ECONOMIC IMPLICATIONS OF ANAEROBIC DIGESTERS ON DAIRY FARMS IN TEXAS

A Thesis

by

RANDY SCOTT JACKSON, JR.

Submitted to the Office of Graduate Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

May 2006

Major Subject: Agricultural Economics

ECONOMIC IMPLICATIONS OF ANAEROBIC DIGESTERS ON DAIRY FARMS IN TEXAS

A Thesis

by

RANDY SCOTT JACKSON, JR.

Submitted to the Office of Graduate Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

Approved by:

Chair of Committee,	James W. Mjelde
Committee Members,	Robert B. Schwart, Jr.
	Saqib Mukhtar
Interim Head of Department,	John P. Nichols

May 2006

Major Subject: Agricultural Economics

ABSTRACT

Economic Implications of Anaerobic Digesters on Dairy Farms in Texas. (May 2006)

Randy Scott Jackson, Jr., B.S., Tarleton State University

Chair of Advisory Committee: Dr. James W. Mjelde

Historically, air and water have been considered common property resources and, therefore, over utilized as waste receptors. Dairy waste is a leading environmental concern in the North Bosque River watershed in Texas. Changing societal attitudes are forcing dairies and policymakers to balance environmental concerns with farm profitability. Dairies are entering a realm filled with technologies to combat waste concerns. Anaerobic digester technology may play a role in helping dairies balance profit and the environment. Digesters capture methane from livestock waste and transform it into electricity which can be sold to utilities or used on-farm. Because a digester facility is confined, air and water pollution can be reduced.

Technological advancement and institutional factor changes allowing the sale of on-farm produced electricity and green power requirements have increased the economic feasibility of digesters. The study of the economic implications of anaerobic digesters for Texas dairies provides producers and policymakers with information to make good decisions concerning adoption and subsidization of this technology.

At the beginning of this study, no digesters were operating in Texas. Dairies operating digesters in four states, therefore, were interviewed on-site to provide necessary data. The expected net present value, E(NPV), of a plug-flow digester is negative with and without selling electricity, indicating it should not be constructed based strictly on its financial contribution. At the current electricity-selling price, digesters are less economically feasible than current waste management strategies, lagoons, even after considering potential environmental penalties. However, selling electricity and capturing by-product heat for cost savings makes the digester's E(NPV) less negative than lagoons. The E(NPV) of a covered lagoon digester is positive. This indicates digesters are a potentially feasible waste management strategy.

For plug-flow digesters to show a positive E(NPV), the selling price needs to be approximately 82.38% higher than the current price. The breakeven selling price is 12% higher than the current price. Below the breakeven price, lagoons have a larger E(NPV) than plug-flow digesters, therefore making lagoons the preferred waste management strategy. Results suggest changes in rules and technology efficiency make digesters economically competitive with current waste management systems.

ACKNOWLEDGMENTS

When I first began working on this, I never envisioned the distances I would cross for facts, figures, and details, but also the various people I would meet along the way. I've seen parts of the country I never thought I'd see. So I say thanks to:

First and foremost Christ: I don't think I realized until now how much He helped me accomplish this. I'm still not there yet (though who is?) but I'm glad for another chance when so many just wrote me off.

My wife, Cindi: Although busy with your own demands, I am grateful for your support. I love you!

My parents: Sometimes you sacrificed for this day and sometimes you scratched your head and wondered what the heck I was really doing. However, your son loves you both for the support.

My committee: Drs. Jim Mjelde, Bud Schwart, Saqib Mukhtar, and my "boss" Dr. Ronald Lacewell. I thank Dr. Mjelde for his ability to not just be my major professor but also a friend and a down-to-earth, alright guy that's always there for his students. To Dr. Bud thanks for the encouragement and for traveling with me. I just want to say we got somewhere! I thank Dr. Mukhtar for providing such a vast knowledge of this subject. I thank Dr. Lacewell for being supportive, open, friendly, and for taking a chance on a student like me.

The State Energy Conservation Office (SECO) in Austin: Thanks for allowing me to participate in this state study and use the information for my thesis.

Dr. John Siebert: You helped me with contacts for my research.

Dr. Richard Woodward: You shared books, articles, and advice with me.

Michele Zinn: You helped me sort out information, appointments, the Chicago Manual, and many fun conversations.

