs that are independent of the length of the pipeline (called distance fixed costs [DFC]), for example, for incremental labor to operate the pipeline. Large pipelines will have a lower unit cost of transport, including operating and capital recovery costs, per unit distance (called distance variable cost [DVC]). Therefore a minimum shipping distance is required for transshipment to be economical, in that the reduction in DVC must offset the increased DFC that arises from transshipment. This analysis of pipelining of manure and digestate is based on economic factors, and we note that other site-specific noneconomic factors can enter into decisions to choose pipelining over trucking, for example, impact on communities from odor concerns and traffic congestion. Such factors played a role in the recently announced AD plant in Maabjerg, Denmark, discussed below in the Discussion section *(33).*

In this study we use Lethbridge and Red Deer counties to model pipeline vs truck transport of manure and digestate to and from centralized AD plants. We consider only manure as a feedstock. Other organic feed streams such as purpose grown crops, crop residues, and various waste streams give higher yields of biogas per mass than manures, which represent material already once processed by bacteria in the gut of an animal. However, the availability of other organic streams is highly site specific, as are regulations that may prohibit the use of ruminant meat scraps or the blending of municipal solid wastes into processes for which digestate will be land spread.

Modeling Pipeline Vs Truck Transportation of Manure

We analyzed two technologies, AD biogas production and digestate return to the source CFO for land spreading, and AD biogas production and digestate processing to solid fertilizer and dischargeable water, for two locations, Lethbridge County and the western half of Red Deer County. For centralized plants we evaluated three transportation modes: trucking of manure plus digestate, pipelining of manure and digestate, and trucking manure and pipelining digestate. In each case we used a 12% pretax return on capital and compared the cost of power production from a centralized AD plant to the cost of a farm or feedlot-based unit.

Point-specific CFO locations were not available for Lethbridge County, only county-wide statistics on beef cattle feedlot population. To simplify comparison, the study areas were assumed to be a square, and manure sources were assumed to be evenly distributed within the area. Red Deer County has manure from many types of CFOs; in this study the reported number of head is the equivalent number of feedlot beef cattle that would generate the same amount of dry mass of manure. A simplified model of a spoke and hub pipeline system was developed (Fig. 1), and contrasted to truck transport for both Lethbridge and the western half of Red Deer County. The study area was divided into five subregions of equal area. Manure in the central region 1 (Fig. 1) was transported to the plant by truck, whereas manure in the remaining four regions was transported by truck to the closest pipeline inlet. Digestate return was by a similar mechanism: truck to region 1, and pipeline plus truck to the remaining four regions. Table 1 shows the key parameters for the model.

Details for the calculation of trucking and pipelining costs were developed in previous studies *(30,31).* Table 2 shows the values of DFC and DVC for trucking, and for pipelining at three different scales of manure and digestate volume. The scale factors for DVC for one- and two-way pipelines were about 0.40; pipeline capital costs were derived from

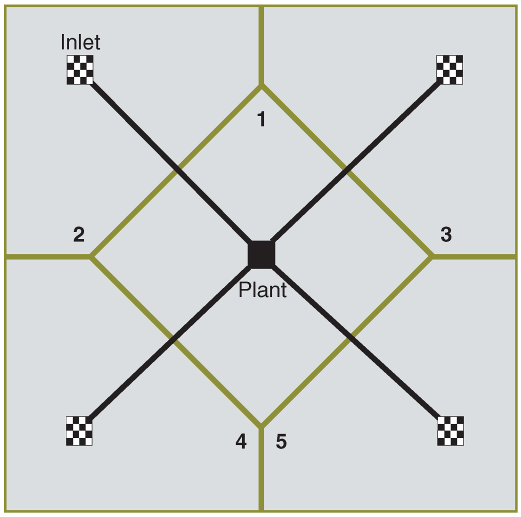

Fig. 1. Simplified model of a spoke- and hub-pipeline system used for both counties.

