University of Alberta

The Economics of Energy from Animal Manure for Greenhouse Gas Mitigation

by

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Abstract

Anaerobic digestion (AD) has significant economies of scale, i.e. per unit processing costs decrease with increasing size. The economics of AD 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: a mixed farming area, Red Deer County, and an area of concentrated beef cattle feedlots, Lethbridge County.

A centralized plant drawing manure from 61 sources in the mixed farming area could produce power at a cost of \$218 MWh^{-1} (2005 US\$). A centralized plant drawing manure from 560,000 beef cattle in Lethbridge County, can produce power at a cost of \$138 MWh^{-1}. Digestate processing, if commercially available, shifts the balance in favor of centralized processing.

At larger scales, pipelines could be used to deliver manure to a centralized plant and return the processed digestate back to the manure source for spreading. Pipeline transport of beef cattle manure is more economic than truck transport for the manure produced by more than 90,000 animals. Pipeline transport of digestate is more economic when manure from more than 21,000 beef cattle is available and two-way pipelining of manure plus digestate is more economic when manure from more than 29,000 beef cattle is available.

The value of carbon credits necessary to make AD profitable in a mixed farming region is also calculated based on a detailed analysis of manure and digestate transport and processing costs at an AD plant. Carbon emission reductions from power generation are calculated for displacement of power from coal and natural gas. The required

carbon credit to cover the cost of AD processing of manure is greater than $150 per tonne of CO_2. These results show that AD treatment of manure from mixed farming areas is not economic given current values of carbon credits.

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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List of Abbreviations

AAFRD	Alberta Agriculture, Food and Rural Development
AARI	Alberta Agricultural research Institute
AD	Anaerobic Digestion
AERI	Alberta Energy Research institute
AFB-net	European Agriculture and Forestry Biomass network
ASAE	American Society of Agricultural Engineers
atm	atmosphere
C	Celsius
CBC	California Biomass Collaborative
CEAA	Canadian Environmental Assessment Agency
CFO	Confined Feeding operations
CHP	Combined Heat and Power
DFC	Distance Fixed Cost
DVC	Distance Variable Cost
EDC	Energy Demand Consulting
EEA	European Environment Agency
EPA	Environmental Protection Agency
EUBIONET	European Bioenergy Network
g	Gram
GE	General Electric
GHG	Greenhouse Gas
GJ	GigaJoule
ha	Hectare
hr	Hour
IC	Internal Combustion
IEA	International Energy Agency
IMUS	Integrated Manure Utilization System
IPCC	Intergovernmental Panel on Climate Change
ISO	International Standard Organization
J	Joule
K	Kelvin

kg	Kilogram
km	Kilometer
kW	Kilowatt
kWh	Kilowatt Hour
LCA	Life Cycle Assessment
LHV	Low Heating Value
m	Meter
M	Million
min	minute
MJ	Mega Joule
MRC	Marbek Resource Consultants
MW	Megawatt
MWe	Megawatt Electricity
MWh	Megawatt Hour
NRCS	Natural Resources Conservation Service
NREL	National Renewable Energy Laboratory
NSERC	National Sciences and Engineering Research Council of Canada
Pa	Pascal
psi	Pounds per Square Inch
RDC	Red Deer County
s	Second
SEATAC	Society of Environmental Toxicology and Chemistry
TS	Total Solids
VS	Volatile Solids

Chapter 1

Introduction

1.1 Research Motivation

Most of the radiation from the Sun is absorbed by Earth and its atmosphere and the rest is directly reflected back to space. After being redistributed by the atmospheric and oceanic circulations, the absorbed energy will also be radiated back to space at longer (infrared) wavelengths. In the long run, and as shown in Figure 1-1, the incoming radiation energy is approximately balanced by the outgoing terrestrial radiation. Climate change is believed to be a result of the disturbance of the balance between receiving and outgoing radiation, or alteration of the redistribution of energy within the atmosphere and between the atmosphere, land, and ocean (IPCC, 2001).

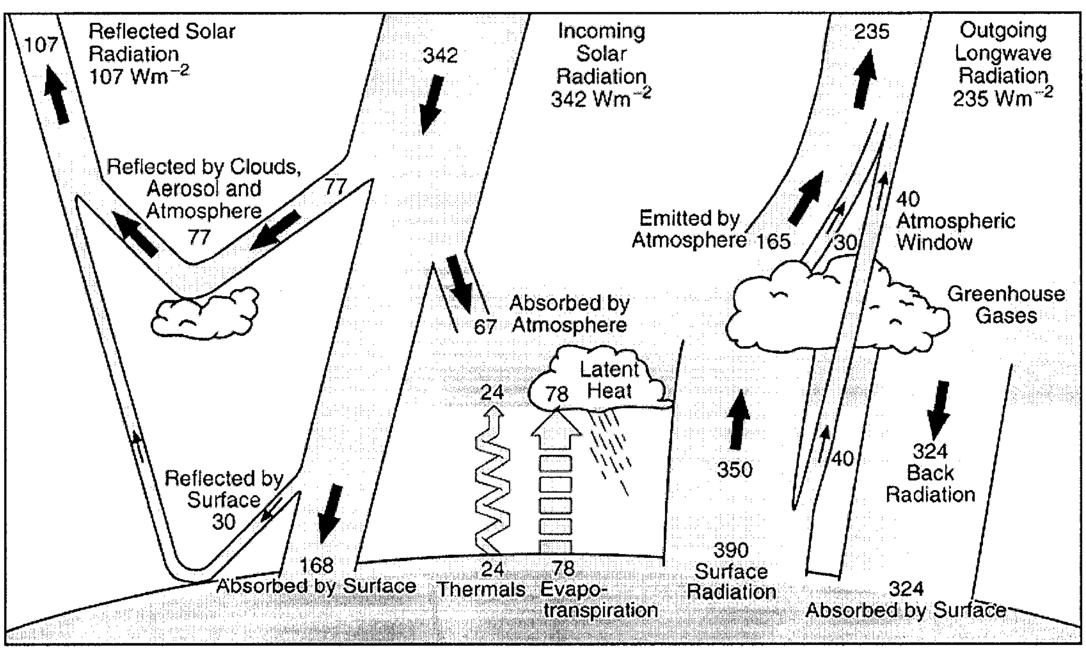

Figure 1-1. Details of Earth's energy balance (source: Kiehl and Trenberth, 1997, reprinted with permission)

Over the past decades a consensus has emerged that the excessive buildup of greenhouse gases (GHGs: carbon dioxide, methane, nitrous oxide, ozone, and water vapor) have the potential to disturb the incoming-outgoing radiation balance, causing a negative impact on the earth's climate (Weart, 2003). Most of the net increase in the GHG emissions over the past decades is attributed to human activities like burning of fossil fuels for industrial use, transportation and electricity generation, and land clearing (CEAA, 2004). While our understanding of climate change and its implications are still developing, concerns about climate change has led to a search for means of mitigating the impact of GHGs by a combination of conservation, sequestration (carbon capture and storage), and substitution of carbon neutral fuels for fossil fuels, including those based on biomass.

Non-fossil organic materials that have intrinsic chemical energy content are called biomass. Examples include purpose grown crops, residues from crop or forest processing, manure, and some components of municipal and industrial solid wastes. Although decomposition of organic matter and plant respiration accounts for release of more CO_2 than that released by human activities, these emissions are in balance with the CO_2 absorbed by terrestrial vegetation and the oceans. Therefore, there is no net emission of GHGs due to organic matter (biomass) decomposition and plant respiration other than from one time clearing such as deforestation. As a result, any substitution of biomass-based energy for fossil fuels energy is ideal because it produces no incremental CO_2 compared to natural decomposition and it avoids the emission of GHGs produced by fossil fuel combustion.

One should note that the use of biomass fuels is not associated with net zero emissions; it results in some excess discharge of GHGs. The amount of emissions in planting, harvesting, processing and transport operations impacts the displacement of net emissions of GHGs. Hence, the potential to displace GHG emissions can be different among biomass based technologies (Adler et al., 2005). Energy yield, capital and operating costs, net GHG emission per unit of output, and socio-economic factors are among the various criteria used to prefer one technology over others.

Historically, the basic use of biomass was producing heat through direct combustion. As energy technologies have advanced far beyond direct combustion, and also due to the flexibility of biomass treatment for different processes, a wide range of products are being developed through various technologies: e.g., ethanol, steam, bio-diesel, electricity, liquid/solid/gaseous fuels, and fertilizers are some products of gasification, pyrolysis, fermentation, hydrolysis, and anaerobic digestion.

Among all technologies to process biomass, anaerobic digestion (AD) of animal manure with subsequent biogas utilization for power generation is the subject of this thesis. While the number of AD plants with subsequent power production is increasing at a high rate, almost all of them are large consumers of public money in the form of grants, subsidies, and low rate loans (H-Gregesersen, 1999; Walla and Schneeberger; 2005). This arises because the cost of power in these small scale units is very high compared to very large fossil fuel based power plants that benefit from economy of scale. As with fossil fuel projects, biomass energy economics are also strongly influenced by scale. In these projects two cost factors compete against each other: as biomass processing plants get larger, the capital cost per unit of output decreases (the economy of scale), but the cost of transporting fuel to the plant increases because of increasing distance traveled. The tradeoff between these two factors means biomass projects theoretically have an optimum size at which costs are lowest. This study is aimed at exploring this effect in depth.

1.2 Research Methodology

The focus of this study is to develop a detailed cost analysis of alternate transportation methods to deliver manure to anaerobic digestion plants at full commercial scale in the Province of Alberta and to assess the life cycle environmental impacts of this process. This study was conducted pursuing the following methodology:

- Finding location and quantity of livestock manure in Alberta.
  Knowledge of the location and quantity of manure is critical in determining the cost of manure transportation for cases that process wastes from multiple sources in a single facility. Two specific cases were analyzed in detail: a) Red Deer Country is

likely typical of many fixed farming areas in Canada, with manure sources from dairies, cow/calf operations, beef cattle feedlots, hog and poultry operations. The feedstock supply for Red Deer County is based on a survey of the different sources of manure by size, type and location within the county, and b) Lethbridge-Calgary feedlot corridor where over one million beef cattle are raised in feedlots. Precise feedlot locations are not known for this region, but cattle numbers are so high in some counties that reasonable transportation numbers can be approximated by using the center of the county as the average transportation distance for shipment outside the county, and assuming the feedlots are dispersed evenly across the county for single county processing. Transportation costs are hence less precise than for Red Deer County but within the accuracy of the overall study.

- Collecting cost information on livestock manure transportation and processing.

  Trucking is the major means of transporting biomass as well as manure, but this work was also extended to consider pipelining of livestock manure, since manure transport via pipelines to centralized facilities has the potential to lower both cost and community impact relative to trucking. Cost estimates were primarily based on literature data, but supported by data collected from the estimating group of an engineering consulting company and an equipment supplier. An economic model was developed to evaluate the cost of pipelining and trucking of manure and identify the minimum capacity at which it is economic to switch from one mode of transport to another. AD plant capital and operating cost data were assembled into an economic model of power production from manure in the two regions noted above. The model is based on a full life cycle analysis over a 30 year project life, and incorporates a discounted cash flow analysis. The model was used to determine the cut off size at which farm or feedlot based processing is more economic than centralized digesters.

- Analyzing life cycle environmental impacts of AD.

  One means of bringing all alternatives to a common measure is to determine the carbon credits that would be required to make the project economic. One benefit of this approach is that it will allow projects that generate power from livestock manure to be compared to projects that produce the same amount of power from other resources. Carbon credits are in essence a form of purchasing carbon that would otherwise end up in the atmosphere and under a market system of trading carbon credits, the lowest cost forms of carbon abatement will emerge. A thorough life cycle assessment (LCA) study was conducted to estimate the net emission savings per unit of generated power in biogas plants. This data then was combined with the results of the above mentioned models to determine the minimum carbon credit values required to make the AD plant economic.

Note that all cost figures in this thesis are reported in 2005 US dollars. Where required, a conversion rate of 1.2 CAD = 1 USD is used.

1.3 Thesis Organization

This thesis follows the paper-based standard of the University of Alberta. Chapters 2 through 7 are each drawn from papers that have been prepared for publication in academic journals. Chapters 2, 3, 6 and 7 have been accepted for publication and are in press; Chapters 4 and 5 are in review. Each paper was also presented at a conference. Each co-author has granted permission for the paper to be included in this thesis, and for each paper that is submitted for publication the assignment of copyright specifically provides for inclusion of the work in a thesis.

In Chapter 2 a detailed model is developed to predict the design requirements of manure pipelines, including the critical cost parameters of pipe diameter and the distance between pumping stations. The model then generates capital and operating cost data for manure and digestate pipelines, and combines these to an overall transportation cost by combining operating costs and a capital recovery factor.

Chapter 3 compares the economics of manure and digestate transport in pipelines vs. trucking. Using the results from Chapter 2 and combining it with various data collected for the cost of moving manure in North America, the minimum capacity at which one or two way pipelines become more economic compared to trucking is determined.

In Chapter 4 an economic model is introduced to help identify whether multiple distributed digesters or fewer centralized digesters are more economic, i.e. to identify whether it is more economic to transport manure to a large capital efficient unit or reduce transportation costs by shipping to smaller units or by processing on farm. The impact of manure gross density (manure production per gross hectare) and digestate processing on the optimum size of the biogas plants is also discussed.

Findings from Chapters 2, 3 and 4 are combined in Chapter 5 to study the logistical implications of optimizing anaerobic digestion of manure.

Chapters 6 and 7 look into the global warming impact of electricity generation from animal manure. Chapter 6 contains life cycle assessment study of the greenhouse gases emitted by a feedlot operation which includes biogas production by anaerobic digestion and subsequent electricity generation. In Chapter 7, these results are combined with the findings in Chapter 4 to determine the minimum carbon credit values required to make biogas plants economic.

A summary of the conclusions of this research is included in Chapter 8 as well as recommendations for possible future research.

There are also 2 appendices to this thesis. Appendix I contains the user's manual and the scope of the economic models developed to conduct this research and Appendix II focuses on the sensitivity of the model results to changes in major parameters used throughout the model.

1.4 Note on Cost Estimate Accuracy

There is an inherent uncertainty about the accuracy of all cost estimates. Numerous factors such as degree of project definition, estimating methodology and the effort and time taken to prepare the estimate impact the accuracy of data (AACE International, 1997). As noted above, the cost data used in this thesis are from various sources; actual capital and operating costs reported by plant or project owners, cost estimates from engineering consultants, estimates in published report, and estimates developed as part of this research.

To put this in perspective, the Association for the Advancement of Cost Engineering (AACE International) suggests a cost estimate classification system that maps the phases and stages of project cost estimating together with a generic maturity and quality matrix (AACE International, 1997). This system helps to avoid misinterpretation of the quality and value of information available to prepare cost estimates. Data used in this thesis fall into the Class 4 of the AACE's estimation matrix with an expected accuracy range of Low: -15% to -30% and High: +20% to +50%.

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Chapter 2*

An Economic Analysis of Pipelining Beef Cattle Manure

2.1 Overview

Anaerobic digestion (AD) of animal manure is a technology to produce a medium heating content gas, consisting primarily of methane, carbon dioxide, and other components such as hydrogen sulfide (Mathony et al., 1999). It has been applied in increasing sophistication, from small scale farm-based plants up to centralized digesters processing manure from multiple farms and other organic and industrial wastes (H-Gregersen, 1999; Kraemer, 2004). Centralized anaerobic digesters are developed to take advantage of the economies of scale as the size of the digester increases (Tafdrup, 1994; H-Gregersen, 1999; Al Seadi, 2000; Nielsen et al., 2002; Raven and H-Gregersen, 2007).

All plants processing biomass from non-internal sources have a theoretical optimum size of operation that arises from a tradeoff between two competing cost factors. As plant size increases biomass is drawn from a larger area, and thus the average transportation cost increases. At the same time, economies of scale in capital equipment and construction and operating cost mean that the unit cost of processing biomass decreases with increasing size. Typically there is an optimum size at which overall processing cost is minimized (Overend, 1982; Nguyen and Prince, 1996; Jenkins, 1997; Larson and Marrison, 1997; Dornburg and Faaij, 2001; Kumar et al., 2003).

In some parts of the world beef cattle CFO's are highly concentrated in the region near beef processing plants. For example, "Feedlot Alley", the area around Lethbridge, AB, Canada contains more than a million head of beef cattle at any point of time (CANFAX, 2006). In the United States, the area around Dodge City, KS has more than 2 million

* A version of this chapter has been accepted for publication. Ghafoori and Flynn. *Transactions of the ASABE*. In press.

head (Dhuyvetter et al., 1998; Ward and Schroeder, 2004; Cattle-Fax, 2006). A result of this high concentration is the production of large quantities of manure. Our research is exploring the optimum processing size of anaerobic digestion of beef cattle manure from CFOs. In this particular study we evaluate the possibility of transporting manure to and returning digestate (the liquid or slurry effluent) from such AD plants via pipelines.

Today the most common transport mode for manure or digestate is by truck. Two goals drive an exploration of alternative modes of transportation than trucking: lower cost of transport and elimination of potential truck congestion at large plant sizes. H-Gregersen (1999) reports that transportation accounts for almost 30% of the overall cost of biogas production in Danish centralized plants. To illustrate congestion, a centralized biogas plant receiving manure 12 hours per day from 100,000 beef cattle would require a 20-tonne truck delivery of solid manure every 11 minutes and a 30-tonne liquid tanker arrival of every 7 minutes to return the digestate. This traffic density may exceed community tolerance. The specific objective of this study is to develop an economic model for manure and digestate pipeline systems. This model then is used to find the optimum slurry concentration at which pipelining costs are minimized, the impact of scale on the overall cost of pipelining, and the economics of two-way pipelines carrying both manure and digestate. The analysis in this paper is for a single manure pipeline or one pair of manure and digestate pipelines. A centralized digester could be served by multiple pipelines delivering manure and carrying away digestate.

All costs in this study are expressed in 2005 USD; where necessary Canadian currency is converted to US at the rate of 1.2 CAD = 1 USD.

2.2 Materials and Methods

2.2.1 Manure Production

Our model incorporates the ASAE Standards D384.1 (2003) for beef cattle manure production. To relate this to the number of animals in a feedlot, we use an average weight of 450 kg per animal. Since feedlot pens are cleaned only a few times a year, we assume that manure dries to 30% solids before being collected for transportation (Li, 2006).

Table 2-1. *Manure production rates and characteristics as excreted*

	per 1000 kg Live Weight [a]	per Animal [b]	Unit
Total Manure	58	26.1	kg day^{-1}
Density	1000	1000	kg m^{-3}
Total Solids	8.5	3.8	kg day^{-1}
	14.7%	14.7%	of total manure
Volatile Solids [c]	7.2	3.2	kg day^{-1}
	84.7%	84.7%	of total solids

[a] ASAE Standards D384.1 February 2003

[b] per average weight of 450 kg

[c] The quantity of solids in a sample which is lost by ignition of the dry solids at 600°C

2.2.2 The Rheology of Manure Slurries

Early experimental work in the pumping of manure slurries focused on feasibility and a gross measurement of pressure drop, without developing a detailed analysis of the rheological properties of the manure slurry. Rolfes et al. (1977) assessed the friction head loss in beef manure PVC pipelines as a function of flow velocity, total solids (TS) concentration, and pipe size and found that head loss increases with increasing TS. They concluded that water head loss criteria were definitely inadequate for use in designing manure pumping systems. Howard (1979) studied pumping dairy and pig manure in steel and PVC plastic pipes at various TS concentrations. He found that at certain concentrations a minimum pressure drop is observed irrespective of flow rate, but also concluded that pressure drops were low enough to be encouraging for the prospect of pipelining manure. Patni (1980) pipelined dairy manure with TS of 8% through a buried 900 m PVC pipe. One focus of the work was equipment design for reliability, e.g. chopper attachments on pumps and easy serviceability coupled with a backup flushing system for the entire pipeline. A second focus was an initial cost comparison to trucking. Patni concluded that for long-term manure transport, factors such as fuel and equipment requirements and enabling continuous transportation of manure makes pipelining competitive with trucking, especially when dealing with large volumes of manure.

Many researchers have tried to do a rigorous rheological analysis of manure slurries, often with a focus on equipment design. Schneider (1958) noted the non-Newtonian behavior of manure slurries. Kumar et al. (1972) found non-Newtonian behavior at TS concentrations above 5%, and used a psuedoplastic model. Psuedoplastic models, used for shear-thinning fluids with lower apparent viscosity at higher shear rates, have also been applied by Achkari-Begdouri and Goodrich (1992), Landry et al. (2003) and El-Mashad et al. (2005) to dairy cattle manure. Chen (1982, 1986a and 1986b) and Chen and Hashimoto (1976a and 1976b) studied beef cattle manure slurries in detail; we incorporate their rheological model into our model of manure and digestate pipelining. Chen (1986a) observed that even a psuedoplastic model of slurry rheology was inaccurate for beef cattle manure at TS concentrations above 4.5%. For these concentrations he proposed the rheological model, $\tau = \eta_o \gamma + K'' \gamma^{n''}$ where τ is the shear stress, γ is the shear rate, η_o is the limiting viscosity, K'' is the rheological consistency index and n'' is the flow behavior index. He also defined the following formulas to calculate the value of η_o, K'', and n'' as a function of temperature and solids concentration:

$$\eta_o = 5.24 \times 10^{-6} e^{(0.0868\,TS + \frac{18100}{RT})} \quad (2\text{-}1)$$

$$K'' = 2.428 \times 10^{-3} e^{(0.2499\,TS + \frac{7390}{RT})} \quad (2\text{-}2)$$

$$n'' = 0.307 \pm 0.054 \quad (2\text{-}3)$$

where T is absolute temperature (K), R is the universal gas constant (J mol^{-1} K^{-1}), and TS is the total solids concentration (%). The default temperature used in the model is 0° C, reflecting a winter design scenario for a northern climate.

Chen (1986b) correlates the friction factor in pipe transport of manure to a generalized Reynolds number, (N_{Re}), which is the reciprocal sum of the reciprocals of the Reynolds number due to the Newtonian effect (N°_{Re}) and that due to the Power Law effect (N'_{Re}):

$$N_{Re} = \left(\frac{1}{N^{\circ}_{Re}} + \frac{1}{N'_{Re}} \right)^{-1} \tag{2-4}$$

where

$$N^{\circ}_{Re} = \frac{\rho V D}{\eta_o} \tag{2-5}$$

and

$$N'_{Re} = \left(\frac{\rho V D}{K''} \right) \left(\frac{8V}{D} \right)^{1-n''} \left[\frac{4n''}{3n''+1} \right]^{n''} \tag{2-6}$$

where V is the flow speed (m s^{-1}), D is the pipe diameter (m), and ρ is the slurry density (kg m^{-3}). We have used this generalized Reynolds number in our model. For inputs to the Reynolds number we use Chen's values for the viscosity parameters and a minimum velocity of 1.5 m s^{-1} in order to maintain the manure in suspension, consistent with the assumptions of Harner and Murphy (2001), Pfost et al. (2001), and NRCS (2002).

Chen (1983) discusses the change in manure bulk density over a wide range of TS concentration. At concentrations above 50%, manure slurry density drops due to entrained gases; for concentrations up to 50%, he suggests the following correlation:

$$\rho = \rho_w (1 - 0.00345 \ TS)^{-1} \tag{2-7}$$

where ρ is slurry density (kg m^{-3}), ρ_w is the water density (kg m^{-3}) at a given temperature, and TS is the total solids concentration (%). This correlation is used in the model, although in practice, changes in density with concentration have a negligible impact on the calculations.

The friction coefficient, f, for livestock slurries flow in pipelines is reported by Chen and Hashimoto (1976a and 1976b). In the laminar tube flow region which ends at $N'_{Re} \approx 3100$, the friction coefficient is:

$$f = \frac{16}{N'_{Re}} \qquad (2\text{-}8)$$

and for the fully developed turbulent region, at which $4300 < N'_{Re} < 10^5$ the friction coefficient is:

$$f = 0.0306 \left(N'_{Re}\right)^{-0.18} \qquad (2\text{-}9)$$

The region at which $3100 < N'_{Re} < 4300$ is typically an area of unstable flow; in our work we apply equation (2-9), which gives the more conservative, i.e. higher, value for the friction factor.

2.2.3 Pipeline Design Basis

We assume a Schedule 40 jacketed carbon steel pipeline, identical to water pipelines, buried below the frost line (burial depth in Alberta is 2.0 m). The first pump station is located at the pipeline inlet and receives the slurry after initial processing. Pumps are centrifugal and have higher impeller clearance than water pumps to accommodate the suspended solids. Solids shearing or crushing can be designed into pumps, but is likely not required for macerated and sieved manure. Sand slurries of up to 40% solids by volume are routinely transported in pipelines (Sanders, 2005); Brebner (1964) reported a maximum concentration of wood chips transported by water (wet basis) of 46%, and pulp slurries of over 50% (wet basis) can be pumped. As noted above, several researchers have demonstrated pumping of manure over a range of solids concentrations.

The pipeline diameter is set by the need to maintain a minimum velocity of 1.5 m s^{-1} to maintain solids in suspension (Harner and Murphy, 2001; Pfost et al., 2001; NRCS, 2002). Pipe diameters are limited to nominal sizes; in the model pipes of 1.5 to 20 inch nominal diameter can be specified; actual pipe inside diameters are taken from Perry et al. (1997). The spacing between pump stations is set by the pressure drop in the pipeline. The model is based on a pump discharge pressure of 4 MPa (600 psi); the model calculates the distance over which the pressure decays to near zero, at which point another pump station is specified. Pump stations are enclosed in heated insulated buildings and have installed standby pumps. Since most beef cattle feedlots are in areas already serviced by an electricity distribution system, power is assumed to be available within a short distance of the pump station; otherwise, additional investment in transmission and distribution equipment would be required.

2.2.4 Inlet and Outlet Facilities

All feedlot manure is likely to start its journey to an anaerobic digester on a truck. Even if a pipeline inlet were located within a feedlot, transport of manure from the individual pens where it is collected to the pipeline inlet would require a short truck haul. Longer truck hauls would be required if a pipeline inlet was to accept manure from many scattered feedlots. Hence, the design basis of a manure pipeline includes equipment for processing manure delivered by truck.

