Economic Feasibility of Anaerobic Digestion of Swine Manure for a Grower-to-Finisher Hog Operation in Quebec

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ABSTRACT

Swine manure creates much public resentment in Quebec due to nutrient overloading, potential water pollution and odour. Anaerobic digestion is one of the solutions that allows to lessen the odour problem. Anaerobic bacteria in manure produce methane. The latter can be burnt to produce heat and electricity on farms. Moreover, there is a potential for receiving carbon emission reduction credits for the capturing of methane.

Investment analysis was performed to assess the economic feasibility of a potential anaerobic digestion system on a grower-to-finisher hog operation. The study was conducted for a case farm, which had plans to expand from 2000 to 4800 pigs. Greenhouse gas emission reduction credits were incorporated into one of the scenarios. A sensitivity analysis revealed the most important variables which affect the economic feasibility of anaerobic digestion.

RÉSUMÉ

Le lisier de porc crée beaucoup de ressentiment au Québec à cause de surcharge nutritive, la pollution potentielle de l'eau et l'odeur. La digestion anaérobie est l'une des solutions qui permet de diminuer l'odeur. Le bactéries anaérobies du lisier produisent du méthane qui peut être brûlé pour produire de la chaleur et de l'électricité dans les fermes. Il est possible de recevoir des crédits pour la réduction d'émission de carbone pour le serrage du méthane.

L'analyse financière d'investissement a été exécutée pour évaluer la faisabilité économique d'un système de digestion anaérobie sur une ferme porcine d'engraissement. Cette analyse portera sur une étude de cas basée sur une ferme qui projette d'élargir le nombre de porcs de 2000 à 4800 porcs. Les bénéfices de la réduction de gaz à effet de serre seront pris en compte dans l'un des scénarios. L'analyse de sensibilité montre les variables les plus importantes qui affectent la faisabilité de la digestion anaérobie.

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NOTATION

Chemical and Physical

BTU - British Thermal Units
CH_4 - Methane
CO_2e - Carbon Dioxide Equivalent
N_2 - Nitrogen
N_2O - Nitrous Oxide
NO_2 – Nitrogen Dioxide
STP - Standard Temperature and Pressure

Legislative

AOR - Agricultural Operations Regulation
CTA - Cities and Towns Act
EQA - Environment Quality Act
LUPD - An Act Respecting Land Use Planning and Development
PALAA - An Act Respecting the Preservation of Agricultural Land and Agricultural Activities

Financial

CCA - Capital Cost Allowance
EBIT - Earnings before Interest and Tax
HRT - Hydraulic Retention Time
i_e = Effective Annual Project Interest Rate
IRR - Internal Rate of Return
i_s = Stated Annual Interest Rate
NPV - Net Present Value
PMT - Annuity Payment
UCC - Undepreciated Capital Cost
WACC - Weighted Average Cost of Capital

Notation Related to Anaerobic Digestion

AD - Anaerobic Digestion or Anaerobic Digester
TS - Total Solids
VS - Volatile Solids

CHAPTER ONE: INTRODUCTION

Chapter One will introduce the problems caused by the hog production in Quebec. Then, anaerobic digestion will be proposed as a possible means of reducing problems associated with swine manure. The adoption of this technology, however, has many challenges and they will be explained. Based on these challenges and the current limited knowledge about anaerobic digestion, the problem statement and some hypotheses will be presented. The last section of this chapter will describe the overall structure of the thesis.

1.1 Overview of Anaerobic Digestion

The growth in hog production in Quebec from 2,909,251 pigs in 1991(Statistics Canada, Census of Agriculture 2001) to 4,280,200 pigs in 2003 (Statistics Canada[a], 2003), has increased the conflict between agricultural production and environmental concerns. In Quebec, the odour from stock raising facilities is one of the main reasons for concern. Swine manure is highly odorous, which creates confrontation between hog producers and local communities. One technological solution to the odour problem is anaerobic digestion (AD). The elimination of odour is one of the primary benefits of the process.

In addition to eliminating odours, AD can be designed to produce heat and electricity. This technology provided alternative power during the energy crises in the 1970s. However, most of these systems failed due to improper design and lack of training about the system among farmers (Lusk 1998). Another problem was that the main benefits, heating and electricity, could not be sufficiently used on-farm or sold to other customers. Without these latter benefits the high capital costs of the AD system could not be justified.

There is a significant potential in using swine manure as a renewable energy source by employing anaerobic digestion technology in Quebec. A report by Helwig et al. (2002) estimated the potential of biogas production from biomass residues in Eastern Canada, in particular from swine manure in Quebec. They concluded that poultry and swine manure have a greater potential for electricity production among the various types of animal manures. For all Eastern Canada (Quebec, Ontario and the Atlantic Provinces) Helwig et al. (2002) estimated the release of 1.2 million tonnes of CO_2 could be prevented on a daily basis if energy produced by AD displaced conventional heating oil.

By assuming the portion of recoverable manure to be 85%, Helwig et al. (2002) estimate that Quebec could produce 5,116 GJ/day of biogas energy from swine manure. This would translate to 406 MW/day of electrical energy. From all livestock waste Quebec could produce 19,580 GJ/day of gross energy and 1,550 MW/day of converted electrical energy. With an assumed conversion efficiency of 20%, each swine farm on average could produce 175 kW-hours/day (Helwig et al. 2002).

Previous studies (Demuynck et al. 1984, Washenfelder 1999) concluded that in order for an anaerobic digestion system to be viable there should be a sufficiently large herd size and the possibility of receiving monetary compensation from energy savings. It has been estimated that AD systems for swine manure could be profitable starting from between 1,500 to 5,000 finisher pigs (Helwig et al. 2002). The cost of digesters is normally expressed in capital cost per pig. For Manitoba, the cost of an anaerobic digester is $ 26 CDN per pig (Danesh et al. 1984 as cited in Helwig et al. 2002).

1.2 Advantages of AD Technology

Farms install AD systems either for economic or environmental considerations or both. Some of the advantages are as follows:

Odour reduction and fly control. Digested manure is virtually odourless because odour-causing bacteria are killed through the process. Odours are caused by the concentrations of ammonia, hydrogen sulfide, mecaptans, and amines (PEI Dept. of Agriculture and Forestry, 2001). Fly propagation also decreases (Nelson and Lamb 2002)

Pathogen and weed seed reduction. Due to the temperatures in the tank, weed seeds and pathogens lose their viability

Greenhouse gas emissions reduction. As a greenhouse gas, methane is 21 times more harmful than carbon dioxide. AD technology captures and burns methane before it is released to the atmosphere. It is estimated that 30% of anthropogenic methane emissions come from farm animals and 23% of this amount comes from manure decomposition (Jewell et al. 1997).

Biological (also 'Biochemical') Oxygen Demand (BOD) reduction. BOD is the amount of oxygen needed for microbes to decompose organic matter in water samples. BOD is a hypothetical measure of potential pollution in a water system. (Bortman 2003). AD decreases BOD.

Preservation of nutrient value. Digested manure has a higher fertilizer value than raw manure. Anaerobic treatment converts some of the nitrogen to ammonia. The latter is absorbed by plants easier and reduces the risk of nitrogen loading, if manure is used as fertilizer. Ernst et al. (1999) asserts that nutrients in digested manure are more evenly distributed.

One of the problems in conducting a feasibility study on AD technology is the quantification of all of these benefits. Benefits associated with odour reduction, fly nuisance, and weed seed and pathogen killed are especially difficult to measure in monetary terms (Tafdrup 1995).

1.3 Disadvantages of AD technology

Some of the potential problems with AD are as follows:

Potential ammonia emissions. Ammonia can be viewed as a source of pollution. Ammonia from treated manure rapidly volatilizes and therefore it is better if the digestion manure is knifed (injected to the ground) rather than just spread (Ellsworth and Abeles 1981, Nelson and Lamb 2002). This would result in an increased cost of spreading unless this technology is currently used. At the time of the farm visit the farmer was planning to obtain the manure injection equipment.

Other emissions. Biogas from manure contains small amounts of hydrogen sulfide, which can be poisonous to humans. The combustion of biogas produces sulfur dioxide, nitrogen oxides and particulate matter (Nelson and Lamb 2002). These amounts are insignificant and were not incorporated into the analysis.

1.4 Roadblocks to Adoption

The following factors are mentioned most frequently as roadblocks that curb widespread adoption of AD technology:

- High capital costs of biodigesters;
- Low energy prices;

- Bad reputation due to previous failures of AD systems;
- Legislation;
- Limited access to low-interest loans

There are also some technological difficulties with AD technology. For example, in some cases energy yields can be insufficient to meet on-farm needs. To enhance energy yields two processes are suggested: lower dilution and co-digestion with concentrated organic wastes (Tafdrup 1995).

The widespread use of antibiotics on modern hog operations is another problem. Not all of the injected antibiotics are digested, and as a result, are excreted with manure. As a consequence, they negatively affect microbial populations producing biogas. Lallai et al. (2002) revealed that some antibiotics, namely amoxicillin trihydrate, oxytetracycline hydrochloride, and thiamphenicol substantially disturb microbes in the digestion process, and therefore reduce biogas yields. A Canadian study by Massé et al. (2000) also found that out of six researched antibiotics, two, penicillin and tetracycline, inhibit biogas production in the low-temperature psycrophilic temperature range in Canada.

1.5 Current Gaps in Knowledge

At present, research associated with greenhouse gas emissions from manure is well established for enteric fermentation of swine, and in particular emissions from production facilities (for example Moss 1993, Laguë et al. 2002). The focus has largely been placed on the biological aspects of methanation. Some information (Massé et al. 2003, Marinier 2003) is known about the greenhouse gas (GHG) emissions from swine manure storage facilities. However, further research in this area is needed to increase their precision. The literature considering greenhouse gas emissions specifically from the combustion of biogas is lacking. As a result, the trading of emission reduction credits specifically from AD has not been fully explored.

1.6 Problem Statement

The adoption of AD technology on a farm requires a substantial investment by the owner. This study will address the economic feasibility of such an investment. Benefits from adopting this technology include: power generation, fertilizer, and environmental benefits. Particular attention will be paid to the potential of receiving carbon credits that could be sold in the domestic carbon offset market. AD provides emission reductions by burning methane, a highly potent greenhouse gas. The potential involvement of farmers in carbon emission trading could improve the feasibility of AD.

The case study that will be analysed is a grower-to-finisher hog operation in south-west Quebec. The operator is planning to expand the operation from 2000 to 4800 pigs. Capital and operating costs for two sizes of AD will be analysed. As a result, the economic feasibility will take into account economies of scale.

1.7 Objectives

The objectives of this study are:

1. To identify if AD systems are economically feasible for Quebec hog producers. The study was conducted for two farm sizes of 2000 and 4800 pigs in inventory.
2. To show the sensitivity of the following parameters on net present value (NPV) of anaerobic digesters:

- variations in electricity rates, which can include price increases or the potential for the utility to buy back excess electricity;
- potential reduction in capital costs of digesters;
- costs of synthetic fertilizers, which could be potentially replaced by digested manure;
- the effects of environmental benefits, such as the sale of carbon credits through an offset system.

1.8 Hypotheses

The following can be hypothesized based on the literature reviewed (Anderson 1982, Axaopoulos and Panagakis 2003, Barnett et al. 1979, Boyd 2000, Bramley and Raynolds 2003, Demuynck et al. 1984, Ellsworth and Abeles 1981, Ernst et al. 1999, Feddes and McQuitty 1981, Forward 2003, Helwig et al. 2002, Higham 1998, Johansson 1999, Kelland 1988, Laguë 2003, Lekakis and Halvadakis 1988, Lusk 1998, Massé and Croteau 1999, Nelson and Lamb 2002, Ralph 1986, System Ecotechnologies Inc. 2000, Washenfelder C. 1999) :

Hypothesis One. For Quebec hog producers it is not economically feasible to install an AD system just to produce heat and electricity to be used on the farm. For Quebec, the three most important factors would not make digesters successful:

- high capital costs of digesters;
- low energy prices;
- low ambient temperatures, which reduce biogas production

Hypothesis Two. AD systems could become economically viable in the following situation:

- if value is placed on environmental benefits, such as odour reduction and carbon reduction;
- for odour reduction and to avoid nuisance;
- if there is a substantial demand for biogas and derived byproducts such as fertilizer, liquid swine manure, fibre etc.;
- if heat and electricity can be used on-farm (heating a barn, a greenhouse etc.) and sold off-farm

1.9 Outline of the Thesis

Chapter Two provides the technical background on AD, its brief history, and a review of the economic and environmental aspects of AD. Legislative aspects pertinent to hog operations are also discussed. Chapter Three will describe alternative investment evaluation techniques and their limitations. Chapter Four starts by describing the case farm to be used in the analysis. A capital budgeting model is then introduced to evaluate this system. The last section of Chapter Four describes how GHG emission reductions were calculated. Chapter Five presents the results produced by the model designed. The first section discusses market variables, benefits and costs, while in the second part environmental benefits were incorporated. Chapter Six presents the conclusions from the study.

CHAPTER TWO: LITERATURE REVIEW

This chapter will provide a much deeper explanation of the AD process than in Chapter One. The chapter will describe the evolution of this technology over time and its state of the art in Canada and other countries. It will be explained why and how this technology could be viable from the economic and environmental perspectives. The chapter will also analyze the existing legislation that regulates hog production in Quebec. It will be explained how regulations can stimulate the adoption of environmentally friendly technologies, like anaerobic digestion.

2.1 A Short Introduction to Literature Review

Anaerobic digestion, also known as 'biomethanation', is a process of producing biogas from organic residues. 'Anaerobic' implies 'without oxygen' as the process occurs in an air-free environment. Biogas consists of approximately 60% methane (CH_4) and 40% carbon dioxide (CO_2) as compared to natural gas which is 85% methane (Bortman et al. 2003). Biogas has some trace gases, such as hydrogen and hydrogen sulphide. Animal manures can be used as a feedstock for the AD process.

Biogas is generated by methane-generating bacteria called 'methanogens'. These bacteria can be found in soil, water, sewage, and animal manure as well as in gastrointestinal tracts of ruminants (Bortman et al.2003). In order to capture useful biogas, manure is placed in a tank, called a 'digestion tank'. The absence of oxygen and appropriate temperature levels enhances biogas yields. The chemical formulas associated with biogas production are provided in Appendix A.

It can take up to a year for the methanogeneric bacteria to reach their maximum growth. Increasing bacterial growth enhances biogas yields (Nelson and Lamb 2002). This can also be done by adding bacteria to the digester and is called 'seeding'.

The time the manure spends in the tank is called the 'hydraulic retention time' (HRT) or 'detention time'. Washenfelder (1999) states that 15-25 days of HRT is the optimal time in order to maintain adequate bacterial populations in a digester and therefore, to maximize biogas yields. The HRT can vary depending on the AD system. For example, Iowa State University states that the HRT design parameter for anaerobic lagoons is 30 to 60 days (Iowa State Universtiy 2003).

Another factor affecting biogas yields is the concentration of volatile solids in manure. A Volatile Solid is organic matter from which biogas could be derived. According to the US Environmental Protection Agency (2003, p. 8-2.4) "Volatile solids are defined as the organic fraction of the total solids in manure that will oxidize and be driven off as gas at a temperature of 1,112°F. Total solids are defined as the material that remains after evaporation of water at a temperature between 217° and 221°F" [1]. Biogas yields increase as the concentration of volatile solids increase.

Loading rate of manure to a digester is expressed as the amount of Volatile Solids (VS) per unit of digester volume. According to Bortman et al. (2003) the loading rate for typical digesters, with a retention time of between 30-90 days is 0.5-1.6 kg/m^3/day. The addition of substrate mixing increases biogas production (this is called a 'high-rate digester' vs. 'standard rate digester') by lowering the HRT to 10-20 days. The loading rate in such digesters is higher: 1.6-6.4 kg/m^3/day.

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[1] 1,112°F is equivalent to 600°C, 217°F is equal to 102.8°C and 221°F is equal to 105°C (Interactive Unit Converter)

There are three ranges of temperatures under which digestion occurs:

• Thermophilic (45-70C°)

• Mesophilic (20-45 C°)

• Psycrophilic (5-20 C°)

Different types of bacteria flourish in different ranges. To keep thermophilic and mesophilic temperature ranges, manure can be heated by circulating hot water in pipes or coils inside the tank (Slane et al. 1975).

2.2 Brief History

In 1884 Louis Pasteur proposed to burn biogas from horse manure as a fuel source for street lights (GTZ 2000). In 1896, street lamps in Exeter (England) used biogas as a fuel source derived from sewage waters (Marchaim 1992). During World War II, Germany encouraged engineers to develop anaerobic digestion from animal manures as an alternative fuel source as part of their renewable energy projects when oil supplies from the Middle East were restricted (Pos 1985a as cited in Kelland 1988).

Anaerobic treatment was introduced in the 1940s in the United States for sewage and industrial waste treatment (Nelson and Lamb 2002). Interest in this technology as a source of alternative energy increased again during the energy crisis of the 1970s. The high energy prices in the 1970s raised interest in AD among even small-scale farms, although it seemed to be more economical to construct centralized facilities able to collect and treat manure. The bulk of American and Canadian AD systems were installed at that time (AD-Net 1999 as cited in Helwig 2002).

Many of the farm-scale systems constructed in the 1970s and 1980s turned out to be unsuccessful due to a number of factors. Lusk (1998) concluded that the main reason for the failure of these digesters was poor design. Failure rates by type of farm-based digester in the US were 70%, 63% and 22% for complete-mix, plug-flow, and covered lagoon digesters respectively (Lusk 1998). A 1984 study undertaken in Europe (Demuynck et al. 1984) indicated that 24 biogas plants failed due to poor operation of the methane digester (in 46% of cases), high investment costs (42%) and other factors (12% of cases).

Renewed interest in low-temperature anaerobic digestion is occurring in Quebec (Massé 2002). Two digesters are being constructed in Quebec to investigate the economic feasibility of low-temperature digestion of hog manure. Capital costs are not yet known, however the manufacturer is trying to bring them down to $ 60 CDN per pig (Royer 2003).

2.3 Biogas Utilization

Biogas is used for generating heat through boilers or gas burners and electricity through engine-generators or turbines. This process of producing both heat and electricity is called 'cogeneration'. The most frequently used engines are spark ignition engines and diesel engines. Diesel engines can run on biogas by adding some amount of diesel to the biogas.

Biogas and natural gas have methane contents of about 60% and 85% respectively. Conventional boilers can be modified to use biogas instead of natural gas. According to Forward (2003), fuel-cell generators can also be driven by biogas, but these generators are highly capital intensive.