Table 1
Key Parameters Used for the Modeling

Parameters (unit)	Value	
	Red Deer	Lethbridge
Total manure produced (dt/yr)	93,000	780,000
Total county area (km^2)	2700	2800
Gross yield of manure (dt/km^2/yr)	34	280
Average trucking distance for entire county (km)	37	37
Average trucking distance for each region (km)	16	17
Length of each pipeline (km)	30	31

Table 2
Impact of Scale on the Values of DVC and DFC for Trucking and Pipelining of Solid Beef Cattle Manure

Head	25,000	50,000	1,00,000
DVC ($/dt/km)			
Manure trucking[a]	0.25	0.25	0.25
Digestate trucking[b]	0.96	0.96	0.96
One-way pipeline	0.54	0.33	0.20
Two-way pipeline	0.86	0.56	0.35
DFC ($/dt)			
Manure trucking[a]	17	17	17
Digestate trucking[b]	64	64	64
One-way pipeline	13	7	3
Two-way pipeline	15	8	4

[a]Solid manure shipped at 70% moisture content.
[b]Digestate returned at 92% moisture content.

(34), and pipeline pump power consumption was developed from detailed pressure drop calculations. Capital and operating costs for the AD plant were also developed in a previous study *(18)*.

For each manure source, the moisture content at time of collection was factored into the volume and mass calculations for manure and digestate. A manure source that has a solids level of 12%, typical of some dairy operations, would be pipelined and processed "as is," and the AD process would destroy 45% of the volatile solids, which represent 85% of the solids in the manure *(35,36)*. Hence for this manure source, digestate volume is about 95% of the original volume of manure. However, beef cattle manure from an Alberta feedlot typically contains 30% solids at time of collection, as noted above in the Introduction section and is diluted to 12% for AD processing *(26)*, so digestate volume is about 2.4 times that of the initial manure. For areas of concentrated beef cattle feedlots such as Lethbridge County, this increase in volume becomes a significant factor in the relative economics of pipelining digestate vs manure. Note that if manure is pipelined it is diluted to 12% solids content at the pipeline inlet rather than the AD plant, as pipeline cost is minimized at this concentration *(31)*. Hence, pipeline inlets would require a significant water supply.

Whether the manure is liquid or solid also affects the cost of digestate return. Solid manure is delivered in an open truck, and the truck is empty on the return route. Digestate from solid manure CFOs is returned in a separate truck. Hence, for solid manures (e.g., all manure sources in Lethbridge County), each truck-load of incoming manure causes 2.4 digestate truck trips in a separate vehicle. Liquid manure makes up 40% of sources in Red Deer County, and digestate is returned by backhaul, which generates an incremental DFC charge for loading and unloading digestate but no incremental DVC.

Results of the Study

Figure 2 shows the cost of farm or feedlot-based processing plants (solid line and upper axis) and large centralized processing plant (bars) for production of power from biogas with digestate land spreading; several conclusions can be drawn.

1. For centralized processing in the mixed-farming area of Red Deer County the lowest cost for moving manure and digestate is by two-way trucking. Note, however, that the cost difference between two-way pipeline transport of manure and digestate through four pipelines is very small compared with two-way trucking.
2. Centralized processing of manure with digestate return is more economical than on-farm processing for up to a farm or feedlot size equivalent to about 10,000 head of beef cattle. As the largest single source of manure in Red Deer County is a feedlot containing 7500