Pipeline inlet equipment includes a truck receiving yard, weigh station, dump pocket, conveyor belt, heated and insulated water tank, mixing tank, and maceration and sieving unit. The location of the inlet is assumed to be close to an acceptable source of raw water, e.g., a well or river. If the inlet is located remote from a water supply additional investment would be required. Ancillary equipment includes equipment to move any manure dumped away from the dump pocket to the pocket. Note that all of the equipment at the pipeline inlet is identical to what would otherwise be required at an anaerobic digester that received manure by truck (a large AD plant would require multiple truck unloading gates). Thus there is negligible incremental investment associated with pipeline inlet equipment since facilities at the inlet displace the need for the same equipment at the plant. In our model, only incremental costs for pipelining are included in the transportation cost.

Digestate return via truck requires one or more storage tanks at the plant to collect and store the discharge from digesters. In case of digestate pipelining, the primary storage of digestate would be shifted to the pipeline outlet, leaving only a minor tank at the site of the AD plant, hence no significant incremental investments is incurred.

Pipeline outlet equipment is negligible if the pipeline slurry concentration is compatible with digestion. As shown below, optimum pipeline slurry concentrations are in the same range at which beef cattle manure anaerobic digesters operate. Hence, the entire slurry stream could pass through feed effluent heat exchangers in the digester plant and then be directly admitted into a digester tank. Bacterial action would occur in the pipeline, releasing gas; however, the amount would be very low because of short residence time (e.g. 18 hours or less for a 100 km pipeline) and low temperature.

A pipeline control room is assumed to be located at the inlet to the pipeline so that the pipeline operator can provide assistance to the person receiving manure, and assist in the weighing of manure trucks. This location ensures two person coverage of the pipeline inlet, which is increasingly a requirement for reasons of safety. However, only the pipeline operator position is treated as an incremental cost to the alternative of an AD plant receiving delivery of manure by truck, since the person assisting in truck unloading would be required in either case. Therefore, the only incremental cost of pipelining is the cost of labor located at the inlet to operate and monitor the pipeline, i.e. one operator position estimated at $50 per hour for a 24×7 operation to cover salary plus benefits.

2.2.5 Pipeline Capital and Operating Costs

Pipeline and pump station capital costs are drawn from estimates for buried water pipelines in the size range of 4 to 16 inch nominal pipe size provided by a major engineering and construction firm (Williams, 2004). From the data provided, we developed a best fit for scale factor; results are shown in Figures 2-1 and 2-2. Both pipeline and pump unit capital costs are highly scale dependent and decrease with increasing capacity. The scale factor for pipeline capital costs is 0.45 against pipeline capacity (0.90 against diameter) and 0.53 for pump and pump station costs against pump power, where scale factor is defined by the relationship:

$$\text{Cost}_{\text{size}_2} = \text{Cost}_{\text{size}_1} \times \left(\frac{\text{Size}_2}{\text{Size}_1}\right)^{\text{scale factor}} \tag{2-10}$$

Other financial and operational parameters used in this study for the pipelining scenario are included in Table 2-2.

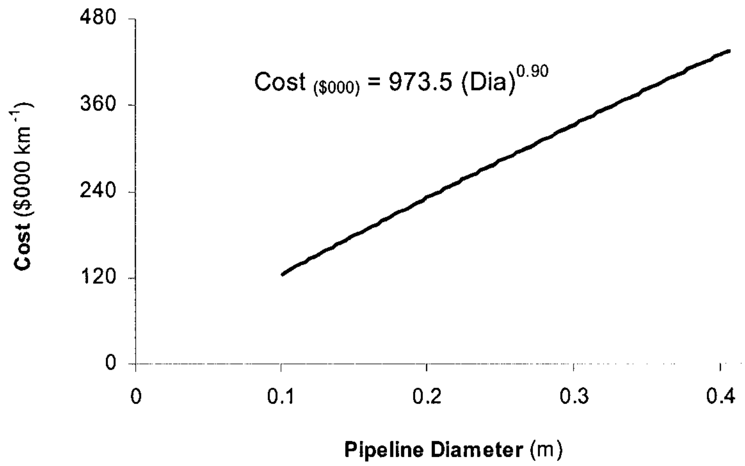

Figure 2-1. Pipeline supply, excavation, and installation costs

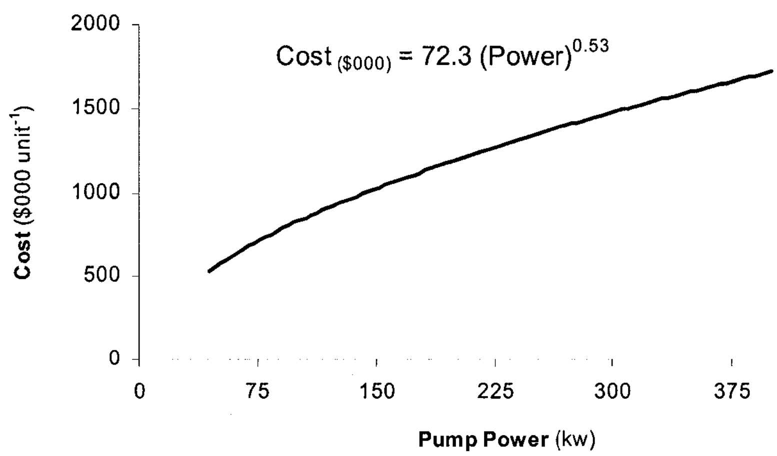

Figure 2-2. Pump supply and pump booster station construction costs

Table 2-2. Financial and operational parameters used in the model

Pipeline Operating Days	360	day
Slurry Design Velocity	1.5	m s^{-1}
Pump Efficiency (Motor & Pump)	80%	
Incremental Labor Requirement	8,640	hr $year^{-1}$
Labor Cost	50	\$ hr^{-1}
Power Cost	56	\$ MWh^{-1}
Pipeline Maintenance Cost	0.5%	of its capital cost
Pump Station Maintenance Cost	3.0%	of its capital cost
Pipeline Operating Life	30	year
Financial Discount Rate	12%	pre-tax return on capital
TS Concentration in Digester	12%	
VS/TS of Feedlot Manure	85%	
Biodegradability	45%	VS destroyed / VS added
Digestate TS Concentration	8%	

2.3 Model Results

2.3.1 Impact of Solids Concentration on Cost of Manure Pipelining

Manure can be pumped over a range of total solids concentrations. At low solids concentrations, the slurry viscosity is low which results in reducing the pumping cost per unit of slurry volume and increasing the slurry volume, hence requiring a larger diameter pipeline. At high solids concentration, total volume is low but pumping costs increase due to higher slurry viscosity, requiring higher pumping energy and more pump stations. The trade-off between capital investment and operating costs in pipeline and the pump stations determines the optimum slurry concentration at which the cost of pipelining manure is minimized.

In Figure 2-3 manure transport cost at various slurry concentrations in a 90 km pipeline is plotted for three different flow rates corresponding to about one hundred, one hundred and fifty, and two hundred thousand head of beef cattle. Pipelining manure at other capacities and distances also show the same pattern as in Figure 2-3.

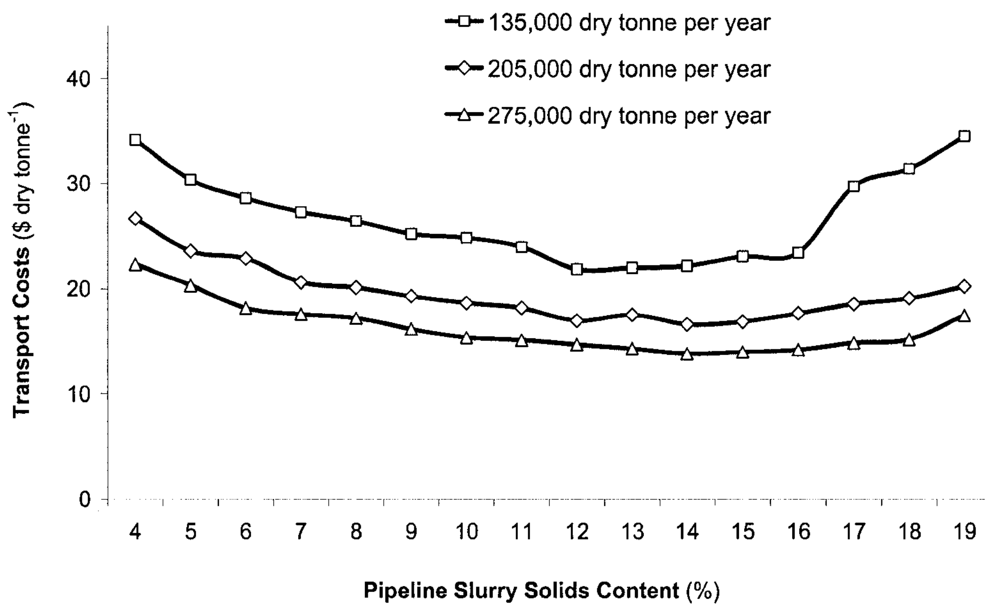

Figure 2-3. Cost of manure transport in a 90 km pipeline at different flow rates

Pipeline costs are not a smooth curve because of the requirement to have pipeline diameters in nominal standard pipe sizes. However, it is evident that overall pipeline transport cost is minimized in the range of 12 to 14% solids concentration. Since complete mix anaerobic digesters for beef cattle manure operate in the range of 12% solids concentration (Li, 2006), we use this concentration for all subsequent calculations illustrated in this paper. For 12% input TS into a digester, digestate slurry concentration is about 8%. In this paper we assume that the digestate will be pumped at the same solids concentration as it is being discharged without further treatment.

2.3.2 Pipeline Transport Cost as a Function of Scale

Virtually all forms of bulk transportation have two components of cost, those that are independent of distance traveled and those that are proportional to distance traveled (Mahmudi and Flynn, 2006). The distance fixed cost (DFC) for trucking, for example, is the cost of loading and unloading the truck, while the distance variable cost (DVC) of trucking is the per km or per hour charge for travel.

For pipelining manure to an anaerobic digestion plant, DFC is very low because, as noted above, there is negligible capital cost for equipment at the inlet and outlet of the pipeline that is incremental to what would otherwise be incurred if manure were delivered to an AD plant by truck. The only component of incremental fixed cost is the labor to operate the pipeline ($432,000 per year).

At 40,000 dry tonne year^{-1}, equivalent to 30,000 head of beef cattle, the DFC per dry tonne is $10.8, while at 100,000 dry tonne year^{-1} it drops to $4.3 dry tonne^{-1}. From an analysis of data reported by numerous operators in Alberta, Canada (AAFRD, 2004; Taylor, 2005) and from studies in the United States (Araji and Stodick, 1990; Brenneman, 1995; Ribaudo et al., 2003; Aillery et al., 2005), a typical value for the DFC for trucking manure is $5.0 tonne^{-1}, comparable to values previously reported for straw and woodchips (Kumar et al., 2004). Assuming 70% moisture level in manure as collected from the feedlot, this is equivalent to $16.6 dry tonne^{-1}. Note, however, that manure is trucked to the pipeline inlet, so that in the case of pipelining both the truck and pipeline DFC are incurred.

The DFC for digestate pipelines is zero because there is no significant incremental investment required at the inlet or outlet and the AD plant operators could operate the pipeline at no incremental operating cost.

Distance variable cost of pipelining includes the cost of capital recovery and maintenance of the pipeline and pumping stations and the cost of power; all of these factors are directly proportional to the pipeline distance. However, pipeline cost is not directly proportional to capacity; as noted above, there is a low scale factor for pipelining.

Figure 2-4 shows the pipeline cost at three scales as a function of distance; DFC is the intercept at zero distance, and DVC is the slope of the curves.

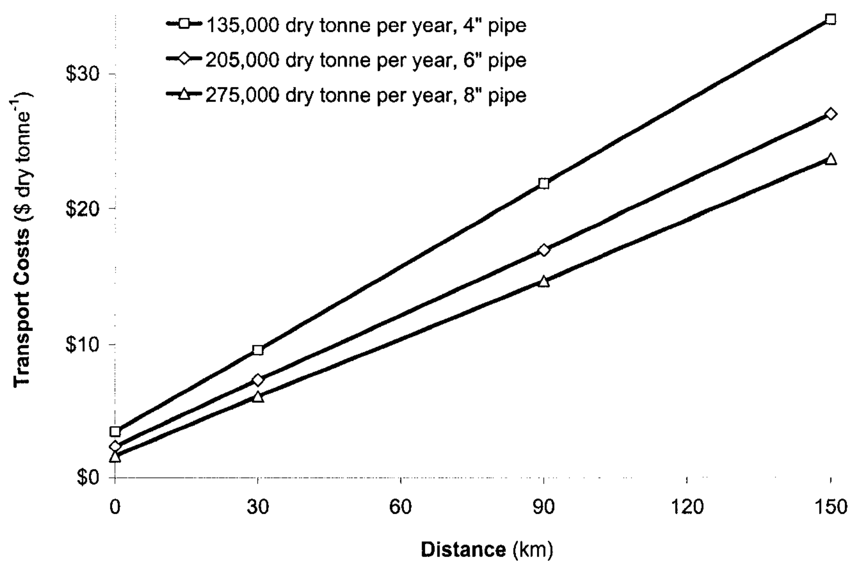

Figure 2-4. Cost of pipelining manure as a function of distance

The impact of scale on the cost of pipelining of manure is illustrated in Figure 2-5, which plots the DVC of pipelining manure per km as a function of the capacity of the pipeline. The average reported value for DVC for trucking manure is \$0.075 $tonne^{-1}$ km^{-1} (Araji and Stodick, 1990; Brenneman, 1995; Ribaudo et al., 2003; AAFRD, 2004; Taylor, 2005; Aillery et al., 2005), which is equivalent to \$0.25 dry $tonne^{-1}$ km^{-1} for feedlot manure. This suggests that pipelining of manure is more economic than trucking at capacities above 125,000 dry tonnes $year^{-1}$, equivalent to 90,000 head of beef cattle. For a fuller analysis of truck vs. pipeline transport of manure, see Ghafoori et al. (2006).

2.3.3 Pipelines Carrying Digestate or Manure and Digestate

Pipelining digestate requires the same amount of capital investment as for pipelining manure except for the lower viscosity of the digestate slurry which results in some savings in pumping costs. Hence, the DVC of pipelining digestate is slightly lower than manure, and as noted above, the DFC of pipelining digestate is zero. Because the volume of digestate trucked away from an AD plant 2.4 times larger than the volume of manure at 30% TS being trucked into the plant, pipelining of digestate is more economic than trucking for the digestate at capacities of 30,000 dry tonne year^{-1} of incoming manure, equivalent to 21,000 head of beef cattle.

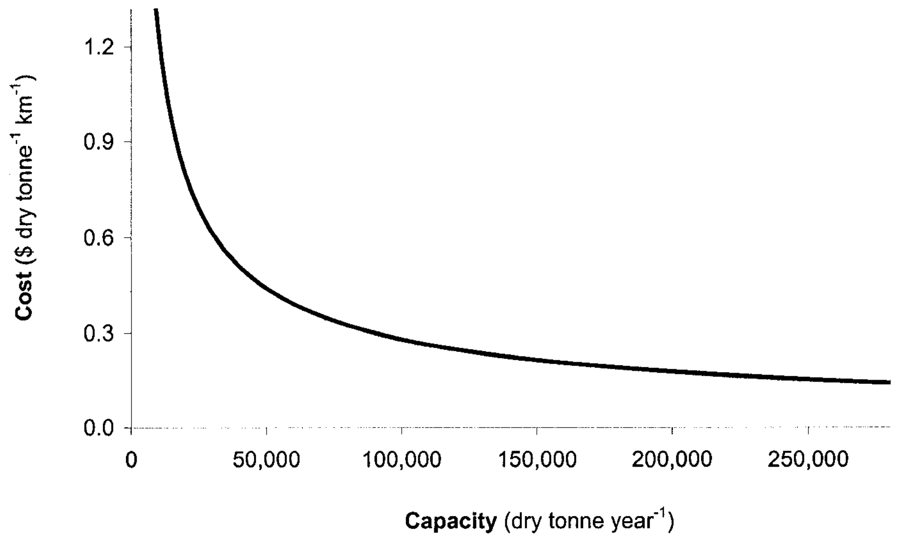

Figure 2-5 Impact of scale on the DVC of pipelining manure at 12% TS

One observation is that in case of a one-way pipeline (either manure or digestate), simultaneously building two pipelines to carry manure and digestate, i.e. a two-way pipeline, would require less incremental investment than two separate pipelines. Much of the savings would be in the cost of surveying, obtaining permits, land acquisition, trenching, and backfilling. Table 2-3 contains a detailed cost analysis of a 90 km pipeline feeding an AD plant processing manure from 60,000 head of beef cattle (82,500 dry tonne year^{-1}) for a one-way manure pipeline, a one-way digestate pipeline and the incremental cost of a digestate pipeline if built with a manure pipeline.

Table 2-3. Cost analysis of pipelining manure only, digestate only, and manure plus digestate for 90 km (to and from an AD plant processing manure from 60,000 head of beef cattle)

Item	One-way Manure Pipeline	One-way Digestate Pipeline	Added Digestate Pipeline	Unit
Slurry TS Concentration	12%	8%	8%	
Pipeline Nominal Diameter	0.102	0.102	0.102	m
Slurry Flow Rate	79.7	76.0	76.0	m^3 hr^{-1}
Actual Slurry Velocity	2.7	2.6	2.6	m s^{-1}
Slurry Apparent Viscosity	4.32×10^{-2}	2.99×10^{-2}	2.99×10^{-2}	Pa s
Pressure Drop in Pipes	2,295	1,889	1,889	m
Pump Power	6.9	5.4	5.4	kW km^{-1}
Pipeline Capital Cost	$125,000	$125,000	$75,000	$ km^{-1}
Pump Station Capital Cost	$933,000	$830,000	$795,000	per station
Distance Between Pump Stations	20	20	20	km
Annual Labor Cost	$432,000	-	-	$ $year^{-1}$
Annual Power Cost	$300,000	$235,000	$235,000	$ $year^{-1}$
Annual Maintenance Cost	$225,000	$195,000	$165,000	$ $year^{-1}$
Annual Cost Incl. Capital Recovery	$3,000,000	$2,400,000	$1,800,000	$ $year^{-1}$

2.4 Discussion

Danish experience with anaerobic digestion indicates that centralized digesters have a significant cost advantage over farm based digesters (Tafdrup, 1994 and 1995; Raven and H-Gregersen, 2007; Maeng et al., 1999). The drive to large scale will increase if digestate is processed to recover nutrients or gas is processed to remove H_2S and CO_2 and produce pipeline quality gas instead of electrical power, because in each case capital intensity (investment per head of beef cattle) increases. Note, however, that no commercial process is available today to process digestate into concentrated nutrient streams and water that can be discharged to a watercourse.

As noted above, selected areas are intensive centers of CFO to support a large beef cattle industry, and in these areas in particular one can imagine anaerobic digestion complexes that in theory could be larger in capacity than the road system will permit for truck delivery. In such cases, multiple manure pipelines could be used to deliver manure to a very large cost efficient centralized plant that produces either pipeline quality gas or power from an efficient combined cycle generator and returns the processed digestate back to the source CFO for spreading.

The model developed in this study can be used to predict the design requirements of manure and digestate pipelines, including the critical cost parameters of pipe diameter and the distance between pumping stations. In doing so it incorporates previous research into the rheological properties of manure slurries. The model then generates capital and operating cost information for a pipeline, and combines these to an overall transportation cost by combining operating costs and a capital recovery factor.

One outcome of this study is that the optimum slurry concentration that minimizes cost trade-offs between large pipelines carrying large volumes of thin slurry and small pipelines carrying small volumes of viscous slurry, is about 12%, a value that is consistent with the concentration required in a well mixed anaerobic digester. Hence, feed preparation steps that would otherwise be done in the plant can be shifted to the pipeline inlet, and slurry delivered by pipeline can be used at the plant without further treatment.

2.5 Conclusions

An economic model is developed to assess the cost of pipelining feedlot beef manure slurries. Pipeline transport of manure is highly scale dependent; the capital cost scale factor for small scale manure slurry pipelines is found to be 0.45 against capacity. The optimum slurry concentration at which the transportation cost is minimized is in the range of 12-14%. Low concentration slurries have a lower viscosity but higher flow rates, while high concentration ones have a higher viscosity and lower flow rates. The only net incremental fixed cost for manure slurry pipelines is the labor cost, as the inlet facilities would otherwise be required at the fermentation plant. There is no significant incremental investment required for digestate pipelines. Two-way pipelining manure and digestate in a single trench can be achieved at lower capital and operating costs compared to two separate manure and digestate pipelines.

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Chapter 3[†]

Pipeline vs. Truck Transport of Beef Cattle Manure

3.1 Overview

Rising energy prices and a desire to reduce greenhouse gas emissions from fossil fuels have continued to spark interest in the production of a medium heating value gas from the anaerobic digestion of manure. While manure to gas projects are often evaluated on an individual farm or feedlot basis, experience, especially in Denmark (Tafdrup, 1995; Gregersen, 1999; Alseadi, 2000; Raven and Gregersen, 2007), has demonstrated that economies of scale can be realized in centralized plants with larger capacities.

All biomass based projects drawing on broad sources of biomass have a theoretical optimum size, because two cost factors compete. As plant size increases, the savings from economy of scale of investment in processing equipment increase, and so do transportation costs, as biomass to feed the larger plant must be drawn from an increased area. Provided there is no constraint on the uptake of the products (e.g. power, pipeline grade natural gas, or heat), the tradeoff between these two factors determines the optimum size (Overend, 1982; Nguyen and Prince, 1996; Jenkins, 1997; Larson and Marrison, 1997; Dornburg and Faaij, 2001; Kumar et al., 2003). The net cost of transportation is thus a critical factor that must be assessed when evaluating appropriate scale for anaerobic digestion of manure; changes in transportation cost will impact optimum size.

The most common form of manure or digestate transportation today is by truck. However, pipelining manure slurry is an alternative form of transportation. Much of the preparation of solid manure for pipelining, such as maceration, dilution with water and

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[†] A version of this chapter has been accepted for publication. Ghafoori, Flynn, and Feddes. *Biomass and Bioenergy Journal*. In press.

mixing is identical to the steps required in an anaerobic digestion plant. Hence, much of the capital investment at a pipeline inlet would eliminate the need for identical equipment at the plant, and therefore is not a net increase. Pipelining of manure requires an evaluation of two competing cost factors related to the extent of dilution. As dilution increases and solids concentration drops, the viscosity of the slurry is reduced, giving lower pumping costs. More dilute slurries require a larger diameter pipeline, requiring additional capital investment. In this chapter we develop the cost of pipelining and trucking of manure and digestate and assess the impact of extent of dilution of manure on the cost of pipelining. Truck costs are based on a standard 30 tonne triaxle truck for solid manure, and a standard 40 tonne "B train" tandem trailer for liquid digestate. For a given truck size, trucking costs have a negligible scale factor: hauling twice the amount of manure by truck typically costs twice as much, for example. Pipelining costs are highly scale dependent (Wasp et al., 1967; Liu et al., 1994; Kumar et al., 2004; Williams, 2004), and hence we determine the manure and digestate rates at which pipelining becomes more economic than truck transport. Since the focus of our ultimate work is an evaluation of large scale anaerobic digesters, we focus on beef cattle in confined feeding operations, i.e. feedlots. Areas in the US and Canada have a high concentration of feedlots, for example the areas around Dodge City, Kansas and Lethbridge, Alberta, and in such cases large digesters could be built as an alternative to one digester per feedlot.

In this chapter, the economics of manure and digestate transport with a single pipeline manure inlet location is considered; results will enable a future evaluation of supply of a single centralized digester by multiple pipelines. Key manure assumptions per 1000 kg of live animal weight are shown in Table 3-1 (ASAE, 2003); for purposes of converting between manure amounts and numbers of animals, an average animal weight in the feedlot of 450 kg is used. Table 3-1 values for manure are "as excreted" from the animal. In beef cattle feedlots manure accumulates in piles and is recovered periodically. We assume a total solids (TS) content of 30% in aged manure recovered from feedlots (Li, 2006). Note, however, that actual moisture content of aged feedlot manure is highly variable and depends on weather.

All values in this chapter are reported in 2005 US dollars and, wherever required, a conversion factor of 1 USD = 1.2 CAD is used.

Table 3-1 Key manure parameters per 1000 kg live animal mass per day (ASAE, 2003)

Parameter	Value	Unit
Total Manure	58	kg
Density	1000	kg m^{-3}
Total Solids	8.5	kg
	14.7%	of total manure
Volatile Solids	7.2	kg
	84.7%	of total solids

3.2 Truck Transport Costs

The point at which pipelining of manure or digestate is more economic than trucking depends on the relative costs of each form of transportation. The literature shows a wide range of values for the cost of truck transport, especially for liquid manure. We have analyzed transport cost data for liquid and solids in Alberta, Canada, and we compare these to previously reported values.

Data from numerous operators hauling solid agricultural products in Alberta, Canada were analyzed to estimate the cost of transporting manure by truck; the results are shown in Figure 3-1 (AAFRD, 2004). (All costs per km in this chapter are per hauling distance, not total travel distance, i.e. the distance is the one way haul distance and the calculated cost covers the charge for both the haul and the truck's return trip.) Figure 3-1 has a profile typical of transportation costs: a cost component for loading and unloading the truck that is independent of distance traveled, labeled "a" in Figure 3-1, and a component that is directly proportional to distance traveled, the slope "b" in Figure 3-1. (Since average travel speed tends to be constant, the slope "b" can be expressed as dollars per tonne km or dollars per tonne per running hour.) We call "a" the distance fixed cost (DFC) and "b" the distance variable cost (DVC). As noted above, DFC and DVC for trucking are independent of scale for a given truck size.