Holly Voges: Thanks for keeping up with the details and notes from the trips!

Bob Whitney from Texas Cooperative Extension (TCE): Thanks for helping me find answers to questions and for the conversations. You're a good guy, Bob.

Dr. Tamily Nennich: Thanks for answering my over-the-phone questions.

Kathi Schiffler at Western United Dairymen: I owe a *huge* debt of gratitude to you for helping me with setting up the dairy contacts, addresses, and for all those e-mails and phone calls with my silly questions. You are so very kind and amazing!

Paul Martin: Thanks for the meeting and helping me understand California more.

All the dairies in California, Washington State, Wisconsin, Minnesota, and Texas for allowing me to tour your digesters and answering questions: Thank you!

Mr. Madhu Kundu and Mr. Joel Ignacio at Inland Empire Utilities: Thanks for the tour and information, it is appreciated and has spurred more curiosity.

I am also grateful to all the friends, both students and professors, here at Texas A&M University who helped me, even when I didn't want the help myself. It's quite a list! I want to send special thanks and blessings out to them all!

Since I try to be funny, I give this as my "inspirational quote":

"It's partly an expression of my teenage angst, but mostly it's a moo cow!"
--Chris Griffin, *Family Guy*, "A Picture Is Worth 1,000 Bucks"

TABLE OF CONTENTS

TABLE OF CONTENTS (CONTINUED)

CHAPTER Page

TABLE OF CONTENTS (CONTINUED)

CHAPTER Page

TABLE OF CONTENTS (CONTINUED)

CHAPTER Page

LIST OF FIGURES

LIST OF FIGURES (CONTINUED)

LIST OF TABLES

CHAPTER I

INTRODUCTION

As society comes to realize the full consequences of air and water contamination, it continues to push towards "environmental friendliness." One sector experiencing this push is animal agriculture, which includes livestock operations such as dairies. In the past, livestock waste management strategies viewed air and water as common property resources. Common property resources are over utilized because of externalities present. Facing increasing pressure for environmental friendliness for waste management, dairies are crossing over into to a new realm filled with increasing regulations and new technologies designed to help promote environmental friendliness. Although in existence for over 20 years, anaerobic digestion technology may play a role in helping dairies find the balance between profit and the environment. Changing energy and environmental regulations, new technologies, and improved efficiency of anaerobic digesters all play a role in the potential for digesters to promote environmental friendliness. A study of the economic implications of anaerobic digesters for dairies in Texas provides both individual dairy owners and policymakers with information to make good decisions concerning adoption and subsidization of anaerobic digester technology for dairy waste management.

Anderson in 1982 concluded anaerobic digesters were too costly and too inefficient for on-farm adoption. Technological and institutional changes over the past 20 years, however, may have altered Anderson's conclusions. Technological advances

---

This thesis follows the style and format of the *American Journal of Agricultural Economics.*

in anaerobic digester systems have improved efficiency (Durand et al.). Several institutional changes also contribute to the potential economic feasibility of anaerobic digesters for dairy waste management. One such change is the rules now allow for electricity produced on-farm can be sold to utilities, coupled with green electricity requirements, allow anaerobic digesters to be more than just a waste management technology (Parsons 2004; Center for Resource Solutions). Anaerobic digesters are a potential revenue source for the dairy. Other institutional factors such as increased government and private subsidies for anaerobic digesters and strengthened environmental regulations also contribute to the potential feasibility of anaerobic digesters. These changes, improved efficiency and institutional, have increased the economic feasibility of anaerobic digesters, which is visible in their expanding adoption by dairies. Some adopters even appear to be in a positive cash flow position in relation to their anaerobic digester, instead of experiencing losses (Parsons 2004; King). Nevertheless, producers using anaerobic digesters face multiple challenges.

Dairies must learn how to manage the anaerobic digester's systems, negotiate with electric utilities concerning the sale of electricity, and comply with state and federal environmental policies. The costs of complying with these policies are expected to increase in to the future. In light of all these issues, there is a need to re-examine the economic implications of anaerobic digesters. Because individuals and not society adopt new technology, it is important to examine the economic feasibility of anaerobic digester technology from the individual's perspective. In addition to the benefits to an individual, adoption of anaerobic digesters may have benefits and costs that accrue to society that the individual may not be able to capture. Such externalities are important from society's perspective. The current study examines anaerobic digesters from both viewpoints, but concentrates on the individual's perspective, which is that of a dairy.