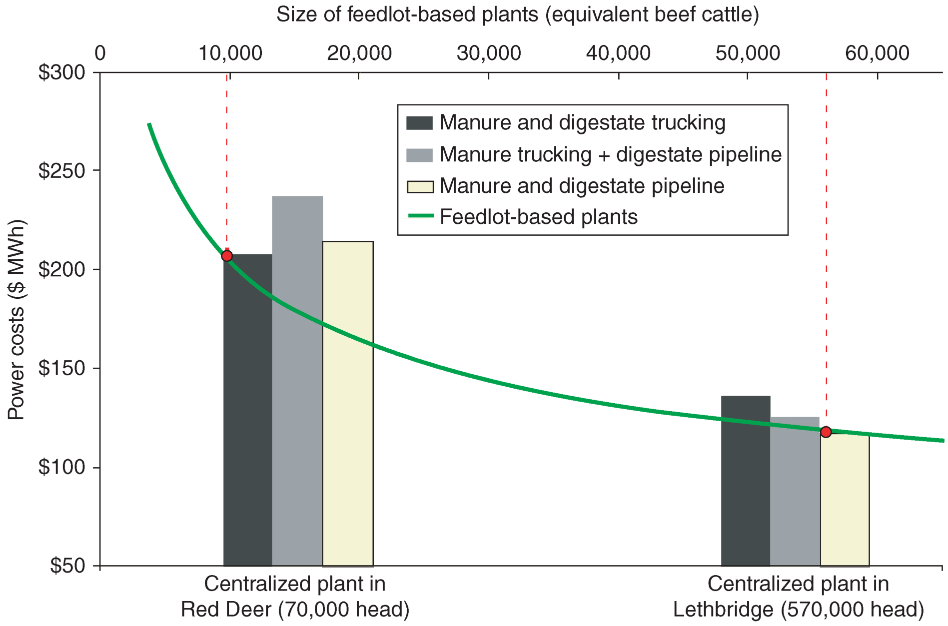

Fig. 2. Biogas power cost at farm-based plants vs centralized plants (the dotted line identifies the size of farm-based plants in which power cost is the same as a centralized plant).

head, centralized processing was the most economical alternative for conventional production of power from biogas *(18).*

3. Third, for the concentrated beef cattle feedlot operations in Lethbridge County the lowest cost for moving manure and digestate was by two-way pipelines.
4. Centralized processing of manure is a more costly method of producing electrical power than feedlot-based processing for any feedlot more than 55,000 head when the most economical transport mode is chosen. Feedlot sizes of 50,000–1,00,000 head are common in North America, and hence there is not a significant incentive to move manure to and return digestate from a centralized plant.
5. For centralized processing the cost in the area of concentrated feedlots is significantly lower than the mixed-farming area, $120 vs $210/mwh. Two factors contribute to this reduction in power cost: an eightfold increase in both plant size and the gross yield of manure per square km. The larger plant size reduces capital recovery and operating costs, and the higher manure yield reduces transportation cost per unit of power output.

Figure 3 shows the cost of farm or feedlot-based processing (solid line and upper axis) and large centralized processing (bars) for production of power from biogas with digestate processing to recover solid fertilizer and

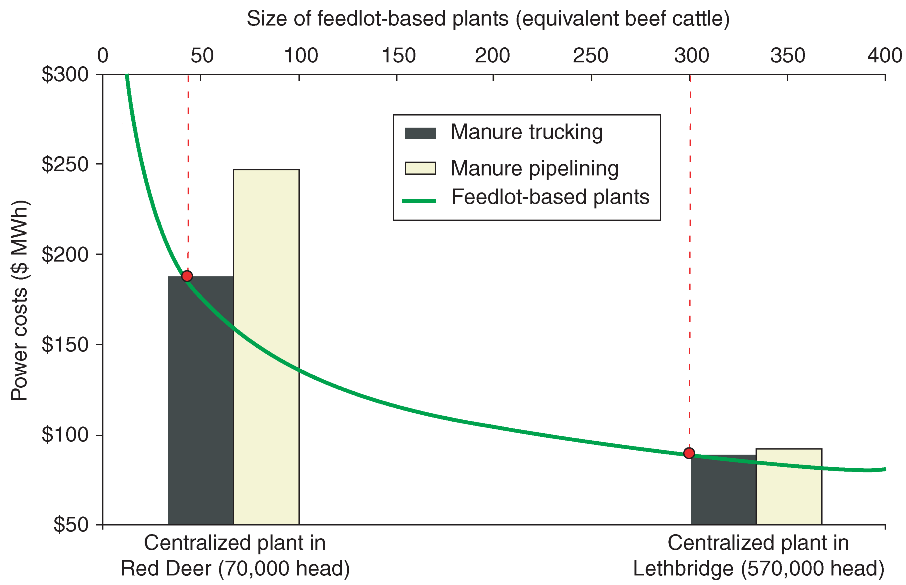

Fig. 3. Biogas power cost at farm-based plants vs centralized plants with digestate processing (the dotted line identifies the size of farm-based plants in which power cost is the same as a centralized plant).

a dischargeable water stream. Note that the power cost does not include any credit for the sale of fertilizer, because fertilizer value will be highly site-specific and based on the expected transport distance to a market for phosphate rich fertilizer, and an offsetting payment to the CFO may be required. For centralized processing in the mixed-farming area the lowest cost-way of moving manure was by truck only and the cost difference between trucking and a single pipeline carrying manure was significant.