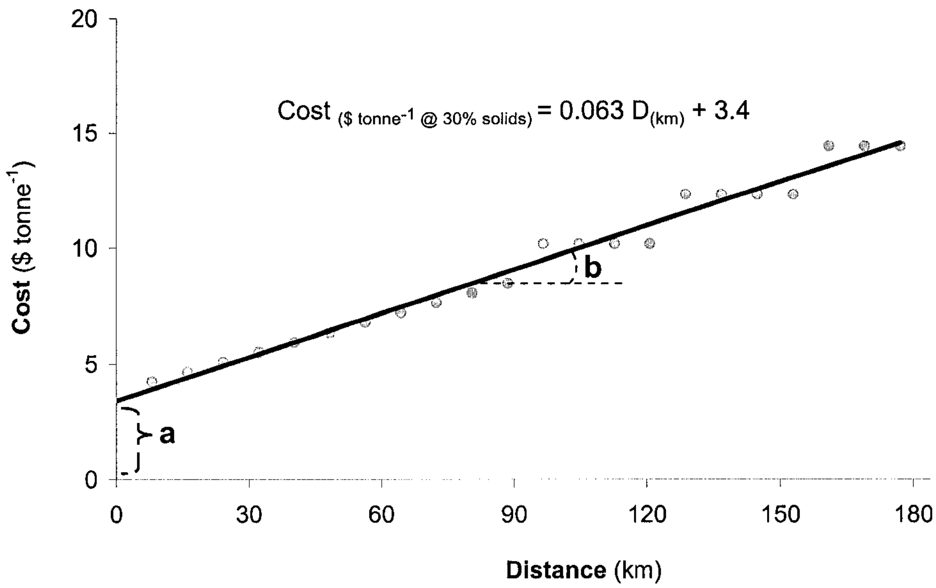

Figure 3-1 Cost of transporting beef cattle manure by truck in Alberta, Canada; "a" is the distance fixed cost, and the slope "b" is the distance variable cost

Data from a liquid hauling trucking company in Alberta were used to estimate the cost of transporting digestate (Taylor, 2005). 40 tonne tandem trailer trucks are charged out at \$88 hour^{-1}, and 30 tonne single trailer trucks are charged out at \$80 hour^{-1}. The time for each of loading and unloading is 1.12 minutes tonne^{-1}. Assuming a utilization rate of 85% and an average transport speed of 80 km hour^{-1}, the DFC and DVC for the 40 tonne truck is \$3.9 tonne^{-1} and \$0.064 tonne^{-1} km^{-1}; the comparable figures for a 30 tonne truck are \$3.5 tonne^{-1} and \$0.080 tonne^{-1} km^{-1}. For long contract duration high volume transport, as would be the case for digestate return to feedlots, the tandem trailer would be chosen.

Table 3-2 shows reported values of DFC and DVC for truck transport of solid and liquid manure and, for comparison, various other forms of biomass. Literature values for liquid manure are high compared to estimates by the trucking firm (Taylor, 2005), and high compared to costs reported for solid manure and other forms of biomass. We do not have an explanation for this discrepancy. In this chapter we have used a DFC of \$4.0 tonne^{-1} and a DVC of \$0.075 tonne^{-1} km^{-1} for both solid manure and liquid digestate.

Higher trucking costs will skew the economic comparison in favor of pipelining at a lower number of animals.

Table 3-2 Values of DFC and DVC for truck transport of various types of biomass [a]

	Moisture Content	**DVC** [b] ($ $\text{tonne}^{-1}\ \text{km}^{-1}$)	**DFC** ($ tonne^{-1})
Manure			
Liquid Manure (Brenneman, 1995)	n/a	0.27	3.4
Lagoon Manure (Aillery et al., 2005)	99%	0.21	2.2
Slurry Manure (Aillery et al., 2005)	95%	0.21	2.2
Dry Manure (Aillery et al., 2005)	50%	0.08	11.0
Solid Manure (Ribaudo et al., 2003)	n/a	0.09	6.6
Liquid Manure (Ribaudo et al., 2003)	n/a	0.21	2.2
Solid Manure (Araji and Stodick, 1990)	45%	0.09	n/a
Other Biomass			
Straw (Jenkins et al., 2000)	11%	0.14	5.0
Straw (Kumar et al., 2003)	16%	0.12	5.4
Wood chips - long term supply (Kumar et al., 2004)	50%	0.06	5.6
Wood chips - short term supply (Kumar et al., 2004)	50%	0.09	4.3

[a] Adjusted to 2005 USD

[b] Based on km hauled

3.3 Pipeline Transport Costs

Solids can be transported in pipelines as slurry, and at any given capacity the cost of transport as a function of distance will have a similar profile to Figure 3-1. In this chapter we developed a scope of equipment for pipeline transport of manure and digestate slurries. The costs of a pipeline that are independent of the distance are the costs of inlet and outlet equipment. Since the outlet of the manure pipeline discharges directly into the anaerobic digestion facility, capital investment at the outlet is negligible. The manure pipeline inlet equipment is substantial, and would include receiving components, e.g. a dump pocket and conveying equipment, maceration equipment, and mixing equipment to create the slurry. However, as noted above the net incremental cost of the inlet equipment for a digester supplied by pipeline vs. a digester supplied by truck is effectively zero, because the equipment required at the pipeline inlet displaces identical investment that would otherwise be required in the plant. Hence, in this chapter the sole net DFC attributed to pipelining manure is the cost of one operator position at the pipeline inlet to run the pipeline, estimated at $50 per hour for a 24x7 operation to cover salary plus benefits. Note, however, that if manure is delivered to a pipeline inlet by truck, as would typically be the case even for a pipeline inlet located within a feedlot, the DFC of loading and unloading the truck would also be incurred. Similarly, digestate might be transported from the pipeline discharge back to the source feedlots if more than one, by truck, and hence the DFC for loading and unloading is incurred.

Table 3-3 lists the scope of equipment and estimated capital cost for the net incremental investment in a 50 km two-way pipeline, i.e. the pipeline, and pump booster stations, at a capacity of 1.43 Mt per year. Pipeline capital costs were developed from discussions with an engineering contractor and draw on the costs of buried water supply lines (Williams, 2004); estimates include power supply to the pump booster stations. The pipeline is carbon steel and buried below the frost line; booster stations are placed to maintain a maximum pressure of 4 MPa (600 psi). A critical design parameter in any slurry pipeline is the minimum velocity required to maintain the slurry in suspension; we assume 1.5 m s^{-1} (5 ft s^{-1}), based on previous studies of manure (Harner and Murphy, 2001; Pfost et al., 2001; NRCS, 2002). Pump power requirements are calculated based on the rheological models proposed by Chen (1986a and 1986b) and Chen and Hashimoto (1976) in standard pressure drop calculations for pipe flow.

Solids concentration in the digestate is based on a 45% conversion of volatile solids during AD and a ratio of volatile solids to total solids of 85% (Li, 2006). For solid manure with a solids content of 30%, digestate is 2.4 times the volume of the original manure. The power required to pipeline digestate in Table 3-3 is lower than a 12% manure slurry, which arises from a volume reduction of 4.2% and a viscosity reduction due to lower solids. However, all pipeline calculations in this chapter are for standard carbon steel pipe sizes in nominal increments of one or two inches, and at the pipeline velocities and sizes in this chapter the digestate pipeline in some cases requires higher power than manure slurry. The cause of this is a transition in flow regime, with manure in a laminar flow regime and digestate in a turbulent flow regime with a higher friction factor. This does not have a significant impact on overall cost. Also note that the cost of a two way pipeline is less than the sum of a stand alone manure and digestate pipeline, because a single trench would be used for both pipelines and permitting costs are not additive for the two way pipeline.

Table 3-3 Estimated cost of a 50 km two-way pipeline at a scale of 1.43 Mt per year (manure from 125,000 animals at 12% solids concentration)

Item	Manure Pipeline	Digestate Pipeline	Unit
Pipeline Slurry Concentration	12%	8%	
Pipeline Diameter [a]	0.1524	0.1524	m
Pumping Efficiency	80%	80%	
Pump Power	7.8	6.1	kW km^{-1}
Pipeline Capital Costs [b]	$150,000	$150,000	$ km^{-1}
Pump Station Capital Costs [b]	$1,200,000	$1,000,000	per station
Distance Between Pump Stations [c]	31	37	km
Annual Operating Costs:			
Labor Costs [d]	$430,000	-	per year
Power Costs [e]	$3,800	$2,900	$ km^{-1} $year^{-1}$
Maintenance Costs [f]	$2,300	$2,000	$ km^{-1} $year^{-1}$
Pipeline Operating Life	30	30	year
Financial Discount Rate	12%	12%	
Annual Costs for a 50km Pipeline [g]	$2,000,000	$1,500,000	$ $year^{-1}$
	$16	$12	$ $animal^{-1}$ $year^{-1}$
	$12	$8	$ dry $tonne^{-1}$ $year^{-1}$

[a] 6" nominal pipe size

[b] Cost values from an engineering contractor (Williams, 2004)

[c] Booster stations placed to maintain a maximum pressure of 4 MPa (600 psi)

[d] Based on 8,640 man-hour per year at $50 per hour. No additional labor for the return pipeline

[e] Based on $56 per MWh

[f] Based on 0.5% of pipeline capital costs and 3% of pump and pump station capital costs

[g] Includes capital recovery at a pre-tax rate of 12%

Pipeline costs were used to determine the optimum slurry concentration in a manure pipeline. Figure 3-2 shows the total cost of pipelining manure from 100,000 animals a distance of 50 km as a function of slurry concentration in the pipeline. Total cost includes a return on capital investment of 12% and a project life of 30 years. Steps and inflections in the curve in Figure 3-2 arise because pipeline diameters are constrained to standard carbon steel pipe sizes. The optimum manure slurry concentration is broad, but is near 12%, the concentration typically specified for anaerobic digestion, and we use this concentration for the balance of the study. Pipelining material at the same concentration as the anaerobic digester operates does not create a penalty in pipelining cost.

Figure 3-2 Total cost of 50 km one-way pipeline carrying manure from 100,000 beef cattle as a function of manure slurry concentration

Pipeline costs are highly scale dependent; based on cost estimates for small diameter water pipelines (Williams, 2004), a scale factor of 0.46 against capacity, equivalent to a scale factor of 0.92 against diameter, was used in this chapter. This compares to values of 0.59 to 0.62 estimated by others for large capacity slurry pipelines (Wasp et al., 1967; Liu et al., 1995; Kumar et al., 2004); note that for small diameter pipelines the scale factor would be expected to drop since costs independent of capacity, such as permitting, become a higher percentage of the total installed cost. Figure 3-3 shows the net incremental cost of transporting manure by pipeline to an anaerobic digester for a range of pipeline sizes. Note that both DFC and DVC are scale dependent. The data for manure at a slurry concentration of 12% can be fitted to

$$DFC_{Manure} = 1450\ C^{-1} \qquad (3\text{-}1)$$

$$DVC_{Manure} = 11.1\ C^{-0.653} \qquad (3\text{-}2)$$

where the units for DVC are \$ dry tonne^{-1} km^{-1}, for DFC are \$ dry tonne^{-1}, and C is the pipeline capacity in tonnes of dry solids in the incoming manure per day. The equations for digestate and two way pipelining are

$$DFC_{Digestate} = 0 \qquad (3\text{-}3)$$

$$DVC_{Digestate} = 9.1\ C^{-0.624} \qquad (3\text{-}4)$$

$$DFC_{Two\text{-}way} = 1450\ C^{-1} \qquad (3\text{-}5)$$

$$DVC_{Two\text{-}way} = 15.0\ C^{-0.614} \qquad (3\text{-}6)$$

Two things are important to note in these equations. First, the capacity C for all pipeline DVC and DFC formulae are expressed in dry tonnes of solids in the manure. In this work we calculate truck transportation costs based on actual tonnes of manure and digestate, and all pipeline costs based on dry tonnes of solids in manure (not digestate), because these are the parameters that control the transportation cost. Truck costs are independent of dry solids, and depend only on total material trucked. For a given slurry concentration manure pipeline cost depends on the dry solids content of manure, and digestate pipeline cost depends on digestate volume, which depends on manure dry solids and is virtually independent of solids conversion during AD, and hence is virtually independent of solids content in digestate. Second, note that $DVC_{Two\text{-}way}$ is expressed per one way distance, i.e. the distance used in calculating two way pipeline cost is the distance between pipeline inlet and AD plant, and the calculated costs cover both manure and digestate pipelining.

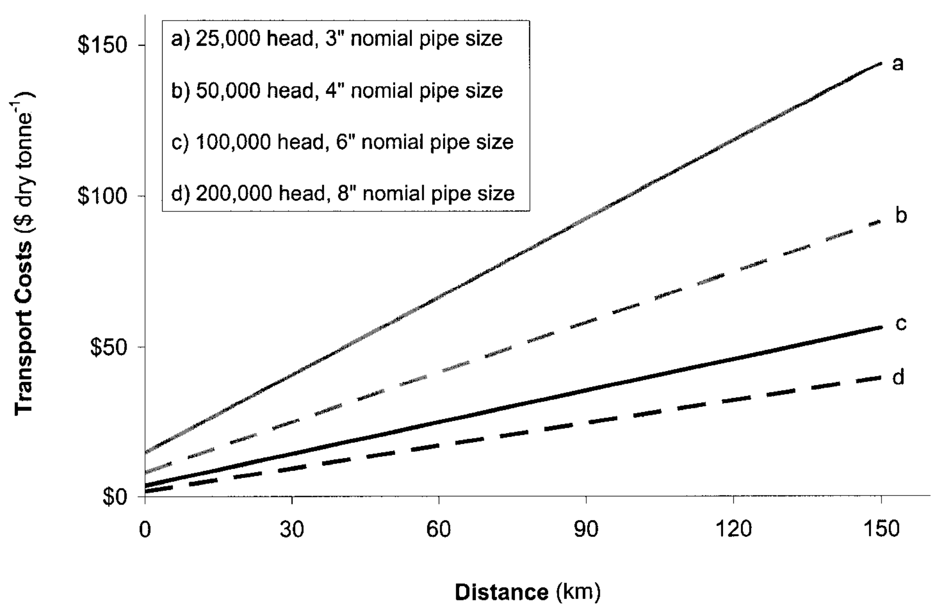

Figure 3-3 Impact of scale on the cost of transporting manure in a one-way pipeline

Figure 3-4 shows the variable cost of transporting manure and digestate per dry tonne of solids in the incoming manure per km, DVC, as a function of the aggregate size of the feedlots generating the manure. Note that truck costs show no scale dependency and are thus a horizontal line, while unit transport costs decrease with capacity for the pipelines. The trucking cost for digestate is about 2.4 times higher than the cost of trucking manure because of the higher volume of digestate relative to the manure, which has a solids content of 30% if trucked to the AD plant. A stand alone manure pipeline competes with trucking at 90,000 head of beef cattle, a stand alone digestate pipeline at 21,000 head, and a two way pipeline at 29,000 head.

3.4 Combined Truck and Pipeline Transport of Manure

Manure starts its journey to a digester on a truck. Even if a pipeline were located at a large feedlot, front end loaders that clean individual pens would place the material on a truck for transport to the pipeline inlet. The fixed cost of loading and unloading a truck must be incurred; trans-shipping from a truck to a pipeline incurs additional fixed costs. Hence, the key issue for a manure transporter is whether it is economic to remove the manure from the truck for shipment by pipeline.

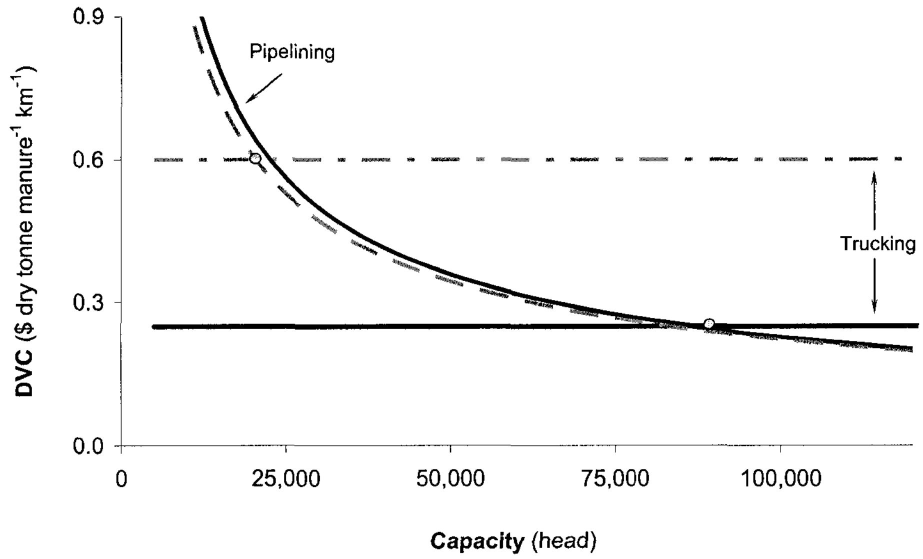

Figure 3-4 DVC of transporting manure (solid lines) and digestate (dashed lines) via pipeline vs. truck as a function of the number of beef cattle

Figure 3-5 shows a conceptual illustration of trans-shipment economics: there is a minimum distance shown as the grey area in Figure 3-5 that must be achieved before the incremental DFC of trans-shipment is offset by the lower pipeline DVC. Pipelines shorter than the minimum economic distance would increase overall manure transport costs relative to transport by truck only. Note that both the DFC and DVC of pipelining are scale dependent: both drop with increasing pipeline capacity, and hence the minimum economic pipeline distance is a function of capacity.

Figure 3-6 shows the calculated minimum pipeline length required for manure trans-shipment to be more economic than transport by truck alone as a function of capacity. Note that below 90,000 animals (manure only) and 29,000 animals (two-way transport) there is no economic distance because the DVC of pipelining is higher than trucking. Given that the net investment in a pipeline inlet station is low, for the reasons discussed above, the incremental DFC of pipelining to a digester is low, and the minimum economic pipeline distance is accordingly low compared to pipelining of other forms of biomass (Kumar et al., 2004). There is no minimum economic distance for digestate pipelining because there is no incremental DFC.

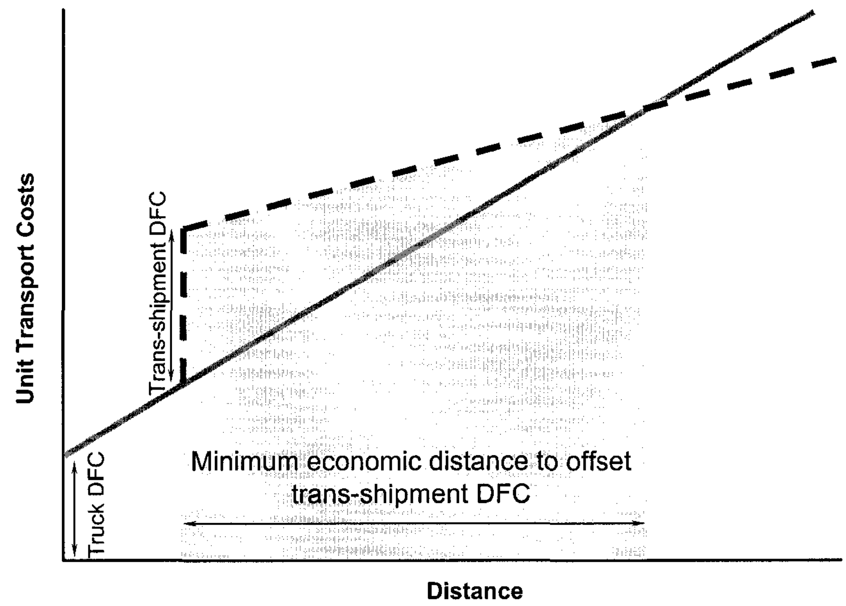

Figure 3-5 Transport cost for single mode (solid line) and trans-shipment (dashed line)

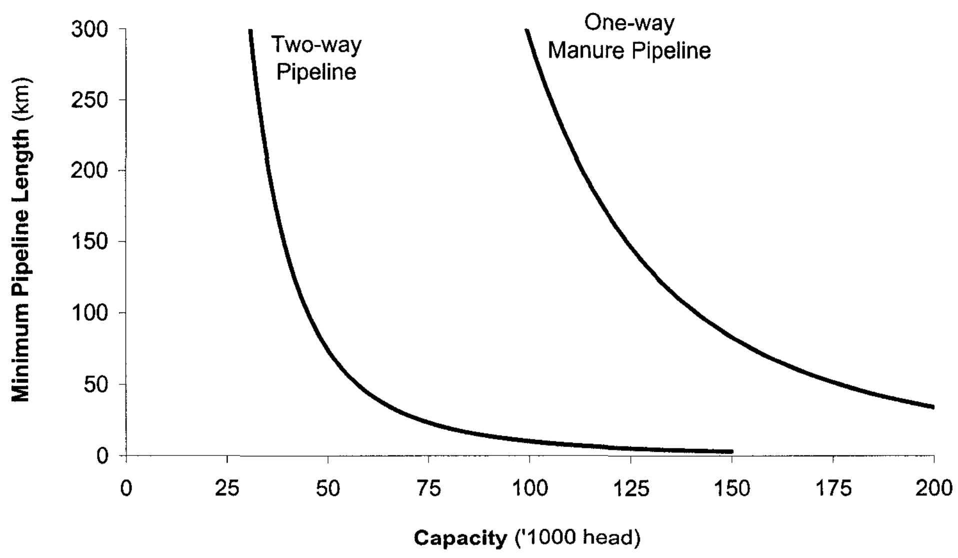

Figure 3-6 The minimum length for a two-way pipeline for which trans-shipment reduces overall transport cost as a function of capacity

3.5 Energy Balance for Manure Transport

A frequent observation of biomass is that its low energy density limits the distance over which it can be transported. Many previous studies have shown that the optimum size of biomass processing is large and involves significant transport distances (Overend, 1982; Nguyen and Prince, 1996; Jenkins, 1997; Larson and Marrison, 1997; Dornburg and Faaij, 2001; Kumar et al., 2003). Manure is a particularly low energy biomass. Standing manure from beef cattle typically has a moisture content of 70%; the dry solids have an energy content of 10.8 GJ dry $tonne^{-1}$ (Row and Neable, 2005). Based on truck fuel consumption of 27 l per 100 km (EEA, 2002) manure could be trucked over 6000 km before the energy used in transport exceeded the energy in the manure. Even with partial recovery of contained energy, e.g. 45% conversion of volatile solids in AD (Li, 2006), theoretical transport distances of more than 2000 km would be required to exceed the energy yield from manure. For a pipeline serving feedlots containing 100,000 beef cattle, the energy required to move one dry tonne of manure solids is about half that of trucking, so even longer distances would be required to exceed the energy yield from manure.

3.6 Discussion

Anaerobic digestion of animal manure can be performed at a wide range of capacities, from on-farm applications to large centralized plants. As digester capacity increases, the need to transport manure over longer distances increases, but an economy of scale in capital equipment is also achieved. Transportation of biomass is a significant cost component of the overall cost of recovering energy from biomass, because the energy content of the biomass is low relative, for example, to hydrocarbons. This is especially true for manure; for beef cattle manure, even after sitting in a feedlot, moisture levels are typically 70%; much of the trucking cost is spent on moving water. For this reason it is appropriate to emphasize minimizing overall transportation cost.

In both Canada and the United States areas of intense confined feeding operations, i.e. feedlots, for beef cattle have emerged. We estimate that more than five million beef cattle are in feedlots in the vicinity of Dodge City, Kansas, and more than one million in the vicinity of Lethbridge, Alberta. This kind of concentration of animals and the associated manure creates the possibility of very large digester plants. In theory, gas production could be sufficient in such locations to switch from small internal combustion power generators to more efficient combined cycle plants, which can be installed at a capacity of 25 MW or greater (Shilling, 2004). It is clear from an energy balance that manure can be transported long distances if the savings in processing cost is greater than the transportation cost.

Pipeline cost as a function of manure slurry concentration shows a broad minimum in the region of 12% TS; since many anaerobic digesters are designed to work in this range, there is no penalty for pipeline transport of manure at a concentration that can be directly fed into the digesters. The manure pipeline itself would act as a digestion tank, although activity would be low unless the pipeline contents were heated. Since heating of incoming manure in a digester is typically done through waste heat, it is unlikely to be economic to utilize a pipeline as a heated reactor unless a very low cost heat source is available near the pipeline inlet.

The results of this chapter show that pipelining of beef cattle manure is more economic than trucking when manure from more than 90,000 animals is available. As the number of cattle increase over 90,000 the unit transportation cost drops because pipelines have an economy of scale and trucking does not. For 300,000 beef cattle, a 50 km pipeline would transport manure at 40% of the cost of trucking. Manure pipelining has a low incremental DFC compared to other forms of trans-shipment such as rail (Mahmudi and Flynn, 2006), because the investment in much of the equipment at the pipeline inlet reduces the investment in plant equipment and is therefore not a net cost to the project. As a result, the minimum economic distance for pipeline trans-shipment is very low. For 300,000 beef cattle, a pipeline as short as 9 km is as economic as continued hauling of manure by truck. The economic benefit of pipelining is large, but only at large scale.

Digestate liquid today must be land spread, as there is no commercial technology to recover sufficient nutrients from the liquid stream to enable discharge of effluent to a watercourse. (Some AD plants separate coarse solids from digestate, but the remaining liquid fraction is still land spread.) If suitable land for spreading is very near a centralized AD plant, digestate pipelining is not necessary. However, given issues of soil contamination by excess phosphate, it is necessary in some cases to return digestate to the manure source, in essence tying the obligation to dispose back to the source. Digestate return to the source is a common practice in Denmark, for example (Tafdrup, 1995; Gregersen, 1999; Alseadi, 2000; Raven and Gregersen, 2007). In such cases, digestate pipelining is economic relative to truck transport for sources of manure as small as 21,000 head of beef cattle.

A two way pipeline, as noted above, has construction economies relative to two one way pipelines, due to lower permitting cost and the use of a single trench to lay two pipelines. A two way pipeline has a lower total cost of transportation of manure plus digestate for manure sources in excess of 29,000 head. In the range of 21,000 to 29,000 head the most economic transportation mode is truck transport of solid manure and pipeline return of digestate.

The transportation costs in this chapter can be used to help evaluate the cost of very large centralized anaerobic digestion plants, which in concept could be supplied by one or multiple pipelines. This chapter has focused on economic parameters, but pipelining of manure can also offer additional benefits such as reduced use of roads, reduced traffic congestion and avoidance of odor complaints from communities along manure hauling routes. One recently announced centralized digester is relying on pipelines for part of its manure supply and digestate return (Maabjerg Bioenergy A/S, 2005).

3.7 Conclusions

- For a given truck size the cost of truck transport of manure is virtually independent of scale, while the cost of pipeline transport of manure is highly scale dependent. The estimated scale factor for the installed cost of manure pipelines in the 6 to 14 inch nominal pipe size range is 0.46.

- Total cost of pipelining beef cattle manure is minimized at a slurry concentration of about 12% TS.

- Pipeline transport of beef cattle manure is more economic than truck transport for the manure produced by more than 90,000 animals. As the number of beef cattle increase above 90,000 pipelining becomes increasingly economic. Pipeline transport of digestate back to a manure source is more economic than truck transport when manure from more than 21,000 beef cattle is available. Two-way pipelining of manure plus digestate is more economic than truck transport when manure from more than 29,000 beef cattle is available.