Research Objectives

The general objective of this research is to determine the economic implications of using anaerobic digesters for dairy waste management within the North Bosque River watershed in Texas. The specific objectives are

1. to provide an understanding of anaerobic digester technology from both an individual's and society's viewpoint,
2. to establish investment and operating costs of installing an anaerobic digester system and a lagoon system for waste management,
3. to provide economic implications of anaerobic digestion systems, and
4. to provide a comparison of anaerobic digestion technology and a representative lagoon meeting environmental requirements.

Specific objective 1 is accomplished by a review of the literature. Issues associated with livestock pollution and regulations to combat these issues are presented. A non-technical overview of anaerobic digester technology provides background information on this technology. The reader gains an appreciation of the complexity of the technology. Reviewing previous studies of economic implications completes the literature review. Conflicting results as to the economic feasibility of anaerobic digesters are noted. To accomplish specific objective 2, dairies currently operating anaerobic digesters for waste management were visited and owners interviewed. These interviews along with previous studies provide the backbone for developing two modified capital budgeting models. The first model represents an anaerobic digestion system to be constructed on a dairy. The second model represents a lagoon, the most common waste management system. Results from the two models are used to achieve objectives 3 and 4. By accomplishing the specific objectives the general objective of this research is reached.

CHAPTER II

BACKGROUND INFORMATION ON POLLUTION ISSUES FROM LIVESTOCK OPERATIONS AND ANAEROBIC DIGESTERS

Livestock waste from concentrated animal feeding operations (CAFOs) has been identified as a source of water and air pollution. CAFOs include cattle feedlots, dairies, confined hog operations, and poultry facilities. Throughout this study manure and urine are collectively referred to as livestock waste. Many contaminants of water and air exist in livestock waste. The contaminants include items such as excessive nutrients, harmful pathogens, odors, and dust (Miner, Humenik, and Overcash; Metcalfe; Fisher et al.; Krapac et al.; Letson and Gollehon; Centner). The pollution of water and air from livestock waste has serious effects on both humans and ecosystems.

Pollution Concerns from Livestock Waste

Nitrogen/Nitrates

Nitrogen in livestock waste exists in ammonia, ammonium, and organic nitrogen forms. An estimated six and a half million tons of nitrogen are contained in livestock waste produced each year in the U.S. (Nolan et al.; Miner, Humenik, and Overcash). For livestock operations utilizing a waste treatment system such as a pit or lagoon, ammonia may be captured and applied to crop fields as a fertilizer. Ammonia and nitrates applied to the soil may result in surface and ground water contamination (Miner, Humenik, and Overcash; Nolan et al.; Hudak). Ammonium decreases surface water acidity, in addition to soil acidity, forest productivity, terrestrial ecosystem biodiversity, and coastal productivity (Galloway and Cowling; National Research Council of the National Academies).

Hudak found that nitrate concentrations in the Texas ground water were substantially higher in the western half of the state. Western Texas is home to many livestock feedlots and other types of CAFOs. Hudak also concluded West Texas residents who obtain water from the Ogallala and Seymour Aquifers, which run under a majority of West Texas, are prone to health problems from nitrate pollution of the water. Hudak and Blanchard note that Texas water quality issues, in regards to nitrates, may be increasing in other areas of the state.

Oenema et al. report that ground water concentrations of nitrates in southern and eastern sections of the Netherlands were five times greater than both Dutch and European standards for drinking water. The high nitrate levels in the Netherlands are attributed to an intensification of agricultural operations and increasing levels of livestock waste (Oenema et al.). Zhang et al. conclude that increases in nitrogen applications to cropland were contaminating northern Chinese water supplies. Nitrate concentrations of ground water and drinking water are above the allowable limits for human consumption (Zhang et al.). The rise in amounts of nitrogen application is an attempt to meet the increasing demands of a growing Chinese population by boosting food production levels (Zhang et al.).

Fisher et al. found evidence of increased nitrogen levels due to thirty dairy operations located along two creeks feeding into the Oconee River in Georgia. Nitrogen levels in these creeks were twice that of normal amounts (Fisher et al.). The results of

Fisher et al. are similar to Datta, Deb, and Tyagi, who found elevated nitrate levels in streams draining animal sheds in the Dhansa region of India. Datta, Deb, and Tyagi note that the elevated nitrate levels led to ground water contamination.