Digestate processing gives centralized processing of manure an even larger advantage over individual farm or feedlot-based units, because AD plus digestate processing is more capital intensive than AD with digestate return. This increased capital intensity increases the impact of the economy of scale in capital recovery cost relative to transportation costs. For the area of concentrated feedlot operations, manure trucking was slightly more economical than pipelining, although it raises congestion problems that are discussed further below in the Discussion section. Because of the increased capital intensity of AD plus digestate processing, centralized AD was more economical than feedlot-based processing of manure for feedlots up to 300,000 head in size. As no individual feedlot in Lethbridge County is even close to that size, we can conclude that digestate processing tips the balance in favor of centralized processing of manure. It also significantly reduces the cost of power from centralized AD, $90 vs $120/mwh for digestate return. This cost reduction reflects the high volume increase in digestate vs incoming solid manure, the need to use a different truck to

Table 3
The Number of Truck Arrivals per Day and the Interval Between Arrivals

	Red Deer		Lethbridge	
Centralized plant at:	Truck only	Truck + pipeline	Truck only	Truck + pipeline
Without digestate processing				
Manure delivery (arrival/d)	69	14	363	73
Digestate return (arrival/d)	59	12	867	173
Arrival intervals at 16/7 (min)	8	38	0.8	4
Arrival intervals at 24/7 (min)	11	56	1.2	6
With digestate processing				
Manure delivery (arrival/d)	69	14	363	73
Digestate return (arrival/d)	–	–	–	–
Arrival intervals at 16/7 (min)	14	70	3	13
Arrival intervals at 24/7 (min)	21	105	4	20

return digestate than to move manure, and the cost of pipeline and truck movement of digestate. Note, however, that the scope of digestate processing is poorly defined and the estimated capital and operating cost has a very high degree of uncertainty.

As noted earlier, large-scale centralized AD plants would concentrate truck traffic and raise questions of both road congestion and nuisance odors. Table 3 shows the number of truck arrivals per day, and the interval between truck arrivals. Digestate processing reduces truck traffic by eliminating the need for return of digestate to the source CFO. Liquid manure, for example, from hog barns and some dairy operations, also reduces net truck traffic because, as discussed above (*see* "Modeling"), digestate can be returned by backhaul rather than by a separate truck going out full and returning empty.

Discussion

Whether pipelining, or truck transport is more economical requires a case-by-case analysis, because pipelining has a strong economy of scale and truck transport does not. Increasing plant size reduces the unit cost of pipelining of manure and digestate relative to trucking. Two-way pipelining of manure and digestate has an economy of scale relative to one-way pipelining of digestate for two reasons: (a) The second pipeline can be laid in the same trench as the first and (b) the cost of building a duplicate facility is estimated to be 95% of the cost of the first *(34)*. The savings on the second duplicate pipeline arises because marshaling costs are saved and efficiencies are realized in construction.

Noneconomic reasons also arise for pipelining manure and digestate, and the recently announced proposed Maabjerg Bioenergy project in

Denmark is an example of this *(33)*. Although this project is half the size of the Red Deer County centralized digester evaluated in this study, it will use a 200-km network of pipelines to move both digestate and manure. The high population density and semirural area of the plant presumably present issues related to community acceptance of a manure-based energy project. Table 3 illustrates the very high traffic density caused by AD plants supplied by truck. Careful siting would be required to manage community resistance to such a project. This study concludes that trucking of manure in Lethbridge County is more economical than pipelining for the case of digestate processing, but the difference in cost is small. We think that traffic congestion and community resistance issues would tip such a project into selecting pipeline delivery of manure.