Although it is possible to pressurize biogas and store it in tanks and to transmit it through pipelines, it is uneconomical. It is preferable to use it on-site (Helwig et al. 2002). If favourable electricity buy back rates are provided by an electrical utility, a farm can be hooked up to an electric grid. An example of this is the Haubenschild Farm in Minnesota. The farm has 750 milking cows whose manure is used to produce electricity for the farm plus 75 homes in the vicinity. They also heat the barn floor space (Nelson and Lamb 2002).

Not as much heat is needed in the summertime, and thus excess heat can be converted and used for refrigeration. Burned biogas also can be used for heating greenhouses. It is possible to dry the solid waste, derived from the effluent, to produce bedding (Mehta 2002). The digested effluent can be dewatered and the solid part can be used as a soil conditioner or can be further composted (Higham 1998). The liquid available after separation can be used for irrigation. Savings from decreased water use can be incorporated into a feasibility study of anaerobic digestion (Washenfelder 1999).

According to Parsons (1986), biogas can also power vehicles. Chichkin (2001) reported that in Scandinavia vehicles have been modified to switch from gas and diesel to biogas. 'Volvo' and 'Scania' automobiles with such engines were produced in the 1980s. Bortman et al. (2003) state that methane has been a motor fuel in Italy for over 40 years and that in Modesto, California there is a small fleet of methane-powered vehicles.

Bucksch and Egebäck (1999) summarized previous studies (mostly Swedish) on the potential of alcohols, natural gas, ethanol and biogas as an automobile fuel. The cost of these alternatives was higher than fossil fuels. Among the examined fuels, biogas had the lowest negative impact on the environment.

In terms of emissions of carbon dioxide, nitrous oxide and benzene, biogas and natural gas rank the lowest and thus were the most acceptable from an environmental perspective. Biogas is followed by ethanol, methanol, and other biomass-based fuels. Another Swedish study by Johansson (1999) examined how competitive alternative transportation fuels were compared to fossil-fuels (diesel and gasoline). The costs of detrimental effects, from carbon dioxide, nitrous oxide, volatile organic compound and particulate emission, were valued using Sweden's carbon tax (US $ 200/tonne C) and consumers' willingness to pay for pollution reduction. It was concluded that biogas is more competitive in comparison to methanol, natural gas, diesel and gasoline. It also was best suited for heavy trucks in urban areas

2.4 The Types of Digesters

There are a variety of digester types, but the following three are most commonly used in North America: covered lagoon, complete mix, and plug-flow (Nelson and Lamb 2002):

• **Covered lagoon digesters** are the simplest type and least expensive. These are used for liquid manure with less than 2% solids. The main part of this digester is the lagoon dug in the ground with a top to capture the biogas. Retention time is from 40 to 60 days (McNeil Technologies Inc. 2000). This type of digester is suitable for processing diluted swine manure.

• **Complete mix digester** (sometimes called 'continuously stirred tank digester') uses a tank similar to a silo that is heated inside by a system of pipes. This type of digester is suitable for manure with concentration of 3 to 10% solids and is suitable for treating swine manure

• **Plug-flow digesters** require solid concentrations of 11 to 14%. The name 'plug-flow' comes from the fact that a portion of the new manure (a plug) is deposited at one end of the tank, causing all the mass to pass through. Deposited manure stays in the tank for 15- 20 days. After depositing a new portion of manure at one end, the same portion of old treated manure comes out from another end. This digester is suitable for digesting cow manure.

Other types of digesters include sequencing (or 'sequential') batch reactors and anaerobic sludge reactors. The digester examined in this study does not fall into any of the digester types above (see section 3.2.1 'Selected Company Digester Description'). The digester used in this analysis is a "partial mix digester" (Nils Semmler 2003). These digesters have been operational in Europe on hog farms. The walls of the digester are well insulated making it suitable for Canadian climatic conditions.

2.5 State of the Art of Anaerobic Digestion Technology

Current research focuses on boosting biogas yields and making the most of the byproducts from digestion. Other directions in research investigate how to make biogas cleaner and cheaper to produce. Biogas technology is combining with other scientific advances, namely solar and fuel cell technology.

Since biogas production is a temperature-dependent process, the temperature in the digestion tank can be stabilized by introducing solar collector panels on the roof of the tank that would warm manure through a heat exchanger. In hot climates the viability of such digesters is evident. Produced heat can warm a nursery building for piglets, be used for lighting and cooking, heating of water and air in grain dryers (Axaopoulos and Panagakis 2003).

Several examples show how biogas yields can be increased by combining manures of different types of livestock and adding non-toxic industrial wastes. Magbanua et al. (2001) demonstrated the compatibility of digesting hog manure with poultry manure and showed a synergistic effect in biogas production.

A joint Swedish-Indian research program showed the potential of constructing small-scale fuel-cell power plants with a capacity of 500 kW in rural India. The feedstock are energy crops, animal dung and other agricultural waste. After primary fuel conversion, when biogas is produced, it is directed to a fuel processor and a fuel cell generator. The carbon dioxide content of biogas helps increase the amount of produced hydrogen, which powers a fuel cell generator (Thyberg and Myrén 1995).

In Denmark centralized plants combine 80% manure with 20% other organic residues in order to optimize the treatment of different types of waste and to enhance biogas production. The residues include gastrointestinal substances from slaughterhouses, wastes from fishing and food industries, tanneries, oil mills, the drug industry and municipal sewage sludge (Tafdrup and Hiort-Gregersen 2003).

The solid effluent of AD is rich in nitrogen in the form of ammonia. Ammonia is highly volatile and is the main concern when the effluent of digestion is spread on agricultural fields. Wojcik et al. (2003) investigated whether ammonia could be an alternative fuel for solid oxide fuel cells. Nitrous oxide (N_2O), a gas with high Global Warming Potential (GWP), is avoided in production. Nitrogen (N_2) is the byproduct that powers a fuel cell. Ammonia is transformed to fuel through liquefaction at room temperatures and low pressure. The research is currently under way, but preliminary results seem promising.

As for the liquid effluent, it is possible to use it to grow water plants such as duckweed and water hyacinths or release it to fishponds to boost algae growth where the latter is eaten by fish (De Lange and Tondeur 2001, Barnett et al. 1979). The effluent is also a good substrate to grow mushrooms (Marchaim 1992).

Hydrogen sulphide, present in biogas, is frequently problematic since it is corrosive and impairs engine-generators. Inexpensive Danish technology reduces its concentration from 2,000-3,000 ppm to several hundred ppm by adding some air to the biogas (Tafdrup and Hiort-Gregersen 2003)

2.6 Psychrophilic Digestion for Cool Climates

An important question to ask is what temperature range (psychrophilic, mesophilic or thermophilic) suits the Canadian climate best. In the low-temperature psychrophilic range, there is no need to heat the manure. However, biogas yields are lower in the psychrophilic range compared to mesophilic and thermophilic ranges.

The reason for lower biogas yields in the psychrophilic range is explained by the fact that mesophilic bacteria are not able to survive in low temperature ranges. For swine manure, in order to produce the same amount of biogas, approximately twice the time is required in the psychrophilic range as compared to the mesophilic. (Kashyap et al. 2003). These researchers refer to previous studies indicating that methanogenesis can occur at temperatures as low as 1°C. Reported biogas yields were 99L/day for the coldest winter months and 1700L/day for the warmest winter months. For swine manure in anaerobic lagoons with a floating cover the amount of biogas produced is 0.11-0.15 m^3/ m^3/day at 11-22°C (Chandler et al. as sited in Kashyap et al. 2003).

A Russian study by Nozhevnikova et al. (1999) investigated the behaviour of methanogeneric bacteria on pig and cattle slurry under psychrophilic and thermophilic conditions. It was found that the communities of fast-growing bacteria in low-temperature ranges (called 'psychoactive' bacteria) can develop. However, these populations require long-term accumulation and are vulnerable to temperature variations. This study did not show how to facilitate significant methanogenesis in low temperature ranges.

In Canada, experiments on AD in the low-temperature psycrophilic range were conducted by Massé (2002) and Massé and Croteau (1999) at the Lexonville Dairy and Swine Research and Development Centre. Results suggest that the pollution potential (expressed in total chemical oxygen demand) is reduced by 41-83% in an anaerobic sequencing batch reactor at 15-20 C°. High concentrations of methane (75-80 %) were achieved. The AD system eliminated pathogens such as coliforms, Escherichia Coli, Salmonella, Yersina enterocolitica, Listeria Monocytogenns, Cryptosporidium, and Giardia. Unlike other systems, in sequencing batch reactors mixing was not required for their system and therefore it could bring substantial electricity savings. 'Bioterre Systems' is investigating the commercial potential for low-temperature AD (Royer 2003). For Canada, widespread utilization of biogas technology is proposed for small and medium sized farms, most likely for heat-related applications rather than electricity generation (Helwig et al 2002).

2.7 Review of Economic Analysis

2.7.1 Farm-Scale Anaerobic Digestion

The major technique used for evaluating the economic feasibility of AD systems is capital budgeting (Boyd 2000, Biswas and Lucas 1997, Demuynck et al. 1984, Gan 1996, Higham 1998, Jewell et al. 1997, Kelland 1988, Lusk 1998, Yang and Gan 1998). The general conclusion in most of the previous studies is that the economic feasibility of AD technology is sensitive to the following factors:

- Capital Cost
- Engineering design

- Energy prices and the possibility or selling electricity
- Ambient temperatures
- Governmental intervention (legislation and subsidies)
- Value of byproducts and the existence of markets for them

Anaerobic digestion technology is popular in the developing world. China and India are leading in the number of biodigesters. One should note that many of them are home made and have tank volumes between one to several cubic meters only. These low-tech digesters do not require high capital and labour costs. In Burundi, a family-size digester costs as much as one cow. In China, its price is equivalent to the price of one bicycle (Nyns 1990).

In North America, the high capital cost of anaerobic digesters requires a sufficient amount of manure to recuperate investment. Estimates range from 1,500 to 5,000 pigs per farm to operate a digester profitably (Helwig et al. 2002). Other estimates have suggested at least 4,000 finishing hogs in inventory be needed (Moser 2003). Yang and Gan (1998) assert that the investment starts to repay with a herd size of 830 pigs. Gan (1996) estimated a herd size as low as 227 pigs when capital costs of the digester are lowered by replacing tank material with high density polyethylene. The lower herd sizes are probably the results of the warm ambient temperature in Hawaii.

The average number of pigs per hog farm in Quebec is 1562[2] as projected for January 1st, 2003 (Statistics Canada 2002). Based on relative proportions of swine types for three regions: Centre du Québec, Chaudière-Appalaches, and Monteregie, the number of

[2] General estimation irrespective of pig types

growers and finishers for an average Quebec farm was only 937. AD is an unpromising option for Quebec if the larger estimates for hog number are required, unless more attention is drawn to its environmental benefits and operators are compensated for these benefits. Environmental regulations could possibly make AD one of the measurements required by legislation to control odours. This has been done in Colorado (McNeil Technologies Inc. 2000). Another option is having electricity prices increase, which has occurred in some deregulated market conditions. The sale of surplus electricity to utility companies is possible. For example, on April 15, 2003 Hydro-Quebec called for a tender to buy up to 100 mw of energy from renewable sources, biomass being one of them (Hydro-Quebec web-site).

Helwig et al. (2002) estimated the potential amount of manure that would be available for anaerobic digestion in Quebec, Ontario and the Atlantic Provinces. Manure quantity was estimated by using daily production rates provided by Midwest Plan Service (1985). For on-farm energy production, Helwig et al. (2002) estimated that Quebec poultry manure has the greatest potential for electricity generation (250 kWh/day per farm) followed by swine (175 kWh/day per farm). They assumed that 30% of the energy was diverted to heat a digester.

Kelland (1988) used a capital budgeting approach to evaluate the economic efficiency of hog farms in Canada. Here the word 'efficiency' was meant in an investment sense as the best of alternative investments. She compared the AD treatment with other investment alternatives and found a negative NPV of $ 318,000 CDN. Increasing the planning horizon *ceteris paribus* by more than 40 years did not provide a positive NPV.

Since swine manure retains some nutrients, Kelland examined the economic effect of refeeding separated fibre from digested swine manure to beef cattle. This fibre is called 'single cell protein'. The results by Kelland concentrated on the single cell protein recovery system, which substantially added to the capital costs of the systems. Total capital costs were around $ 325,000 CDN, while the protein recovery system was around $ 96,000 CDN (1986 dollars). The introduction of this additional equipment was not justifiable, given that feed values would have to increase by approximately 450% to attain a positive NPV.

In a more recent study, McNeil Technologies Inc (2000) compared costs and benefits of several waste management options for Colorado swine farms. They estimated that heated complete-mix digesters would provide the highest positive NPV.

Axaopoulos and Panagakis (2003) conducted a sensitivity analysis using a profitability index (defined as the ratio of NPV value per initial investment cost) using the investment cost and the cost of replacing conventional fuel at different biogas utilization rates. At existing conventional fuel prices in Greece (4 cents per kWh) and if the discount rate is assumed to be 10%, the technology is commercially viable if the utilization factor is greater than 25%. This is a modest rate which could increase up 75% and higher. For Greece this technology was found to be a worthwhile investment.

Barnett et al. (1979) presented some useful reflections on biogas technology in the Third World and some of the points are also useful for industrialized countries. Compared to other studies this one looked at biogas technology in a much wider context by including social structures in rural communities and the distributive effects in particular. Barnett pointed out that biogas technology should be appraised by establishing a set of alternative investments, for example composting and the ability to meet energy demands compared to other fuels and that the comparison should be made with the 'next best alternative investment'. Barnett et al. (1979) asserts that "it does not matter how good the methods of social and economic evaluation are if they are applied to the wrong set of alternatives" (Barnett 1979, p. 71).

While valuing the input (manure) some problems arise because of the nutrient content (N,P,K) of manure and the prices of factory produced fertilizers. The price of factory produced fertilizer may be distorted by taxes and subsidies and not reflect the social cost of production (Barnett et al. 1979). One way to avoid such distortions is to consider production costs and not market prices (Johansson 1999). In addition, the assumption that synthetic fertilizers and manure of the same nutrient content are perfect substitutes is incorrect. Manure adds humus that helps retain moisture and prevents erosion (Barnett et al. 1979). In addition, if carbon dioxide from biogas is separated and pumped to a greenhouse to enhance plant growth, then the net benefit is the amount of increased crop output minus the cost of separation and delivering the CO_2 to the greenhouse.

Fehrs (2000) analysed the electricity production potential from organic wastes in Vermont. Organic wastes considered were dairy, hog, horse, goat and sheep manures, cheese whey, food processing residuals, brewery residuals, food waste and biosolids. For the estimation of excreted manure per 1000 lb. of live weight the author used manure generation factors developed by the USDA Soil Conservation Service. Energy generation potential for the State of Vermont was estimated to be approximately 30,000 kW from all organic wastes.

A case study for a 110 sow operation that marketed 1500 hogs and 300 feeder pigs a year was performed by Ernst et al. (1999). Assuming 4.5 ft^3 of biogas per pound of VS removed, the annual production of biogas was estimated at 382,757 ft^3 for a case farm in Iowa. It was assumed that 50% of the biogas was used for heating, 35% was transformed to electricity and 15% was wasted. This partition would bring annual heat savings of $ 920 US assuming the price of 1 cents/kWh. Annual electricity savings accounted for $ 3,154 US (with a price of 6 cents/kWh). However, the study found a NPV of the digester to be $ (202,573 US). The benefit / cost analysis only quantified benefits from heat and electricity produced by the digester. Even though the digester was not feasible, the operator kept running the digester in order to avoid conflicts related to odour with his neighbours.

The effect of proximity of hog operations on residential property values in nine counties of south-eastern North Carolina was investigated by Palmquist et al. (1997). The sale prices of 237 homes were considered. Environmental damages included odours and the decrease of water quality. Results suggested that within a radius of between 1-2, 0.5-1 and 0-0.5miles from hog farms, residential values decreased. Another significant result was that the expansion of farms in the areas of low livestock density had sharper effects on residential values than the expansion in areas with already high livestock density.

2.7.2 Centralized Plants

A macroeconomic analysis of biogas technology was performed by Mæng et al. (1999). The analysis estimates the impact on employment and the state budget of biogas production from 20 centralized plants in Denmark. The policies of the Danish government caused a dramatic drop in the price of biogas. From 1984 to 1997, the price of biogas decreased 7 times and almost equalized with the price of natural gas. Biogas plants in Denmark have improved the balance of payment by 240 million DKK[3]. The increase in employment was estimated at 4,200 man-years. Lost income from energy and CO_2 taxation was 520 million DKK. However, saved expenditures on unemployment benefits were 400 billion DKK and tax revenues for the state budget were 240 million DKK.

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[3] At the time when the study was conducted, 1DKK equalled 0.14 US$

The possibility of constructing centralized anaerobic digesters in Canada was discussed by Sullivan et al. (1981). For south-western Ontario, they calculated the theoretical production costs of $1m^3$ of biogas to be \$ 0.18 US assuming the existence of a pipeline through which the gas could be delivered to users. In this study a collectability factor of manure from swine farms is 100%. This percentage for confined operations was plausible (Fleming 2003).

In Sullivan's study a logistics computer program was developed which optimizes the locations of digesters given livestock types and the amounts of manure. The number of digesters in the program increases from a single digester serving many farms in a given region, to multiple digesters, to a maximum of one digester per farm. The program computed appropriate tank volumes, costs of facilities, fertilizer savings, and revenues from electricity sale. This mathematical program was applied to Huron County in south-western Ontario for 23 types of animals. The number of digesters was increased from 1 to 16. Eleven digesters gave the lowest cost of biogas equal to \$ 0.167 US/ m^3, while the highest cost was \$ 0.239 US/m^3 US for a single digester. At the time, biogas production was not a feasible option given these costs.

More recently Jewell et al. (1997) conducted a study on the possibility of constructing a centralized AD system for dairy farms. The centralized plant could serve about 100 dairy farms around the town of York, in New York State. The farms in that area had approximately 30,000 cows. Jewell et al. (1997) suggested the construction of a 4,000 to 6,000-cow facility, which was calculated to be an optimal size. For a facility of this size, an AD was economical due to the sale of electricity and fibre.

In the United Kingdom, GIS technology was employed to optimally locate centralized plants for treating non-toxic industrial waste, hog, and poultry manure. The study was undertaken in East Anglia, an area where hog and poultry production is dense. To minimize expenses on a distribution network the program finds the best location for the facility and electricity sub-stations based on the types and amounts of manure, their organic content and the proximity of farms to major roads (Dagnall et al. 2000). Similar GIS methods have been employed in the US (McNeil Technologies Inc. 2000).

In spite of significant economies of scale, the treatment of manure in a centralized facility can bring several problems. First, there are substantial transportation costs. Secondly, farmers might demand back digested manure from their own farm, not from a neighbour, due to a worry about invasive pathogens and weeds (Forward 2003).