- Pipelining of manure to an anaerobic digester incurs very low incremental net fixed costs, because the equipment at the pipeline inlet duplicates equipment that would otherwise be required at the digester plant. The cost of a pipeline operator is the only net incremental cost identified in this chapter. Pipelining of digestate incurs no incremental fixed costs because the AD plant operator can oversee the operation of the pipeline as well as the AD plant.

- At any given capacity there is a minimum distance that a pipeline must run for the incremental net fixed costs to be recovered. At 300,000 animals the minimum economic pipeline distance for manure is 9 km.

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Chapter 4[‡]

Optimizing the Size of Anaerobic Digesters

4.1 Overview

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 from 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 thermophilic AD plant or mesophilic AD plants with a sanitization step. 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,

[‡] A version of this chapter has been submitted for publication. Ghafoori and Flynn. *Transactions of the ASABE*. Under review.

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.

$$Cost_{size2} = Cost_{size1} \times \left(\frac{Size_2}{Size_1} \right)^{scale\ factor}$$

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 chapter 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 chapter 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.

4.2 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} km^{-2}. 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 than literature values 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 chapter) is in turn directly dependent on distance traveled. In this chapter 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 4-1 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 Figure 4-1 a scale factor of 0.6 is used in this chapter, 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 Figure 4-1 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 chapter 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 Figure 4-1 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.

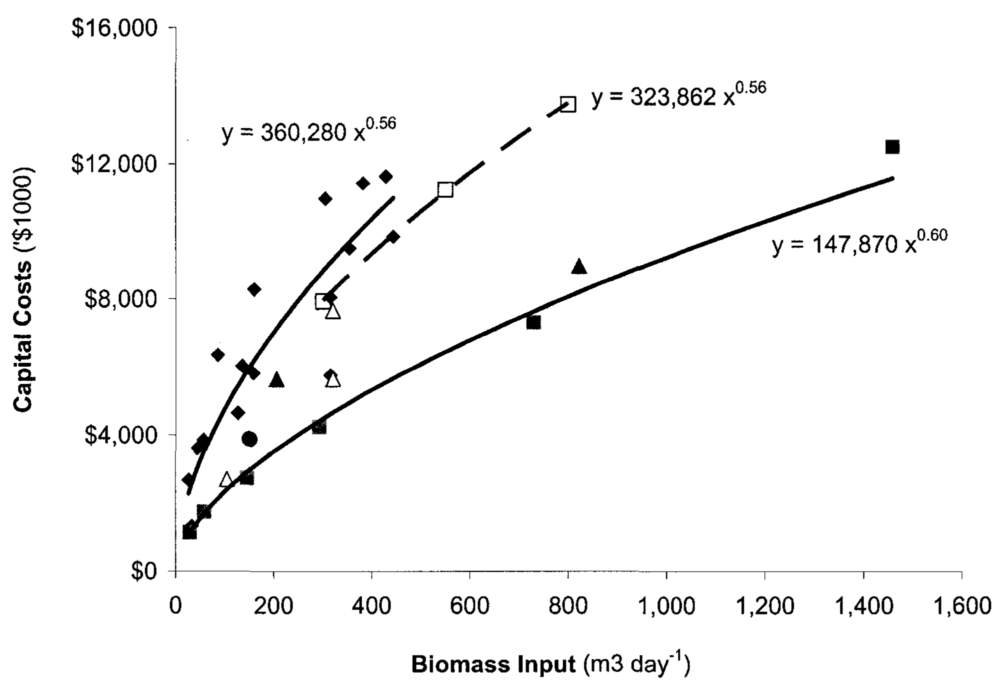

Figure 4-1. The estimated cost of biogas plants generating electric power (■ Hashimoto et al. (1979); ✸ Mathony et al. (1999); ◆ H-Gregersen (1999); □ Nielsen and H-Gregersen (2002); ▲ Row and Neable (2005); △ Tofani (2006))

The model is designed to allow for revenue from the sale of power, heat, by-product fertilizer, subsidies, and carbon credits. In this chapter 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 chapter; for an analysis, see Ghafoori et al. (2006a and 2006b).

4.3 Results

4.3.1 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 4-2 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).

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 2.4 times.

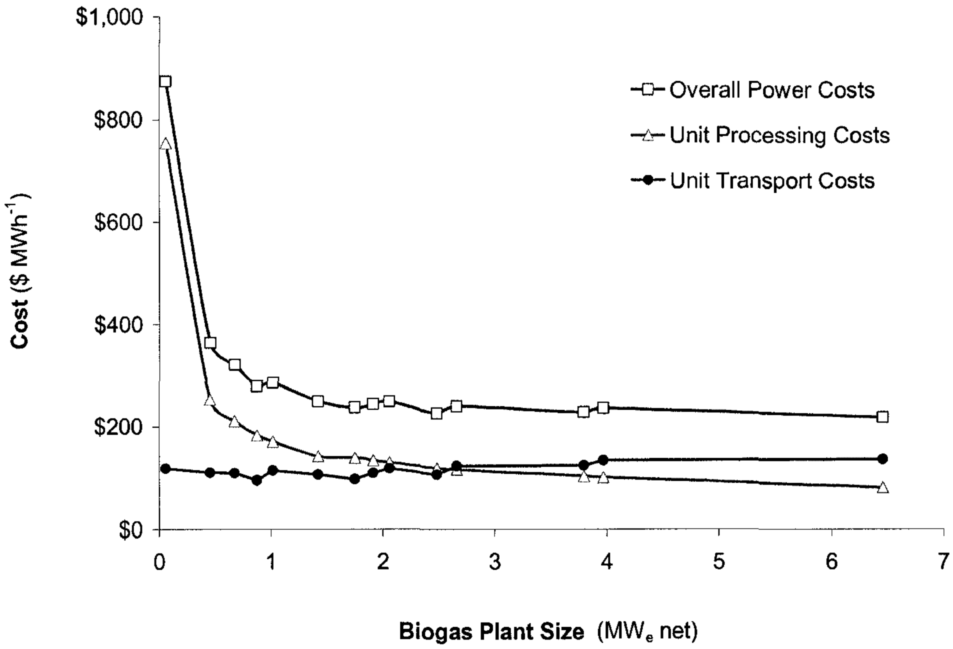

Figure 4-2. Estimated power cost at individual centralized plants in Red Deer County.

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 Figure 4-2 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 4-3 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).

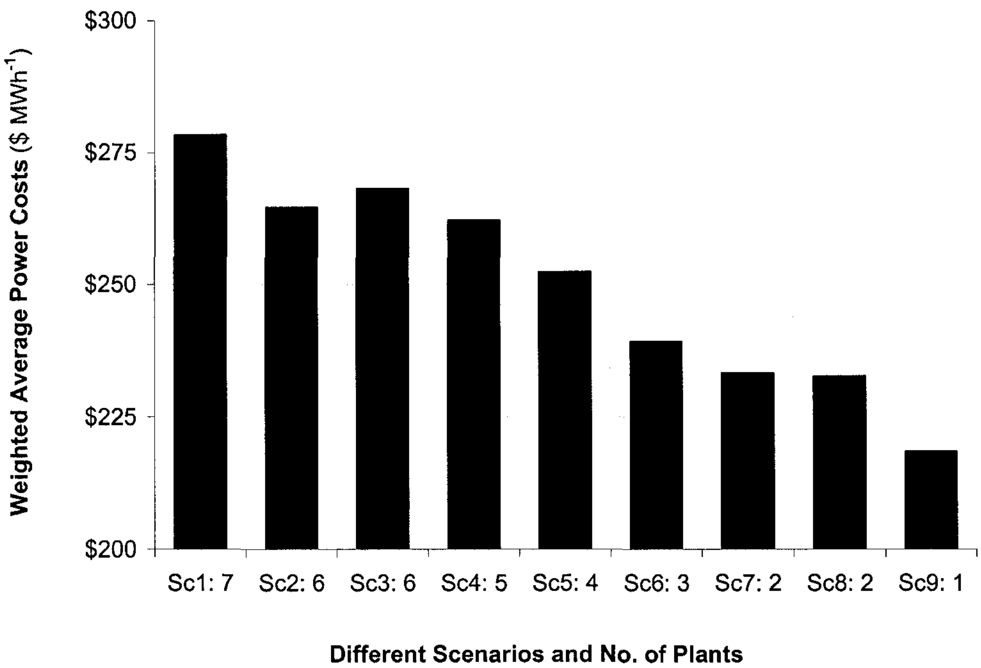

Figure 4-3. Estimated average biogas power cost in Red Deer County.

The cost of generating power at the farm or feedlot was next calculated for each of the 61 CFOs, and results are shown in Figure 4-4. 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 Figure 4-4 that no CFO in Red Deer County can produce power from AD of manure at a lower cost than a single centralized plant.

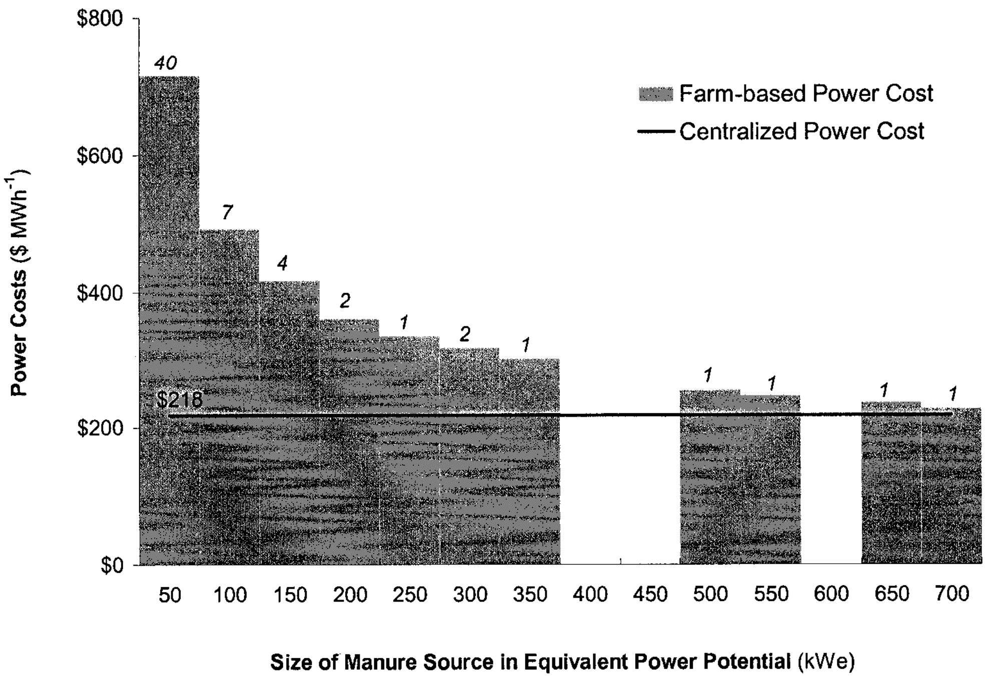

Figure 4-4. Farm-based power cost as a function of capacity vs. centralized processing in Red Deer County (number of manure sources at each capacity is identified at the top of bar charts).

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.

4.3.2 *"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 $year^{-1}$ km^{-2}). 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 Figure 4-5 (lower axis) are compared to the cost of a plant operated at a feedlot level (upper axis).

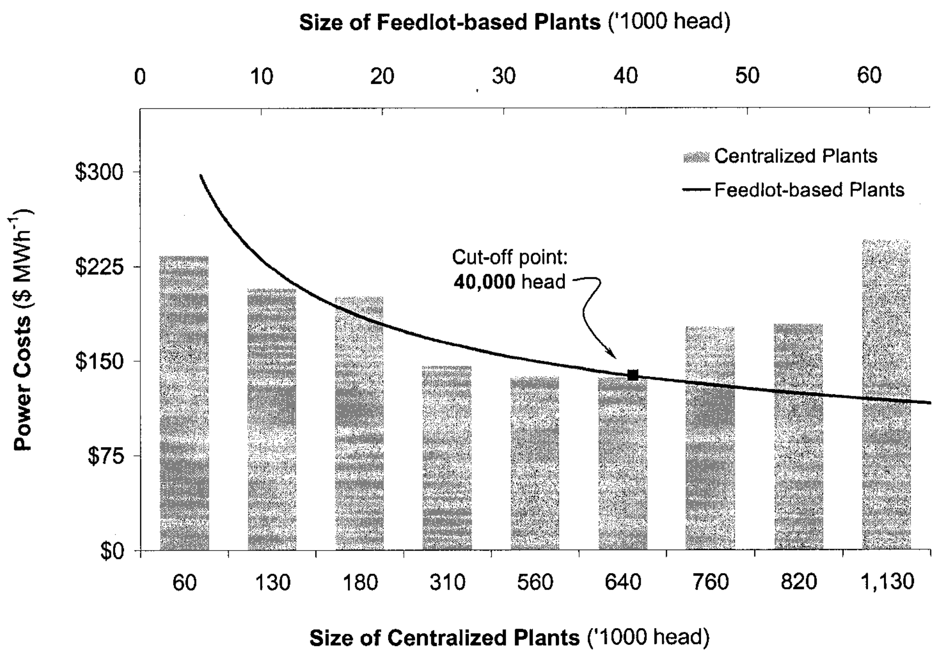

Figure 4-5. Feedlot-based power cost vs. centralized processing in concentrated feedlot areas in the absence of digestate processing.

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 4-5 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 4-6 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.

From Figure 4-6 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 chapter 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.

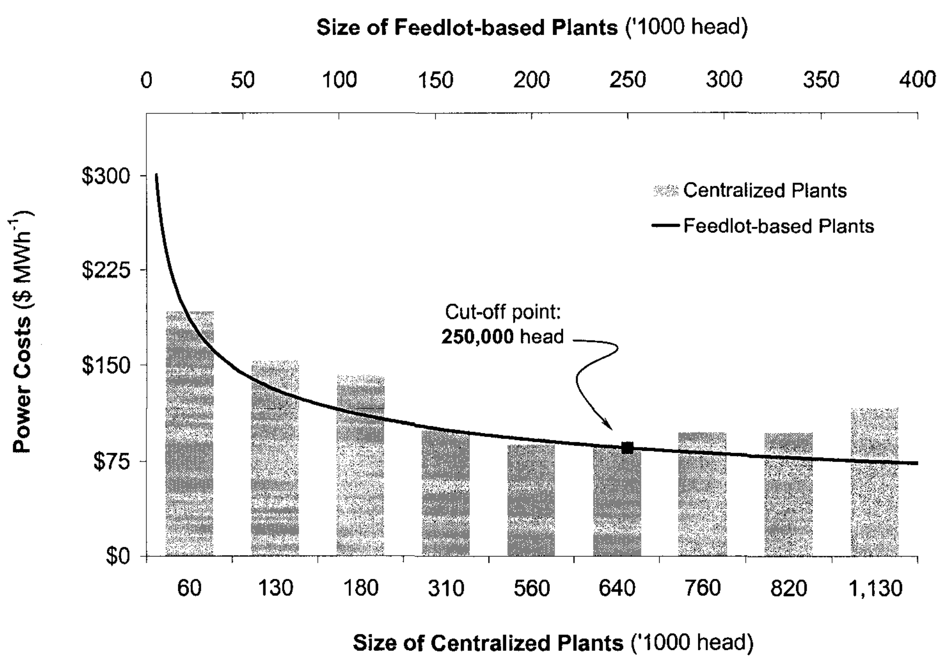

Figure 4-6. Feedlot-based power cost vs. centralized processing in concentrated feedlot areas with subsequent digestate processing.

4.4 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 chapter, 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 chapter 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 chapter: 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.

4.5 Conclusions

- In the western half of Red Deer County, a mixed farming area generating 34 dry tonnes km^{-2} $year^{-1}$, 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 $year^{-1}$ km^{-2} 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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Chapter 5[§]

The Logistical Implications of Optimizing Anaerobic Digestion of Livestock Manure

5.1 Overview

There are two current and one prospective reasons to process manure to biogas through anaerobic digestion (AD). The first reason is to recover useable energy that contributes no net carbon to the atmosphere (Martin, 2003; Schneider and McCarl, 2003). Biogas as produced contains about 60% methane, 35 to 40% carbon dioxide, and small concentrations of oxygen, nitrogen, ammonia and hydrogen sulfide. The amounts of trace gases depend on the concentration of nitrogen and sulfur in the feed, and on the amount of air introduced into the AD process with the manure. Biogas from small AD plants is typically used for heat or combined heat and power (CHP), with power being produced from an internal combustion (IC) engine driven generator. Typical generator efficiencies based on lower heating value (LHV) are 37% to 43% (Harrison, 2005; GE Energy, 2006). The amount of heat recovered depends on the available heat sink; European AD plants often feed biogas to a CHP plant that utilizes waste heat in a district heating system (Mahony et al., 2002). Larger amounts of biogas can be processed in a combined cycle power plant with thermal efficiencies of 55% or higher (Shilling, 2004). As an alternative, biogas can be scrubbed to remove H_2S and CO_2 and compressed to produce a pipeline quality natural gas (QuestAir Inc. 2004; Environmental Power Inc., 2005). 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 (Ghafoori et al., 2006).

A second reason to use AD for biogas is to reduce the risk from pathogens in the manure. Animal manure from confined feeding operations (CFOs) such as beef cattle

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feedlots, dairy farms, hog barns, and poultry farms is spread on land today. Raw manure contains pathogens that have potential risk to humans through water contamination, e.g. *E. Coli.* Thermophillic AD or mesophillic AD with a santization pre-treatment step destroys all or virtually all pathogens (Birkmose, 2000; Sahlstrom, 2003; Demirer and Chen, 2005). 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, 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 in areas of intense livestock production by producing a concentrated fertilizer that can be economically moved to areas that need the nutrients. For example, excess phosphate in soil can generate human health risk in drinking water supplies (Cooke and Williams, 1973; Hooda et al. 2000, Savard, 2000). The only commercially available and demonstrated treatment of digestate today is solid liquid separation, which can remove an estimated 60% of phosphate into a transportable solid fraction that has a moisture level of about 70% (Moller et al., 2000 and 2002). Capturing the remaining phosphate by processing of the liquid fraction of digestate would help management of this nutrient in areas with a high phosphate index. This issue is particularly important for manure because the ratio of phosphate to nitrogen is higher than in normal crop fertilizers.

AD has a strong economy of scale. Both analysis of cost data from Danish plants and theoretical studies show a scale factor of about 0.6 (Ghafoori and Flynn, 2006), where scale factor is the exponent in the relationship:

$$\text{Cost}_{\text{plant}_2} = \text{Cost}_{\text{plant1}} \left(\frac{\text{Capacity}_{\text{plant2}}}{\text{Capacity}_{\text{plant}_1}} \right)^{\text{scale factor}} \qquad (5\text{-}1)$$

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 (Overend, 1982; Nguyen and Prince, 1996; Jenkins, 1997; Larson and Marrison, 1997; Dornburg and Faaij, 2001, Kumar et al., 2003). As biomass availability per 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 explore the economics of AD of manure in centralized plants vs. plants based at the CFO, which we refer to as farm or feedlot based plants (Ghafoori and Flynn, 2006). The two locations are Lethbridge County and the western portion of Red Deer County. Lethbridge County is an area of intense processing of beef cattle and is unique in Canada; feedlots in the county contain an average of 570,000 beef cattle (CANFAX, 2006), typical feedlot sizes are 25,000 to 100,000 head, and average gross manure yield is 280 dry tonnes per square km per year (For clarity, gross manure yield is the yield per total area in the county). A similar area in North America is the large meat processing industry in the area of eastern Colorado, western Kansas, western Oklahoma, and North Texas (Dhuyvetter et al., 1998, Ward and Schroeder, 2004). Manure from feedlots is a solid with an estimated moisture content of 70% (Li, 2005).

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 (RDC Office, 2005). The gross yield of manure in the mixed farming areas was 34 dry tonnes per square km per year. 40% of manure is in the form of a liquid and would be shipped in a tanker truck; the remaining 60% would arrive as a solid with a moisture content of 70%.

The analysis of centralized vs. farm based production of biogas from AD (Ghafoori and Flynn, 2006) assumed that manure was the only feed and power was produced from biogas by IC engine powered generator below 20 MW and by combined cycle above that. Heat recovery was not included in the analysis as a cost or revenue source, reflecting the limited opportunities for use of low grade heat in rural and semi-rural North American settings. Whole digestate was returned from a centralized plant to the source

CFO for land spreading. Transport of manure and digestate was by truck. Digestate returned to CFOs generating solid manure requires a separate tanker truck, while digestate returned to CFOs generating liquid manure would be by backhaul in the same truck that delivered the manure. One key finding of the study was that centralized processing of manure in the mixed farming area was more economic than farm based processing. Even the largest single source of manure in Red Deer County, a beef cattle feedlot with 7500 head, could not process manure as economically as a centralized plant serving the entire region and producing 8 MW of power. However, in Lethbridge County centralized processing of manure with digestate return by truck was not economic compared to individual plants in feedlots above a critical size, for truck transport, of about 30,000 head. With an approximate estimate of digestate processing capital cost of 60% of the AD plant itself (Li, 2005) the increased capital intensity of manure processing tipped the balance in favor of centralized processing unless feedlots were larger than about 250,000 head.

Pipeline transport of manure and digestate is an alternative to truck transport (Ghafoori et al., 2005). Pipelining of biomass has a significant economy of scale, with a scale factor less than 0.5 (Kumar et al., 2004; Ghafoori et al., 2005), 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 economic than truck transport. Since all pipelined manure initially is moved by truck, either from farm or individual feedlot pen, the fixed cost of loading a truck, about $4 to $5 per tonne, is always incurred. (All costs in this study are reported in 2005 US dollars; a conversion factor of 1 USD = 1.2 CAD was used.) Trans-shipment 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 per unit distance (called distance variable cost (DVC)), for example the total cost including operating and capital recovery costs for moving one tonne of material one kilometer once manure is in the pipeline. Therefore a minimum shipping distance is required for trans-shipment to be economic, in that the reduction in DVC must offset the increased DFC that arises from trans-shipment. This analysis of pipelining of manure and digestate is based on economic factors, and we note that other non-economic factors can enter into decisions to choose pipelining over trucking, e.g. impact on communities from odor concerns and traffic congestion. Thus a recently announced centralized manure digester processing about 500,000 tonnes of biomass per year in Maabjerg, Denmark proposes to use a total of about 200 km of pipelines for transport of both manure and digestate through a relatively congested semi-rural area (Munster & Kristensen, 2005, Maabjerg Bioenergy A/S, 2006). The piping network will have a star formation running from the plant and stretching approximately 16 km into the surrounding areas (Maabjerg Bioenergy A/S, 2006). Non-economic factors based on community issues are always site specific.

In this study we use the two counties, Lethbridge and Red Deer, to analyze in more detail the logistical implications of economical processing of manure. We explore pipelining vs. truck transport for digestate and manure, and look at the truck traffic intensity for various supply alternatives. As with previous studies, we consider only manure as a feedstock. We note, however, that other organic feed streams such as purpose grown crops, crop residues, municipal organic wastes and meat processing wastes 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.

5.2 Materials and Methods

Point specific CFO location is not available for Lethbridge County, only county wide statistics on beef cattle feedlot population. We therefore develop a simplified model of a spoke and hub pipeline system as shown in Figure 5-1, and contrast this to truck transport for both Lethbridge and the western half of Red Deer County. To simplify comparison the study area is assumed to be a square, and manure sources are assumed to be evenly distributed within the area. The study area is divided in five sub-regions of equal area. Manure in the central region (1 in Figure 5-1) is transported to the plant by truck, while manure in the remaining four regions is transported by truck to the closest pipeline inlet. Digestate return is by similar mechanism: truck to region 1, and pipeline plus truck to the remaining four regions. Table 5-1 shows the key parameters for the modeling.

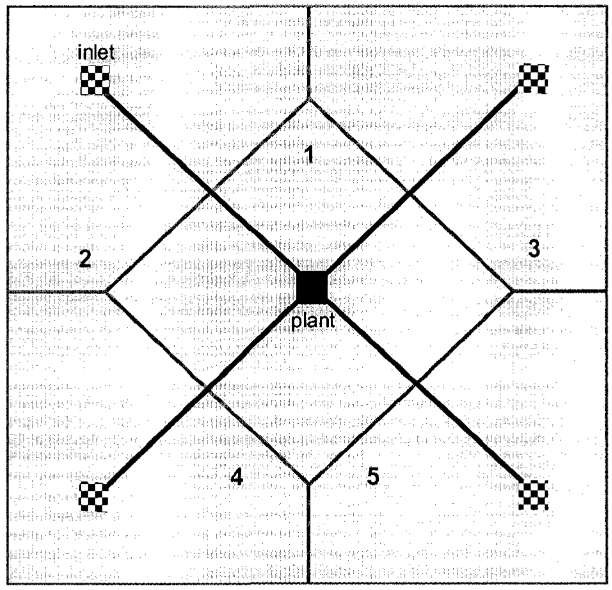

Figure 5-1. Simplified model of a spoke and hub pipeline system used for both counties

Table 5-1. Key parameters used for the modeling

Parameter	Unit	Value	
		Red Deer	Lethbridge
Total manure produced	dry tonne yr^{-1}	93,000	780,000
Total county area	km^2	2,700	2,800
Gross yield of manure	dry tonne yr^{-1} km^{-2}	34	280
Avg. trucking dist. for entire county	km	37	37
Avg. trucking dist. for each sub-region	km	16	17
Length of each pipeline	km	30	31

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. The simplified model of the western half of Red Deer County gives an average truck transportation distance of 37 km, which compares to a weighted average transportation distance of 22 km using specific location data for all manure sources in the county (Ghafoori and Flynn, 2006).

Details for the calculation of trucking and pipelining costs are developed in previous studies (Ghafoori et al., 2005). Table 5-2 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 are about 0.40; pipeline capital costs were derived from Williams (2004), and pipeline pump power consumption was developed from detailed pressure drop calculations.

For each manure source, the moisture content at time of collection is 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 (ASAE, 2003; CBC, 2005). Hence for this manure source digestate volume is about 95% of the original volume of manure. However, beef cattle manure from a feedlot typically contains 30% solids at time of collection, as noted above, and is diluted to 12% for AD processing (Li, 2005), 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, since pipeline cost is minimized at this concentration (Ghafoori et al., 2005).

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, for example 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.

Table 5-2. Impact of scale on DVC and DFC for trucking and pipelining solids manure

Head	25,000	50,000	100,000
Distance Variable Costs, DVC		*$ dry tonne^{-1} km^{-1}*	
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
Distance Fixed Costs, DFC		*$ dry tonne^{-1}*	
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 88% moisture content

5.3 Results

We analyze four cases: 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 Lethbridge County and the western half of Red Deer County. In each case we compare the cost of power production from a centralized AD plant to the cost of a farm or feedlot based unit. The cost of power from an AD plant is calculated assuming a 12% pretax return on capital. For centralized plants three transportation options are evaluated: truck haul of manure and digestate, truck haul of manure only with digestate return by pipeline plus truck, and truck plus pipeline transport of manure and digestate.