The erosion of soils in regions where livestock waste and nitrates have accumulated over several years is polluting surface water supplies (Filip and Middlebrooks; Miner, Humenik, and Overcash; Fisher et al.). Livestock waste entering a lake, river, or stream may accelerate the process of eutrophication. Eutrophication is defined as "the natural aging of water bodies brought on by nutrient enrichment" (Sharpley et al.).

Nitrate pollution is a serious problem with adverse effects on humans. Nitrates in drinking water can decrease oxygen levels in the bloodstream, which in infants is a potentially fatal condition known as blue-baby syndrome (Nolan et al.; Miner, Humenik, and Overcash; Rejesus and Hornbaker). Other serious medical conditions possibly correlated with nitrate pollution of drinking water are increases in non-Hodgkin's lymphoma and cancers of the stomach and esophagus (Nolan et al.; Zhang et al.).

Phosphorus/Phosphates

Though phosphorus exists in many forms in nature, for this study both phosphorus and phosphates are referred to as phosphates. Phosphates are essential for plant and animal life growth yet hazardous in excessive amounts. Phosphates can bind to soil particles and through erosion travel into nearby watersheds. Unassimilated phosphates can remain in a watershed for years through deposition in bottom sediments (Krapac et al.; Parker). One form of phosphate, orthophosphate, is present in dairy waste runoff and is of major concern because of its capability to accelerate eutrophication (Filip and Middlebrooks; Oenema et al.; Correll; Centner; Edwards, Twist, and Codd). Orthophosphate is considered a major contaminant of some surface watersheds and their ecosystems (Parker; Correll).

Fisher et al. found that the presence of dairy waste runoff into creeks and rivers has led to higher phosphate levels. Miner, Humenik, and Overcash discovered intensive dairying in central Florida led to a buildup of phosphates in lake sediments, damaging the nearby Everglades' ecosystem. Excess phosphates resulting from livestock waste application to crops and occasional overflows of dairy lagoons due to flooding or neglect has polluted some sections of the North Bosque River (NBR) in central Texas (Osei et al.). The NBR feeds into Lake Waco, 100 miles downstream, a source of drinking water for the City of Waco, Texas. There are concerns of water taste, aesthetics, and quality due to the dairy wastewater runoff polluting the NBR (Metcalfe).

According to the United States Environmental Protection Agency (U.S. EPA), under the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA), phosphates in elemental, black, and red forms are regulated as hazardous substances. These three forms are the primary make-up of materials such as artillery shells, smoke bombs, and pesticides. Agricultural sources of phosphorus and phosphates are not regulated under the CERCLA. Under CERCLA orthophosphate is considered normal and acceptable (U.S. EPA 1998).

The impact of excess phosphates on humans has also become a major issue. Excess phosphates are correlated with eutrophication and rapid algae growth. Rodecap reports evidence of increased neurological damage among some East Coast residents.

Pathogens

Numerous types of pathogenic organisms exist in livestock waste. Contact with livestock waste has led to the transmission of diseases from livestock to humans (Miner, Humenik, and Overcash). Public awareness of the problem of pathogenic organisms in watersheds has risen due to multiple incidents over the past twelve years. In 1993 cryptosporidium from hog waste contaminated public drinking water in Milwaukee, resulting in more than 100 deaths and 403,000 reports of illnesses (Metcalfe). Another incident occurred in 1997 in the Chesapeake Bay with an outbreak of *Pfiesteria piscicida* (Parker). This microbe, present in livestock waste runoff, was found in rivers entering into the Bay. The *Pfiesteria* outbreak was responsible for several fish kills in Maryland and coastal resulting in reports of dizziness and memory loss among affected residents and fishermen (Parker).

Fisher et al. discovered elevated fecal coliform levels in creeks due to waste runoff from dairies. The Texas Institute for Applied Environmental Research found livestock waste application to fields was positively correlated with elevated fecal coliform levels in streams (Fisher et al.). Krapac et al. sampled ground water near confined hog facilities in Illinois and showed presence of high levels of fecal streptococcus (*Streptococcus faecalis*). Krapac et al. concluded that the streptococcus levels found would pose a serious risk to human health if the ground water were used as a source of potable water. Additionally, flies contribute to the spread of pathogens from livestock waste (Miner, Humenik, and Overcash).