The potential construction of a centralized manure treatment plant in Quebec was suggested for the Montéregie and Centre du Québec by Helwig et al. (2002). They proposed that the plant accept various organic residues, for example from slaughterhouses and the food industry. Centralized facilities in Denmark, for example, mix animal manures with non-toxic industrial waste (Mæng et al. 1999). Using a similar process as in Denmark would improve economic feasibility if the plant charged a tipping fee (Helwig et al. 2002).

2.8 Environmental Aspects of Anaerobic Digestion

2.8.1 Is Anaerobic Digestion Beneficial?

The impartial and precise quantification of the emissions from biogas combustion is very important (Mæng et al 1999). Only when accurate estimates of these benefits and costs have been measured and valued, can a complete economic feasibility study be undertaken.

For example, the bulk of the benefit/cost analyses overlook the environmental impacts of trace gases in biogas and the products of combustion. Golbert et al. (1995) investigated environmental hazards associated with the combustion of biogas from the Miron Quarry municipal solid waste landfill site in Montréal, the third largest landfill site in North America. Over 35 chemical compounds were revealed that are potentially hazardous to human health. Statistical analysis on the registry of births concluded that there are risks of low birth weights and pre-term births in several zones adjacent to the landfill.

Ernst et al. (1999) refers to Fischer et al. (1984) who revealed that when animal manure was digested, the concentration of nitrogen in the form of ammonia increases from 30% to 70%. Therefore, there is a higher possibility of atmospheric pollution as ammonia nitrogen is highly volatile and does not completely dissipate in the soil unless there is rain after manure application (Ernst et al. 1999). Manure can also be injected in the soil to reduce the ammonia volatility problem. Nitrogen in the form of ammonia in digested manure can be viewed as an increase in fertilizer value. However, Ernst et al. (1999) mention that digested manure still has a higher ratio of phosphorous to nitrogen than is needed for corn.

2.8.2 Does Anaerobic Digestion Solve the Phosphorous Pollution Problem?

Leached phosphorous from agricultural sources causes eutrophication in lakes and results in a subsequent decline in marine life. The insoluble fraction of phosphorous in swine manure can be removed by natural sedimentation and screening, however the insoluble part requires biological treatment. The latter was investigated by Luo et al. (2002). Their results suggest that anaerobic pre-conditioning of swine manure before aeration aids in the removal of phosphorous. Helwig et al. (2002), however, argued that aerobic treatment of manure may be more efficient (in physical terms) in the reduction of nutrients compared to AD.

A study in Quebec by Massé (2002) found that up to 60-80% of the phosphorous can be concentrated in the sludge fraction of the treated manure which accounts for only 15-30% of the total volume. Massé (2002) concluded that since the solid sludge is a much smaller volume, it could be transported to fields deficient in phosphorous.

2.8.3 Greenhouse Gas Aspects

In Canada greenhouse gas emissions from primary agriculture account for 61% of the total emissions of nitrous oxide, 38% of methane and less than 1% of carbon dioxide (Environment Bureau of AAFC 2003). In 1995 manure-related greenhouse emissions in Canada reached 4,500 kilotonnes in CO_2e[4] (Haites and Giraldez 2000). Claude Laguë (2003) indicated that total Canadian GHG emissions specifically from hog production are estimated at 1,835 kilotonnes in CO_2e per year, which constitutes about 3% of the emissions from agricultural sources. This amount correspond to 0.3 % of Canada's anthropogenic emissions and only 0.006% of the global emissions.

If biogas that is recovered from animal manures replaced heating oil, then 1.2 million tonnes of CO_2 would be prevented from release in Quebec, Ontario and the Atlantic Provinces (Helwig et al. 2002). In addition, useful heat and electricity could be produced. From all livestock wastes Quebec could produce 19,580 GJ/day which is equivalent to 1,550 mW-hrs/day. Helwig et al. (2002). provided the following amounts of potential biogas and electricity production for the three regions in Quebec with the highest livestock densities:

[4] According to the National Round Table on the Environment and the Economy (2004) "CO_2 equivalent is a unit used to standardize measurements and facilitate emissions trading. For example, tonne for tonne, methane is a greenhouse gas that is 21 times more powerful than carbon dioxide in causing the global greenhouse effect. Therefore one tonne of methane represents 21 tonnes of CO_2 equivalent."

Table 1. The Potential of Energy Production from Manure by Employing Anaerobic Digestion.

Name of region	Recoverable manure (tonnes/day)	Energetic value of produced biogas (GJ/day)	Energetic value of biogas (if converted to electricity, kW-hrs/day)
Montéregie	9,005	6,106	338,576
Chaudière-Appalaches	7,555	4,633	256,913
Centre du Québec	5,330	3,497	193,938

Source: Helwig et al. (2002).

The creation of an emission trading system specifically for enteric fermentation and manure was already considered as a possibility. Farmers could trade credits associated with their efforts to reduce emissions from enteric fermentation and the type or manure handling system (Haites and Giraldez 2000).

There are three main reasons why such a system could be hampered. First is the number of emission sources in agriculture. The second is the high variability in emissions originating from the production of different agricultural products. The system was planned, but rejected in Australia (Hinchy, Fisher and Graham 1998 as cited in Haites and Giraldez 2000). Haites and Giraldez (2000) propose an incentive system through which claims for credits can be quantified by emission coefficients associated with a certain manure handling system.

Finally, Haites and Giraldez (2000) state that for Canada, emission trading would be hampered by the fact it is an active livestock exporter, which distorts the amount of traded emissions from those Canada is responsible for under the Kyoto Protocol. Canada is responsible for emissions that come from livestock raised in Canada. But the authors state that the emissions associated with exported livestock and products would not be covered by the trading system. They also argue that the emissions associated with imported livestock and products purchased by the Canadian processing industry would be covered by the trading system even though they are not included in Canada's emission inventory.

In addition to the aforementioned problems, Bramley and Raynolds (2003) pointed out a number of other potential issues with emission reduction credits in the hog industry. The first one is the additionality problem, i.e. quantifying and granting credits for GHG emission reductions in Canada that would have happened in any case. They also mentioned the timing and measurement problems.

The incorporation of the environmental benefits of an AD in an economic analysis can be found in Kelland (1988), but it was Boyd (2000) who made a serious attempt to actually quantify them. In the first part of her dissertation Boyd (2000) considered only financial benefits accrued from anaerobic treatment of pig slurry. Capital budgeting, a number of sensitivity analyses and cost-benefit analysis were employed. The viability of the system was dependent on the sale of fibre, which was derived from digestate. Digestate is a soil conditioner and was used in place of peat. Her conclusion was that if only financial benefits were included in the analysis then AD technology was not economically viable.

However, Boyd (2000) hypothesized if the environmental benefits of AD technology were incorporated into the economic feasibility analyses, then the NPV would be positive and thus economically viable. Boyd calculated reduced and avoided amounts of greenhouse and other gases which would have been emitted in the absence of this technology. The gases considered were:

• Carbon dioxide;

• Methane which has a Global Warming Potential (GWP) 21 times higher than carbon dioxide;

• Nitrous oxide with a GWP 310 times that of carbon dioxide

Boyd (2000) estimated the potential monetary gains from reduced inorganic fertilizer use, reduced methane emission, and the reduction of emissions arising from electricity generation. The methods and results were as follows:

1. From reduced inorganic fertilizer use:

• Boyd (2000) assumed nitrogen contents of between 3.9 to 4.5 kg per tonne of slurry and that 100 kg of total nitrogen in digested slurry could replace 70 kg of mineral fertilizer nitrogen (70% efficiency). The amount of nitrogen was multiplied by the price per ton given by a local supplier.

• To estimate nitrous oxide emissions from nitrogen fertilizer, a coefficient of 0.0297 was multiplied by the amount of fertilizer[5]. Savings were calculated knowing nitrous oxide's GWP of 310, multiplied by BP Amoco's permit trading price of carbon dioxide ($ 20 US per tonne).

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[5] Boyd (2000) obtained the coefficient of 0.0297 from the British Ministry of Agriculture, Fisheries and Foods

• It was assumed that 2kg of mineral oil was needed to produce 1kg of nitrogen fertilizer[6]. Saved energetic value of 43.2J per tonne of mineral oil was assumed

For Norfolk, the potential substitution of synthetic fertilizers reduces the emissions of nitrous oxide by 32 tonnes (which is equivalent to 9,920 tonnes of carbon dioxide) and potential savings are $ 198,400 US.

2. From reduced methane emissions:

The number of pigs in Norfolk was calculated. Given the GWP of 21 for methane, the value of carbon dioxide equivalents was calculated using BP Amoco's permit trading price. The potential saving for Norfolk was estimated to be $ 187,420 US.

3. From the reduction of emissions arising from electricity generation.

The amount of electricity that could be derived directly from pig slurry was calculated for Norfolk. This amount of electricity (12,820 MWh) was compared with emissions from a modern coal-powered station. This translated into the mitigation of 11,133 tonnes of carbon dioxide, which given BP Amoco's prices, was equal to $ 222,660 US. For a single farm this translates into $ 2,938 US.

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[6] This assumption Boyd (2000) took from the calculations done by Haber Bosch System cited in Klinger B. in European network for anaerobic digestion www.ad-nett.org, 1999

2.9 Other Approaches to Manure Problems

2.9.1 Enviropigs

Runoff from agricultural fields that have high nutrient concentrations causes the depletion of aquatic life because the decomposition of nutrients decreases the amount of oxygen in water. This leads to algal growth and fish kills. The simplest answer to reducing the amount of phosphorous in excreted manure would be if farmers purchased feeds with lower phosphorous content. An alternative to this would be to genetically modify the pig. This has been done at the University of Guelph and the animals are trademarked as "Enviropigs" (University of Guelph Web-Site 2003).

The manure from "Enviropigs" contain up to 70% less phosphorous than manure from regular pigs. The researchers combined the gene from the E-coli bacteria and the mice gene and implanted the transgene to pig embryos. The transgene helps pigs produce a special enzyme phytase in the pigs' saliva, which digests phytate (a molecule in plants containing phosphorous) in cereal grain feed (University of Guelph Web-Site 2003).

With more efficient digestion the need for dietary phosphorous supplement is no longer required. This results in a $ 1.14 CDN feed savings per pig. Researchers from Guelph have not observed any abnormalities in the transgenic pig. At the present time, the meat cannot be sold for human consumption. Enviropigs are currently being evaluated by the Canadian Food Inspection Agency (University of Guelph Web-Site 2003).

2.9.2 Dry Pellets Plant

Another potential solution to the pollution problems from manure is to treat the manure. The first manure treatment plant in Quebec was constructed in 2001 in the region of Chaudière-Appalaches(Centre Québécois de Valorisation des Biotechnologies 2000). The region was chosen because of its high density of hog farms and problems of soil overfertilization. The main purpose of the plant was to produce dry fertilizer pellets. Initially it was planned to treat 50,000 tonnes (140,000 cubic meters) of raw poultry, dairy, and hog manure and produce 5,000 tonnes of dry fertilizer pellets. However, the plant had to close due to the violation of manure storage requirements of the Ministry of the Environment and other financial problems.

2.10. Legislative Framework: *The Essence of the Problem: "The Right to Produce" vs. "The Right to a Clean Environment"*

Quebec legislation tries to balance the right to practice agriculture with the right for a clean environment. AD technology can be seen as a means of decreasing some of the environmental impact of hog manure in agriculture.

Strict legislative measures were adopted in Colorado which forced large hog operations to employ technologies to reduce odour and water pollution. Anaerobic digestion was one of the control technologies. Other approved technologies were covers and aerobic lagoons (McNeil Technologies Inc 2000).

The following laws regulate manure handling and storage in Quebec. The oldest of these laws was adopted in 1978 and all have undergone several amendments. The laws considered here are updated as of 2002.

At the federal level

Fisheries Act, chapter F-14 (Updated to August 31, 2002)

At the Québec provincial level

An Act Respecting the Preservation of Agricultural Land and Agricultural Activities, chapter P-41.1 (updated to 1 November, 2002), further denoted **PALAA.**

An Act Respecting Land Use Planning and Development, chapter A-19.1 (updated to 1 November,2002), further denoted **LUPD.** In force since June 15, 2002 (except some sections).

Environment Quality Act, chapter Q-2 (updated 1 November, 2002), further denoted **EQA.**

Agricultural Operations Regulation, chapter Q-2, r. 11.1 (updated 26 November, 2002), further denoted **AOR.**

Cities and Towns Act, chapter C-19 (updated 1 November, 2002), further denoted **CTA.**

The most general statements with respect to water pollution can be found in the federal Fisheries Act. According to the Act, manure can be regarded as a 'deleterious substance' because it degrades the quality of water (section 34). Subparagraph 3 of Section 36 allows no person to deposit deleterious substances in water frequented by fish.

At the provincial level, issues related to manure would fall under the provisions in the Environment Quality Act. Section 19.1 of Quebec's EQA states that "*Every person has a right to a healthy environment and to its protection*", but one limitation of this right can be found in section 113 of the Land Use Planning and Development (LUPD). The latter prescribes zoning by-laws to regulate land uses for agricultural purposes. Zoning by-laws go into detail with respect to odours from agricultural activities. For example, zoning by-laws establish separation distances between agricultural facilities and residential houses.

Another limitation of an individual's right to a clean environment is evident in Quebec's Act Respecting the Preservation of Agricultural Land and Agricultural Activities. Section 79.17 of PALAA states that in an agricultural zone no proceedings can be brought against a farmer for reasons of odours, noise, or dust. This piece of legislation in Quebec is similar to the one known in the US as "right-to-farm" (Centner 2002).

Subparagraphs 16 and 16.1 of section 113 of LUPD empower municipalities to "*regulate or prohibit all or certain land uses, structures or works...for reasons of public safety, public health or general welfare*". Certainly, farms fall into this category. In addition, subparagraph 19.1 of section 412 of CTA authorizes the council of municipalities to make by-laws, in particular "*to regulate or prohibit the keeping of animals, or categories of animals, and limit the number of animals that a person may keep in or on any immovable*".

It should be noted that, rules established in zones by PALAA have more power than those established by LUPD (Cain Lamarre Casgrain Wells 2002). Should any dispute arise regarding the restriction of agricultural activities, paragraph 2 of the first division of the third chapter (PALAA) provided an operator with the following condition that could allow a dispute to be eventually resolved for his/her benefit. Section 79.3 specifies that a farmer can appeal against a municipal by-law or nuisance by-law if they restrict the farmer in exercising agricultural acrivities. Section 100 of PALAA empowers farmers to establish and expand their operations. It states that once an operator has obtained a certificate of authorization from the government, authorizing him to establish or enlarge an agricultural operation, then the neighbours cannot prevent the development of the operation nor can they claim damages from odours and noise within the conditions specified in the certificate (section 100, PALAA).

Liability for damages cannot be avoided in cases of "gross or intentional fault" (section 79.19.1). In this case, a plaintiff can claim damages for inconvenience caused by farm odours, however, the burden of proof of any violation is levied on plantiff (section 79.18).

Farmers are obliged to obtain a certificate of authorization that they comply with the Environment Quality Act when they start agricultural activities. A petitioner for a certificate of authorization must identify 'the quantity or concentration of contaminants expected to be emitted, deposited, issued or discharged into the environment through the proposed activity' (section 22, EQA).

Projects with potentially negative environmental impacts are subject to an assessment and review procedure as well as the acquisition of certificate of authorization. Biogas plants treating manure and other types of manure treatment facilities are automatically subject to an assessment and review procedure. This is because they fall under Schedule A of EQA as "storage and water supply reservoirs related to works intended to produce electricity" (line d) and also line (l) as "systems for the collection and disposal of residual materials".

The new Agricultural Operations Regulation came into force on June 15, 2002 replacing the previous Regulation Respecting the Reduction of Pollution from Agricultural Sources (Règlement sur la réduction de la pollution d'origine agricole). This regulation is aimed at protecting 400,000 km of watercourses and ditches around Quebec (Quebec Ministry of Environment, 2001). The regulation focuses on the reduction of pollution from agricultural practices, in particular phosphorous from excreted manure. Any deposit, discharge, spreading and keeping of manure must follow the conditions outlined in AOR (section 4, AOR).

The regulation prohibits establishing barns or having a manure storage facility within 15 meters of a watercourse, lake, swamp, natural marsh or pond. The condition is only effective for watercourses with a flow area larger than 2 square meters[7] (section 6, AOR). Municipal by-laws forbid the spreading of manure on shorelines of watercourses. In the absence of such laws, manure cannot be spread within 3 meters of the shoreline of bodies of water with a minimum area of 10,000 square meters (section 30, AOR).

AOR also provides a number of strict technical requirements on manure storage (sections 7-18, AOR). The doctrine of "coming to the nuisance", by which agricultural operations previously in existence have a freer hand, (Centner 2002) is evident in Quebec legislation. For example, facilities with an annual phosphorous production exceeding 1600 kg that were in operation prior to the regulation (June 15, 2002) are required to install fully watertight tanks for animal waste by April 1, 2010, whereas those established after April 1, 2005 should have them immediately (Quebec Ministry of Environment 2001).

Operators whose phosphorous production exceeds the threshold of 1600 kg are also required to provide an agro-environmental fertilization plan delineating the spreading limits of manure for each plot of land planted with the same crop (sections 3, 22, AOR).

In addition, manure can only be spread between April 1 and October 1 (section 31, AOR). The reason for this is the ease with which manure can move into watercourses when snow melts (Kee 2001).

Section 32 specifies that from April 1, 2005 liquid swine manure will have to be spread with low-ramp equipment. Low ramp technology is a mechanism designed to spread manure closer to the ground (Quebec Ministry of Environment 2001). The use of this technology decreases the manure problem.

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[7] Here a flow area is defined as a product of an average height and an average width.

Sections 45-48 outline the restrictions on swine production. Schedule Two of the regulation lists the agricultural zones that are designated "limited activity zones" (ZAL, zones d'activités limitées) because of manure problems. It is forbidden to establish sites for swine production inside these zones; however outside these zones facilities can be established only if the manure undergoes full treatment (sections 46, 47). Full treatment requires a complete transformation of the manure into solid granulates. This process eliminates pathogens (section 45, see also section 2.9.2 'Dry Pellets Plant'). The by-product of full treatment should be used outside the limited activity zones (section 47). Unless the condition of full treatment is satisfied, "an increase in the number of sows or of more than 250 hogs, in relation to operating rights, may not be authorized" for facilities existing on June 15, 2002 (subparagraph 2, section 47). This condition of expansion is in force until 15 June 2004 for facilities inside limited activity zones and December 15, 2003 for facilities outside limited activity zones (section 56).