Figure 5-2 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. First, 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 to two way trucking.

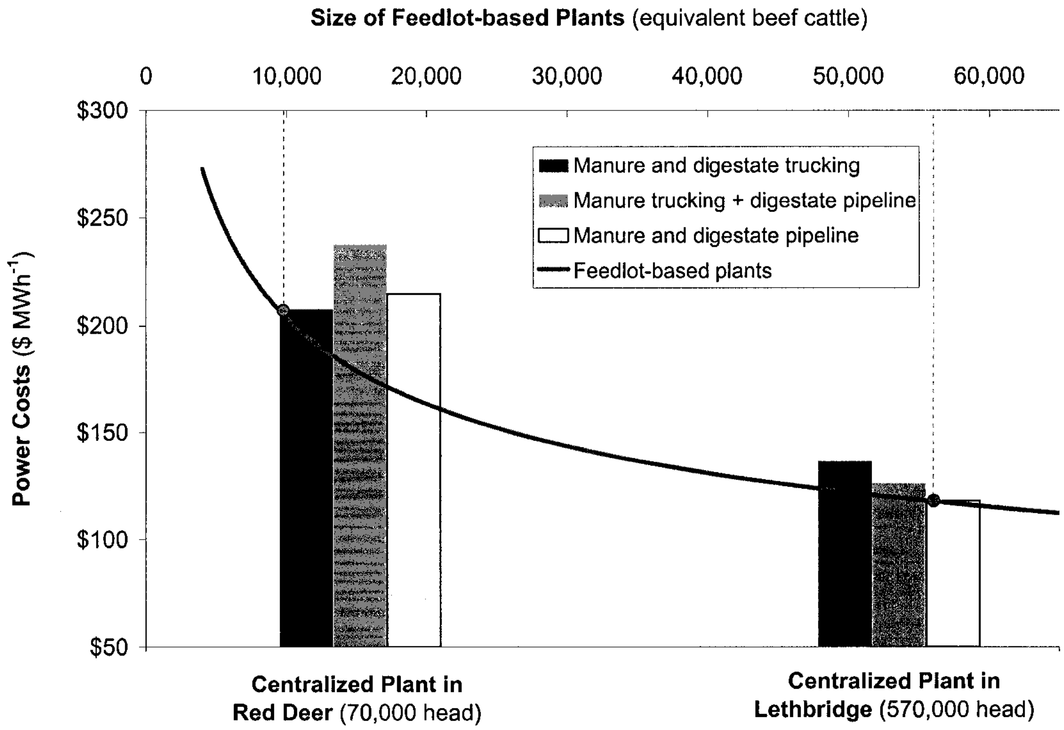

Figure 5-2. Biogas power cost at farm based plants vs. centralized plants (● identifies the size of farm based plants in which power cost is the same as of a centralized plant)

Second, centralized processing of manure with digestate return is more economic than on farm processing up to a farm or feedlot size equivalent to about 10,000 head of beef cattle. Since the largest single source of manure in Red Deer County is a feedlot containing 7500 head, centralized processing is the most economic alternative for conventional production of power from biogas (Ghafoori and Flynn, 2006). Third, for the concentrated beef cattle feedlot operations in Lethbridge County the lowest cost for moving manure and digestate is by two way pipelines, and this logistic alternative is more economic than two way trucking. Fourth, centralized processing of manure is a more costly method of producing electrical power than feedlot based processing for any feedlot greater than 55,000 head when the most economic transport mode is chosen. However, feedlot sizes of 50,000 to 100,000 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. Fifth, for centralized processing the cost in the area of concentrated feedlots is significantly lower than the mixed farming area, $120 per MW vs. $210. Two factors contribute to this reduction in power cost: an eight fold 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 5-3 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 a dischargeable water stream. Note that the power cost does not include any credit for the sale of fertilizer, since fertilizer value will be highly site specific and based on the expected transport distance to a market for phosphate rich fertilizer. For centralized processing in the mixed farming area the lowest cost way of moving manure is by truck only and the cost difference between trucking and a single pipeline carrying manure is significant.

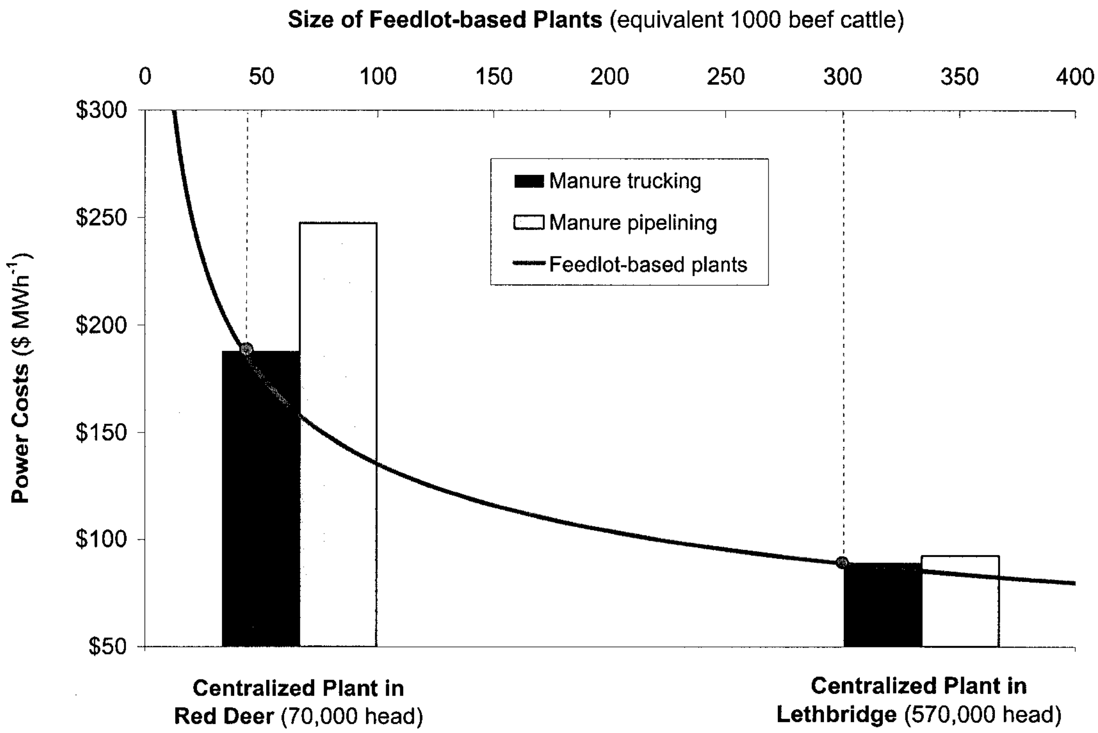

Figure 5-3. Biogas power cost at farm based plants vs. centralized plants with digestate processing (● identifies the size of farm based plants in which power cost is the same as of a centralized plant)

Centralized processing of manure has 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, and this 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 is slightly more economic than pipelining, although it raises congestion problems that are discussed further below. Because of the increased capital intensity of AD plus digestate processing, centralized AD is more economic than feedlot based processing of manure for feedlots up to 300,000 head in size. Since 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 per MWh vs. $120 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 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 above, large scale centralized AD plants would concentrate truck traffic and raise questions of both road congestion and nuisance odors. Table 5-3 shows the number of truck arrivals per day, and the interval between truck arrivals, for the four cases. 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, digestate can be returned by backhaul rather than by a separate truck going out full and returning empty.

5.4 Discussion

Whether pipelining or truck transport is more economic requires a case by case analysis, because pipelining has a strong economy of scale and truck transport does not. Increasing plant size reduces the 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. First, the second pipeline can be laid in the same trench as the first, and second, the cost of building a duplicate facility is estimated to be 95% of the cost of the first (Williams, 2004). The savings on the second duplicate pipeline arises because marshalling costs are saved and efficiencies are realized in construction.

Table 5-3. The number of truck arrivals per day and the interval between arrivals

Centralized plant at:	**Red Deer**		**Lethbridge**	
Without digestate processing	*truck only*	*truck+pipeline*	*truck only*	*truck+pipeline*
Manure delivery, *arrival day*$^{-1}$	69	14	363	73
Digestate return, *arrival day*$^{-1}$	59	12	867	173
Arrival intervals @ 16/7, *min*	8	38	0.8	4
Arrival intervals @ 24/7, *min*	11	56	1.2	6
With digestate processing				
Manure delivery, *arrival day*$^{-1}$	69	14	363	73
Digestate return, *arrival day*$^{-1}$	-	-	-	-
Arrival intervals @ 16/7, *min*	14	70	3	13
Arrival intervals @ 24/7, *min*	21	105	4	20

Non-economic reasons also arise for pipelining manure and digestate, and the recently announced proposed Maabjerg Bioenergy project in Denmark is an example of this (Maabjerg Bioenergy A/S, 2006). Although this project is half the size of the Red Deer County centralized digester evaluated in this study, it will be using a 200 km network of pipelines to move both digestate and manure. The high population density and semi-rural area of the plant presumably present issues related to community acceptance of a manure based energy project. Table 5-3 above shows the very high density of truck traffic that would occur for a single centralized manure project in Lethbridge County, with a truck arrival every one minute if trucking is the only transportation method chosen. Even for the mixed farming area a centralized plant has a manure truck arriving every 8 minutes based on receiving shipments 16 hours per day. 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 economic than pipelining for the case of digestate processing, but the difference in cost is small. Given the requirement to have a 20 tonne truck of manure arrive every three to four minutes, 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 (Overend, 1982; Nguyen and Prince, 1996; Jenkins, 1997; Larson and Marrison, 1997; Dornburg and Faaij, 2001, Kumar et al., 2003). Centralizing manure processing improves the economics up to a cut off 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. For the mixed farming area included in this study no individual farm or feedlot can process manure to electrical power at a lower cost than a single centralized digester. (In a previous study Ghafoori and Flynn (2006) demonstrated that a single AD plant in Red Deer County was more economic than any combination of smaller centralized plants). This conclusion is reflected in the practice widespread in Denmark of forming farmer cooperatives to centrally process manure (Gregersen, 1999; Al-Saedi, 2000). The widespread use of district heating in Denmark provides a ready heat sink for waste heat for much of the year.

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 few individual feedlots are 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.

Soil nutrient contamination creates a strong incentive for digestate processing, in that manure has a high phosphate level relative to nitrogen, and phosphate buildup in soil is a critical issue in many areas of the world, presenting in the extreme a human health hazard due to high phosphate levels in drinking water supplies that interfere with calcium regulation in humans. Digestate processing to produce all phosphate as an easily transportable solid, some as separated fiber and some as crystallized phosphate salts, gives the potential to sell a phosphate rich fertilizer in areas that need the nutrient. However, the challenge of total nutrient recovery from phosphate is daunting and requires additional research to develop a commercially viable process. To date, only physical separation of the solid fraction of digestate has been commercially demonstrated. Given the developmental stage of digestate processing, capital and operating cost estimates in this study are approximate. One critical area of research for manure processing is digestate processing to achieve a dischargeable water stream that does not need to be land spread.

The absolute cost of energy from manure is worth noting. For the mixed farming area the calculated cost of power from manure is about $210 per MWh, about three times the cost of power from straw in a study based on the same area (Kumar et al., 2003). For the concentrated feedlot county, the calculated cost of power is about $120 per MWh, still higher than power from straw. Energy from manure with land spreading of digestate is feasible but on a strict economic basis is costly relative to other sources of biomass based power. We note, however, that control of pathogens in manure offer a potential incentive for using biomass as an energy source. Digestate is safer to land spread than raw manure.

Digestate processing shows the promise of significantly reducing the cost of energy recovery from manure. This study forecasts that the price of power from a centralized AD plant in an area of concentrated feedlots can be reduced by 25% by digestate processing, and the resulting power cost, $90 per MWh, while high, may be close enough to existing wholesale power prices to make power from AD socially attractive, given the other benefits related to soil contamination.

This study is of 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 that 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 size and distance of transport. Hence, in optimizing transport to centralized AD plants specific locational factors will have to be analyzed.

Finally, it should be noted that while 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 IC engine powered generator with efficiencies below 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.

5.5 Conclusions

For a very large centralized AD plant in an area of concentrated beef cattle feedlot operation the least cost means of moving manure and digestate in the case of return of digestate to the source CFO for land spreading, is pipeline. As the size of AD plants reduces, trucking becomes competitive with pipeline transport because pipeline transport has a significant scale factor while the cost of trucking is virtually independent of size. When digestate is processed and hence manure only is transported, truck hauling has a 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 to 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. This study illustrates the need for a case specific analysis of alternative transportation modes.

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Chapter 6**

Global Warming Impact of Electricity Generation from Beef Cattle Manure: a Life Cycle Assessment Study

6.1 Overview

Environmental concerns around large feedlot operations have led to many environmental impact assessment studies looking at feedlot operating emissions (Sandars et al., 2003, Ogino et al., 2004, Boadi et al., 2004, Beauchemin and McGinn, 2005). The common practice of applying feedlot manure to the surrounding cropland may become unsustainable for large feedlots, as it can exceed the carrying capacity of local ecosystems leading to environmental and health concerns (Kellogg et al. 2000). This over-saturation occurs because the low nutrient density and relatively high transportation cost of manure makes it unfavorable to move it greater distances to crops where it would be in demand (Fleming et al., 1998).

Several manure management practices and technologies have been introduced to reduce the environmental and economic burdens associated with confined feeding operations (CFO). Conversion to value-added products (composting, pelletizing and livestock feed additives) and conversion for use as an energy source (gasification, co-firing, anaerobic digestion and methanol production) are the two common categories of practices and technologies used in the industry (EPA, 2001).

The widely used manure anaerobic digestion (AD) process with subsequent use of the biogas has the potential to offset energy inputs and environmental impacts of a feedlot (Sandars et al., 2003). In the AD process, manure is converted to valuable by-products. Biogas is used to generate electricity and/or heat. The digestate, the liquid left after AD, can be either spread on land "as is" or the effluent can be separated into a solid and

** A version of this chapter has been published. Ghafoori, Flynn, and Checkel. 2006. *The International Journal of Green Energy*. 3:1-14.

liquid component. If solids are separated they are typically used as a biological fertilizer. The liquid component can either be spread on land or added to irrigation water as a dilute liquid fertilizer, or nutrients can be recovered in a concentrated form by a variety of techniques, e.g. ammonia stripping, phosphate precipitation or concentration of nutrients by reverse osmosis. Given sufficient processing, liquid water suitable for discharge to a public waterway can be produced, although this has not been demonstrated at commercial scale to date.

This chapter uses Life Cycle Assessment (LCA) to evaluate the greenhouse gases (GHG) emitted by a feedlot operation which includes biogas production by anaerobic digestion and subsequent electricity generation (the AD case). The process basis is combustion of biogas in a dedicated internal combustion engine-powered generator and separation of the liquid digestate into a solid that is disposed of by land application and a liquid that is disposed of by addition to existing irrigation water (The liquid component is stored in open ponds during winter months). The choice of this basis reflects current uncertainty about processing of digestate for concentrated nutrient recovery. The AD case is compared with the "business as usual" case of a feedlot where the manure is spread directly on surrounding fields and electricity is generated by a grid power plant off site. Estimates of spreading manure hauling times and distances reflect current regulated practices in the Province of Alberta, Canada (AAFRD, 2004b).

The LCA method follows the mass and energy balances through a system of interest from "cradle to grave". This ensures considering real improvements rather than simply displacing emissions up or down the chain (SEATAC, 1993). This method was initially developed for assessment of energy and material flows of industrial products, but over time has been applied in a range of applications, from identifying improvement possibilities to supporting marketing claims and political decisions (ISO, 1997).

6.2 Scope Definition

In this chapter a typical North American feedlot is assumed for both cases with 50,000 head of beef cattle housed in 250-head pens. The population is assumed to be 50% feeders (backgrounders) and 50% finishers; average animal weights are 320 and 450 kg respectively. Operating practices for the "business as usual" and AD cases are based on data from the Highland Feeders CFO located in Vegreville, Alberta, which has installed the first phase of an Integrated Manure Utilization System (IMUS) anaerobic digestion plant (Li, 2005).

In the "business as usual" case manure is collected every six months and transported to the fields. In summer the manure is spread directly; in winter it is stockpiled on the field to be spread in summer. In the AD case, manure is collected every two months and is directly transported to the fermentation plant; the more frequent collection period reduces the loss of energy in the manure from anaerobic and aerobic digestion in the feedlot pen. The IMUS process intends eventually to filter solids from digestate for use as a solid biofertilizer and then recover nutrients from the liquid, recycling some of the recovered water to the start of the process. However, the current state of development of the process produces a slurry digestate that is spread on land.

6.2.1 System Boundary

This chapter covers the carbon life cycle flows in an animal production system, where environmental carbon is absorbed during feed/crop production and re-emitted by animal respiration, enteric fermentation, manure disposal, and biogas combustion. In the AD case electricity is generated from biogas. For completeness of the systems being compared, the chapter includes electricity generation from the existing Alberta power network, which is predominantly associated with use of fossil fuels, for the "business as usual" case. Note that disposal of manure and solid digestate by land spreading are outside the system boundary; implicit in this is the assumption that both materials, when land spread, undergo aerobic decomposition and that the carbon converts to CO_2 with no significant emissions of CH_4. Note also that emissions from the manufacture of AD equipment and construction of the plant are outside the system boundary. We assume that construction of power generation capacity in a feedlot displaces future investment in power generation from traditional fossil fuel sources; net emissions associated with equipment manufacturing and construction would be comparable.

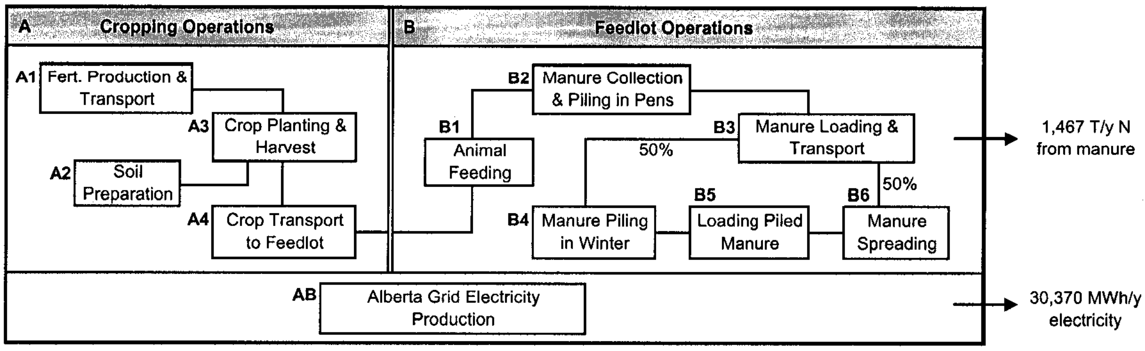

Figure 6-1. System boundary for the "business as usual" case

Figure 6-1 and Figure 6-2 show the system boundaries of the two practices included in this chapter. The life cycle net emissions for both systems were calculated independently; the two systems were scaled to produce an equal amount of products. The AD system produced 30,370 MWh/year of electricity and 1,467 tonne/year of nitrogen in the form of manure or digestate. The "business as usual" system produced the same amount of nitrogen and 30,370 MWh/year of grid-average electricity was added to balance the electricity production of the AD system.

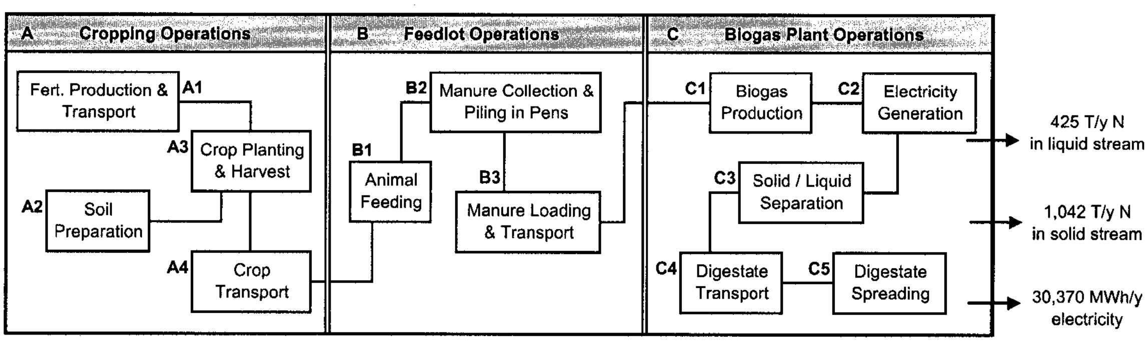

Figure 6-2. System boundary for the AD case

6.2.2 Functional Unit

Although both systems produce beef and a byproduct that is applied to land for use of its contained nutrient value (manure for the "business as usual" case and digestate for the AD case), the distinction of the AD process is electricity production. Hence, *one MWh of* *electricity* is considered as the *functional unit* and all emissions are calculated based on this unit. Emissions rates used in this chapter are based on a system that produces 4 to 5 MW from the manure from approximately 50,000 cattle by using an internal combustion engine to combust the gas and drive the generator; overall electrical efficiency in this chapter based on gas input to the engine is 36% (Kristensen et al., 2003).

Emissions are related to overall energy efficiency and the technology used to produce and combust the biogas. Larger systems using internal combustion engines would be expected to be slightly more efficient; a significant increase in efficiency would occur if sufficient gas were available to support a combined cycle technology, which has an estimated minimum size of 25 MW of electricity production (Shilling, 2004).

6.2.3 Biogenic Emissions

The inventory in this chapter does not include any biogenic CO_2 emissions. The IPCC guidelines suggest assigning an emission factor of zero to all CO_2 emissions originating from biomass combustion or degradation because that carbon is considered biogenic and is a part of the natural carbon cycle (Houghton et al. 1996). For an annual crop such as forage the carbon released to the atmosphere has typically been absorbed in the previous growing season and, for an on-going system, will be re-absorbed during the next growing season.

However, as per IPCC guidelines, CH_4 and nitrous oxide produced from the AD system are included in the inventory since these would not have otherwise been formed in the "business as usual" case, and as well incremental CH_4 production in the "business as usual" case associated with longer collection periods for manure are avoided in the AD case (ICF, 2004). Figure 6-3 shows the major input and output flows of carbon identified in the system.

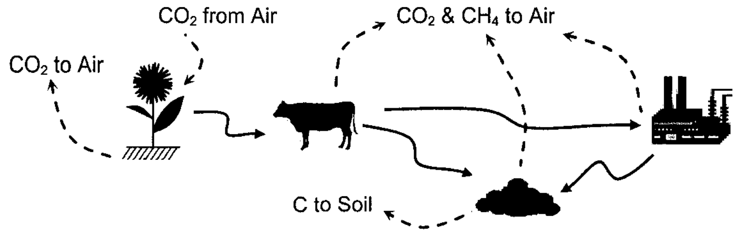

Figure 6-3. Biogenic carbon mass flow in the system boundary

Ideally, as recommended by IPCC guidelines, biogenic carbon flows would be calculated for completeness. Due to the complexity and the variability of the many systems, we have not calculated biogenic carbon flows for each individual unit process. However, to ensure that the zero net emissions of biomass-originating carbon is reasonable within the proposed system boundaries and also to check the validity of the emission factors used, the carbon mass flows into and out of the system were evaluated. As shown in Table 6-1, the net difference of estimated inputs and outputs has an error of about 5%, which is within the accuracy of the factors used and confirms the validity of the assumption of zero net emission of biogenic carbon.

Table 6-1. Biogenic carbon mass flow into and out of the system

	Quantity	Carbon mass (tonne/year)
Animal Feed (tonne DM/year)	171,000	76,900
Total Carbon In		***76,900***
Average Daily Gain (tonne/year)	20,400	7,400
Manure (tonne DM/year)	58,700	22,300
Manure Pack Emission	-	12,400
Enteric Fermentation	-	21,300
Biogas Combustion (GJ/year)	404,900	9,400
Total Carbon Out		***72,800***

6.3 Inventory Assessment

6.3.1 Livestock Feeding

Any combination of pasture, high/low quality forage or grain silage, high/low quality hay, high-moisture grain, and dry grain can potentially be fed to the livestock. Each feed type is given to an animal group that best utilizes the available nutrients. For example, high quality forage and a high fraction of grain is preferred for feeding finishing cattle and lower quality forage and a lower fraction of grain is normally fed to backgrounders (Rotz et al., 2005).

Table 6-2 shows a typical diet formulation, ignoring mineral and other organic supplements, for commercial feedlots in Western Canada containing a corn diet for backgrounders and a barley diet for finishing cattle (IPCC, 2000; Beauchemin and McGinn, 2005; Boadi et al., 2004).

Table 6-2. Diet formulation in Western Canadian beef cattle feedlots

Feedlot Cattle	Average Weight	Dry Matter Intake	Body Weight Gain	Corn Grain (88% DM)		Corn Silage (42% DM)		Barley Grain (88% DM)		Barley Silage (34% DM)	
	kg	kg/d	kg/d	%	kg/d	%	kg/d	%	kg/d	%	kg/d
Backgrounder	320	9.4	0.68	25%	2.35	75%	7.05				
Finisher	450	9.6	1.55					85%	8.16	15%	1.44

The average crop transportation distance from farmyard to the feedlot was assumed to be 50 km. The crops were hauled using a 30-tonne truck, which is also typical transport equipment in Western Canada (AAFRD, 2004a). Table 6-3 contains the crop production and transportation emission factors used for this chapter (West and Marland, 2002 and 2003; Ruser et al., 2001; Kim and Dale, 2005; Tidaker, 2003; Flessa et al., 2002; Shapouri et al., 1995; Mummey et al., 1998; and EEA, 2002).

Table 6-3. Crop production and transportation emission factors per kg of feed

Unit Process	Operation	CO_2 g/kg	CH_4 g/kg	N_2O g/kg
A1 - A3	Corn Grain Growing & Harvest	60.36	n/a	0.30
A1 - A3	Corn Silage Growing & Harvest	30.96	n/a	0.14
A1 - A3	Barley Grain Growing & Harvest	53.21	0.034	0.33
A1 - A3	Barley Silage Growing & Harvest	21.82	0.014	0.32
A4	Crop Transportation	2.92	0.001	0.001

6.3.2 Enteric Fermentation

Enteric fermentation is the major source of methane emissions in the livestock production industry (Casey and Holden, 2004). The enteric emission per unit of meat produced is less in feedlot operations compared to grazing systems, due to faster growth rate and shorter time to market (Clemens and Ahlgrimm, 2001). Enteric methane from cattle accounts for 2-12% of the gross energy (GE) feed intake (Johnson et al., 2000). Varying level of feed intake and diet composition are the reasons for the range of emissions (Johnson and Johnson, 1995; Moss et al., 2000; Benchaar et al., 2001).