Air Quality

Another source of pollution related to livestock waste is air quality. According to the National Research Council of the National Academies (NRC), contaminants from livestock waste entering the atmosphere include ammonia, nitrous oxide, nitric oxide, methane, and hydrogen sulfide. Additionally, there are other air contaminants, known as volatile organic compounds, including organic sulfides, disulfides, C_4 to C_7 aldehydes, trimethylamine, C_4 amines, quinoline, dimethylpyrazine, C_3 to C_6 organic acids, C_4 to C_7 alcohols, ketones, and aliphatic hydrocarbons. These pollutants are found in odors and particulate matter (dust) from dry livestock waste (NRC; Miner, Humenik, and Overcash).

Half of total air emissions in the U.S. are attributed to livestock waste (NRC). Ammonia can enter soils and watersheds; however, ammonia can dissipate into the atmosphere from uncovered dairy lagoons (Innes). Atmospheric ammonia impacts visibility and contributes to acid rain (Miner, Humenik, and Overcash). Accumulations of nitrous oxide and nitric oxide limit ozone production (NRC). Nitrous oxide may be nearly 300 times more damaging to the atmosphere than carbon dioxide (NRC). Methane, a greenhouse gas, may contribute to global warming. Methane is 23 times more damaging to the atmosphere than carbon dioxide (NRC). Hydrogen sulfide from livestock waste has regional effects, primarily through odors (NRC).

Dust

Dust enters the atmosphere from animal activity, especially in arid to semi-arid regions. Animals in feedlots walk on soils with little to no vegetation and their waste forms a pack on the soil surface (Miner, Humenik, and Overcash). Livestock activity stirs up dust containing materials from the pack which enters the atmosphere (National Research Council of the National Academies; Miner, Humenik, and Overcash). This dust is fine particulate material capable of entering the human body through the alveoli of the lungs, causing breathing difficulties, and possible lung damage (National Research Council of the National Academies).

Odors

Odors are considered a nuisance and are of serious concern due to increases in human populations in agricultural regions of the country (Morse). Odors can travel up to four miles (Hopey). In Ohio, one doctor noted increases in patients' cases of neurological problems such as memory loss, less equilibrium control, and mood swings attributed to odors from local confined hog operations (Lee). This is not an isolated event. Toxins in odors from livestock operations are cited as a health concern across the U.S., including reports of seizures, lack of oxygen, vomiting, and nerve damage (Lee). Besides health concerns, there is a link between livestock waste odors and decreased property values (Hopey; Herriges, Secchi, and Babcock). With the growing awareness of environmental concerns, livestock operations face increasing pressure to become environmentally friendly, from both the public and the private sectors.

Policies on Pollution from Livestock Operations

Under current federal regulations, pollution is classified as either point (identifiable source) or nonpoint (unidentifiable source). Nonpoint sources of pollution include forestry, mining, construction, urban development, and agriculture (Centner). Two examples of agricultural point sources of pollution are concentrated animal feeding operations (CAFOs) and animal feeding operations (AFOs). AFOs are “an animal production operation that confines and feeds animals for a total of 45 days or more during any 12 month period” (Centner). Livestock facilities and operations not confining animals for at least 45 days or allow animals to graze freely are neither CAFOs nor AFOs (Centner).

A three-tier structure has been set in place by the United States Environmental Protection Agency (U.S. EPA) to determine if the AFO meets point source or nonpoint source regulations (Centner). In one tier, livestock operations with more than 1,000 animal units (AU) are classified as CAFOs. CAFOs are considered point sources of pollution under the National Pollution Discharge Elimination System (NPDES) (Metcalfe; Centner). Operations between 300-1,000 AU are in the second tier. These smaller operations also face federal regulations on water pollution as point sources. The third tier is determined on a case-by-case basis by either the U.S. EPA or a state agency. Under this tier, an AFO may be labeled a CAFO if it is found to be a major cause of water pollution (Centner). Some smaller AFOs with less than 1,000 AU, though, have been considered non-point sources and were placed under the Environmental Quality Incentive Program for assistance (Metcalfe; Centner).