2.11 Conclusion

The historic development of anaerobic digestion technology and the review of current legislation suggest that there can be a stimulus for the adoption of this technology in two cases:

1. When traditional sources of energy become very scarce or expensive;
2. When legislation is stringent enough to force farmers to adopt environmentally friendly technologies

CHAPTER THREE: METHODS OF ANALYSIS

This chapter will explain the existing capital budgeting techniques that are used to evaluate investment projects. By comparing different methods, this chapter will provide a justification for choosing a particular approach that will be used in this thesis.

3.1 Introduction to the Capital Budgeting Approach

Woelfel (1994) defines capital budgeting as "Long-term planning for capital expenditures and for the financing of such expenditures". Capital budgeting concerns only the investment in long-term assets. The primary objective of capital budgeting decisions is the maximization of the market value of the firm. Since capital budgeting concerns long-term assets, the capital budgeting decisions have very important implications for the firm's success or failure (Dayananda et al. 2002)

Barry et al. (1983) identified the following stages of the capital budgeting process:

- Identification of investment alternatives
- Selection of an appropriate method
- Collection of relevant data
- Analysis of data
- Interpretation of results

A very powerful tool in capital budgeting is sensitivity analysis. It allows changing key parameters in order to test the effect of these changes on final results. Normally, in sensitivity analysis most variables are held constant, whereas one or a few of them are varied in a certain range. This can reveal the variables that affect results relatively more significantly (Bierman 1988).

3.2 Investment Evaluation Techniques in Capital Budgeting

There are four major capital budgeting techniques (Bierman 1988):

- Payback Period
- Return on Investment (ROI)
- NPV
- Internal Rate of return (IRR)

The payback method demonstrates the amount of time (usually in years) that is needed to recover initial investment (Bierman1988). In case of several mutually exclusive projects, the preference is given to the one with the shortest time required to recover the initial capital expenditure (Pearce 1992).

Return on Investment is the average income divided by the average expenses during the project lifetime. This method does not take into consideration the time value of money (Bierman1988).

Net Present Value represents the sum of discounted future net cash flows after tax deduction. The rule is that projects with a positive NPV are acceptable, and projects with a higher NPV are preferred (Bierman1988).

Internal Rate of Return indicates the discount rate at which the present value of future cash flows equals to zero. In other words, IRR is the discount rate when NPV is zero (Bierman1988).

3.3 The Limitations of Capital Budgeting

The major limitation of the capital budgeting technique is its static nature. All the assumptions are set at the beginning of a project. This approach ignores the possibility of "real options", i.e. the ability to alter decisions once a project has started. The example of real options can be the occurrence of additional projects if the first project proves to be viable. This can enhance the value of the first project. In addition, capital budgeting technique does not take into consideration that operating parameters can vary, for example fuel sources due to price changes (Cotter et al. 2003).

Cotter et al. (2003) proposed a Monte Carlo simulation in the capital budgeting process. A researcher sets the nature and distribution of input variables. After several thousand iterations a computer calculates the average, median, and standard deviation of NPV. This process estimates the likelihood of reducing shareholder's value by observing the proportion of simulations that produce negative Net Present Values.

There are also problems with the choice of investment evaluation techniques in capital budgeting. For example, payback period is a simple method of calculation, but it suffers from several drawbacks. First, it does not account for the earnings after the payback date. Second, this method demonstrates the speed of recovery of initial outlay rather than showing project profitability. Third, no attention is drawn to the timing of cash flow prior to the end of the payback period (Barry et al. 1983). Bierman (1988) indicates two more drawbacks. First, it does not take into consideration the concept of time value of money. The dollar values of cash flows in different years of an investment project are exactly the same. Second, the concept implicitly assumes that projects with shorter payback periods are less risky and therefore preferable, which is not always the case

Discounted Cash Flow techniques include Internal Rate of Return and Net Present Value. These investment evaluation techniques are considered to be superior methods because they involve the concept of time value of money (Pearce 1992). NPV, however, is a more realistic approach for the case when the interest rate is determined by the opportunity cost of capital. Both IRR and NPV use the same discounting procedure, but for NPV the discount rate is set, whereas for IRR it the one that produces zero NPV. NPV and IRR can give different conclusions about the acceptance of investment projects, because the former method assumes that net cash flows can be reinvested at the existing cost of capital, but the latter method assumes the reinvestment at IRR rate (Barry et al. 1983). Barry et al. (1983) states that "NPV rate has the advantage of being consistently applied to all investment proposals" (p. 212).

CHAPTER FOUR: DESIGN OF A CAPITAL BUDGETING MODEL

This chapter will first introduce the case farm on which a potential anaerobic digester could be constructed. A tailor-made Excel model was constructed for this case farm. All underlying assumptions will be explained. The model consists of 10 interlinked worksheets: "Input", "Costs", "Manure, Biogas, Sizing", "Energy Use", "Cash Flows", "Greenhouse Gases", "Nutrients-Fertilizer", "Climate Data", "Charts" and "Budgeting". The first nine worksheets allow the major parameters in the model to be varied in order to estimate their impact on the economic feasibility of AD. The "Budgeting" worksheet calculates Net Present Value that demonstrates the viability of AD.

4.1 The Case Farm

4.1.1 Overview

The case farm is located in a small township in the Monteregie region of Quebec. The operator constructed a new 2000 grower-to-finisher barn and has plans to expand to 4800 in the near future. The construction of the barn was completed in early 2003 and the barn was fully operational in February.

The land base for manure spreading is equal to the area of crop land totaling 350 acres. Grain corn and sweet corn occupy 250 acres. Fifty acres are under soybeans and another 50 acres are under peas.

The production facility is located about 1,500 meters away from a public road and the farmer's house. The closest residence is located 2,000 meters away. Initially, the farmer had the option to construct the barn near both the road and his house, but ultimately decided to construct it in a wooded area in order to reduce odours to the surrounding environment. The operator stated that there have been no serious confrontations with the neighbours concerning odours, however, before the construction, the operator faced resistance from the public during the municipal permit granting process.

4.1.2 Herd size

The growers are bought at approximately 26 kilograms and are finished at 108 kg. The size of the last batch was 2007 pigs. The next batch is expected to be 2000 pigs. Given the insignificant deviations, the number of pigs in inventory is rounded to 2000 in order to facilitate the calculations and ease the presentation of results. When the finishers are trucked away, one week is used to clean and disinfect the building before the new batch arrives. An average of 108 days is assumed to be the time required to raise the pigs, with one week for cleaning and disinfecting (Table 2). Mortality normally varies around 3%, however, for the purposes of this study, the number of pigs is assumed to be net of mortality.

When the moratorium on hog production is lifted in December 2003[8], the operator plans to start the construction of another barn containing 2800 finishers. This would increase the new facilities production to 4800 pigs. The new barn is planned to be 150 meters away from the first barn.

[8] In fact, in November 2003 the moratorium has been prolonged until the end of 2004 (Jobin and Barrette 2003)

Table 2. Time that Pigs Spend in the Production Facility and the Time for Hygienic Maintenance.

Production time	108 days * 3.17 batches = 342 days
Time for cleaning and disinfecting	7 days * 3.17 intervals = 22 days
Total	365days

4.1.3 Manure Handling System on the Case Farm

There are two main methods for calculating the amount of excreted manure. The first is based on per 1,000 pounds of animal live weight. The other is based on an average amount of excreted manure per pig for a certain age group. The first method requires precise data on weight gain in pigs. These data were not available from the case farm. Thus, the latter method was chosen to be feasible for this study.

A publication by CREAQ (Comité de Références Economiques en Agriculture du Québec 1999), "Fumier de ferme", estimates that 5.8 litres of manure is produced per day per grower/finisher with weights between 20 and 100 kilograms. Due to a low concentration of solids in liquid swine manure, it was assumed that 1,000 litres of swine manure was equal to 1 metric tonne.

Pigs are raised in confinement, and there is no loss of manure outside the manure handling system. The barn floor is partially slatted. Excreted manure is transported by under-slat mechanical scrapers into temporary pit storage (pre-pit) below grade. Inside the pit there is a submersible pump which transfers manure into an above-ground concrete cylinder storage. The latter is situated about 20 meters away from the barn. Its diameter is 120 feet wide and its depth is 14 feet. The volume is therefore ($V=\pi r^2 h$, 158,366 ft^3=3.14*3600*14) 158,366 ft^3 (4484 m^3), which is equivalent to 305 days of storage capacity for 2000 pigs.

The producer attempts to minimize the addition of water to manure. An efficient water supply system prevents spillage. Pigs are not showered as there is a wind cooling system. Unlike other manure collection systems, he does not flush manure and uses mechanical scrapers instead. Water is only added during the cleaning of the interior barn walls and floors during the week between batches.

Some manure is transported off the farm to two organic corn producers. The first has 450 acres of land and would like to receive up to 4,000 tonnes of manure. The second would like to receive 3,800 tonnes of manure to be spread on 400 acres. There is a third corn producer with 1,000 acres of land who would also like access to the manure. The producer does not pay for hauling manure away and does not receive any remuneration for it. He asserts that 99% of the grain grown in the vicinity is transported away and that there is insignificant manure production in the area for fertilizer use on crops.

The rest of the manure is spread on the farmer's crop fields. The crops include grain corn, sweet corn, soybeans, and peas. Currently, the operator spreads manure with low-ramp equipment, however, injection equipment is expected to be obtained in the near future.

Fertilizer value of manure on the case farm was provided by an independent agronomist who analyzed manure samples. Manure on the case farm is higher in nutrient value as compared to a sample analysed in another study done by CREAQ as demonstrate in Table 3 (1999).

Table 3. Fertilizer Value of Swine Manure

	Case Farm[1]	La Ferme Beauchamp[2]
Total Nitrogen (N)	4.1 kg/tonne	3.0 kg/tonne
Phosphorous (P_2O_5)	2.7 kg/tonne	2.36 kg/tonne
Potassium (K_2O)	3 kg/tonne	1.2 kg/tonne

Reference:

(1) Jacques Nault, agronomist

(2) Comité de Références Economiques en Agriculture du Québec, "Fumier de ferme"AGDEX 538/400.27, 1999

4.1.4 Electricity Consumption on the Case Farm

Since the barn is new, there is very limited data on its electricity consumption. In order to derive monthly electricity consumption, the operator was asked about the projected electricity consumption for the barn that is planned to be constructed in the near future. The operator reported that the annual electricity expenses are expected to be $ 1.25 per marketed pig. The current price for electricity was 6.88 cents/kWh.

In order to show seasonal variations in consumption, electricity bills were obtained from an established hog farm in l'Assomption region in Quebec. Electrical bills from Hydro-Quebec are based on 60 days of electrical consumption. Monthly spending on electricity for the case farm was calculated by taking annual projected spending on electricity and then distributing it proportionally to the seasonal variations in consumption on the farm in l'Assomption. Monthly spending was estimated by dividing the 60 day distribution in half (Table 4).

Table 4. Electricity Needs of the Case Farm

2000 pigs in inventory				4800 pigs in inventory		
month	kWh	Payment Due		month	kWh	Payment Due
January	12727	$ 876		January	30545	$ 2,102
February	8955	$ 616		February	21493	$ 1,479
March	8955	$ 616		March	21493	$ 1,479
April	7488	$ 515		April	17970	$ 1,237
May	7488	$ 515		May	17970	$ 1,237
June	6410	$ 441		June	15384	$ 1,059
July	6410	$ 441		July	15384	$ 1,059
August	6782	$ 467		August	16276	$ 1,120
September	6782	$ 467		September	16276	$ 1,120
October	10776	$ 742		October	25863	$ 1,780
November	10776	$ 742		November	25863	$ 1,780
December	12727	$ 876		December	30545	$ 2,102
Annual	106276	$ 7,313		Annual	255064	$ 17,551

4.2 The Technical Potential for Introducing Anaerobic Digestion on the Case Farm

4.2.1 Selected Company Digester Description

An AD company was contacted to verify specifications and capital costs of an anaerobic digestion system. The company is a distributor that imports technology from Europe to Canada. The digester tank is dual-chambered and does not fall into a conventional "complete-mix" category.

The fermentation tank consists of two chambers: prefermenter and postfermenter. The top parts of the two chambers are interconnected by gas pipes and the bottom parts by orifices for moving manure between chambers. First, manure enters the prefermenter. As biogas is evaporated, pressure builds up in the prefermenter and it pushes manure in the postfermenter to go back into the prefermenter. This process is continuous, which maximises biogas production. Hydraulic Retention Time, the time of treatment, is approximately 30 days. The output is high quality biogas with 60% methane.

Inside the fermenter, 30 kWh of heating energy per metric tonne of manure is required in the Canadian climate conditions (Rentec web-site 2003). Temperature is maintained at 38-39° C. The distributor provided the estimated heating output of the system, net of the heating requirements of the tank. It was calculated that from the primary energy output, approximately 38% is converted to electricity, 48% to heating, and about 13% is wasted. This is the case when the farm uses a combined heat and power unit (CHP). The lifetime of the system is 25 years, although the distributor points out that there are digesters of this type which have exceeded this lifetime and are still operational in Europe.

The equipment includes a desulphuration unit to clean the biogas of hydrogen sulphide. Hydrogen sulphide is a corrosive gas and is particularly harmful to the engine and generator. It is also linked to acid rain. The negative impact of hydrogen sulphide is excluded from the analysis as it is captured during the digestion process.

4.2.2 Calculation of Biogas Production from Hog Manure

Biogas production depends on the concentration of volatile solids, which are the fraction of total solids in manure. A publication by Comité de Références Economiques en Agriculture du Québec, "Fumier de ferme" (1999), estimates that 91% of excreted swine manure is water and therefore 9% is total solids. Nine percent of TS is thought to be a reasonable estimate because on the case farm manure is collected by under-slat mechanical scrapers. If the operator had an anaerobic digestion system, manure would be pumped from the pre-pit to the digestion tank and then to the concrete manure storage. Dilution from precipitation would only occur during outdoor storage.

Volatile solids are 80% of TS (Semmler 2003). According to the distributor, only 55% of the volatile solids are destroyed and converted to biogas. Of this amount, each kilogram would produce 0.8 cubic meters of biogas. This corresponds to a biogas production coefficient of 0.44 cubic meters per kg of VS added. However, (Demuynck et al. 1984), in her book "Biogas Plants in Europe: A Practical Handbook", estimates a range of values from as low as 0.16 to 0.34 cubic meters per kg of VS added. A sensitivity analysis will be undertaken on this value. The methane content in biogas is 60% (Semmler 2003). It is assumed that all the biogas that is not used is flared to prevent the release of methane to the atmosphere.

Hashimoto et al. (1980) provided the following equation for the calculation of biogas production:

$$\gamma_v = \frac{B_0 S_0}{\theta}\left(1 - \frac{K}{\theta \mu_m - 1 + k}\right), \text{ where}$$

γ_v = volumetric CH_4 production rate, i.e. L CH_4/ L digester volume per day (V-digester volume, L-litres)

S_0 = VS concentration in the influent substrate, g/L

B_0 = ultimate CH_4 yield, L CH_4/ g VS added as $\Theta \rightarrow \infty$

Θ = hydraulic retention time in days

μ_m = maximum specific growth rate of microorganisms, day^{-1}

K = kinetic parameter, dimensionless

The gas output is summarized in Table 5. Note that the annual gas production was derived by multiplying daily output by 365 and not 342 because old manure still produces gas. Therefore, gas is still produced during the time between when the finishers are trucked away and a new batch is received.

4.2.3 Sizing the Digester

Digester volumes were calculated as the product of daily manure production and the HRT. Postfermenter and mixing buffer volumes were left the same for two herd sizes. The distributor stated that gasholder volume would be the same for two sizes. In fact, it can be different in order to insure sufficient amount of gas for peak electricity demand.

Loading rates were calculated as a quotient of daily volatile solids production and the total digester volume. As seen from Table 6, the retention time for a digester treating manure from 2000 pigs is 34.5 days and 32.3 days for 4800 pigs. These estimates were provided by the distributor.

Table 5. Summary of Calculations of Daily and Annual Biogas Production Based on a Manure Excretion Rate, Total and Volatile Solids Concentration in Manure.

	Units		
Total Number of Pigs		[redacted]	
Manure Production per Animal	liters/day	5.80	5.80
Manure on Farm	cu m/day	11.60	27.84
Total Solids Concentration	% of manure	0.09	0.09
Total Solids Produced	kg/day	1044	2506
Volatile Solids Concentration	%	0.8	0.8
Volitile Solids on Farm	kgs/day	835	2004
Selected Company Biogas Production Coefficient	cu m/kg VS	0.44	0.44
Daily Biogas Production Based on VS destroyed	cu m	367	882
Annual Biogas Production	cu m	134133	321919

Table 6. Digester Sizing

Total Number of Pigs		2000	4800
HRT (RT)	days	34.5	32.3
Loading Rate	kg VS/cu m of DV	1.392	1.824
Gas Production per Unit Digester Volume	cu m/cu m of DV	0.612	0.802
Fermenter Volume		400	899
Postfermenter Volume		200	200
Total Digester Volume (DV)	cu m	600	1099
Mixing Buffer Volume	cu m	50	50
Gasholder Volume	cu m	400	400

4.2.4 Energy Output

Energy content of biogas is 6.46 kWh per cubic meter of biogas as reported by the distributor company. This figure was compared with a technical report by an environmental technology company GBU (GBU 1999). The latter provides an estimate of 7 kWh per cubic meter of biogas, but for biogas with 70% methane. The lower estimate, 6.46, is justified as the methane content is assumed to be 60%.

Energy is produced by a combined heat and power (CHP) installation. In the analysis, the CHP unit is assumed to be in operation 24 hours a day. According to the data received from the distributor, primary energy output will be converted to the following products: electricity (38%), 49% to heating, and 13% is wasted. The energy produced from the two scenarios is given in Table 7.

Table 7. Daily Energy Output of a Combined Heat and Power Unit.

Total Number of Pigs		[redacted]	
Daily Biogas Production Based on VS destroyed	cu m	367	882
Annual Biogas Production	cu m	134133	321919
[redacted]	cu m	220	529
	cu m	80480	193152
Energy Content of Biogas	kWh/cu m	6.46	6.46
Primary Energy Output	kWh/day	2374	5698
is converted to			
Electricity	kWh/day	902	2165
Heating	BTU/day	3968997	9525593
Heat Loss	kWh/day	309	741

Note: 49% of primary energy output is converted to heating. Heating value is normally expressed in British Thermal Units (BTU) rather than kWh. One kWh is equal to 3412 BTU (Interactive Unit Converter 2003)

4.3 Investment Analysis of the AD System

4.3.1 Introduction

The investment analysis was performed in Microsoft Excel. The model consists of a number of linked worksheets that allows for scenario analysis by changing variables from the base case to estimate their impact on Net Present value (NPV). NPV is defined as "the sum of the discounted project benefits less discounted project costs" (New South Wales Government 1997). The standard NPV formula employed in the analysis is:

$$NPV = -E + \sum_{t=1}^{T} \frac{C_i}{(1+r)^t} + \frac{SV_T}{(1+r)^t}, \text{ where}$$

$-E$ = Initial Investment (Equity Financing). In the sensitivity analysis equity financing can be reduced by a potential grant from the government.