This study illustrates the significant impact of processing plant size on the overall economics of utilizing manure as an energy source, a result found for other biomass sources *(19–24)*. Centralizing manure processing improves the economics up to a cutoff size of farm or feedlot because the increase in capital and operating cost efficiency is greater than the cost of transporting even a low-energy density material like manure. This conclusion is reflected in the practice widespread in Denmark of forming farmer cooperatives to centrally process manure *(37,38)*, usually with heat recovery into a district heating system.

The impact of economy of scale is further illustrated by the impact of digestate processing on the relative economics of feedlot vs centralized processing of manure. In the absence of digestate processing increasing transportation cost exceeds incremental capital saving in the concentrated feedlot area at about 55,000 head of beef cattle. However, if digestate processing is included then a larger amount of capital is subject to the benefit of economy of scale, and this tips the balance to centralized processing against feedlots up to 300,000 head in size. In North America no individual feedlot is larger than 150,000 animals, perhaps to control the magnitude of loss in the event of an epidemic disease. Hence, a key conclusion of this study is that extensive digestate processing will favor very large centralized AD plants.

Digestate processing to recover phosphate as a transportable solid, some in separated fiber and some as crystallized phosphate salts, gives the potential to sell a phosphate rich fertilizer in areas that need the nutrient, whereas reducing phosphate buildup in areas of excess. However, the challenge of total nutrient recovery from phosphate is daunting and requires additional research to develop a commercially proven process. Given the developmental stage of digestate processing, capital and operating cost estimates in this study are approximate. However, they demonstrate that digestate processing has the potential to significantly reduce the cost of energy production from manure by eliminating the need to return digestate to the source CFO for land spreading.

For the mixed-farming area the calculated cost of power from manure is about \$210/mwh, about three times the cost of power from straw in a study based on the same area *(24)*. The estimated power cost of \$120/mwh from the area of intense feedlots is also significantly higher than power from straw. We note, however, that control of pathogens in manure is a potential incentive for using biomass as an energy source; digestate is safer to land spread than raw manure.

The model accuracy will be improved if additional data on capital and operating costs, and biogas yield specific to manure types become available. The model uses an idealized configuration that assumes that manure sources are evenly distributed throughout an agricultural area and a processing plant can be located central to that area. In real cases farms and feedlots will have specific locations, and plus the distribution of population will influence plant siting. The conclusions of this study illustrate the sensitivity of decisions about mode of transport and centralized vs farm or feedlot-based processing to specific factors of cost, yield, size, and distance of transport. Hence, in optimizing transport to centralized AD plants project specific factors will have to be analyzed.

Finally, it should be noted that although this study uses electrical power as the end product of biogas, production of pipeline-grade natural gas is an alternative. Natural gas may have higher value than electrical power, particularly if that power is produced from an internal combustion engine-powered generator with efficiencies less than 43%. Production of pipeline-grade natural gas also produces a byproduct stream rich in CO_2, creating the possibility of carbon sequestration and a double carbon credit if a suitable sink can be found *(9)*.

Conclusions

For Lethbridge County, an area of concentrated beef feedlots, pipeline is the least cost means of moving manure and digestate to a centralized AD plant when digestate is returned to the source CFO for land spreading. This conclusion is dependent on manure quantity because pipeline transport has a significant scale factor whereas the cost of trucking is virtually independent of size. When digestate is processed and hence only manure is transported, truck hauling has a slightly lower cost than pipelining. However, road congestion factors would likely lead to the selection of pipelines for very large AD plants. Centralized processing of manure is favored for AD plants that return digestate to the source CFO compared with processing at farm or feedlot up to a size equivalent to 55,000 head of beef cattle. If digestate is processed, then based on a preliminary estimate of the capital cost of digestate processing, centralized processing of manure is favored up to a size equivalent to 300,000 head of beef cattle. This size is larger than any known feedlot in North America, and hence digestate processing will tip the balance in favor of large centralized AD plants for all CFOs. For Red Deer County, a typical mixed-farming area, truck transport of manure and digestate is the least cost means of moving manure and digestate to a centralized AD plant for either digestate return or processing. Centralized processing of manure is more cost effective than farm-based processing for all manure sources in the county. This study illustrates the cost effectiveness of centralized processing of manure, and the need for a case specific analysis of alternative transportation modes for AD plants.

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