Livestock waste regulatory policies take multiple forms, ranging from strict regulations to research and subsidization of new pollution abating techniques and technologies. Pollution permits are used alongside other control methods to help protect air and water quality (Centner). The Clean Water Act (CWA) allows state governments to set quality standards for navigable waters within the state, especially in recreational and ecological areas (i.e. state/national park) which are to be maintained and protected (Centner). Water quality, however, may be lowered to allow for economic development (Centner). One goal of the CWA is to prevent or limit further environmental damages because of high contamination clean up expenses; given the water affected is actually cleanable (Nolan et al.). Another regulation, the Coastal Zone Acts Reauthorization Amendment (CZARA) requires best management practices (BMPs) in place on operations with at least 50 AU (Innes). The CZARA addresses nonpoint source pollution attributed to agricultural erosion (Westenbarger and Letson). BMPs are defined as:

> schedules of activities, prohibition of practices, maintenance procedures, and other management practices to prevent or reduce [water] pollution (Centner).

Examples of BMPs include buffers, nutrient management plans filed with state authorities, composting along with treatment, operating procedures, and practices to control livestock waste runoff, spills or leaks, disposal, or drainage (Centner). CAFOs and AFOs face regulations in the construction and engineering of facilities to handle livestock waste, administration, management, and in the location and method of waste application. Examples of these requirements include geological testing of soils near the livestock operation, public hearings, and conservation certification programs (Metcalfe; Centner; Parker).

Three examples of state level concerns follow. In Maryland, the Water Quality Improvement Act of 1998 was passed to reduce pollution and environmental damage of Chesapeake Bay from excessive nutrients from agricultural sources (Parker). Some Georgia residents have launched complaints against local agricultural operations (Fisher et al.). In 2005, Pennsylvania announced that environmental regulations for farm waste and nutrient management will be strengthened, along with a new requirement for vegetative buffer zones (*U.S. Water News Online*). In Texas, the City of Waco has filed litigation against dairies upstream to prevent further phosphate and pathogen pollution of their drinking water (Coggins; Shlachter; Smith; *Texas Dairy Review*). A debate has risen as to whether waste from dairies is really the culprit, if the waste has cumulative effects, and whether there should be compensation to the city for environmental damages. Despite the debate, livestock operations are incurring the costs of complying with environmental regulations.

Costs of Environmental Compliance

Environmental policies and regulations are designed for contamination abatement. New proposals, such as the reauthorization of the CWA, have been presented which include stiffer controls on livestock waste and transferring federal funds from crop-based conservation programs to livestock waste management (Westenbarger and Letson). These new proposals entail an increase in livestock waste management costs for operations in locations of the U.S. vulnerable to pollution (Westenbarger and

Letson). Costs of compliance with environmental regulations and policies may decrease a CAFO and AFO's economic viability (Metcalfe; Centner; Innes; Leatham et al.; Masud et al.). Several studies estimate costs incurred by livestock operations to comply with state and federal air and water pollution regulations.

Westenbarger and Letson studied the costs of livestock and poultry producers to comply with the CWA and the CZARA. The CZARA imposes livestock waste management regulations on livestock and poultry producers in coastal regions. With CZARA, the costs of compliance for the agriculture sector increase, with those in certain "impaired" areas facing considerable costs (Westenbarger and Letson). Of the total costs of the agriculture sector to comply with the CWA and CZARA, 70% would be paid for by the dairy and broiler industry. On an AU basis, the dairy industry would spend nearly two and a half times as much on regulation compliance than beef cattle, swine, broilers, or layers (Westenbarger and Letson). Their results show that it would cost an estimated $5,400 per dairy annually to comply with the new CWA proposals.

Parker concluded for agricultural and livestock operations to comply with the Maryland Water Quality Improvement Act of 1998 the numbers of state-filed nutrient management plans would increase. Parker showed an estimated 1.2 million new plans would be filed. The costs for every new plan filed are approximately $6.62 million or $5.52 per plan (Parker).

Centner estimated the costs of compliance for CAFOs and AFOs under the EPA's multi-tier structure system. AFOs around 500 AU would expend approximately $831 million a year before taxes. Given there are 25,540 CAFOs in this tier, this results in $32,537 per operation. For AFOs with at least 300 AU, the costs of compliance are approximately $925 million a year (Centner). Centner reports these figures under the assumption that all current CAFOs have adopted a livestock waste management practice or technology to comply with federal law. Centner also states only 20% of the total CAFOs nationwide have done so, implying a policy enforcement issue and understatement of the costs. For 100% of CAFOs to comply with the EPA's proposals, the costs exceed $925 million (Centner).