C_i = Annual Net Cash Flows

t = year

T = Expected Lifetime of the System (Final Year)

SV = Salvage Value. It is assumed to be equal to the Undepreciated Capital Cost at the end of year 25, the expected lifetime of the system.

r = discount rate

The discount rate was calculated using the Weighted Average Cost of Capital (WACC) formula below. Equity capital was assumed to be 75% and debt capital 25% of the cost of the system.

$$r_{WACC} = r_E \frac{E}{E+D} + r_D \frac{D}{E+D}(1 - T_m), \text{ where}$$

r_{WACC} = Weighted Average Cost of Capital

r_E = return on equity capital (a rate of 4% was chosen)

r_D = long run interest, return on debt (a rate of 10% was chosen)

E = equity capital

D = debt capital

T_m = marginal tax rate (38%)

4.3.2 Base Case Identification

For the base case calculations the following assumptions apply:

- Volatile Solids were 80% of Total Solids.
- Biogas production coefficient was 0.44 cubic meters of biogas per kg of volatile solids.
- Derived energy was only used on site.
- Energy savings were calculated as the cost of replacing purchased propane and electricity at their current prices. Propane costs 35 cents per litre and electricity 6.88 cents/kWh.
- Repairs and maintenance costs were assumed to be 2% of the capital costs. Annual labour costs were calculated using a wage rate of $ 7.5/hour. The system is in operation 365 days a year and 30 minutes per day are required to look after the system.
- The operator was contacted to find out a probable equity portion of financing. Ten percent of the total capital cost for either case would be self-financed and 90% of the investment cost was therefore borrowed from a lending institution.
- Return on equity capital was assumed to be 4%.
- The debt would be retired in 20 years and the life expectancy of the system was assumed to be equal to this time span, whereas the real life expectancy can be 25 years.

- Long-run interest rate in the business was 10%.
- The discount rate was the weighted average cost of capital and was calculated to be 4.55%.
- The effective interest rate on borrowed capital is 5.63%.
- Marginal tax rate was estimated to be 38%.
- The Capital Cost Allowance rate for all pieces of equipment was assumed to be in Class 8 "Machinery and Equipment and All Property Not Listed Elsewhere". The rate was 20% (Cavanagh 1994).

Table 8 provides an excerpt from Agriculture and Agrifood Canada's Medium Term Policy Baseline from 1997 to 2007 with base year 1992. Growth rate projections from 2001 to 2007 are assumed over the 25 years of the life expectancy of the project.

These rates were used to calculate nominal cash flows. For each category, the first 4 rates were used and the growth rate for 2001-2007 was assumed to be constant over the remaining 21 years.

The general inflation rate was calculated from Statistics Canada's Consumer Price Index with 1992 being the base year. The average rate from 1992 to 2002 was 1.9%.

Variables included in the sensitivity analysis and their prospective ranges

The economic feasibility of the project was evaluated using a sensitivity analysis around the following parameters:

Table 8. Canadian Farm Input Prices

Retail Price Indexes and % change	2004	2005	2006	2007	Growth Rate 2001-2007
Petroleum Products	2.2%	1.8%	1.8%	1.8%	0.9%
Machinery Repair	2.1%	2.1%	2.2%	2.2%	2.3%
Fertilizer	1.5%	1.7%	1.1%	1.2%	1.2%
Electricity	0.6%	1.1%	1.1%	0.4%	0.4%
Custom Work	1.4%	1.5%	1.5%	1.5%	1.5%
Interest	-0.7%	-0.3%	-0.3%	-0.3%	0.3%

Source: Agriculture and Agrifood Canada, Medium Term Policy Baseline from 1997 to 2007 (Base Year=1992).

Herd Size. It was only possible to test the sensitivity for 2 herd sizes: 2000 and 4800 pigs that correspond to respective 6,340 and 15,216pigs marketed annually.

Operational Costs. For repair and maintenance cost, the range used was 1.5%, 2%, 2.5%, and 3% of capital costs. The wage rate remained constant over time.

Debt/Equity Proportions. This proportion was changed from 100%/0% to 50%/50% by increments of 10%

Energy prices and a possibility to sell-back electricity. Energy prices ranged from 5 to 11 cents per kWh (see Table 16).

Volatile Solids Concentration. VS are a percentage of given TS. The range for the sensitivity analysis was 62.4%-**80%.** The low estimate was provided by the agronomist who sampled the tank on the farm and the second was estimated by the AD distributor.

Biogas Production Coefficient estimates the conversion of cubic meters of biogas per kilogram of volatile solids. The range of conversion values was 0.16, 0.28, 0.29, 0.34, and 0.44.

Investment Cost. Excel's "Goal Seek" function will be used to get NPV = $ 0. If NPV is negative a project should be rejected and if NPV is positive, it should be adopted (Barry et al. 1983). By equalizing NPV to zero, "Goal Seek" function in this case can indicate the investment cost at which the farmer should be indifferent about the adoption of AD technology. Thus, a lower investment cost can generate a positive NPV.

Capital Cost Subsidy. The difference between the current system costs and break-even investment cost was considered as a potential subsidy from the government

Emission Reduction Credits (price per tonne of CO_2). In the base case, the price was set at $ 10/tonne. This value was varied from $ 8to $ 15/tonne.

4.3.3 Capital Costs

Capital costs were provided by a distributor company that brings European digesters to Canada. These were equal to $ 604,487 and $ 945,234 for a herd size of 2,000 and 4,800 pigs respectively. The capital costs are summarized in Table 9.

Table 9. Capital Costs of an Anaerobic Digestion System.

Number of Pigs per Batch		[redacted]	
Marketed Pigs			
	unit		
Transfer and Mixing Systems		$ 56,736	$ 56,736
Digester Tank Sediment Extraction System Wet Gas Storage			
Biogas System		$258,326	$ 497,742
Desulphuration Unit Gas Transport System CHP Unit Gas Flare			
Energy System		$240,353	$ 341,684
Control Unit Electrical Cabinets			
Process Automation - Electrical Installation		$ 49,072	$ 49,072
Total Capital Costs		$604,487	$ 945,234
Capital Cost per Unit DV	$/cu m	$ 1,007	$ 860
Capital Cost per Pig Marketed		$ 95	$ 62

4.3.4 Base Case Calculations: Benefits

Constructing an AD on the farm will generate savings on electricity and heating produced by the CHP unit. For electricity, the benefit was calculated by multiplying kilowatt-hours produced by the CHP unit by the current price of electricity. According to the bills received from the producer, the average price was $ 0.0688 per kilowatt-hour.

Saved kilowatt-hours were equal to all kilowatt-hours produced by the generator only if energy output did not exceed the electric needs of the farm. However, if it does, then only the required kilowatt-hours multiplied by the current price were considered to be saved and the excess is wasted. In other scenarios, excess electricity was sold back to the electric grid.

Similarly, heating savings were calculated by comparing the energy value of propane, in BTU's, with the energy value produced by thermal output. The thermal output was waste heat produced by the generator and is in the form of water circulating around the engine. Table 10 illustrates the benefits from energy savings in the first and last years of the life expectancy of the digester. Benefits change over time due to inflation.

4.3.5 Base Case Calculations: Costs

Costs were calculated as the sum of labour, repairs, and maintenance costs. The general labour rate was assumed to be \$ 7.50/hour. If 30 minutes per day are devoted to the digester, then annual labour costs were \$ 1,369 (7.5*0.5*365). In the base case, repairs and maintenance costs were assumed to represent 2% of the capital outlay (Table 11).

Cavanagh (1994) assumed that operating cash flows occur at the end of each year and this coincides with timing of tax payments. They also assumed that the tax year and the calendar year coincide. These two assumptions were used in the analysis. The benefits and costs are summarized in Appendix B.

Debt is amortized according to the following formula, which was an incorporated function in Excel:

$$PMT = D\frac{i_e}{1-(1+i_e)^{-T_i}}, \text{ where}$$

PMT = annual payments (on both Principal and Interest)

Table 10. Annual Nominal Cash Inflows from Energy Savings

	2000 pigs		4800 pigs	
	1st year	20th year	1st year	20th year
Electricity (Farm Needs Only)	$ 7,313	$ 8,015	$ 17,551	$ 19,237
Heating (Farm Needs Only)	$ 3,510	$ 4,329	$ 8,424	$ 10,389

D= Debt

i_e = effective annual project interest rate

T_i = investment term

The Valleyfield office of La Société de financement agricole du Québec, (former l'Office de Credit Agricole du Québec), was contacted to determine loan conditions. For both amounts, $ 544,038.30 and $ 850,710.60 (the debt portion of the system cost was 90%), the interest rate was 5.55% with the debt amortized over a 20 year period. The rate of 5.55% was a stated annual interest rate. Annuities are paid monthly and an effective interest rate must therefore be calculated. Compounding was semi-annual. In order to calculate the effective annual rate a formula provided in Ross et al. (1999) was employed.

Table 11. Annual Operating Costs of an AD System

Number of Pigs per Batch	2000	4800
Repairs and Maintenence Costs (assume 2% of capital costs of AD system)	$ 12,090	$ 18,905
Labour Cost (Half an hour a day at a rate of 7.5$/hour 365 days a year)	$ 1,369	$ 1,369
Total Operating Costs	$ 13,459	$ 20,274

$$i_e = (1+\frac{i_s}{m})^m - 1, \text{ where}$$

m = the number of compounding periods a year

i_s = stated annual interest rate

i_e = effective annual project interest rate

$$5.63\% = (1+\frac{0.0555}{2})^2 - 1$$

Salvage value was assumed to be equal to the undepreciated capital cost at the end of the economic life of the system. It was estimated with the following formula:

$$UCC_T = C(1-\%CCA)^T, \text{ where}$$

UCC_T = Undepreciated Capital Cost at the time of salvage

C = Capital Cost of an Anaerobic Digestion System

$\% \, CCA$ = Capital Cost Allowance Rate

T = Expected Life Expectancy of the System

Cash flows were calculated in nominal terms as the derived WACC discount rate was nominal. Instead of using one general inflation rate for all input variables, individual inflation rates were used.

4.4 Greenhouse Gas Emissions

4.4.1 Chemistry Background

This section summarizes the chemistry required to understand the discussion of GHG emissions related to AD and regular manure management practices. The information in this section was used to calculate the GHG emissions in metric terms.

One mole of any gas occupies 0.0224 m^3 (Boyd 2000). Boyd calculated that 1 mole of CH_4 weighs 0.016 kg and one mole of CO_2 weighs 0.044 kg.

1 m^3 of biogas (60% CH_4, 40% of CO_2) would contain:

0.6*0.016/0.0224 = 0.42857 kg of CH_4

0.4*0.044/0.0224 = 0.78571 kg of CO_2

1 m^3 of biogas thus weighs 0.42857 + 0.78571 = 1.2143 kg

In accordance with calculation by Boyd:

1 m^3 of CH_4 weighs 0.016/0.0224 = 0.71429 kg of CH_4

1 m^3 of CO_2 weighs 0.044/0.0224 = 1.96429 kg of CO_2

Marshall (2003) provided the following equations for the combustion of biogas:

$$(1) \qquad CH_4 + 2O_2 \xrightarrow[\Delta]{} CO_2 + 2H_2O$$

$$(2) \qquad CO_2 \xrightarrow[\Delta]{} CO_2$$

There are two sources of CO_2 in exhaust gases. First, each tonne of burnt CH_4 is converted to 2.75 tonnes of CO_2 after combustion (Laguë 2003). This reaction is demonstrated in formula 1 above. Secondly, 40% of the CO_2 fraction of the biogas is not affected by combustion (formula 2 above).

Nitrous oxide emissions exist in regular manure management practices, but under anaerobic conditions there are no N_2O emissions. Even if there were some minimal amounts of N_2O in biogas, as a result of combustion they would be converted to NO_2 (Marshall 2003). This is shown in the formula below. NO_2 is a pollutant contributing to acid rain and smog, but it is not a greenhouse gas (VCR Inc. 2003)

$$(3) \qquad 2N_2O + 3\,O_2 \rightarrow 4NO2$$

4.4.2 GHG Emissions from Hog Manure Storage Tanks Without Anaerobic Digestion

In order to estimate net environmental benefits, emissions associated with AD should be compared with emissions when manure is handled in a conventional way, i.e. kept in an outdoor concrete manure storage tank. Under conventional storage conditions the following gases are produced: methane (CH_4), nitrous oxide (N_2O) and carbon dioxide (CO_2). Clark et al. (2003) found that emissions of CO_2 are close to zero in undisturbed pig slurry. Therefore, CO_2 emissions from an outdoor storage tank were assumed to be zero.

CH_4

Massé et al. (2003) estimated CH_4 emissions from swine manure storage tanks. In their study, manure characteristics and storage conditions were typical of Canadian farms. Methane emissions from swine manure kept at a mean temperature of 10°C were estimated to be 45.82 L CH_4 per kg VS per day. This was thought to be an appropriate estimate for the analysis, although according to the data from the nearest weather station the yearly mean temperature was 6.4°C (Environment Canada 1971-2000). As a result, there is an overestimation of the methane release.

1 m^3 of CH_4 weighs 0.016/0.0224 = 0.71429 kg

1 m^3 contains 1000 liters. (Interactive Unit Converter 2003)

In order to estimate the annual methane release in metric tonnes, the amount of VS produced over 342 day was multiplied by 0.04582 m^3 CH_4 per kg VS (45.82 litres = 0.04582 m^3), then multiplied by 0.71429 and divided by 1000 to arrive at metric tonnes.

N_2O

Roger Phillips (1997) as cited in Laguë et al. (2002) found that emissions of N_2O in a storage tank were insignificant. However, VCR Inc. (2003) calculated N_2O emissions to be 0.01044 kg N_2O per head per year. This calculation was based on "Canada's Greenhouse Gas Inventory 1990-2000" of Environment Canada. This estimate compares with Marinier (2003), whose measurement was 0.012 kg N_2O per head per year. The latter was measured at two Canadian swine farms (Guelph and Warburgh). The emission factor was based on pigs in inventory and not the total number of marketed pigs per year.

The value by Marinier (2003) is preferred because her work clearly states that the emission factor refers only to the manure storage tank. In the VCR Inc. (2003) estimate, it did not state whether the emissions from the production building had been included.

4.4.3 GHG Emissions when Anaerobic Digestion is Employed

<u>**Avoided GHG Emissions from Replacing Synthetic Fertilizers**</u>

Nitrous oxide emissions arise from the process of nitrification and denitrification of nitrogen (Granli and Bockman 1994 as cited in Dustan 2002). According to VCR Inc. (2003), each kilogram of N generates 0.0125 kg of N_2O emissions whether or not the N is from a synthetic fertilizer or animal wastes applied as fertilizer.

Avoided GHG Emission from Replaced Electricity Purchases

Emissions of GHG related to electricity consumption were drawn from VCR Inc. (2003). Emission estimates were for thermal generating plants. Emissions related to hydroelectric reservoirs were not included. In the report by VCR Inc. (2003), indirect emissions were estimated for Quebec over the 1990-2001 timeframe. Over this period, each kilowatt-hour of electricity results in a mean emission of 0.004617 kg of CO_2e.

Avoided GHG Emissions from not Using Propane

VCR Inc. (2003) used the emission factors from "Canada's Greenhouse Gas Inventory 1990-2000". These emission factors (1.500 kg CO_2/L, 0.000024 kg CH_4/L, 0.000108 kg N_2O/L of propane) were multiplied by the corresponding global warming potentials of GHG (CO_2-1, CH_4-21, N_2O-310) and then summed. The combustion of one litre of propane was estimated to produce emissions of 1.533984 kg of CO_2e (Table 12).

4.4.4 Calculation of GHG Emissions and Emission Reduction Credits

GHG emissions from AD were calculated using 4 steps. For demonstration purposes, GHG emissions from 1 metric tonne of swine manure over a period of 33 days, an average HRT, was examined.

Whether or not GHG emission reduction credits can be claimed will depend on the GHG emissions from regular manure management practices. Producers should claim GHG emission reduction credits if the GHG emissions from AD are lower than the emissions from regular practices. In our case, the regular storage facility is an outdoor cylinder storage without a cover.

Table 12. GHG Emission Factors from the Combustion of Propane

[redacted]				
units	CO2	CH4	N20	
kg/l (calculated by VCR.Inc.)	1.500	0.000024	0.000108	Weighted Average
kg CO2e/l	1.500	0.000504	0.033480	1.533984

Calculation of the GHG Emissions Generated over a Period of 33 Days from One Metric Tonne of Anaerobically Treated Swine Manure

Step One considers the methane content of biogas, before it is burnt (expressed in CO_2e)

First, the amount of methane generated from one tonne of manure was calculated:

Manure in kilograms * % TS* % VS in TS * B_0 (Biogas Yield Coefficient) * % CH_4 in biogas

1000 * 0.09 * 0.8 * 0.44 * 0.6 = 19 m^3 of CH_4

This amount weighs 19 * 0.71429 = 13.6 kg of CH_4

Step Two subtracts the emissions of CO_2 (40% of biogas plus CH_4 converted by combustion to CO_2)

Carbon dioxide is generated in two ways. The first is the generation of biogas. This amount is not affected by combustion (see formula in section 3.4.1). The second is the combustion of methane. These two amounts were summed.

CO_2 content of biogas = Manure in kilos * % TS* % VS in TS * B_0 * % CO_2 in biogas * a conversion rate to kilograms

1000 * 0.09 * 0.8 * 0.44 * 0.4 * 1.96429 = 24.9 kg of CO_2e

Over the treatment period of 33 days, this equals to:

24.9 * 33 = 821.7 kg of CO_2e

After combustion, CH_4 is converted to CO_2 by a factor of 2.75 (Laguë (2003)

One tonne of swine manure produces 13.6 kg of CH_4 daily

CO_2 emitted daily is thus 13.6 * 2.75 = 37.4 kg

Over the period of full AD treatment it is equal to

37.4 * 33 = 1,234.2 kg of CO_2

Total Emissions of CO_2 over 33 days

821.7 + 1234.2 = 2055.9 kg of CO_2

Step Three subtracts the emissions associated with electricity generation and the combustion of propane

Avoided emissions from electricity generation:

One metric tonne of manure generates 1000 * 0.09 * 0.8 * 0.44 = 31.68 m^3 of biogas daily (0.09 – TS content, 0.8 – VS content in TS, 0.44 – biogas production coefficient).