There is no specific value for enteric CH_4 production in North American feedlots. Actual measurements report a range of 21-70 kg CH_4/head per year for cattle in Western Canadian feedlots (Beauchemin and McGinn, 2005; Boadi et al., 2004; and Basarab et al., 2005). An average value of 44.4 kg CH_4/head per year was used for this chapter.

6.3.3 Manure Pack Emissions

Livestock age, weight, feed ration, and climatic conditions influence the amount and quality of manure produced. Based on standards published by the American Society of Agricultural Engineers, a 50,000-head feedlot annually produces around 58,700 tonnes of dry manure (ASAE, 2003).

The manure decomposes and releases GHG emissions while it accumulates and is stored at the feedlot. Factors such as diet formulation, amount and source of bedding, pack moisture level and temperature influence the manure pack GHG emissions (Boadi et al., 2004); we assume identical feed and bedding regimes for the two cases. However, the collection period for manure is different. In the "business as usual" case the manure pack is collected once every six months, while in the AD case it is collected every two months.

Holter (1997) studied emission rates over time from individual dung pats. Emissions vary based on temperature and season, but in all cases the emission of methane from an individual pat approaches zero within 10 to 18 days. Methane emissions have a sharp peak around day 3 and a steady decline thereafter; Chadwick (2005) found a similar peaking pattern in stored manure. From Holter's data a typical average emission rate during this period is 5 to 10 ml CH_4 per day per kg of dung. Extrapolating these figures to a feedlot pen gives an average emission rate of 1.5 to 2 g CH_4 per animal per day assuming 58 kg of manure per 1000 kg of live weight (ASAE, 2003). Boadi et al. (2004) measured actual emissions of CO_2, CH_4 and N_2O from several sample points in a beef cattle feedlot manure pack in Western Canada. They note that emission rates vary significantly not only with feed ration but also across a given manure pack. Emissions in particular are higher where the bed depth is thicker, giving a warmer pack temperature. CO_2 emissions increase significantly over the life of the manure pack, confirming ongoing biological activity, but CH_4 emissions do not increase, perhaps because an aerobic microorganism culture develops that converts CH_4 to CO_2. CH_4 emissions per animal per day range from 0.7 to 1.2 g per animal per day (Boadi et al. 2004). These figures are in reasonable agreement with the extrapolation of Holter's work on individual pats (Holter, 1997), with the somewhat lower value for CH_4 emissions perhaps reflecting the existence of an active aerobic bacterial culture within the manure pack that aids in converting CH_4 to CO_2. N_2O emissions from the manure pack are similarly steady over time. Hence, we use values of 1.0 g CH_4 and 0.15 g N_2O per head per day for emissions from the manure pack.

The impact of more frequent manure collection for the AD case is negligible relative to other emission impacts. The maximum impact of more frequent manure collection can be estimated as a five week interruption in methane emissions from the pack every six months, assuming that, in the extreme, manure collection completely disrupts methane emissions for an 18 day period after collection. Even with this very high estimate, the net impact is equivalent to 29 kg of CO_2 per MWh. When compared to the impact of biogas production and electricity generation, discussed below, the impact is less than 1%. Note that this finding is consistent with a conclusion of Holter (1997) that emissions of methane from pats in the field are 0.8% to 4% of the emissions from slurried manure (in which anaerobic digestion is taking place).

6.3.4 Manure Collection and Handling

Diesel fuel is burned in the process of collecting, handling and spreading manure. The feedlot operation was modeled as housing 250 head in a pen and each pen's manure pack was collected twice a year for the "business as usual" case and six times a year for the AD case. A 100 hp tractor-mounted front-end loader was assumed to pile the manure and then load it onto 20-ton trucks equipped with manure spreaders. The trucks were assumed to haul manure for an average distance of 5 km to a designated field.

For half the year, the manure is unloaded to a pile for spreading during the summer, and for the other half of the year, the manure is spread directly from the transport truck. Hence, emissions are based on an average manure loading of 1.5 times. For the AD case the hauling distance was assumed to be negligible, as the AD plant would be located at the feedlot. The diesel consumption for the tractor and the truck were assumed to be 16.6 liter/hr and 14.5 liter/hr, respectively (Cross and Wills, 2001; Li, 2005).

Table 6-4 shows the assumed equipment times spent for manure collection, transport and spreading, based on actual measurements in a feedlot (Li, 2005). The diesel consumption emission factors in heavy duty trucks are 2,569 g CO_2/liter and 0.21 g CH_4/liter of diesel fuel respectively (EEA, 2002).

Table 6-4. Time spent for manure collection, transport, and spreading

Task	length	Unit
BAU, Piling up in pen	60	min/pen
AD Case, Piling up in pen	30	min/pen
Loading on truck	10	min/load
Truck driving out	20	min/load
Truck driving in	15	min/load
Spreading manure	30	min/load

6.3.5 Biogas Production and Electricity Generation

The AD plant consists of all necessary equipment for feedstock preparation, fermentation, gas cleaning, electricity generation, solid/liquid separation, and production of a dry solids and liquid bio-fertilizer. Considering a biogas yield of 40 cubic meters (25 C, 1 atm) per cubic meter of wet manure (based on actual data from an operating biogas plant (Li, 2005)), the manure produced in a 50,000-head beef feedlot has the potential to produce 19.5 million cubic meters of biogas per year.

Based on an assumed gas composition of 63% CH_4, 33% CO2, and the balance trace nitrogen and oxygen (Li, 2005), the heating value is 20.7 MJ per cubic meter or 19.6 MJ/kg. Assuming an average electrical efficiency of 36% for under-25 MW biogas engine combined heat and power (CHP) units (Kristensen et al., 2003), and a parasitic (inside the AD plant) power consumption of 25% of produced power (Li, 2005), this corresponds to a net 30,370 MWh of electricity per year coming out of the system to the external power grid. Parasitic power consumption for AD plants is estimated to run from 15 to 25%; we have used the high end of the range to reflect pumping of digestate liquid into irrigation canals.

The emission factors for biogas combustion were taken as 323 g CH_4/GJ and 0.5 g N_2O/GJ input as reported by Kristensen et al. (2003); CH4 emissions arise from unburned methane. The net impact of methane, expressed in CO_2 equivalent with a factor of 23 times impact (Houghton et al., 1996), is small: 7.4 kg/GJ of thermal input to the engine, while the net impact of the CO_2 is 83 kg/GJ of thermal input. Other unburned hydrocarbon emissions from the engine have a small impact relative to CH_4, and hence have been ignored in this analysis.

In addition to electricity, the AD case produces two digestate streams, a solid and a liquid. The solid stream contains about 56% of the input dry matter in the manure; as produced from the solid/liquid separator it has an estimated moisture content of 70% by weight and total weight of 108,700 tonnes per year (Li, 2005). The separated solid digestate loading, hauling and spreading time was assumed to be the same as that used for manure in the "business as usual" case of Table 6-4. The separated liquid digestate is pumped into an irrigation channel; in this chapter, the pumping distance is assumed to be short, less than 10 km.

Note that a biogas plant also produces heat, but it was considered unlikely that this low grade heat would be used in Western Canada so the heat generated has not been considered as a valuable product and no GHG offset has been considered for displacing other heat production. This situation might be different in Western European countries like Denmark and Finland which have significant district heating infrastructure or in the situation of a feedlot integrated with a major heat consumer such as a greenhouse operation.

For the "Business as Usual" case, the Electricity Generation unit process values are based on the Alberta grid electricity average production emissions (EDC, 2004). Power generation in Alberta is dominated by coal and natural gas plants. Average CO2 equivalent emissions for the existing coal generation (2003 actual) are 1069 kg per MWh, and for the existing natural gas generation are 388 kg per MWh. Given the mix of power generation over a year in Alberta, the weighted average equivalent CO_2 emission rate is 973 kg per MWh.

6.4 Inventory of Emissions

The non-biogenic carbon dioxide, methane, and nitrous oxide emissions for each of the unit processes within both system boundaries are calculated and illustrated in Table 6-5. To calculate the CO_2 equivalent emissions, the IPCC global warming potential values of 1, 23, and 296 were used for CO_2, CH_4 and N_2O, respectively (Houghton et al., 1996).

The results in Table 6-5 show the total emissions of 3,845 kg CO_2.eq/MWh for the "business as usual" case compared to 2,965 kg CO_2.eq/MWh for AD case. A total savings of 880 kg CO_2.eq/MWh was achieved by the system which utilized livestock manure for biogas production and electricity generation. Note that some data values in Table 6-5 are the result of consolidating two or more unit processes, e.g. Crop Growing and Harvest (unit processes A1, A2 and A3) or unit process B2 (Manure Collection and Piling emissions plus manure pack emissions.

Table 6-5. Inventory of life cycle emissions (CO_2.eq) excluding biogenic carbon

Unit Process	Operation	Business as Usual		Anaerobic Digestion	
		tonne/year	Kg/MWh	tonne/year	kg/MWh
A1 - A3	Crop Growing & Harvest	33,752	1111	33,752	1111
A4	Crop Transportation	921	30	921	30
B1	Enteric Fermentation	51,014	1680	51,014	1680
B2	Manure Collection and Piling	1,172	38	978	29
B3	Manure Loading and Transport	191	6	191	6
B4, B6	Manure Spreading	182	6	-	-
B5	Loading Stockpiled Manure	35	1	-	-
AB, C1-C3	Electricity Generation	29,536	973	3,068	101
C4	Digestate Transport to Field	-	-	104	3
C5	Digestate Spreading	-	-	101	3
	Total Emissions	**116,776**	**3,845**	**90,047**	**2,965**

6.5 Discussion

Figure 6-4 compares the emissions generated by each unit process within the two systems. For the "business as usual" case, Enteric Fermentation, Crop Production and Electricity Generation were the major sources of emissions, representing 44%, 29%, and 25% of total emissions, respectively. In the AD case, Enteric Fermentation and Crop Production were the major sources of emissions, representing 57% and 37% of the smaller total. Electricity Generation emissions with the AD system were only 3% of the total emissions.

As is evident from Table 6-5 and Figure 6-4, all but one of the unit processes within the two systems were similar, generating nearly the same amount of emissions. The major difference was in Electricity Generation (unit processes AB and C1-C3). The non-biogenic equivalent CO_2 emissions per net MWh for the AD case are 101 kg per MWh, mainly due to unburned methane during combustion while for power drawn from the Alberta grid the comparable rate is 973. The AD case has the potential to reduce GHG emissions by 90% per MWh against the current Alberta blended emission rate. This means utilizing feedlot manure in a biogas plant to generate electricity is nearly equivalent to creating an emission free small-scale power plant in Alberta.

Animal feeding and feedlot management practices are virtually identical between the two cases, with the exception of more frequent collection of manure for the AD case. As noted above, the impact of this difference on life cycle emissions is negligible, and hence this is not a significant sensitivity in the analysis. Combustion and power generation efficiency is a critical sensitivity; in particular, methane and nitrous oxide emissions during combustion account for the non-biogenic CO_2 equivalent impact of power generation for the AD case. Kristensen et al. (2003) showed a wide range of emissions from existing combustion engines in Danish CHP plants. Note that power generation efficiency depends on the combustion technology. Most existing AD plants are relatively small, e.g. 0.2 to 2 MW, based on one farm or feedlot, and use an internal combustion engine to drive the power generator. However, many locations have a very large concentration of beef cattle feedlots: Lethbridge, AB, Canada has approximately one million beef cattle in feedlots within a 50 km radius, and Dodge City, KA, USA has approximately five million within a 150 km radius. This kind of concentration of beef cattle could enable a significantly larger AD plant with a combined cycle power plant achieving an efficiency of approximately 55% compared to the 36% efficiency assumed in this chapter.

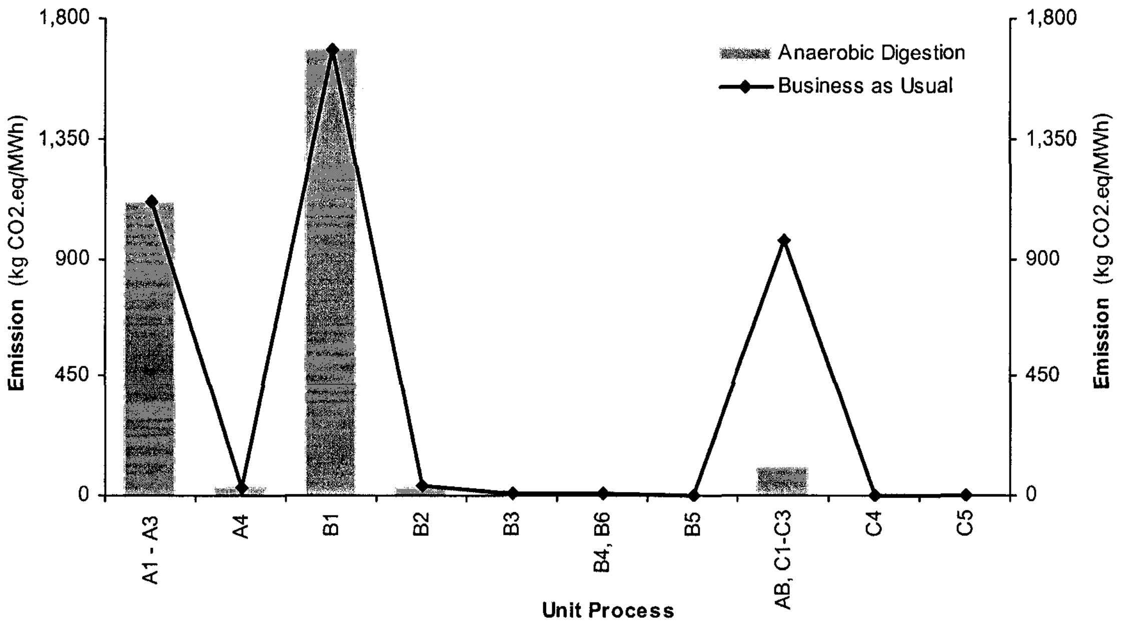

Figure 6-4. GHG emissions produced per unit process in both systems

A second significant sensitivity is what power generation source is displaced when power generation from an AD plant is commissioned. We assume 7x24 operation of the power generator in this chapter, and hence assume that the displaced emissions are based on average Alberta electrical power generation emissions. During the day the marginal power generation source in Alberta is typically natural gas fired power, while in off peak hours (late evenings, early morning and weekends) the marginal power generation source is coal. Depending on when the AD power generator operates and whether there is any gas storage to allow variable diurnal operation, net displaced emissions could vary.

6.6 Conclusions

Enteric fermentation is the main source of GHG emissions in a livestock production system, regardless of using or not using the manure for energy purposes. However, anaerobic digestion of manure can reduce the greenhouse gas impact relative to the current practice of spreading manure from confined beef cattle feeding operations. The anaerobic digestion process converts the raw manure to a fuel biogas and a solid and liquid bio-fertilizer. Using the biogas to produce electricity generates a net 880 kg CO_2.eq/MWh in GHG reduction credits with further credits available if waste process heat could be used. The major difference between "business as usual" systems and manure-biogas-electricity systems is the reduction of GHG emissions for electricity produced in either system; other impacts are negligible. Generating electricity in a manure fermentation plant emits about 90% less GHG compared with the grid average electricity for Alberta power plants. Utilizing feedlot manure in a biogas plant to generate electricity can be considered equivalent to creating an emission free small-scale power plant.

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Chapter 7[††]

Carbon Credits Required to Make Manure Biogas Plants Economic

7.1 Overview

The need to mitigate greenhouse gas (GHG) emissions provides a motivation to pursue a variety of carbon neutral or low carbon energy developments, of which biomass utilization is one class. With rare exception most of these projects are not economically competitive with fossil fuels, and hence will require some form of public mandate or cash injection to proceed, for example through direct public support via government grants or through the sale of greenhouse gas credits. In effect society is pursuing a "negative resource triangle", in which ideally the least costly GHG mitigating projects will be selected.

Anaerobic digestion (AD) of manure with subsequent use of the biogas has the potential to offset energy inputs and environmental impacts of a farm or feedlot (Sandars et al., 2003). AD of manure and use of the biogas for on-site energy production currently does not compete economically with heat or power derived from fossil fuels. Because manure fermentation has the potential to reduce greenhouse gases, the sale of carbon credits is an important factor in AD project economics. This study focuses on the value of carbon credits necessary to make AD profitable in a mixed farming region in central Alberta, Canada.

Previous studies show a wide range of estimated or reported emission reductions through utilization of biogas, mainly for producing electric power. Table 7-1 shows values from four previous studies for estimated reductions in equivalent CO_2 emissions from biogas power plants. Emission credits per tonne of input material can be expected

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to vary with feed type: plants that use only manure produce significantly less biogas per unit input than plants that blend organic wastes in with manure (Jepsen 2002; Nielsen and Gregersen, 2002; Kottner, 2001; Gregersen, 1999). However, variations in CO_2 reduction per unit of biogas production are much more difficult to explain, since variations in biogas quality (methane concentration or net heating value) are far less than the range of carbon credits claimed. Ghafoori et al. (2006) based emissions credits on reducing fossil fuel power generation from the average mix of generation in the Province of Alberta, Canada, which relies predominantly on coal for power generation. The specific mix is 66% coal, 30% natural gas and 4% others (EDC, 2004).

Table 7-1. Estimated emission reductions reported at various biogas power plants

Reference	Input Feedstock	Location	Input	Emission Reductions	
			tonne/year	kg CO_2 / tonne	kg CO_2 / m^3 biogas
West, 2004	mixed feed	Canada	100,000	150	n/a
Munster & Kristensen, 2005	mixed feed	Denmark	450,000	118	3.6
Row and Neable, 2005	manure	Canada	75,000	104	2.8
Ghafoori at al., 2006	manure	Canada	490,000	55	1.4

Little credit was taken in this study for reduced methane emissions from more frequent collection of manure from feedlot pens, based on studies that show that methane emissions from individual cow pats and manure piles decline rapidly, presumably as aerobic bacterial cultures form at the surface of manure (Chadwick, 2005; Holter, 1997). Row and Neable (2005) of the Pembina Institute cite higher emissions reductions for the same study area as Ghafoori et al, (2006), with the main difference being a claim of reduced methane emissions from manure prior to AD. Given that the power generation mix in Denmark includes a higher proportion of hydro power, one would expect lower carbon emission reductions, and we cannot explain the high values of the Munster and Juul-Kristensen (2005). The study area for West (2004) is not defined, and hence the basis for emission calculations is not clear.

Table 7-1 makes evident the merit of building a future consensus on a clear and reproducible basis for computing emission reductions. In this study emission reductions are calculated based on backing out 100% coal or 100% natural gas fuel from an alternate power generation facility, giving emission reductions of 977 kg per MWh, equivalent to 1.5 kg per m^3 biogas, for coal, and 296 kg per MWh, equivalent to 0.5 kg per m^3 biogas, for natural gas. In our base case no credit is taken for methane reduction from more frequent removal of manure from confined feeding operations (CFO's) based on the analysis in Ghafoori et al. (2006). However, given the range of emission reductions presented in the literature we show the impact of assuming higher values as sensitivity.

Scale issues are critical in all biomass projects processing field sourced biomass, and these projects have an optimum size, which arises from competition between two major cost elements in the overall cost of processing biomass. Transportation cost increases with increasing scale as biomass is transported over longer distances, while processing costs per unit of throughput decrease due to lower capital and operating costs per unit of throughput (the economy of scale). Most biomass projects show a similar pattern of overall cost as a function of scale: a steep rise in cost below a critical plant size, and a relatively flat profile of cost at large plant sizes, with an optimum at a given plant size (Jenkins, 1997; Larson and Marrison, 1997; Nguyen and Prince, 1996; Dornburg and Faaij, 2001, Kumar et al., 2003).

In this study we evaluate the cost of AD plants producing either electrical power or compressed pipeline grade natural gas from manure drawn from a mixed farming area, the western portion of Red Deer County, Alberta, Canada, over a range of AD plant sizes. All plants in this study are centralized plants receiving manure from multiple sources. A previous study demonstrated that centralized processing of manure was more economic than farm or feedlot based AD plants for the study area (Ghafoori and Flynn, 2006). The largest single source in the study area is a beef cattle feedlot containing 7,500 head. Even for this size of manure source the economic benefit of centralized processing arising from capital and operating cost efficiency is greater than the cost of manure transport to and digestate transport from a large centralized digester.

We calculate the cost of producing power or gas including a 12% return on capital, and calculate the carbon credit available to the plant. For electrical power production we develop two cases for assumed other income: none, and a more optimistic case based on the following assumptions: sale of 50% of the waste heat from the generation of power at a value of $4 per GJ (half the value of natural gas used in this study) plus receipt of a subsidy of $20 per MWh. For pipeline natural gas production we develop two cases for assumed other income: none, and a subsidy of $2.2 per GJ of natural gas (the same value per unit of biogas as the power subsidy). We then calculate the value of the carbon credit that would be required to make the AD plants competitive, i.e. covering all costs including capital recovery, assuming market values of $60 per MWh for power and $8 per GJ for pipeline grade natural gas. Required carbon credit costs are a means of evaluating AD against other methods of reducing carbon emissions such as green power or carbon sequestration. Note that all values in this study are in year 2005 US dollars and, wherever required, a conversion factor of 1 USD = 1.2 CAD is used.

7.2 Scope of the Model

Red Deer County, Alberta, is a mixed farming area that includes grain and forage crops plus dairy farms, beef cattle (cow calf and feedlot), hog and poultry CFO's that are sources for centralized AD plants. All major manure sources in Red Deer County were identified by size, type and location within the county (RDC Office, 2005), and originate in the western half of the county. Manure production is 34 dry tonnes per square km per year in this region. In the initial stage of model building, seven major areas were thought to produce enough feedstock to potentially supply a stand alone biogas plant. In order to evaluate all options, the cost of power from each of the seven initially identified areas was developed by sizing a plant to the adjacent manure sources. Comparable calculations were done for additional plants of a larger size, so that the county could be served by any of seven, six, four, three, two or one AD plants. As a result a total of 14 AD plant sizes were analyzed.

A detailed model for AD biogas power plants was developed in a study to compare centralized and individual farm based plants. This model, discussed in detail in Ghafoori and Flynn (2006), is used in this study. The model includes transport of solid or liquid manure from the CFO to a centralized plant, processing of manure in thermophilic well mixed digesters, minor cleanup of the biogas to partially remove H_2S and reduce moisture, combustion of the cleaned biogas in an internal combustion engine driven electrical generator, and transport of whole digestate back to the originating CFO for land spreading. Waste heat is available from the internal combustion engine as a circulating hot fluid.

Power generation from biogas is a continuous process unless there is a provision for gas storage. It takes place at small scale (0.5 to 5 MW) and low efficiency (about 40%) compared to natural gas fired power plants: new combined cycle units are typically larger than 100 MW and operate at efficiencies over 55%. Because natural gas is normally considered too valuable a fuel to be used for base load power generation, production of pipeline grade natural gas is being considered as an alternative end product from biogas (Environmental Power Inc., 2005). In this study we add the cost of cleaning and compression of biogas to produce a pipeline grade natural gas at a pressure of 1.5 MPa, as an alternative to the production of electrical power. In this case gas cleanup consists of two separate steps to remove H_2S and CO_2; compression is assumed to be powered by residual methane in the waste gas from the CO_2 removal step. Overall recovery of pipeline grade natural gas is 85% on a methane basis, i.e. 15% of methane in the biogas is exhausted from the gas cleanup stage and used to fuel the engine driving the compressor (Mezei, 2006). Note that power production from AD biogas is far more widely practiced today than production of pipeline quality natural gas, and hence cost estimates are more reliable.

In the case of power generation, 20% of produced power is parasitic, i.e. used internally; in the case of natural gas generation, this power is purchased from the grid at $70 per MWh (the difference between the sale price of power, $60 per MWh, and the purchase price of power, $70 per MWh, is the assumed cost of dispatch and transmission).

7.3 Model Findings

7.3.1 Cost of Producing Power or Gas

Figure 7-1 shows the cost of producing power and pipeline grade gas from AD of manure at a wide range of scales. The various plant sizes shown by the specific data points are based on plants processing part of the available manure, with the largest plant size being a single digester processing manure from all identified sources in the County of Red Deer. Scatter in the points in Figure 7-1 arises because transportation costs are based on specific manure source locations.

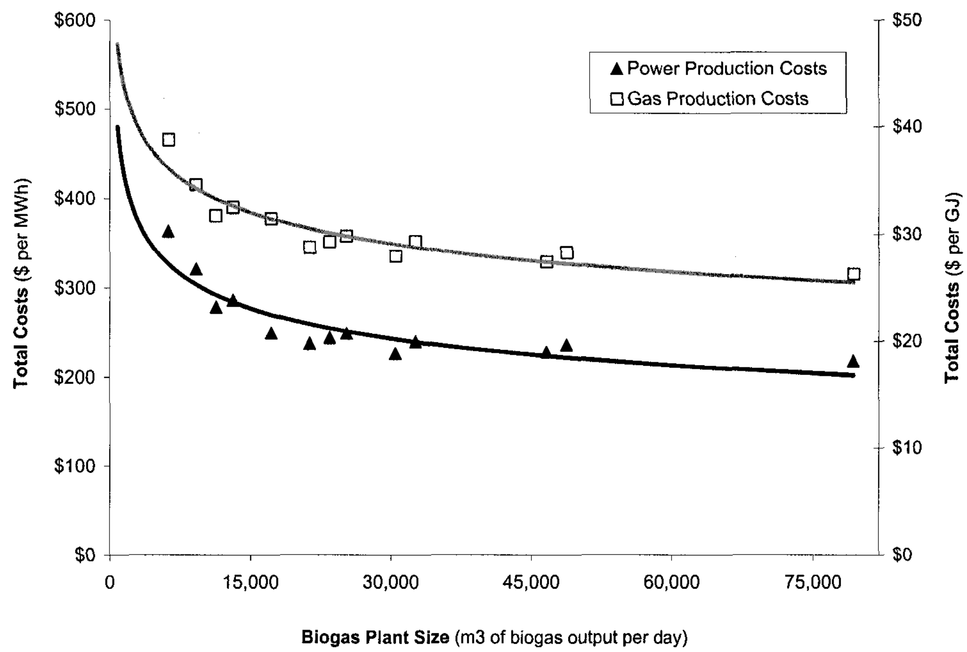

Figure 7-1. Overall cost of producing power or gas at different capacities

Several observations can be made from Figure 7-1:

- A single large centralized digester serving the entire county has a lower cost of production than any smaller size plant, and hence than any combination of smaller sized plants. In a mixed farming area such as Red Deer County the cost of transporting manure to and from an AD plant is less than the processing cost savings from a large efficient plant.