Leatham et al. analyzed the costs of complying with state water quality regulations on dairies in the NBR. With the application of Monte Carlo simulation models, the results showed that costs and additional investment needed per cow on representative 300 and 720-cow dairies increase and net farm income decreases (Leatham et al.). Compliance costs increased by $60 per cow for the 300-cow dairy, or $18,000 total, and $81per cow for the 720-cow dairy, or $58,320 total (Leatham et al.). In addition, for the 300 and 720-cow dairies, an investment of $357 and $209 per cow, respectively, is required (Leatham et al.).

In regards to net farm income, both the 300 and 720-cow dairies showed a decrease. For the 300-cow dairy, after compliance, their net farm income would be negative (Leatham et al.). For the 720-cow dairy with low position, net farm income decreases by 27%, while if the dairy had a high debt position income decreases 63%. The probability of survival of a high debt dairy is 33% (Leatham et al.). The low debt dairies had a 100% chance of survival but a probability of 0.281 of achieving a positive net farm income (Leatham et al.).

Livestock Waste Management and Operating Costs

Livestock waste has value, despite the perception as a negative externality. Value of livestock waste is not only due to its nutrient content as fertilizer, but also in the distance the waste must be transported before being applied on the field (Vukina; Fleming, Babcock, and Wang; Masud et al.; Adhikari et al.). Livestock waste transported to nearby fields by custom applicators has been shown to reduce producers' capital and labor expenses and handling losses while increasing crop production (Vukina; Fleming, Babcock, and Wang). However, this benefit of livestock waste is limited. Livestock waste disposal and application costs have increased because of the high concentration of dairies in the NBR, coupled with insufficient amounts of available land to properly apply the waste (Masud et al.). Over applying livestock waste to land threatens nearby surface and ground water quality and the dairy's economic viability (Masud et al.).

In terms of nutrients, livestock waste value increases if commercial fertilizer usage diminishes (Fleming, Babcock, and Wang; Adhikari et al.). Another factor affecting livestock waste value is the livestock operation's waste management system (Vukina). If treated in an uncovered lagoon, livestock waste value decreases because most nutrients are either lost to the atmosphere or settle to the bottom. Liability for damages caused by contaminants from livestock waste can act as an incentive for livestock operations to become good stewards of the environment (Vukina).

Livestock operations face the costs of environmental compliance and waste management, in addition to the costs of normal day-to-day operations. Peebles and

Reinemann determined that among normal uses of power on a dairy (i.e. vacuum pumps, lighting, ventilation, chiller units, and heating), water heating, cooling milk, and vacuum pumping are the three largest consumers of electricity. Because of these costs new practices, management techniques, and technological advancements are needed to help CAFOs and AFOs to become more cost efficient at managing livestock waste. One technology showing potential for this is anaerobic digesters. Anaerobic digesters have multiple benefits, including alleviating air and water pollution from excess nitrates, phosphates, and pathogens, reducing harmful odors, dust, and greenhouse gas emissions. Anaerobic digesters block the release of pollutants into air and water through the aid of a cover and/or concrete (U.S. EPA 2002). In addition, anaerobic digesters allow for the production of renewable energy from livestock waste and for CAFOs and AFOs to comply with environmental regulations (Parsons 2004; U.S. EPA 2002).

CHAPTER III

OVERVIEW OF ANAEROBIC DIGESTERS

The review of literature focuses on three areas of anaerobic digesters. First, a description of anaerobic digestion is presented. Second, anaerobic digester benefits, including pollution abatement and energy generation, are discussed. Finally, a review of the literature on the economic feasibility and implications of anaerobic digester technology is presented

What Are Anaerobic Digesters?

Anaerobic digesters transform livestock waste from what once was a single use product, fertilizer, into a multi-use product. Uses include compost, bedding, and methane for the generation of heat and electricity (U.S. EPA 2002). Anaerobic digesters are:

> a manure management tool that promotes the recovery and use of biogas as energy by adapting manure management practices to collect biogas. The biogas can be used as a fuel source to generate electricity for use or sale (U.S. EPA 2004, page 1-1).

Five components necessary for anaerobic digesters to be used for waste management are collection, anaerobic digester, effluent storage, and gas handling and use (U.S. EPA 2004).