One m^3 of biogas has an energy content of 6.46 kWh, 38% of which is converted to electricity. Over 33 days the amount of produced electricity is:

31.68 * 6.46 * 0.38 * 33 = 2566 kWh

Taking the number of kWh and multiplying it by the average coefficient of avoided CO_2 emissions from electricity production provides an estimate of the CO_2e that would be avoided. Coefficients were estimated by VCR Inc. (2003) and were 0.00462 kg CO_2e/kWh for Quebec and 0.21067 kg CO_2e/kWh for Ontario.

2566.08 * 0.00462 = 11.9 kg of CO_2e (Quebec)

2566.08 * 0.21067 = 540.6 kg of CO_2e (Ontario)

Avoided emissions from replacing propane:

Heating content of biogas generated from one tonne of swine manure over 33 days is

3309 kWh = 31.68 * 6.46 * 0.49 * 33, where

31.68 m^3 – the amount of biogas generated from one metric tonne of swine manure per day

6.46 kWh – the energy content of biogas

49% – the percentage of primary energy that was converted to heating,

33 days – HRT

One kWh is equivalent to 3412 BTU (Interactive Unit Converter 2003).

3309 * 3412 = 11,290,308 BTU

It was assumed that the energy value of propane was 91,600 per gallon (Buffington 2002). This translates to 24,200 BTU per litre since one gallon is 3.785 litres (Interactive Unit Converter 2003). The Excel model demonstrated that annual heating production from the

CHP unit exceeds the heating needs of the farm 5.97 times. The heat generated from one tonne of swine manure over 33 days can therefore replace 78 (11,290,308 /24,200/5.97) litres of propane.

Avoided CO_2 emissions, were estimated as 1.533984 CO_2e per litre of propane (see subsection "Avoided GHG Emissions from not Using Propane" in section 3.4.3). Replacing propane with biogas energy avoids 119.7 (78 * 1.533984) kg of CO_2e during 33 days

Avoided emissions from electricity generation and propane were estimated to be:

11.9 + 119.7 = 131.6 kg of CO_2e (Quebec)

540.6 + 119.7 = 660.3 kg of CO_2e (Ontario)

Step Four adds the emissions associated with the increase in fertilizer value:

Only the GHG emissions from the increased fertilizer value of manure were estimated. This was because that part is created by AD. The estimation of 1.45 kg (IrBEA 2000) is used (see section 4.2.1 "Estimation of the Benefits from Increased Fertilizer Value"). This estimate is per 1 m^3 of manure and we assume it to be equal to 1 tonne due to low solids content in swine manure. The factor of 0.0125 kg of N_2O emissions is taken from VCR Inc. (2003). GWP of N_2O is 310.

1.45 * 0.0125 * 310 = 5.6 kg of CO_2e[9]

Total Emissions of CO_2e arising from AD over 33 days are:

2,055.9 - 131.6 + 5.6 = 1,929.9 kg of CO_2 (Quebec)

2,055.9 - 660.3 + 5.6 = 1,401.2 kg of CO_2 (Ontario)

[9] Note that for fertilizer use we do not multiply by 33 days since these emissions are not linked directly to HRT

GHG Emissions from an Outdoor Storage Tank

This section estimates the GHG emissions from one metric tonne of swine manure held in outdoor storage for 33 days

CH_4 emissions in a storage tank

A. Emissions of CH_4 were estimated using the amount of VS in a tonne of swine manure:

   VS = Manure in kilos * % TS* % VS in TS

   1000 * 0.09 * 0.8 = 72 kg VS

B. VS content is multiplied by Massé's (2003) estimation of 45.82 litres CH_4 per kg VS daily (45.82 litres = 0.04582 m^3),

   72 * 0.04582 = 3.299 m^3 of CH_4

Since a cubic meter of CH_4 weighs 0.016/0.0224 = 0.71429 kg of CH_4,

Daily emissions of CH_4 are equal to 3.299 * 0.71429 = 2.4 kg of CH_4

Daily emissions of CH_4 in CO_2e are equal to 2.4 * 21 = 50.4 kg of CO_2e

Over 33 days, the emissions are equivalent to 50.4 * 33 = 1663.2 kg of CO_2e

N_20 emissions from a storage tank

Nitrous oxide emissions were estimated at 0.012 kg N_2O per head per year (Marinier 2003). Estimation per tonne of swine manure daily can be calculated knowing that one pig produces 5.8kg of manure per day and the production period is 342 days.

One grower/finisher produces 5.8 * 342 = 1984 kg of manure annually, and

0.012 kg N_2O are therefore emitted from 1984 kg of manure annually

Therefore, the equivalent emissions from one tonne is

0.012 * 1000 / 1983 = 0.006 kg of N_2O per tonne of manure annually

In CO_2e this amount is equal to

0.006 * 310 = 1.9 kg of CO_2e per one tonne of manure annually

Daily, this corresponds to 1.9 / 365 = 0.005 kg (5 grams) of CO_2e per one tonne of manure (note the division by 365 days and not 345, because emissions persist while there are no pigs in a production facility; manure is still kept in storage)

Over 33 days it is equal to 0.005 * 33 = 0.165 kg of CO_2e

Total GHG emissions from a manure storage over 33 days are 1663.2 + 0.165 = 1663.4 kg of CO_2e

Table 13 summarizes all the calculations above and estimates the potential emission reduction credits from AD.

It is concluded that one tonne of anaerobically treated swine manure gives Ontario farmers an opportunity to claim 0.262 tonnes of captured CO_2e. In Quebec hog producers will not be able to claim captured CO_2e from AD since emissions from AD exceed emission from regular manure management practices. These figures are valid for operations that use a comparable outdoor manure storage facility.

Table 13. GHG Emissions from One Tonne of Swine Manure: 33 days in an Outdoor Storage Compared with the Complete AD Treatment over 33 Days (tonnes of CO_2e) and the Potential for Claiming CO_2 Emission Reduction Credits.

	Outdoor Storage	AD	Amount Claimable for CO2 Emission Reduction Credits
column	1	2	3 (1-2)
Quebec	1.663 tonnes	1.930 tonnes	-0.267 tonnes
Ontario	1.663 tonnes	1.401 tonnes	0.262 tonnes

CHAPTER FIVE: RESULTS

This chapter will explain the base case of the model that was introduced in the previous chapter. Then a number of sensitivity analyses will evaluate the viability of anaerobic digestion. A particular attention will be drawn to the incorporation of environmental benefits into the economic analysis.

5.1 Economic Viability

5.1.1 Base Case NPV for Two Herd Sizes

Benefits in the base case include:

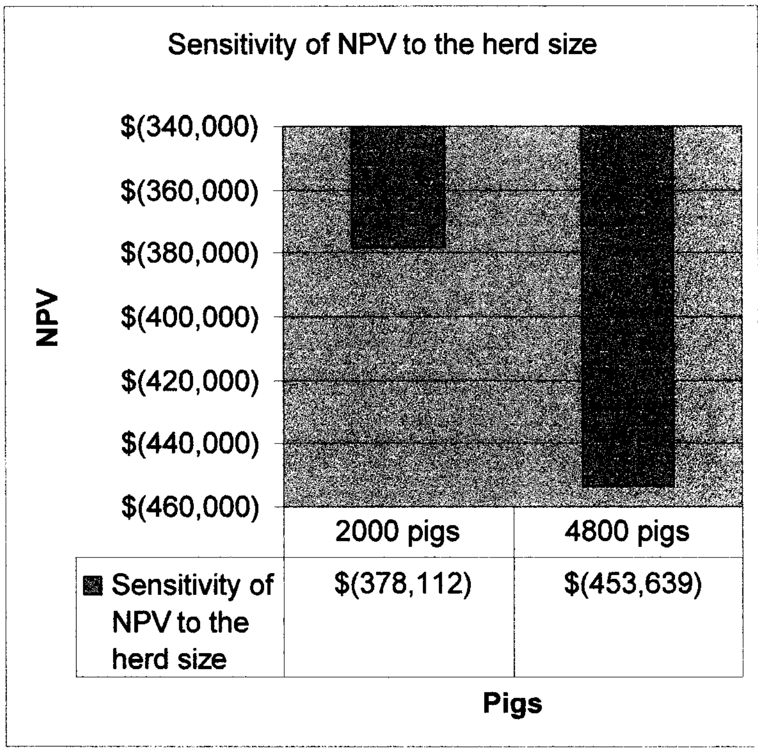
- Savings on electricity at the rate of 6.88 cents / kWh. No excess electricity is sold back to electric utilities.
- Savings on propane (35 cents / litre). Excess heating is wasted.
- The increase in nitrogen fertilizer value of manure

Costs include:

- Repairs and maintenance costs (2% of capital costs)
- Labour costs ($ 7.50 / hour) for operation at 0.5 hours/day

A herd size of 2,000 pigs corresponds to 6,340 marketed pigs annually. Increasing the size to 4,800 pigs produces 15,216 marketed pigs per year. The NPV for both herd sizes was negative as demonstrate on the chart below (Figure 1). Large operational costs override the benefits from energy savings because in the base case it is not possible to use excess heat

Figure 1. Base Case NPV



and electricity. It is generally advised that anaerobic digestion is feasible for larger operations. However, as it can be seen from this case, a smaller operation can be more feasible if the energy benefits match the needs of the farm. Otherwise the investment can be wasteful.

5.1.2 Sensitivity of NPV to Operational Costs

Only repairs and maintenance costs were varied, with a possible range of 0%, 0.5%, 1%, 1.5%, 2%, and 2.5% of capital costs. From Table 14, it is evident that even if repairs and maintenance cost are dropped to zero (labour expenses are still counted), the NPV for the investment is still negative.

Table 14. Sensitivity of NPV to Operating Costs.

2000 pigs	Operational Costs as a % of Capital Costs	Operational Cost	NPV
	0.0%	$ 1,369	$ (258,057)
	0.50%	$ 4,391	$ (288,071)
	1.0%	$ 7,414	$ (318,085)
	1.5%	$ 10,436	$ (348,098)
	2.0%	**$ 13,459**	**$ (378,112)**
	2.5%	$ 16,481	$ (408,126)
4800 pigs	Operational Costs as a % of Capital Costs	Operational Cost	NPV
	0.0%	$ 1,369	$ (265,909)
	0.50%	$ 6,095	$ (312,842)
	1.0%	$ 10,821	$ (359,774)
	1.5%	$ 15,548	$ (406,707)
	2.0%	**$ 20,274**	**$ (453,639)**
	2.5%	$ 25,000	$ (500,572)

5.1.3 Sensitivity to the Debt Portion

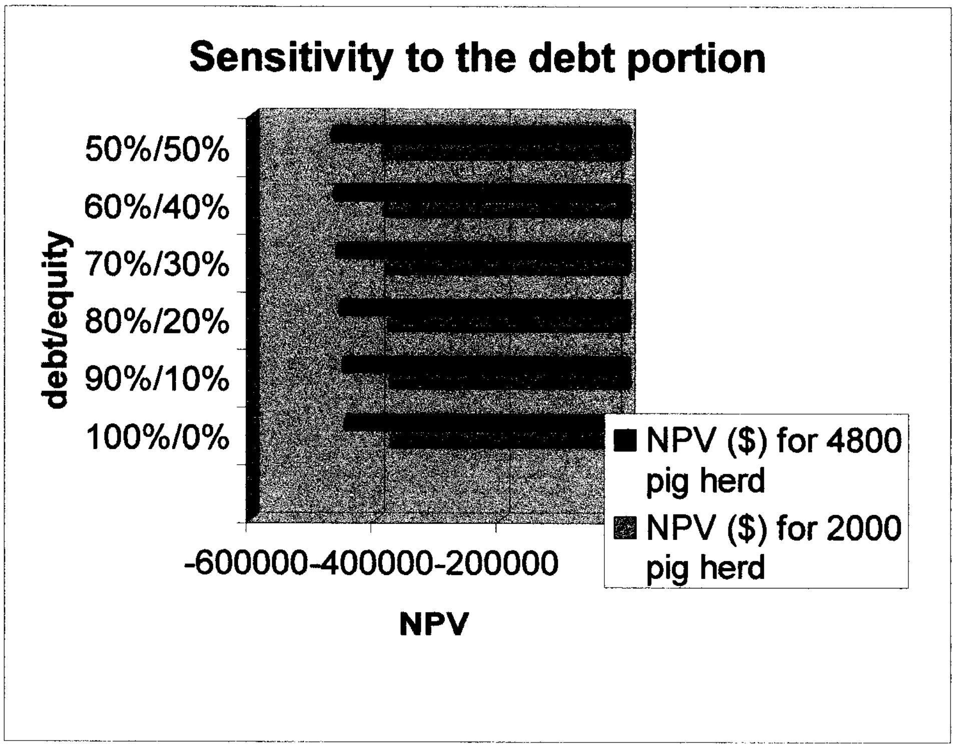
After discussions with the case farm operator, a debt/equity ratio for this type of investment was assumed to be 9:1. If the operator decided to reduce borrowed capital from 90% to 50%, then the NPV would decrease by 3% and 4% for the 2000 and 4800 herd sizes respectively (Table 15 and Figure 2).

NPV also decreases as the proportion of debt decreases as demonstrated on Table 15 and Figure 2. This is because equity downpayment, being a negative cash outflow, occurs at t=0 and at this initial year the discount factor is equal to 1. Therefore, when debt declines, cash outflow at t=0 increases, which results in lower NPV (Baker 2003).

Table 15. Sensitivity of NPV to the Debt Portion of Cost of Investment. Note: Bold figures indicate the base case scenario.

Debt/Equity	NPV 2000 pigs	NPV 4800 pigs
100%/0%	$ (375,237)	$ (449,144)
90%/10%	**$ (378,112)**	**$ (453,639)**
80%/20%	$ (380,987)	$ (458,135)
70%/30%	$ (383,862)	$ (462,630)
60%/40%	$ (386,737)	$ (467,125)
50%/50%	$ (389,611)	$ (471,621)

Figure 2. Sensitivity of NPV to the Debt Portion of Cost of Investment.



5.1.4 Energy Prices and the Potential to Sell-back Electricity

One of the scenarios to be investigated was the economic impact of selling excess electricity from the AD process back to Hydro-Quebec. With this scenario it was assumed that the buy back price of Hydro-Quebec would never be greater than its selling price. The NPV of the investment increases as the price of electricity rises. This is due to two factors. First, there are increased savings for the on-farm use of electricity generated from the AD process. Second, the increased benefit from selling excess electricity to the utility, Hydro-Quebec.

Table 16 provides 42 scenarios for the sell-back of electricity. Only one of them results in a positive NPV and it is for the 4800 pig herd size. Both purchase and sell-back prices have to be high enough to assure the economic feasibility of AD. If only one of these prices is sufficiently high, the feasibility is not assured. The purchase price of electricity would have to increase substantially from 6.88 cents to 11 cents. In this case, the sell-back price would have to be 10 cents.

Table 16. Sensitivity of NPV to Electricity Rates.
(cents / kWh)

NPV under Different Electricity Prices (2000 pigs)						
[redacted]						
Purchase Price ($)						
0.05						
0.06	-307,720				Implausible Options	
0.0688	-300,424	-281,948				
0.08	-293,472	-273,605	-256,106			
0.09	-288,722	-267,906	-249,570	-226,273		
0.1	-284,923	-263,347	-244,341	-220,194	-198,618	
0.11	-281,814	-259,616	-240,063	-215,220	-193,022	-170,824
NPV under Different Electricity Prices (4800 pigs)						
[redacted]						
Purchase Price ($)						
0.05						
0.06	-301,982				Implausible Options	
0.0688	-284,472	-240,130				
0.08	-267,787	-220,107	-178,108			
0.09	-256,388	-206,429	-162,422	-106,510		
0.1	-247,269	-195,486	-149,873	-91,920	-40,137	
0.11	-239,808	-186,533	-139,606	-79,983	-26,708	**26,567**

Note: 6.88 cents/kWh is a current average electricity price for the operator

5.1.5 Sensitivity to Volatile Solids Concentration

By varying the percentage of volatile solids, one changes the amount of generated biogas and, subsequently, energy output. However, by changing the percentage of VS from 80% to 62% of the total solids, it was found that NPV stays constant (Table 17). This can be explained by the fact that in the base case there is no use for excess energy output. In both cases it is only possible to meet the energy demand of the farm.

Table 17. Sensitivity of NPV to Volatile Solids Concentration

% Volatile Solids	NPV (2000 pigs)	NPV (4800 pigs)
62	$(378,112)	$ (453,639)
70	$(378,112)	$ (453,639)
80	$(378,112)	$ (453,639)

NPV changes by considering two variables simultaneously: percentage of volatile solids in total solids and a potential sell-back price of excess electricity. It was found that with 62% VS, the break-even electricity price is 15 cents per kilowatt-hour. With 80% VS concentration, NPV is equal to zero at a price of 10 cents per kilowatt-hour. This is for a herd size of 4800. For 2000 pigs these numbers are 29 and 20 cents respectively (Table 18).

Of the six prices in Table 18, none are feasible considering the current price of electricity (6.88 cents/kWh) and assuming that a sell-back price should not exceed the purchase price. In this scenario excess heat is wasted.

Figure 3. Relationship between the Percentage of Volatile Solids and Break-even Sell-back Price of Electricity.

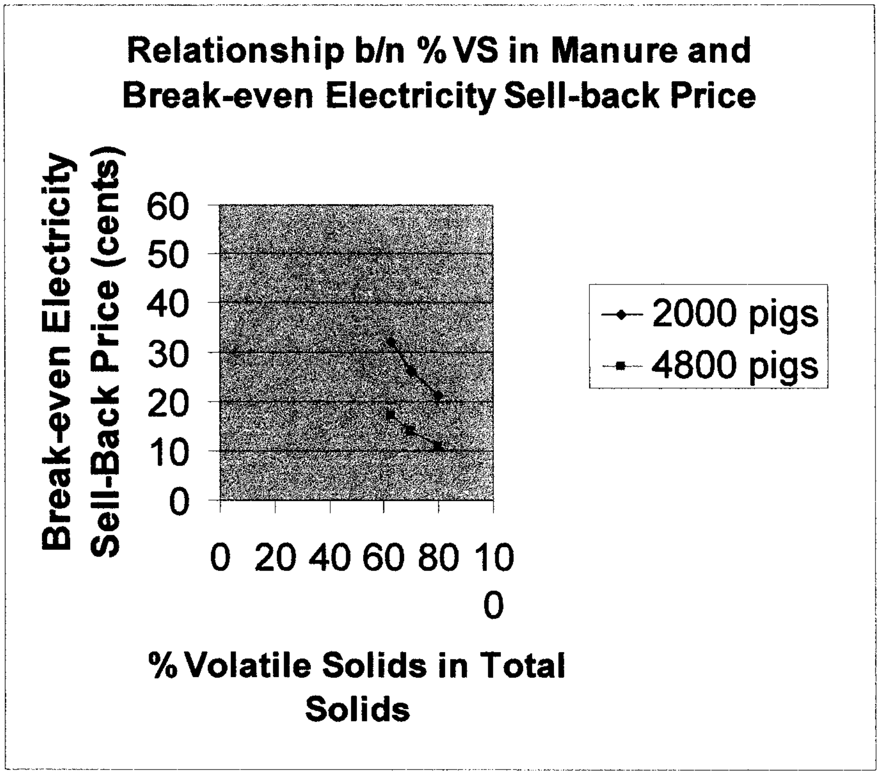


Table 18. Break-even Sell-back Prices of Electricity under Different Volatile Solids Concentrations.