- The trend line of costs, while flattening, is still decreasing, meaning that an optimum size plant is not reached even with manure from all identified sources in the county. The addition of manure from nearby locations in adjacent counties would provide small but incremental reductions in the cost of power or gas.

- Costs of producing energy from manure biogas are high: the lowest cost of power is over $220 per MWh (22 cents per kWh), and the lowest cost of gas is over $25 per GJ. One factor in the high cost is the relatively low yield of biogas from manure streams (in this study, 35 m^3 of biogas per m^3 of manure); many AD plants add organic waste streams such as food processing wastes or crops to increase gas yield and reduce production costs.

At the largest plant size in Figure 7-1, more than 60% of the cost of produced energy is transportation, of which more than half is the cost of digestate return because of the increase in volume of digestate compared to solid manure streams. Digestate processing to produce a compact dry fertilizer and a dischargeable water stream would significantly reduce the transportation cost of centralized AD processing of manure, but the overall cost impact of this is not known because commercially available processes to recover fertilizer from the liquid component of digestate are not available. However, given the complex chemical and physical processing steps involved in the liquid digestate treatment steps, we believe that this will be uneconomic in small distributed plants. Hence, one benefit of large centralized digesters in addition to the cost savings identified in Figure 7-1 is the potential enabling of digestate processing in the future.

7.3.2 Carbon Credits

As noted above, the amount of carbon credits generated in a biogas plant depends on various factors, including:

- Biogas yield per tonne or m^3 of input
- Whether emission savings arise from reduced on-farm manure storage time
- The source of displaced power for power generation
- Whether the CO2 stream could be sequestered for gas production, for example through collection and injection into depleted gas reservoirs

CO_2 sequestration would make the project eligible for a double carbon credit, one for using renewable rather than fossil fuel and one for removing carbon from the atmosphere. Note that CO_2 sequestration would likely only be economic for larger scale

AD plants. Due to lack of reliable data on the required capital investment, in this paper we have assumed no CO_2 sequestration after CO_2 removal. Hence the only source for carbon credits is the amount of fossil CO_2 reduced by the amount of natural gas being displaced by the biogas methane generated, i.e. 2.75 tonne CO_2 per tonne of CH_4. For power generation we calculate carbon credits based on two alternative scenarios for the displaced fuel source, coal and natural gas. As noted above, carbon emission reductions are 977 and 296 kg of CO_2 per MWh respectively, and the cited range of carbon emission reductions is considered as sensitivity.

Emission reductions for the production of pipeline gas are independent of AD plant feed rate. For power generation, electrical efficiency is estimated to increase from 37% at smaller scales up to 43% at 3 MW and above. Figure 7-2 shows the carbon credits as a function of AD plant size.

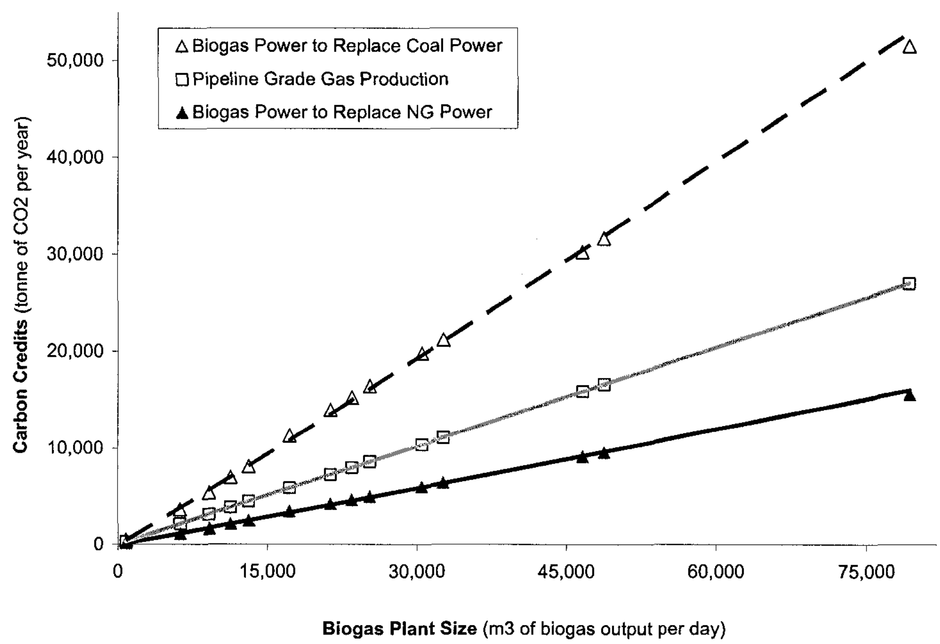

Figure 7-2. Carbon credits generated in gas or power production at different capacities

Figure 7-2 illustrates that the carbon credit available from the production of pipeline grade gas is greater than the credit available from power if the displaced fossil fuel is natural gas. The reason for this anomaly is that power generation from fossil fuel natural gas takes place in large co-gen or combined cycle units; as noted above, size is typically over 100 MW and efficiency is greater than 55%, whereas production of power from biogas fuelled internal combustion engine driven generators, even the largest one in this study, has an efficiency of 43%. From a carbon management perspective, it is more effective to produce pipeline grade gas and transport it to a large efficient power plant.

7.3.3 Revenue Streams to Offset Costs

The prime source of income for an AD plant comes from the sale of energy; in this study we assign a value of $70 per MWh for power and $8 per GJ for gas. Three other income sources are included in this study: the sale of waste heat (power generation cases only), direct subsidy payments, and the sale of carbon credits.

For waste heat, in one case the study assumes that 50% of the available heat can be sold as a hot water stream to a nearby user at a price of $4 per GJ, or half the equivalent value of natural gas (the rest of the heat is assumed either to be used to warm up the digesters or to be lost, for example in flue gas). Subsidy payments are in effect a social payment to achieve a social goal, either green power or manure management. In the optimistic case the study includes an arbitrarily set value of $20 per MWh for the power cases and $2.2 per GJ for the pipeline gas production case, equivalent subsidies per unit of biogas input.

In theory, two other revenue sources might be possible for AD plants: fertilizer sales and tipping fees (a charge per tonne of manure paid by the farmer or feedlot operator). Current AD technology can produce fertilizer by two possible alternatives, either a single digestate stream with a solids concentration of about 7%, or a moist solids cake with a 70% moisture content and a liquid digestate stream. Both whole digestate and the liquid fraction have a low fertilizer value given their mass and volume, and hence are land spread near the source.

A future goal for AD plants is a digestate processing technology that produces the moist solids cake and a dry or very concentrated liquid fertilizer derived from recovering nutrients from the liquid fraction of the digestate, leaving a water stream that can be discharged to surface waters (Xergi, 2005). This technology is not available today, and hence AD plants do not eliminate the need for land spreading of a low grade fertilizer, they simply shift the material spread from raw manure to processed digestate. Centralized digesters typically return digestate to the farm or feedlot that generated the manure, which is then responsible for its disposal through land spreading.

Since from the farmer's perspective the alternative is spreading manure or digestate, we assume that the fertilizer values have no net value to the AD plant, in that they neither pay the farmer for the incoming fertilizer value nor do they receive a payment for the returned fertilizer value. For the same reason we do not include a tipping fee, since the farmer does not have a net saving from having the AD plant process manure. From the perspective of the farmer, land spreading is still required, and we believe that farmers would resist paying a fee to the AD plant if their net cost is not reduced.

7.3.4 Carbon Credit Required for a Profitable AD Plant

In this study the value of a carbon credit required to balance cost and revenue is calculated, with cost including a 12% pre tax return on capital. Figure 7-3 and Figure 7-4 show the results for the two cases in this study, sale of power or gas, and sale of power or gas plus a subsidy plus sale of waste heat generated in power generation cases.

The required carbon credit value for an AD plant to cover all costs shows a pattern similar to the cost of power and gas from an AD plant: there is a strong impact of scale, required carbon credits are very high for small plants, and the most economic alternative, i.e. lowest required carbon credit value, in this study is for a single AD plant processing manure from all sources in the study area. For a single AD plant with power or gas sales only, the minimum values of carbon credits are $320 per tonne of CO_2 for production of pipeline gas, $150 per tonne for the production of electrical power to displace coal, and $500 per tonne for power to displace natural gas. For the optimistic case, required carbon credit values are $290, $125 and $410 respectively.

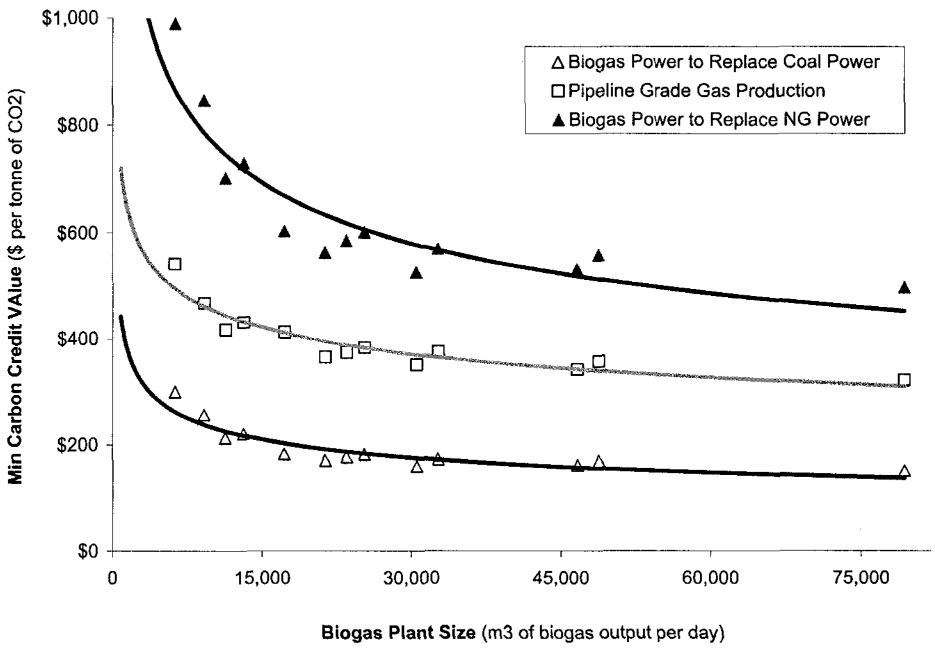

Figure 7-3. Minimum value of carbon credits to offset revenue shortfalls (power or gas sales only)

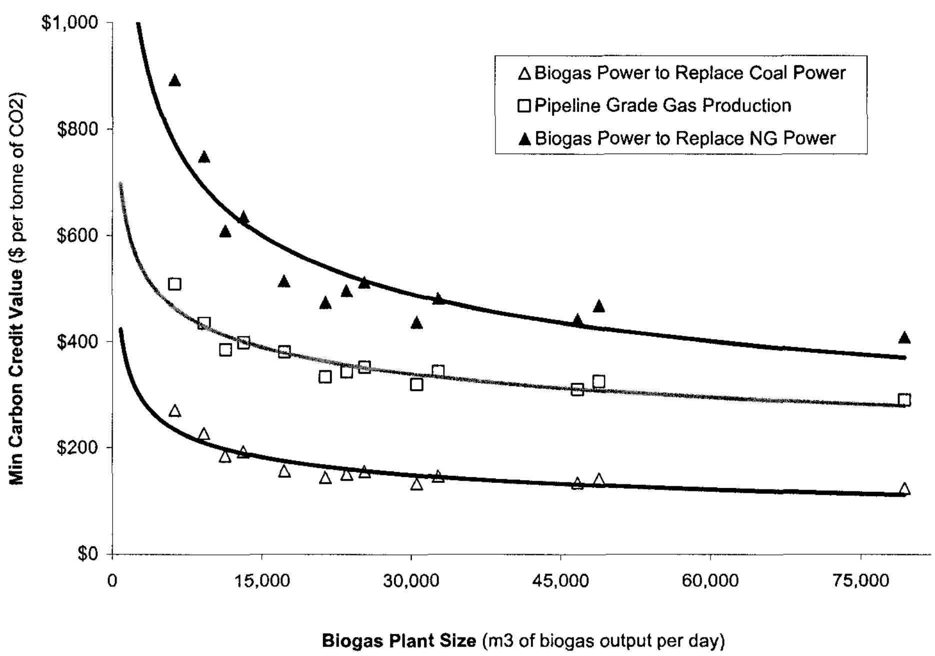

Figure 7-4. Minimum value of carbon credits to offset revenue shortfalls (power or gas and heat sales plus subsidy)

7.4 Discussion

Anaerobic digestion of animal manure to produce biogas and thereafter electrical power or pipeline grade natural gas has a significant economy of scale. The capital savings from large centralized plants outweigh the cost of transporting manure. Centralized plants incur a cost for trucking manure to the plant and digestate back to the source, and get the benefit of lower capital cost per unit of throughput (the economy of scale). As noted above, for a mixed farming area such as Red Deer County, Alberta no farm or feedlot based digester could produce power at a cost lower than that from a single centralized digester processing all manure sources in the county (Ghafoori and Flynn, 2006). A 500 kW power plant using the manure from, for example, 2500 dairy cattle, has a cost of power that is 1.2 times that from an 8 MW power plant, the largest size evaluated in this study.

Despite the savings from large centralized AD plants in mixed farming regions, energy from AD of manure is very expensive. The lowest calculated cost of power in this study, $220 per MWh, is more than twice the average wholesale cost of power in North America. Similarly, the lowest cost for production of pipeline quality gas in this study, $25 per GJ, is more than twice the current wholesale cost of gas in North America. Part of the reason for this is the low yield of biogas from manure: the value used in this study is 35 m^3 of biogas per m^3 of input manure (12% solids basis). This biogas yield reflects the fact that manure has already been processed by the source animal to extract readily available energy. Ruminants in particular subject forage feeds to an anaerobic digestion step in their fore stomach. AD plants feeding municipal solid wastes or purpose grown crops show gas yields three to six times higher per unit of input.

Required carbon credit values to give a return on investment in AD are very high, even in the optimistic case that has a significant social subsidy and, in the case of power generation, the sale of waste heat. The long term value of carbon credits is uncertain, and will depend on a number of factors including the extent to which reduction in fossil fuels is mandated. However, in 2006 carbon credits have a value less than $50 per tonne of CO_2, and this study shows a level well over $150 is required. Even for a sensitivity case using the highest cited value of carbon emission reduction per m^3 of biogas for power generation from AD, 3.6 kg of CO_2 (Munster and Juul-Kristensen, 2005), plus the assumptions of the optimistic case including a significant social subsidy and heat sales in addition to the carbon credit, the value of the required carbon credit is $50.

The implication for AD is that relative to other methods of reducing fossil carbon AD plants processing manure from mixed farming areas appear to be relatively uneconomic. The emergence of AD in such areas may arise from requirements to treat manure in order to address water quality concerns or odor issues, but it will not likely emerge from the economic value of the carbon credit. One other possible factor to motivate AD processing of manure is avoidance of phosphate buildup in soils. More sophisticated digestate treatment could recover phosphate in forms that could be economically transported to areas that need phosphate addition.

It was noted above that from a carbon management perspective production of pipeline quality natural gas from biogas gives a larger carbon emission reduction than production of power from biogas if natural gas is the fossil fuel power source that is displaced. The greater efficiency of large combined cycle power plants compared to the less efficient small internal combustion engine powered generator associated with small power generation plants creates a larger carbon savings. There is an additional benefit from producing pipeline grade gas in this circumstance: the gas can be stored within the pipeline system itself (through small changes in the pipeline pressure level) so that power from natural gas can be generated at periods of peak usage. In deregulated power markets this can result in the sale of power at peak pricing. AD plants that generate power do not have an economic form of gas storage and hence typically generate power on a continuous basis, whereas many large power plants using natural gas as a fuel are designed to be peaking plants. Hence if biogas is being produced in a place where the incremental fossil fuel for power generation is natural gas, then production of pipeline quality natural gas from the biogas gives a double benefit of higher generation efficiency and higher value at time of generation.

7.5 Conclusions

One key finding of this study is that anaerobic digestion of manure from mixed farming areas has a significant economy of scale. Larger plants produce power or gas at a lower cost than smaller distributed plants because the savings from more capital efficient large plants exceeds the added cost of transporting manure. For the area studied, a single large anaerobic digester treating all manure in the county is more cost effective than any plant of a smaller size. Even for the most cost efficient plant in this study, the cost of power or pipeline quality natural gas is very high, more than twice the value of fossil fuel derived power or gas. The carbon credit value required to support AD processing of manure is more than $125 per tonne of CO_2. While AD processing of manure may be warranted by concerns over water quality, odor, or excess phosphate levels in soils, these results show that AD processing of manure is not an economic means of reducing fossil carbon emissions relative to current values for carbon credits.

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Chapter 8

Conclusions and Recommendations for Future Research

8.1 Conclusions

In summary, the key conclusions of this study are:

- The calculated costs of power from AD show a pattern typical of many biomass processing projects involving the transportation of biomass: costs rise slowly above an optimum plant size, and very sharply below that.

- Power from anaerobic digestion of manure is not cheap relative to other alternatives for carbon neutral energy such as power from straw ($50 MWh^{-1} at their optimum size):

  a) Red Deer County, AB is a typical mixed farming area; for the portion of the county included in this study the production of manure is 34 dry tonnes per square km per year. The cost of power from AD processing of manure is high, greater than $218 MWh^{-1} for all cases evaluated. Here, a single centralized AD plant is more economic than any combination of multiple plants, including farm-based plants. The critical factor favoring a centralized digester is the lower capital cost per unit of input/output realized in a large economically sized plant; this savings is greater than the cost of transporting manure to and digestate from the plant.

  b) One portion of Alberta, from north of Calgary through the County of Taber south and east of Lethbridge, has over one million beef cattle in feedlots at any point of time. In this area (280 dry tonnes of manure per square km per year), an individual feedlot with more than 40,000 animals would have a lower cost of power than the most economic large centralized plant that returned digestate.

This centralized plant near Lethbridge treating the manure from 560,000 beef cattle could produce power at \$138 MWh^{-1}. Pipeline transport of manure and digestate would be warranted if a large centralized plant were built near Lethbridge. The 40,000-animal cutoff for feedlot-based processing being more economic than centralized processing would rise to 250,000 if digestate processing were adopted

- Centralized manure processing offers advantages other than those factored into the cost calculations in this study. These include:

  a) The potential to economically process digestate into a concentrated dry fertilizer and a disposable water stream, which could not be economically achieved in small distributed plants.

  b) The potential to produce pipeline gas rather than electric power. Producing pipeline grade natural gas also produces a CO_2 rich vent stream that has the potential to be sequestered if suitable geological formations are available. In such a case, a double carbon credit could be earned.

- The fixed cost of transportation, i.e. the cost of the truck and trucker while loading solid or liquid manure, is a large component of transportation cost for any configuration of AD. Unlike trucking cost, which is virtually independent of scale, the cost of transport by pipeline is highly scale dependent. Hence at larger scales, manure pipelines could be used to deliver manure to a centralized plant and return the processed digestate back to the source CFO for spreading. Pipeline transport of beef cattle manure is more economic than truck transport for the manure produced by more than 90,000 animals. Pipeline transport of digestate is more economic when manure from more than 21,000 beef cattle is available. Two-way pipelining of manure plus digestate is more economic when manure from more than 29,000 beef cattle is available.

- Power produced from biogas from AD of manure reduces the GHG emissions by 880 kg CO2.eq MWh^{-1} with further credits available if waste process heat could be used. However, required carbon credit values to give a return on investment in AD are very high (over \$150 $tonne^{-1}$), even in the optimistic case that has a significant social subsidy and, in the case of power generation, the sale of waste heat.

To conclude, biogas power is not cheap compared to current fossil fuel based power or power from other renewable resources such as straw. For AD biogas power to make sense there would need to be some other driver, for example phosphate, pathogen or odor control. Biogas from manure is an agricultural issue, not an energy issue.

8.2 Recommendations for future research

There is no commercial scale digestate processing technology available for biogas plants; only simple solid-liquid separation technologies are available with the liquid stream still requiring to be land spread. Digestate processing, in which nutrients are recovered from digestate and a dischargeable water stream is created, is an appropriate area of research. Relative to incoming solid manure, there is a 2.4 fold increase in the volume of digestate; the cost of returning this amount back to the manure source for spreading is a large portion of the overall costs. Another critical factor that would drive digestate processing is managing an excess of phosphate in local soils, a problem that is critical, for example, in some parts of North America. Excess phosphate in soils can contaminate water and lead to human health issues, since high phosphate concentrations interfere with human calcium balances. Digestate processing would allow the sequestration of phosphate, for example through precipitation with lime, so that it can be moved to areas where it is needed as a soil nutrient and not re-spread on land that has a high phosphate index.

Pipelining manure is another appropriate field of research. Dairy and pig manure is routinely pumped, but pumping of slurried beef cattle manure is not a common practice, and distance pipelining of beef cattle manure slurry has not been demonstrated over long periods of time. More research is needed on the degree of maceration required for input manure to avoid plugging problems from straw and other bedding material that is mixed with manure.

Integrated bioenergy projects are gaining more and more attention these days due to enabling the inter-utilization of by-products and providing an efficient and closed system of producing bioenergy. In these projects, for example, a biogas plant is coupled with a biodiesel production facility to use some of its by-products to produce biogas and in turn supply the biodiesel plant with the heat and power. The digestate stream can be spread as fertilizer on the crop fields feeding the biodiesel plant and the solids stream from the bio-diesel plant can be fed to animals producing manure for the biogas plant. Overall, this integration should result in savings for both plants and cooperating farms and feedlots. Economics of these integration projects are not fully known and yet to be studied in detail.

Appendix I

An Economic Model to Evaluate Cost of Biogas Power at Different Scales:

User's Manual & Scope of the Model

Note:
Two generalized versions of the model for farm-based and centralized processing are included in a CD ROM attached to this thesis, and may be used without permission. The CD ROM also includes two specific cases of the model for the Red Deer County, AB and the Feedlot Alley, AB (details of these two areas are discussed in Chapter 4.)

Section I: User's Manual

Model Overview: Centralized and Farm-Based

The generalized economic models are developed to calculate the cost of producing power at anaerobic digestion (AD) plants utilizing animal manure. The purpose of the models is to help identify whether multiple distributed digesters or fewer centralized digesters are more economic, i.e. to identify whether it is more economic to transport manure to a large capital efficient unit or reduce transportation costs by shipping to smaller units or by processing on farm.

The technology is assumed to be thermophilic anaerobic digestion followed by minor gas cleanup (moisture control) and combustion of the gas in an internal combustion engine electrical generation module. Cost of transporting manure from farms to a centralized anaerobic digestion (AD) plant and the digestate from the AD plant back to the farms are integrated with the cost of processing manure and producing power at the AD plant. The detailed scope of the model can be found in the second part of this document.

The models are based on Microsoft Excel® software and consist of multiple spreadsheets put together in order of calculation. The user first enters required data on the location plus the type of farming practice and the number of animals for each source. After this, the model calculates the cost of producing power at 9 different centralized plant settings plus the cost of producing power, if each of those manure sources had its own small scale plant. Assumptions used in each of the options are discussed in detail below:

Centralized Biogas Plants

To better explain the way the general centralized model works, consider the following example:

Suppose 10 different manure sources are located in an area crossed by the "Road 44", "Highway 10" and "Highway 11a". Figure 1 shows the location of these sources in the area. To enter the locations of these sources into the model, you need to assume an arbitrary base point and calculate the relative grid distances of each of these sources from that base point. This location of the base point has no impact on the final results of the model. For the purpose of this example, we choose the intersection of "Road 40" and "HWY 10", identified with a black circle. Note that location and distance inputs to this model have to be based on grid measurements (in km) and not direct distances.

In areas that have rectangular road layouts, grid measurements are an accurate measure of transportation distance. Where many or most roads run at an angle the model may overstate transportation distances. However, the impact is minor, particularly since for most centralized digesters the distance fixed cost of transportation, i.e. loading and unloading, far exceeds the distance variable cost of transportation, i.e. time on the road. Table 1 contains the input farm data plus the relative distance of each of the sources from the base point (we assume each grid is 1x1 km). Note that by choosing this base point, the relative distance of Farm #8 on the Y-axis is negative.

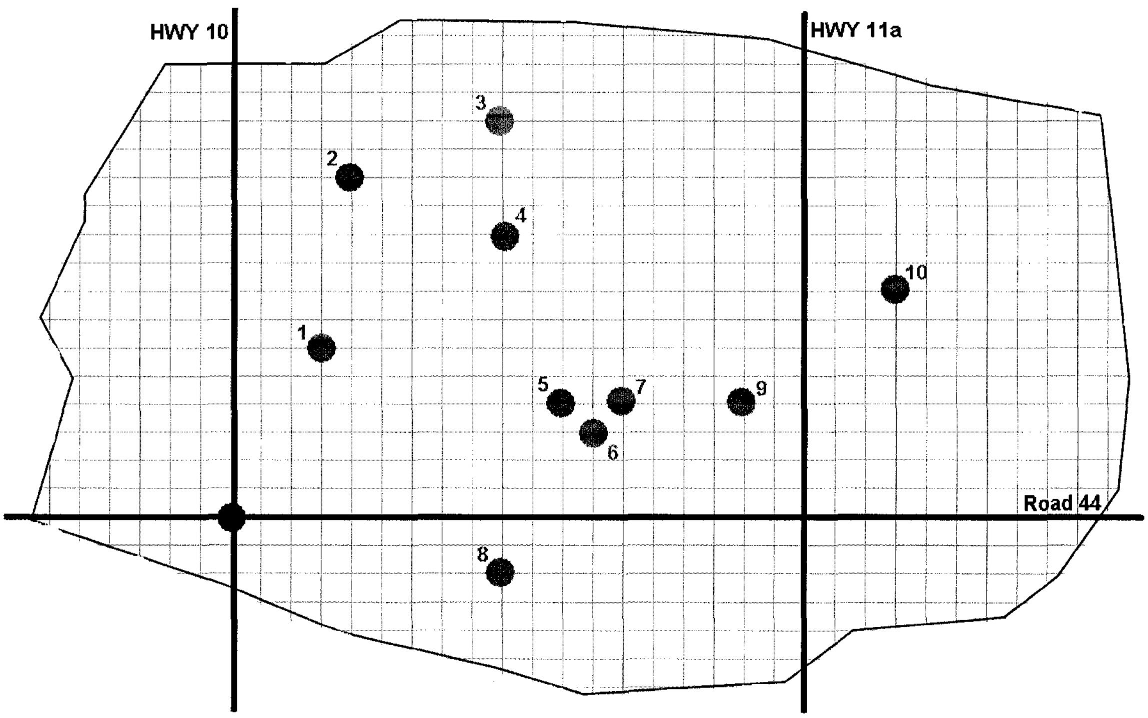

Figure 1. Manure Sources Scattered in an Assumed Area

After entering input data, the model breaks the original area into 4 equally sized sub-areas, as shown in Figure 2, and dedicates these sub-areas to 9 different combinations of centralized plants, as shown in Table 2. For example, Plant 2 uses all manure produced in area 2, Plant 5 processes manure produced in areas 1 and 2, and Plant 9 processes manure from all four areas.