% VS	2000 pigs	4800 pigs
	Break-even Sell-back Price (cents/kWh)	
62	29	15
70	24	12
80	20	10

5.1.6 Sensitivity to the Biogas Production Coefficient

While varying the biogas production coefficient, it was found that NPV is constant in the B_0 range 0.23-0.44 m^3/kg VS when the ferment has no opportunity to sell excess electricity (Table 19). The gas yield coefficient of 0.16 does not provide enough gas to satisfy energy needs of the farm. Therefore, the NPV is different in this case. All other coefficients provide the same NPV, because similarly to the situation with VS concentrations, it would require the use of the excess energy in order for the NPV to change.

As seen from Table 20, the lowest break-even price was 11 cents. This can only occur under the most optimistic biogas yield of 0.44 cubic meters of biogas per kg VS. At the current electrical price it is not realizable, as any value below 0.44 substantially decreases its feasibility. It is evident from the graph below that the break-even electricity prices would have to increase rapidly when gas yield drops below 0.23 cu m/ kg VS (Figure 4).

Table 19. Sensitivity of NPV to Gas Yield Coefficient When Electricity Sell-back is not Possible.

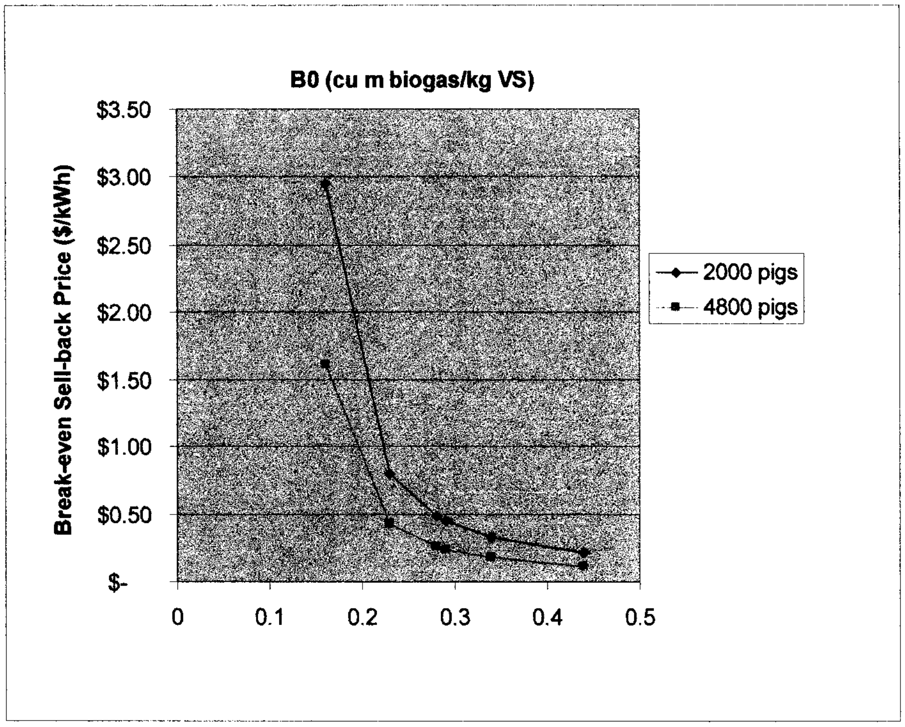
Biogas Production Coefficient	NPV (2000 pigs)	NPV (4800 pigs)
0.16	$ (399,404)	$ (522,023)
0.23	$ (392,804)	$ (506,184)
0.28	$ (392,804)	$ (506,184)
0.29	$ (392,804)	$ (506,184)
0.34	$ (392,804)	$ (506,184)
0.44	$ (392,804)	$ (506,184)

Note: The value of 0.44 cubic meters of biogas per kg VS was provided by the company. Other values are taken from Demuynck et al. (1984).

Table 20. Break-even Electricity Sell-back Prices Under Different Gas Yield Coefficients (expressed in dollars)

Biogas Production Coefficient	2000 pigs Break-even Sell-back Price (cents/kWh)	4800 pigs
0.16	$ 2.95	$ 1.61
0.23	$ 0.80	$ 0.43
0.28	$ 0.48	$ 0.26
0.29	$ 0.45	$ 0.24
0.34	$ 0.33	$ 0.18
0.44	$ 0.21	$ 0.11

Figure 4. Break-even Electricity Sell-back Prices Under Different Gas Yield Coefficients (expressed in dollars)



5.1.7 Sensitivity of NPV to Investment Cost

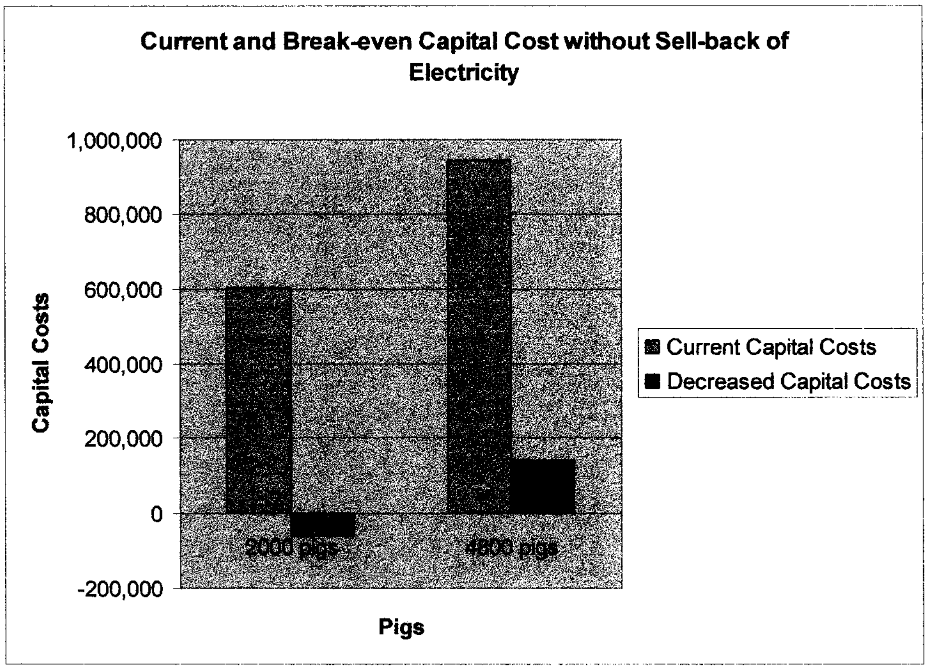
When the farm electricity and heating needs are included in the NPV calculation, the economic feasibility of AD is not achievable. This is due to the electric output of the CHP unit producing almost 6 times more heating than its on-farm needs and 3 times more electricity. In the base case scenario this excess is wasted. One question that should be addressed is: what would be the level of capital costs for the AD system that would make it economically feasible taking into account the energy needs of the farm?

Table 21 and Figure 5 show that, for the case of 2000 pigs, capital costs must drop below zero to provide a zero NPV. For a herd size of 4800 pigs, the digester's price would have to decrease by 85% in order to provide a zero NPV.

Table 21. Current and Break-Even Capital Costs Without Sell-back of Electricity.

	2000 pigs	4800 pigs
Current Capital Costs	$ 604,487	$ 945,234
Decreased Capital Costs	$ (58,210)	$ 141,259
Required Subsidy	$ 662,697	$ 803,975

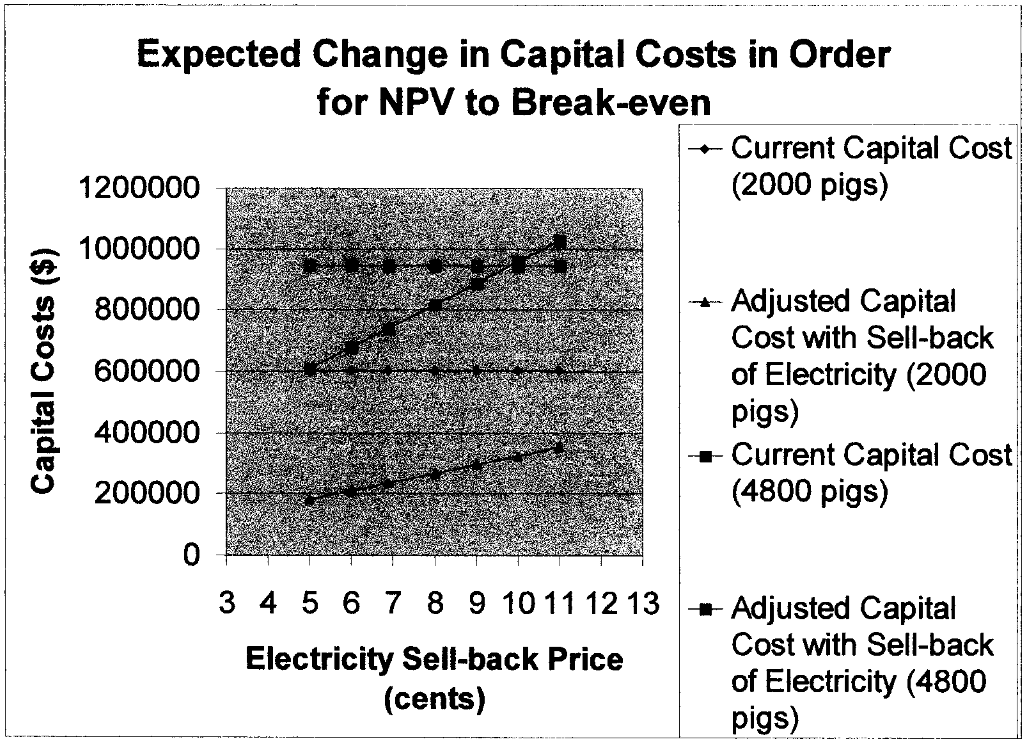
Figure 5. Current and Break-Even Capital Costs Without Sell-back of Electricity.



The possibility of selling surplus energy substantially improves the economic feasibility of the investment. In Figure 6 below, there are two straight lines signifying the capital cost of an AD system for two herd sizes. For each line there is a corresponding graph with data points for different electricity sell-back prices. These points denote capital costs under which NPV is zero.

From Figure 6, one can notice that the current capital cost line for 2000 pigs does not cross the adjusted capital cost line. This means that in the examined range of prices from 5 to 11 cents, there is no price that would make the system feasible.

Figure 6. Expected Change in the Capital Costs in Order for NPV to Break-even



For the herd size of 4800 pigs, it is possible to identify a break-even capital cost position with the current system cost. This can occur when the electricity sell-back price is between 11 and 12 cents per kilowatt-hour. This is substantially higher than the current rates of 6.88 cents/kWh.

5.1.8 Estimation of an Optimal Capital Cost Subsidy

In the previous section, break-even capital costs were calculated under different electricity sell-back prices. In this section, an expected capital cost subsidy is calculated as the difference between the current capital costs and the adjusted capital costs. The results demonstrate that as energy prices rise, the required grant decreases.

At the current electricity price, 22% of capital cost would comprise a subsidy (for 4800 pigs), and as high as 61% of capital cost (2000 pigs) for the NPV to break-even. If the electricity price increases to 11 cents per kilowatt-hour, the subsidy is as high as 41% of the capital cost for the small herd size (Table 22 and Figure 7). However, under current conditions this subsidy is improbable.

The situation changes in the case of a herd size of 4800 pigs. If the sell-back price is between 9 and 10 cents per kilowatt-hour, the grant becomes zero and therefore a zero NPV is achieved. A positive NPV is reached with sell-back prices of 10 cent per kilowatt-hour and higher. Note that negative values in table 23 indicate that a positive NPV occurs and therefore a negative grant is needed to break-even (Table 23 and Figure 8).

Table 22. Estimated Subsidy Under Different Sell-back Prices (2000 pigs)

2000 pigs Electricity Price (cents/kWh)	Current Capital Cost ($)	Expected Grant with Sell-back of Electricity ($)
5	$ 604,487	$ 424,670
6	$ 604,487	$ 395,679
6.88	$ 604,487	$ 370,143
8	$ 604,487	$ 337,698
9	$ 604,487	$ 308,707
10	$ 604,487	$ 279,716
11	$ 604,487	$ 250,725

Figure 7. Estimated Subsidy Under Different Sell-back Prices (2000 pigs)

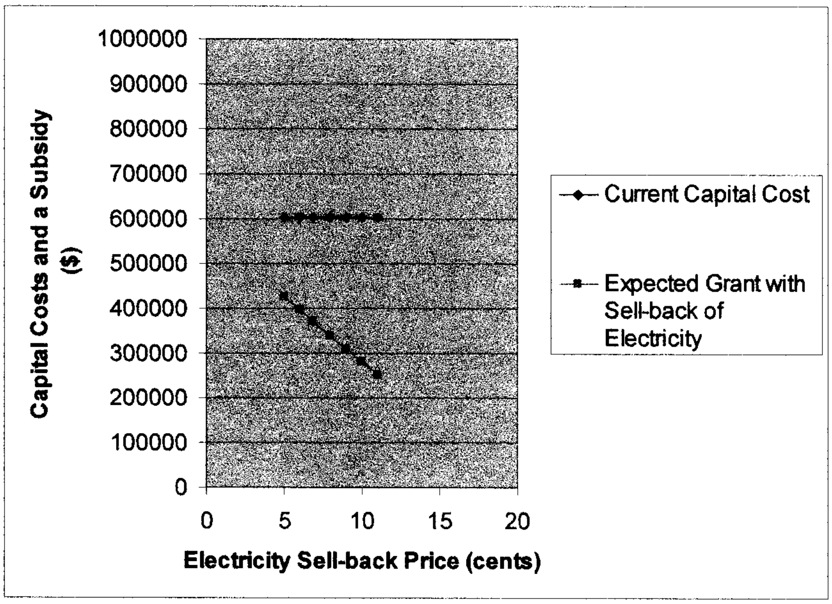
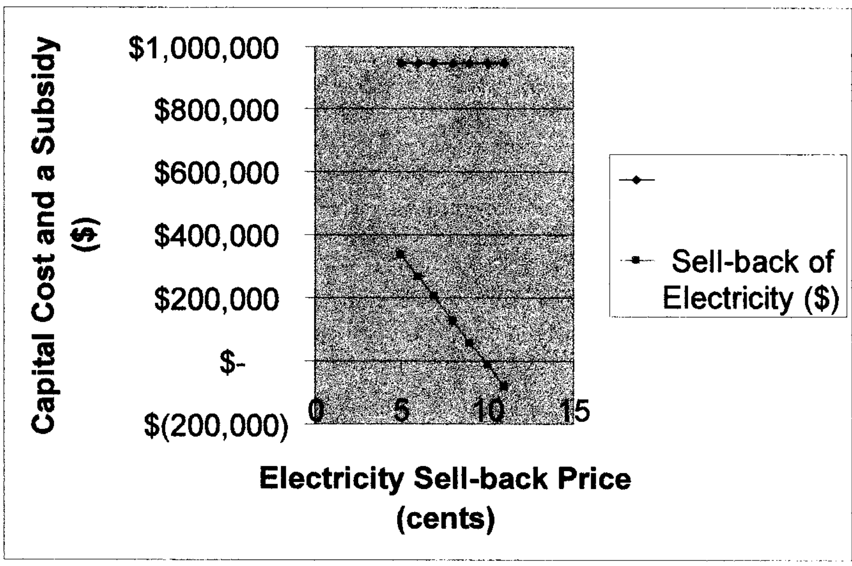


Table 23. Estimated Grant Under Different Sell-back Prices (4800 pigs)

4800 pigs Electricity Price (cents/kWh)	Current Capital Cost ($)	Expected Grant with Sell-back of Electricity ($)
5	$ 945,234	$ 335,515
6	$ 945,234	$ 265,937
6.88	$ 945,234	$ 204,649
8	$ 945,234	$ 126,781
9	$ 945,234	$ 57,203
10	$ 945,234	$ (12,375)
11	$ 945,234	$ (81,953)

Figure 8. Estimated Grant Under Different Sell-back Prices (4800 pigs)



5.2. Environmental Aspects of Anaerobic Digestion

5.2.1 Estimation of the Benefits from Increased Fertilizer Value

Boyd (2000) in her dissertation included the sale of digested slurry and attributed the proceeds to anaerobic digestion. This analysis considered this, but thought it to be inappropriate since the solid fraction of the pig slurry can be separated and sold without an AD system. Cash inflows will be overestimated if the total fertilizer value of swine manure is incorporated. Therefore, only the benefits from the increase in fertilizer value of manure were included. This increased value was from increasing the nitrogen content of the fertilizer. Some environmental benefits of AD are still questionable. Boyd (2000) considered the benefits from the sale of fibre, which comes from the separation of liquid digested slurry. Solid separation could take place without anaerobic digestion. Peterson and Fabozzi (2002) explain that "the difference between the cash flows of the firm with the investment project and the cash flows of the firm without the investment project – both over the same period of time – is referred to as the project's incremental cash flows" (p. 13). Bierman (1988) further states that "only incremental cash flows are included in the cash flow stream" (p.40). Therefore, for the case of anaerobic digestion, the proceeds from the sale of nitrogen in manure slurry should not be counted, except for those that come from the increased nitrogen content in manure after AD. Boyd (2000), however, has included the total value of nitrogen in her analysis and, therefore, has overestimated cash inflows.

IrBEA (2000) calculated that anaerobic digestion increases the fertilizer value per m^3 of swine manure by 1.45 kg of synthetic nitrogen fertilizer. A local fertilizer company was called to estimate the price of synthetic nitrogen fertilizer. The current price of ammonium nitrate is $ 380/tonne. Manure generated over 342 days was multiplied by 1.45 and divided by 1000 to get metric tonnes of saved fertilizer. The increased fertilizer value was multiplied by $ 380to calculate fertilizer savings. They are summarized in Table 24.

5.2.2 Summary of the GHG Emissions from the Manure Storage

Table 25 summarizes the total GHG emissions from outdoor manure storage. Annual GHG emissions were calculated by summing annual N_2O and CH_4 releases multiplied by their corresponding global warming potentials.

5.2.3 Avoided GHG Emissions from Replacing Synthetic Fertilizers

Table 26 summarises avoided emission from the replacement of synthetic fertilizers by swine manure. Note that emissions reductions are calculated only for the increased fertilizer value.

5.2.4 Avoided GHG Emissions from Replacing Electricity Purchases

Four scenarios are shown in table 27. They estimate the savings from the inclusion or exclusion of kilowatt-hours in excess of energy needs of the farm. Kilowatt-hours were multiplied by 0.004617 kg of CO_2e and then divided by 1,000 to get metric tonnes.

Table 24. Savings from Replacing Synthetic Fertilizers by Anaerobically Digested Manure

Number of Pigs per Batch	units	2000	4800
Annual Manure Production	metric tonnes	3,967.20	9,521.28
Total Nitrogen Content	metric tonnes	16.27	39.04
Synthetic Fertilizer Saved Annually	metric tonnes	5.75	13.81
Total Nitrogen Content	metric tonnes	2.19	5.25
Annual Fertilizer Enrichment Value	$	$ 2,186	$ 5,246

Table 25. Total GHG Emissions from Manure Storage

Growers / Finishers in Inventory	unit	2000	4800
Annual CH4 Release	metric tonnes	9.185	22.043
Annual N2O Release	metric tonnes	0.024	0.058
Annual GHG Emission in CO2e	metric tonnes	200.316	480.759

Table 26. Avoided GHG Emission from the Replacement of Synthetic Fertilizers.

Growers / Finishers in Inventory	unit	2000	4800
Avoided N2O Emissions	metric tonnes	0.000200	0.000479
Avoided Emissions (CO2e)	metric tonnes	0.062	0.149
Emissions from Larger Nitrogen Content (CO2e)	metric tonnes	0.008	0.020
Net Benefit (CO2e)	metric tonnes	0.054	0.129

Table 27. Avoided GHG Emission from Replacing Electricity Purchases.

Growers / Finishers in Inventory	unit	2000	4800
With Sell-back of Electricity			
Kilowatts counted	kWh	329,270	790,248
CO2e	metric tonnes	1.520	3.649
Without Sell-back of Electricity			
Kilowatts counted	kWh	106,276	255,064
CO2e	metric tonnes	0.491	1.178

5.2.5 GHG Emission Reduction by the Replacement of Propane by Biogas

The emission factor of 1.533984 kg of CO_2e was multiplied by the heating needs on the farm and then divided by 1000 to get metric tonnes. The results are summarize in Table 28.

5.2.6 Break-even Price of Carbon Dioxide

The following calculations were performed to estimate the cash inflows from the potential trading of CO_2 emission reduction credits. The amount of potentially claimable CO_2 emission reduction credits (see section 3.4.4 "Calculation of GHG Emissions and Emission Reduction Credits") was multiplied by 365 and then multiplied by the daily manure production. This quantity of CO_2 reductions was multiplied by the price per tonne for CO_2 credits. In the base case, it was assumed that price for credits was \$ 10 per tonne.

Table 28. Possible GHG Reduction from Reducing Propane Use on the Case Farm

Growers / Finishers in Inventory	unit	2000	4800
Propane Needs	litres	10,029	24,069
CO2e	metric tonnes	15.384	36.921

For example, the cash inflow for carbon credits for a 2000 grower-to-finisher hog operation in Ontario:

Emission reduction credits * days * daily manure production * price per tonne of CO_2

0.262 * 365 * 11.6 * 10 = $ 11,093 annually

The initial price of $ 10/tonne CO_2 was adjusted with Excel's "Goal Seek" function by setting the NPV value equal to zero. Table 29 provides break-even prices of CO_2. The results indicate that the most favourable conditions were for a 4800 grower-to-finisher hog operation in Ontario.

Table 29. Break-even Prices per Tonne of CO_2 With and Without Sell-back of Surplus Electricity at a rate of 5 cents/kWh.

	2000 PIGS		4800 PIGS	
	w/o sell-back	w sell-back	w/o sell-back	w sell-back
Ontario farms	$ 11.41	$ 8.73	$ 6.13	$ 3.44

CHAPTER SIX: CONCLUSIONS, LIMITATIONS AND RECOMMENDATIONS

Summary of the Study

This study evaluated the economic feasibility of installing a potential anaerobic digester for a large grower-to-finisher hog operation in Quebec. In order to evaluate the technology, a model was constructed in Microsoft Excel that calculated NPV by varying key technical and economic parameters. The model showed that economic feasibility could be achieved under certain conditions. First, NPV could be positive if electricity prices increased sufficiently above the current level. Given this, the farmer would have an opportunity to sell surplus electricity produced by a combined heat and power unit. Secondly, the possibility of participating in carbon dioxide emission trading coupled with electricity sale could substantially improve the economic feasibility of installation.

It was concluded that assigning fertilizer savings to AD in previous studies was somewhat speculative and should be re-examined. In contrast to other studies, this study sought to dissect environmental benefits that could truly be attributed to AD.

Conclusions

The analysis demonstrated that under current conditions, the capital cost of AD systems is the primary factor affecting economic feasibility. In the base case, when no environmental benefits were included and the farm is energy self-sufficient, installing a digester for 2000 and 4800 head grower-to-finisher hog operations was not feasible. A digester servicing a 2000 head farm would require a subsidy as large as 61% of the capital costs. For a "4800 head digester" it was assessed that a drop of 78% in the investment cost would provide a zero NPV. Thus, this conclusions confirms Hypothesis One that was presented in Section 1.8.

Herd size was also determined as an important factor. Though the analysis showed that the larger herd size is crucial for technical feasibility, it does not necessarily improve economic feasibility. It was speculated that herd size is an issue for the AD feasibility up to the point where energy needs of a farm are met. The key finding is that a larger herd size could only be afforded a larger digester at higher costs. However, in the base case of this analysis, a larger herd resulted in an excessive energy output that could not be utilized, and was therefore wasteful. This means that, if there is no opportunity to use excess energy, the farm has to find an optimal, less expensive digester size. For the farm this could mean treating only a fraction of the manure produced.

Herd size becomes important when there is a possibility of connecting to the grid of electric utilities in order to sell the on-farm surplus. Installing a digester with a CHP unit solely for energy needs of the production facility does not seem to be economically viable. Since excess heat is difficult to market, the sale of surplus electricity could provide an improvement for the feasibility of AD for farms having a comparable of 4800 growers/finishers in inventory.

Varying electricity purchase prices and sell-back prices from 5 to 11 cents/kWh (by increments of 1 cent) provides 21 plausible price combinations for each herd size. None of these price combinations provides a positive NPV for a 2000 head herd size. For a 4800 head herd size, one scenario provided a positive NPV. For this, a sell-back price should be in the order of 10 cents/kWh combined with at least 11 cents/kWh for purchased power. This would provide energy savings sufficient to have a positive NPV. Given that the farmer currently pays 6.88 cents/kWh, a potential sell-back price should be lower. Such prices would not provide sufficient remuneration for investment. The sensitivity analysis with electricity prices has also confirmed Hypothesis One.

For two herd sizes, both biogas production coefficient and volatile solids concentration are not an issue if the farm is not connected to the grid. Changing these variables is only reflected in the amount of wasted surplus energy, but economic benefits are the same. However, if surplus electricity is sold back at a high rate of 11 cents/kWh (4,800 pig case) and 21 cents/kWh (2,000 pig case), it then would require at least 80% VS and a biogas yield coefficient of 0.44 m^3/kg VS.

Should a farm install an AD system with energy recovery, it would most likely require subsidization. The amount of a minimum subsidy would depend on electricity retail prices (assuming that no value is placed on environmental benefits). For the current 6.88 cent/kWh the 2000 herd size digester would require 61% of the investment cost ($ 370,143) to be granted. For the 4800 herd size digester 22% of the investment cost ($ 204,649) must be a grant. Both amounts do not seem to be achievable, since the Canadian renewable energy support program, "Redi – Penser", provides a maximum of $ 80,000for renewable energy projects, i.e. given the calculated subsidies, it is not sufficient to keep the AD technology viable. If a minimum of 10 cents/kWh is paid for electricity from a "4800 head digester", then a grant would not be required. But the current price of 6.88 cents/kWh makes this scenario unfeasible.

By considering only incremental increase in fertilizer value of swine manure after AD and assuming that the farmer is actually paid for increased nitrogen value of all swine manure produced on farm, NPV could increase by a maximum of 5% for a 2000 head herd. For a 4800 head herd, the increase would be 9%, but NPV would still stay negative. It is also questionable that the sale of single-cell protein can be attributed to AD (e.g. in the research by Kelland 1988). This environmental benefits rejects Hypothesis Two in Section 1.8.

Remuneration for reducing GHG can improve the feasibility of digesters. If a farmer in Ontario uses an outdoor cylinder manure storage with its corresponding GHG emissions, we conclude that he can claim 0.262 tonnes of captured CO_2e per tonne of anaerobically treated swine manure. A farmer in Quebec would not be able to claim CO_2 emission reduction credits from AD. This is because of the difference in CO_2e emissions associated with electricity generation in two provinces. The replacement of "cleaner" electricity in Quebec provides a negative amount of claimable CO_2e. Thus, for Quebec Hypothesis Two is rejected.

The model demonstrates that break-even prices of CO_2 in Ontario can be reasonably matched with the current levels of \$ 10 to \$ 15per tonne. In considering \$ 12 per tonne as a threshold, it is concluded that AD would only be feasible for both 2,000 and 4,800 head operations in Ontario, even if electricity sell-back is not possible. The model calculated that 4800 head operations in Ontario that can sell surplus electricity, could, in fact, have a break-even CO_2 price as low as \$ 3.4 per tonne. This scenario confirms Hypothesis Two for Ontario.

Limitations

Limitations in Data

The major limitation of this thesis is the absence of extensive information about the AD capital costs for different pig herd sizes. Therefore, it was not possible to calculate a break-even herd size. Capital cost estimates were provided by a distributor company for only two herd sizes. The numbers were provided for estimation purposes only. There was no detailed on-site engineering assessment by the company. Capital cost and the types of AD systems may significantly differ between companies.

The conclusions of this thesis should not be extrapolated to other types of swine operations (e.g. farrow-to-finish) or different livestock types. Different AD system designs are expected for these and, therefore, different conclusions. Heating and electricity outputs depend on the percentages of total and volatile solids. These vary between different age groups of swine and evidently between different livestock types.

While calculating the environmental benefits of AD, GHG emissions resulting from the burning of biogas were compared only with emissions from outdoor manure storage. The difference here is the amount that the farmer can claim for emission reduction credits. Net emissions could be different if compared to lagoons, ponds or other systems promoting anaerobic environment. AD could be even more beneficial in this case

Previous studies indicate that ammonia volatilizes faster from anaerobically digested manure. A comparative study on ammonia volatilization from anaerobically treated manure versus regular manure was not found. Moreover, there was no certainty whether to consider ammonia as a source of pollution.

Limitations in Assumptions

One limiting assumption of this study was that antibiotics on the farm are not used. According to the personal communication with the AD distributor, antibiotics can substantially disrupt microbial microflora in a digestion tank, and deteriorate methanogenesis. Information about antibiotics could not be obtained from the farmer.

It was also assumed in this study that the reduction of smell had no economic value. In fact, AD brings about avoided costs of conflicts of the farmer with his neighbours.

No value was placed on the reduction of biological and chemical oxygen demand. The reduced organic load has a benefit of reduced pollution of watercourses. It was not certain how this benefit could be counted with precision.

There were 2 main limiting financial assumptions. The first assumption was that the salvage value of the digester would to be equal to UCC, but in fact it can be negative due to the cost of removing the old equipment from the farm (Stickney 2003). This would reduce the NPV. The other main financial assumption was that operating costs are represented as a percentage of capital costs, 2% in this study. In sensitivity analysis, varying the percentages resulted in the linear changes in NPV.

Recommendations for Further Research

If the case farm installed a digester, about 32 % of the current manure production could satisfy all its electricity needs. The annual surplus electricity amounts to 3.1 times of the farm's needs and 5.97 times for heating. In order for the investment to be worthwhile, the use of this energy is indispensable. From May until the end of October the farmer does not buy propane, but potential heating could still be produced. It would require some ingenuity to decide how to use this energy. There were suggestions for converting waste heat to use it for refrigeration.

Another technical aspect is the difficulty to compress and store biogas, which is a substantial burden for feasibility. This technical restraint confines the farm to the on site transformation of biogas to electricity, a more transportable energy form. Further research can reveal how to find ways to store or transport biogas more efficiently.

As suggested by the distributor, feasibility improvement in treating hog manure should be achieved through mixing with other substrates. More research is needed to find which substrates are most compatible with swine manure in the Canadian weather conditions.

Finally, economic feasibility of centralized biogas plants in Quebec could be evaluated. A potential centralized facility could resolve some institutional issues that individual farms would have to confront. For example, it seems that for a large biogas plant it would be easier to negotiate a sell-back price with electric utilities.

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APPENDICES

APPENDIX A: CHEMICAL FORMULAS

The US Environmental Protection Agency (2003) has identified 3 stages to the methanation process. These are:

1. Hydrolysis. This occurs when the bacterial enzymes break down proteins, fats, and sugars into simple sugars.

2. Acid formation. Acid-generating bacteria convert the sugars into acetic acid, CO_2, and hydrogen

$$C_6H_{12}O_6 + 2H_2O \rightarrow 2CH_3COOH + 2CO_2 + 4H_2$$

Glucose + Water → Acetic Acid + Carbon Dioxide + Metabolic Hydrogen

1. Methane generation. Acetic acid is transformed to methane and CO_2; CO_2 and hydrogen are combined to produce methane and water

$$2CH_3COOH \rightarrow 2CH_4 + 2CO_2$$

Acetic Acid → Methane + Carbon Dioxide

$$4H_2 + CO_2 \rightarrow CH_4 + 2H_2O$$

Metabolic Hydrogen + Carbon Dioxide → Methane + Water

APPENDIX B: BENEFITS AND COSTS

	2000 growers/finishers		4800 growers/finishers	
Benefits				
	Year 1	Year 20	Year 1	Year 20
Electricity				
farm needs only	7925	8686	19020	20847
sell back at 5 cents/kWh	18630	20420	44711	49007
sell-back at 11 cents/kWh	31475	34499	75541	82799
Heating	3510	4329	8424	10389
Fertilize Value	2186	2761	5246	6626
GHG (10$/tonne)	35693	51037	85662	122490
(GHG cash flow is valid only for Ontario)				
Costs				
Labour	1369	1815	1369	1815
Repairs and Maintenance	12090	18514	18905	28951
Principal and Interest	46006	46006	71939	71939

APPENDIX C: STATISTICS ON THE EXPANSION OF THE HOG INDUSTRY IN QUEBEC

On January 1st, 2003 Québec continued to lead as the major pork producing province of Canada, followed by Ontario and Manitoba (see table 30). However, the expansion of the pork industry was curbed by the 2-year moratorium on the installation of new hog farms (see Agricultural Operations Act / Règlement sur les Exploitations Agricoles, sections 46, 47) due to the growing concern regarding phosphorous pollution of watercourses. The annual production of pig manure in Québec is 5,872,120 tonnes (Helwig et al. 2002). Swine inventories as of January 1st, 2003 are shown below by province.

Table 30. Pigs on Farms, Quarterly, by Province, East, West and Canada, 2003

	Nfld. / Lab.	PEI	NS	NB	Que	Ont	EAST	Man	Sask	Alta	BC	WEST	CANADA	
							'000 head							
January 1, 2003														03 / 02 %
Breeding Stock	0.3	13.3	10.4	12.4	420.4	398.4	855.2	335.2	118.3	222.4	18.8	694.7	1549.9	102.8
Sows & Bred Gilts	0.3	12.8	9.9	12.0	413.5	385.7	834.2	327.2	113.6	213.8	18.1	672.7	1506.9	103.0
Boars, 6 mths plus	0.0	0.5	0.5	0.4	6.9	12.7	21.0	8.0	4.7	8.6	0.7	22.0	43.0	96.8
All Other Pigs	2.2	116.5	113.6	114.1	3859.8	3263.0	7469.2	2534.8	1111.7	1917.5	143.2	5707.2	13176.4	102.5
Under 20 kg	0.9	31.1	39.5	41.4	1280.2	1150.9	2544.0	885.2	322.1	611.9	46.0	1865.2	4409.2	104.0
20 -60 kg	0.8	45.6	40.0	37.2	1291.3	1067.6	2482.5	835.5	422.4	619.3	45.5	1922.7	4405.2	101.6
Over 60 kg	0.5	39.8	34.1	35.5	1288.3	1044.5	2442.7	814.1	367.2	686.3	51.7	1919.3	4362.0	101.8
TOTAL	2.5	129.8	124.0	126.5	4280.2	3661.4	8324.4	2870.0	1230.0	2139.9	162.0	6401.9	14726.3	102.5

Source: Statistics Canada, "Hog Statistics: Fourth Quarter 2002" http://www.library.mcgill.ca/govdocs/cdinfo/estat.html , March 2003

As seen from the table below, the average number of pigs per farm in Quebec is 1,562 as of January 1st, 2003

Table 31. Average Number of Pigs per Farm Reporting, Quarterly, by Province, East, West and Canada, 2000 to 2003

	Nfld. / Lab.	PEI	NS	NB	Que	Ont	EAST	Man	Sask	Alta	BC	WEST	CANADA
	Average Number of Pigs per Farm												
2000													
Jan-01	147	541	665	564	1,405	631	870	1,174	486	588	135	624	752
Apr-01	150	587	665	585	1,407	639	878	1,213	518	609	139	651	770
Jul-01	133	600	660	621	1,468	663	916	1,297	538	629	141	683	805
Oct-01	117	625	650	662	1,482	673	929	1,324	559	662	143	707	824
2001													
Jan-01	107	630	635	677	1,474	677	930	1,377	579	682	146	734	838
Apr-01	90	630	625	692	1,492	683	942	1,428	601	704	147	760	857
Jul-01	100	658	648	718	1,582	702	982	1,495	634	738	148	797	895
Oct-01	83	682	651	718	1,586	714	999	1,564	664	773	149	833	921
2002													
Jan-01	80	687	651	672	1,586	727	1,000	1,610	674	764	150	850	930
Apr-01	90	679	651	682	1,555	745	1,010	1,612	691	781	151	865	937
Jul-01	90	674	641	700	1,589	760	1,032	1,668	711	805	149	880	960
Oct-01	87	684	638	684	1,605	779	1,049	1,721	705	820	147	898	977
2003													
Jan-01	83	683	636	666	1582	779	1,035	1729	711	823	143	899	971

Source: Statistics Canada "Livestock Statistics: Fourth Quarter 2002" Catalogue no. 23-603-XIE

The three regions with the highest concentration of pigs in Québec are: Monteregie (33.8%), Chaudière-Appalaches (29.3%) and Centre du Québec with 14.1% (Statistics Canada, Census of Agriculture 2001).