Table 1. How to Input Farm Data into the Model

Farm Name	Relative Distance X	Relative Distance Y	Farm Type	No. of Animals
	km	km		head
Farm #1	3	6	feedlot	10000
Farm #2	4	12	dairy/cow	200
Farm #3	9	14	feedlot	1500
Farm #4	9	10	hogs/brs	1000
Farm #5	11	4	hogs/sow	2500
Farm #6	12	3	cow/calf	100
Farm #7	13	4	hogs/brs	1000
Farm #8	9	-2	hogs/sow	800
Farm #9	17	4	hogs/suc	6000
Farm #10	22	8	dairy/rep	150

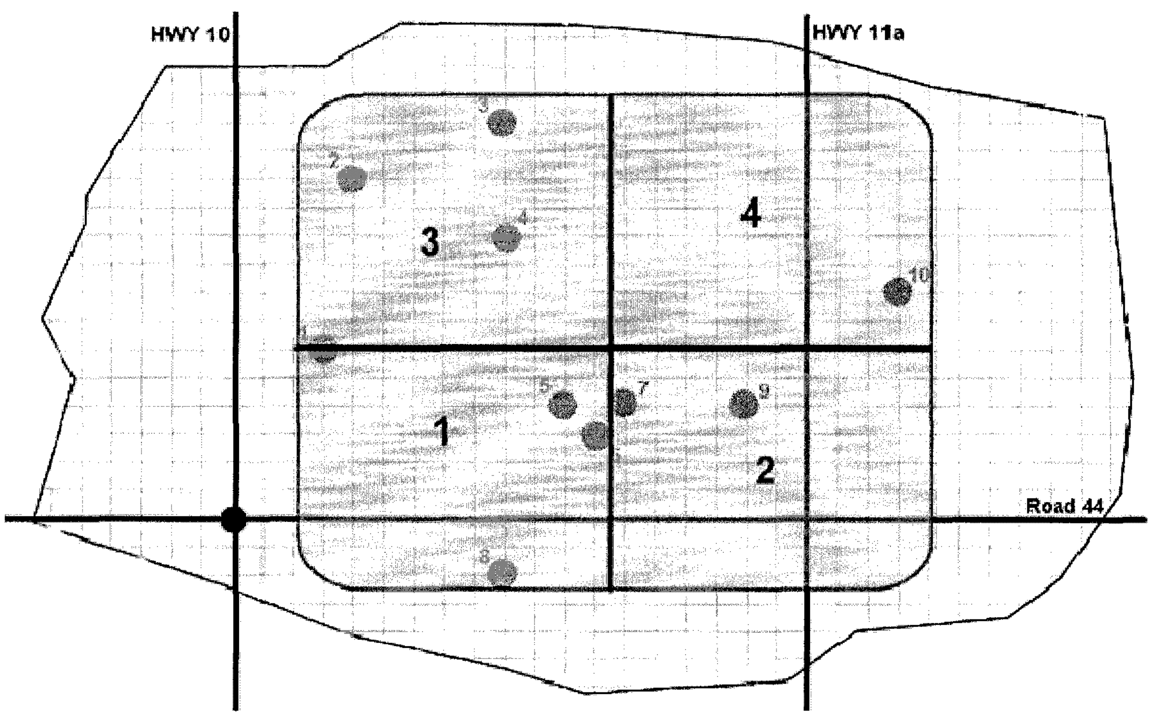

Figure 2. Four Sub-areas Identified by the Model

Table 2. Combination of Areas Dedicated to Each Centralized Plant

Area Name	Plant 1	Plant 2	Plant 3	Plant 4	Plant 5	Plant 6	Plant 7	Plant 8	Plant 9
Area 1	■				■	■			■
Area 2		■			■		■		■
Area 3			■			■		■	■
Area 4				■			■	■	■

The location of each of these plants is decided in a way that the cost of manure and digestate transport is minimized; using the weighted average method, the plants are closer to the sources producing more manure. The size of each of these plants is determined by the volume of input manure. The model estimates the biogas potential and assigns a proportional co-gen unit to each plant. The cost of manure transport, biogas plant capital and operating costs (including maintenance and labor costs and a 12% internal rate of return on investment), and the cost of digestate return are calculated thereafter. The default parameters used in each part of the model are explained in the second part of this document: Scope of the Model.

The model then combines plants into scenarios, where every scenario processes all of the manure identified within the area. Thus, one scenario will be four separate plants, and one scenario would be a single plant serving all manure sources in the area. The Table 3 shows the configuration of the various scenarios. Weighted average power cost is calculated for each scenario.

Table 3. Scenario Definition within the Generalized Centralized Model

Scenario	# of Plants	Configuration*
1	4	1, 2, 3, 4
2	3	1+2, 3, 4
3	3	1+3, 2, 4
4	3	2+4, 1, 3
5	3	3+4, 1, 2
6	2	1+2, 3+4
7	2	1+3, 2+4

* Configuration numbers refer to the areas identified in Figure 2

Farm-based (or Feedlot-based) Plants

The parameters used for the farm-based plants are similar to those used for centralized plants with 2 exceptions:

- Unlike the centralized plants that incur double transportation (manure from farm to plant and digestate return to farm), there is no additional transport in farm-based plants since the biogas plants are located either within or beside the farms.

- Due to smaller size of the farm-base plants compared to the centralized ones, it can be assumed that the farmers are capable of operating their plants (some technical training maybe required). This will eliminate the cost of dedicated professional operating labor from overall cost of running the plants. Caution should be taken while applying this assumption to the large farm-based plants (e.g., 500 kW and over) as running these plants maybe complicated enough and sufficiently time consuming to require hiring professional operators.

The model calculates the cost of producing power in small scale farm-based plants considering the assumptions made above and compares that with the cost of producing power in the centralized plant among the 9 plants discussed above that produces the cheapest power.

Centralized Model Structure

A complete list of worksheets in the centralized model is included below with a short description for each worksheet:

"START HERE - Enter Farm Data"

Used for complete farm data input to the model. Very similar to Table 1 mentioned above. This is the only place users enter manure source data. If one farm has more than one animal type, the data is entered on successive lines, with the same location parameters. There is also room for adding other type of farming practices.

"1. Model Parameters"

Contains a complete list of parameters used within the model. All other worksheets are linked to this sheet, hence, users can change any of these parameters based on their own judgment and the change will be applied automatically throughout the model. A complete list of these parameters is included at the end of this appendix.

"2. Biomass Sources"

Used by the model to calculate amount of manure produced from each source and also each source is assigned to an appropriate area. Some other calculations are also done for further use throughout the model.

"3. Plant Combinations"

An illustration to show the user how the sources are assigned to areas and how the plants are dedicated to different combinations of areas. Similar to Figure 2 and Table 2 discussed above.

"4. Summary of Plants"

This sheet contains a summary of all information about the capacity and location of each plant plus the annual manure and digestate transport costs for each plant option.

"5. Biogas Potential"

Biogas yield and the gross and net power potential for each plant are calculated in this sheet.

"6. Manure Transport Costs"

The unit cost of transporting manure from sources/areas to each plant is calculated here.

"7. Manure Processing Costs"

Calculates the capital cost of building the biogas plants plus the annual maintenance and operating labor costs to run the plants.

"8. Digestate Return Costs"

The unit cost of returning digestate to each source is calculated here.

"9. Total Power Costs"

Contains a summary of the overall power costs at each plant. Also 8 different scenarios are developed to process all manure produced in the area in different combinations of plants.

"Chart-PowerCosts if Centralized"

A graphic illustration of the overall costs at each plant. The minimum power cost is also identified here.

"Chart-WeightedAveragePowerCosts"

The weighted average cost of producing power for the entire area is included in this chart.

"10. Revenue Analysis"

Four different revenue streams are identified in the model. In this sheet the annual sales revenue for each plant is calculated.

"11. Cost-Revenue Analysis"

The annual costs with or without capital recovery are compared against the annual revenues.

"Chart-RevenueVsCost"

A graphic illustration of the overall costs against the annual sales revenues for different scenarios.

"12. Farm-based Plants"

Assuming each manure source is supposed to have its own plant, the overall cost of producing power at each of these individual farm-based plants are calculated here. To facilitate further comparisons, farm-based plants are divided into groups with 100 kW incremental capacities. The weighted average power costs for each group are calculated and used thereafter.

"Chart-Centralized or Farm-based"

A graphic illustration of the overall costs of producing power in farm-based plants compared to the minimum cost scenario in centralized plants.

Farm-based Model Structure

The structure of the farm-based model is identical to the centralized model with the exception that some unnecessary worksheets are removed. This model includes the following worksheets, with the description as above for the centralized model.

"START HERE - Enter Farm Data"

"1. Model Parameters"

"2. Biogas Potential"

"3. Manure Transport Costs"

"4. Manure Processing Costs"

"5. Revenue Analysis"

"6. Cost-Revenue Analysis"

"Chart-RevenueVsCost"

Section II: Scope of the Model

General Assumptions

- The process utilized for feedstock processing is anaerobic digestion (AD) with subsequent biogas utilization in a cogeneration unit to produce both heat and electricity.

- The plants are located in the weighted average center of the areas based on the sources feeding the plant. Hence, the plant is closer to those sources producing higher amount of feedstock, and the location of the plant minimizes total transportation cost.

- All cost components are converted to cost per net MWh of power output.

Feedstock

- The current feedstock sources in the model are livestock manure (hog, dairy, beef, etc.). Other biomass sources (organic wastes, slaughter house waste, etc.) are not included in the model due to insufficient information about the amount and type (e.g. moisture level) produced in each one. The model is fully capable of adding these sources in the future if information becomes available.

- Manure from dairy and hog operations is assumed to be delivered as liquid in tank trucks. Manure from these sources is shipped at the same moisture content that it is produced from livestock.

- Manure from feedlot operations is assumed to be delivered as solid in open trucks. Manure as produced in the feedlot has a moisture level of 88%; however, the manure moisture level reduces while sitting in the pen. The moisture level of shipped feedlot manure is a variable in the model; the default value is 75%.

- The cost of transporting liquid and solid manure is estimated based on specific cost data for liquid and bulk transport. The transportation cost is broken down into two components. The first is a distance fixed cost (DFC, charges independent of the haul distance), which primarily arise from loading and unloading. The second is a distance variable cost (DVC, charges proportional to haul distance). Both DFC and DVC for solid and liquid transport are variable in the model. Default values for DFC and DVC for liquid transport have been based on per hour charges for a 20 and 40 tonne truck provided from the trucking industry. In each case, the default value of DVC is 11 cents per tonne km. The default value of DFC is $6 per tonne for dry manure and $4.20 per tonne for liquid manure.

- The density of manure is assumed to be the same for all types of manure; 1000 kg/m3 is used in this model based on standards published by the American Society of Agricultural and Biological Engineers (ASABE). Manure density is a model variable.

- Incoming materials to each plant are mixed and water is added as needed to achieve a moisture level of 88% in the processing plant.

- Materials receiving and digestate shipping take place 360 days per year.

- The plant is responsible to transport the feedstock to the plant and also to return the digestate back to the sources, i.e. the costs for transportation each way is included in the model. Each source will receive a proportional return of digestate based on the dry solids shipped to the plant. Each source of liquid manure is assumed to have underground storage of more than 40 cubic meters for raw manure, to allow year round pick up. All manure sources are assumed to have constructed lagoon capacity equivalent to 10 months of storage capacity for digestate, reflecting the short time window in which digestate is spread on fields. The model assumes that each source of manure is also responsible for spreading the digestate on fields, i.e. no cost for land spreading is included in the model.

- Digestate processing to recover nutrients or a semi-dry solids stream is not included in the base model since technologies have not been demonstrated at a commercial scale. Solids removal would still require land spreading of the liquid only digestate due to its high nutrient content.

Biogas Plant

- The plant includes all necessary equipment for receiving feedstock, feedstock processing, biogas generation, power generation and digestate buffer storage and loading.

- The plants provide both solid and liquid storage capability for incoming materials.

- The model assumes an annual shutdown of 12 days and unscheduled downtime of 13 days per year (340 days of operation). Hence, the combined availability of the plant, considering both scheduled and unscheduled downtime, is 93.2%. Plant availability is a model variable.

- All proposed plants have a typical design similar to existing Danish centralized AD plants and the IMUS biogas plant, developed by the Alberta Research Council and the Highmark Renewables Inc. in Vegreville, AB.

- Input total solids to the digesters is 12%, default values in the model are volatile solids content of 85% of the total solids, and 45% of the added volatile solids are biodegraded/destroyed. The process produces 0.48 m3 of methane gas per kg of destroyed volatile solids. Hence, volume shrinkage due to gas production is 5%, i.e. digestate output volume is 95% of the incoming plant volume.

- The produced biogas is assumed to contain 63% methane, 33% carbon dioxide and 4% trance gas; the biogas LHV is 20.7 MJ/m3.

- The cogeneration unit electrical and thermal efficiency is based on the size of the unit, ranging from 37-43% (electrical) and 44-49% (thermal).

- The plant parasitic power consumption is 20%; the net power output is 80% of the gross power production.

- The default cost estimate for an installed biogas plant is based on the actual cost of Danish centralized biogas plants adjusted for inflation. A cost factor is a model parameter to scale estimated cost in proportion to actual Danish plant cost. The default value of the cost factor is 80% based on IMUS estimates of the cost of future plants in Canada.

- Based on the published literature and also the cost of actual plants built, there is a strong economy of scale in building a biogas plant: doubling the size of the plant would not double the costs. A scale factor of 0.60 is used for the purpose of scaling up/down the size of the plants.

- The operating staff working hours are 12 hours a day on a 7 day week basis and the flat rate of 35 $/hr is paid including the salary and benefits.

- The required operating staff varies with the plant size. The model assumes 1 staff for the capacities up to 1500 kWe, 2 staff for capacities up to 3000 kWe, and 3 staff for capacities greater than 3000 kWe.

- The plant annual maintenance costs are estimated at 3% of the total capital costs.
- For the purpose of recovering the capital costs, the assumed pre tax return on capital is 12%; a plant life of 30 years is assumed. Both of these values are variable in the model.

Table 4. Complete List of Parameters and Their Default Values Used within the Model

Model Sections	Value	Unit
Manure Properties		
As shipped moisture content of solid manure	75%	feedlot, cow/calf, poultry
Manure density	1.00	tonne/m3
Manure and Digestate Transport		
Shipping days	360	day/year
Solid manure (un)loading costs	6.00	$/tonne
Solid manure hauling costs	0.11	$/tonne.km
Liquid manure (un)loading costs	4.19	$/tonne
Liquid manure hauling costs	0.11	$/tonne.km
Truck capacity	20	tonne
Digestate solids content	7.4%	
Biogas Potential		
Operating days in a year	340	day/year
TS in input manure	12%	
VS/TS in input manure	85%	
Methane yield	0.48	m3/kg VS destroyed
Biodegradability	45%	VS destroyed/VS added
Methane content in biogas	63%	
Manure Processing and Biogas Utilization		
Operating days in a year	340	day/year
Plant operating life	30	year
Capital cost scale factors	0.60	based on biomass input
Capital cost coefficients	192,640	based on biomass input
	15,663	based on biogas yield
Relative capital cost reduction	80%	of Danish plants
Working hours (7 day week)	12	hour/day per employee
Staff average salary	35	$/hour
Plant parasite electricity use	20%	of generated electricity
Maintenance costs	3%	of capital costs/year
Discount rate	12%	

Revenue Items

Power sales	70	\$/Mwh$_e$ net
Fraction of available heat sold	40%	
Heat sales	7	\$/GJ$_{th}$ gross
CO2.eq emission savings	0.880	tonne/Mwh$_e$ net
Carbon credits	15	\$/tonne CO2.eq
Subsidies	20	\$/Mwh$_e$ net

Plant Operating Labor

for capacities (in kW) over	assumed operating labor requirements	
0	1	person
300	1	person
1,500	2	person
3,000	3	person
5,000	3	person

Co-Gen Unit Electrical Efficiency

for capacities (input biogas in m3/day) over	assumed electrical efficiency
0	37.2%
4,000	37.6%
6,000	38.0%
7,000	38.2%
9,000	39.0%
11,500	40.2%
15,000	42.9%
17,500	42.7%
23,000	42.4%

Co-Gen Unit Thermal Efficiency

for capacities (input biogas in m3/day) over	assumed thermal efficiency
0	45.4%
4,000	49.2%
6,000	49.0%
7,000	49.0%
9,000	48.7%
11,500	45.9%
15,000	43.6%
17,500	43.8%
23,000	43.7%

Appendix II

Sensitivity of the Power Costs to Parameter Changes

Sensitivity Studies

A major benefit from developing a model for manure digestion is that it allows the analysis of "what if" questions. For example, what if biogas yields were 10% higher - what is the impact on the cost of power? What if the cost of the manure digester plant is 30% less than the default value in the study? What if trucking costs increase by 50% because the cost of fuel goes up?

The default values in the model of Red Deer County show that a single centralized digester could produce electrical power for $262 per MWh (26 cents per kWh) (All costs in this Appendix are in 2005 CAD). The four figures below show the impact on power cost for the following cases:

- Yield of biogas over the range of 35-105 m^3 per m^3 of manure (at 12% solids level).
- Concentration of methane in the biogas of 57% to 71%.
- The solids in the digestate are separated and sold for $0 to $70 per tonne.
- The plant receives a carbon credit, calculated based on an Alberta generation mix of 66% coal, 30% natural gas, and 4% from other sources, of $0 to $15 per tonne.

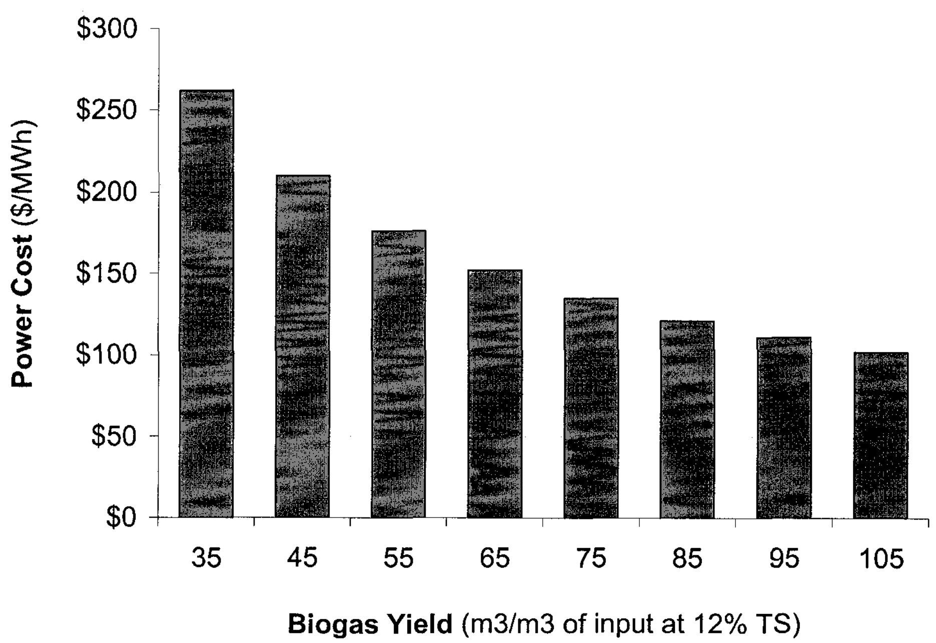

Figure 1. Sensitivity of Power Costs to Changes in Biogas Yield

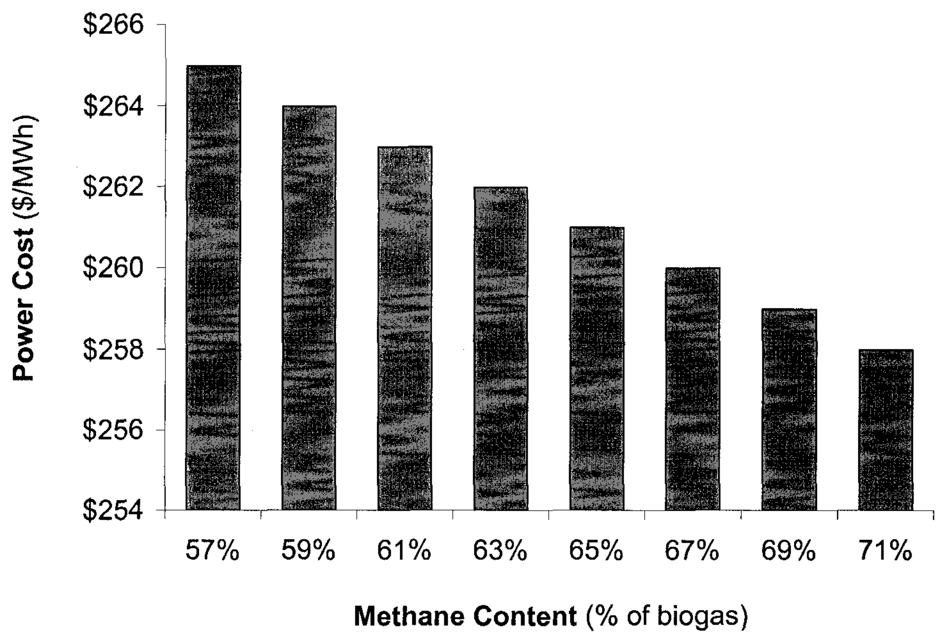

Figure 2. Sensitivity of Power Costs to Changes in Methane Content

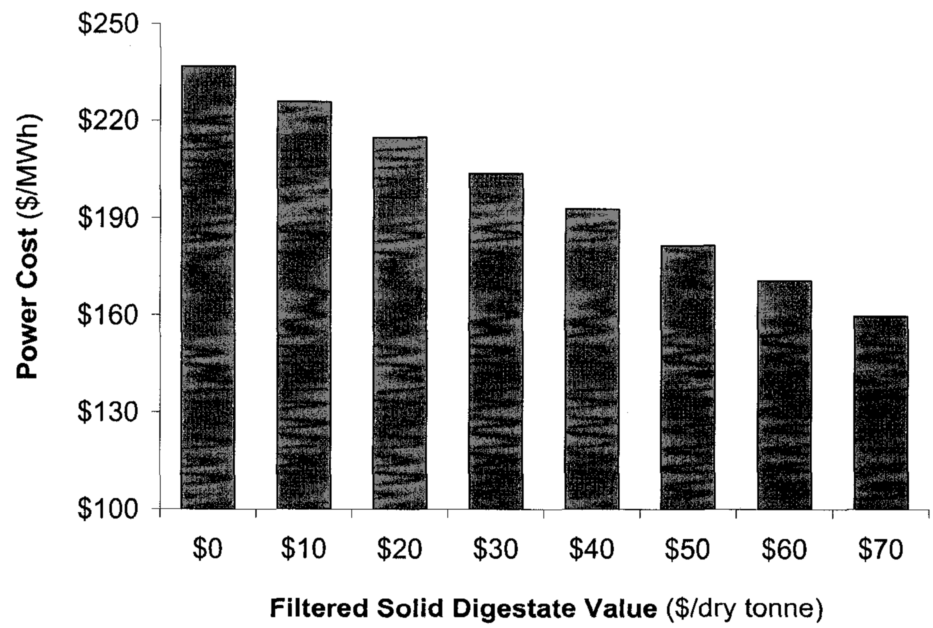

Figure 3. Sensitivity of Power Costs to Changes in Digestate Value

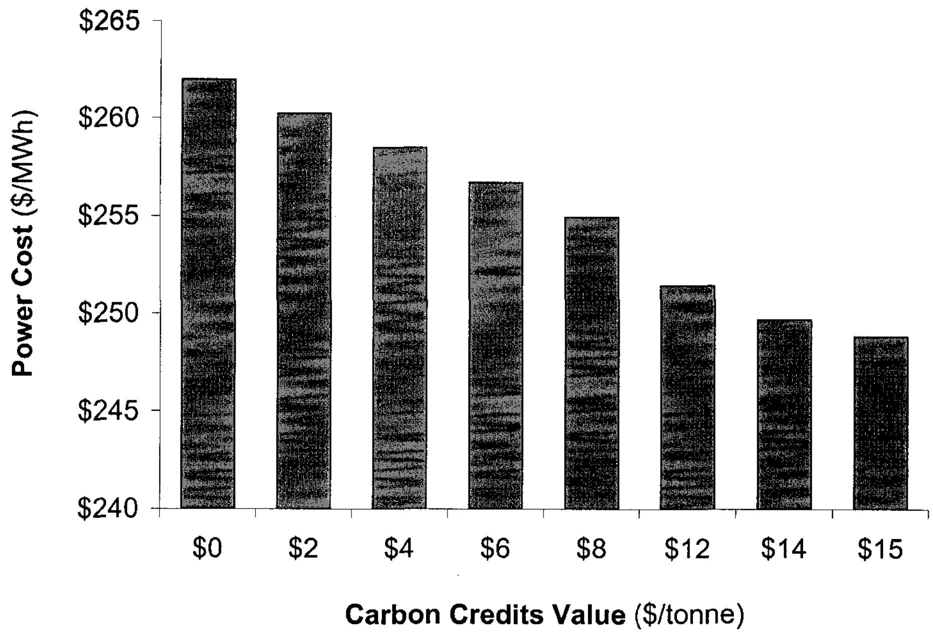

Figure 4. Sensitivity of Power Costs to Changes in Carbon Credit Values