Livestock Waste Collection

Depending on the animal species, raw livestock waste has a total solids percentage between 8% and 25%. Livestock waste is categorized by the percentage levels of total solids and classified in four types: liquid, slurry, semi-solid, and solid. Liquid livestock waste has total solids content less than 5%, slurry between 5-10%, semi-solid between 10-20%, and any percentage above 20% is considered solid. Liquid, slurry, and semi-solid types show the greatest potential for biogas production and greenhouse gas emission reduction (U.S. EPA 2004).

Liquid livestock waste is "flushed" by fresh or recycled water into treatment tanks or storage facilities such as ponds or lagoons. For biogas potential, liquid waste systems work well in warm climate regions (Mattucks and Moser; U.S. EPA 2004). In colder climates biogas recovery from liquid livestock waste systems can still take place though gas is usually flared (burned) for odor control (U.S. EPA 2004). Slurry livestock waste is collected by a scraper, then stored in ponds or lagoons and mixed with water. Slurry livestock waste shows potential for biogas production; however, like liquid waste systems, it is dependent on the climate (U.S. EPA 2004). Semi-solid livestock waste is scraped, but water is usually not added. Solid livestock waste is not recommended for biogas production. Solid waste contains insufficient moisture levels for anaerobic digestion (U.S. EPA 2004). Livestock waste less than one week old in age can be used for biogas. For this age of waste, heat is necessary for the activation of the biogas production process.

What Is Anaerobic Digestion?

Anaerobic digesters use anaerobic digestion, a naturally occurring process, which is:

> the symbiotic action of a complex consortium of bacteria. Microorganisms, including common food spoilage bacteria, break down complex organic wastes. These sub-units are then fermented into short-chain fatty acids, carbon dioxide, and hydrogen gases (Biogas Works).

An anaerobic digester may operate in three different temperature ranges: psychrophilic (less than 68°F), mesophilic (68°-113° F), and thermophilic (113°-140°F) (Lusk 1991; Lusk 1995; U.S. EPA 2004). Microorganisms convert fatty acids to acetic acid (acetate) with the additional production of hydrogen and carbon dioxide (Rivard and Boone). Methane producing bacteria then produce biogas from the acetic acid, hydrogen, and carbon dioxide (Rivard and Boone). The operating temperature of an anaerobic digester is crucial to growth of the biogas-producing microorganisms (Wohlt et al.). A diagram detailing the anaerobic digestion process is provided in Figure B.1 in Appendix B.

Types of Anaerobic Digesters

Anaerobic digesters are designed to trap the released biogas. There are four different types designed to accomplish biogas recovery: covered lagoons, complete mix, plug-flow, and fixed film (U.S. EPA 2004). Covered lagoons employ the use of large storage tanks resembling ponds or lagoons approximately 10-12 feet in depth to store liquid or slurry livestock waste. The lagoon is then covered to capture the biogas. The type of cover, usually made of thin plastic, varies depending on the climate (U.S. EPA 2004). In warmer climates, the cover can float on the lagoon surface. In cooler climates the entire lagoon is covered with the cover being permanently attached to the sides of the lagoon.

Complete mix anaerobic digesters are tank systems either above or below ground, which may be heated (U.S. EPA 2004). The system treats slurry waste, yet is also compatible with scraped livestock waste. Plug-flow anaerobic digesters are similar to the complete mix in that it can make use of a heated tank system, however plug-flow digesters can only treat scraped dairy waste. The plug-flow's design is that of a trough, or channel, with an airtight cover (Hansel). A new "plug" of livestock waste is pushed through the system with each new daily load of waste, thereby pushing material already in the system further along (Hansel). Confined hog operations are unable to use a plug-flow system because of the insufficient quantities of fiber present in swine waste for anaerobic digestion (U.S. EPA 2004).

Fixed film anaerobic digesters are a tank system containing a plastic medium. This medium, known as biofilm, supports a layer of anaerobic bacteria. As livestock waste passes through the film, biogas is produced and collected in a method similar to that of a covered lagoon. This digester type is best used with flush waste systems. Fixed film digesters can be used with either dairy or swine waste. However, use with dairy waste requires removal of slowly degradable solids that are present in the waste (U.S. EPA 2004).

Effluent Storage

One product of the anaerobic digestion process is effluent. Effluent is "a stabilized organic solution that has value as a fertilizer and other potential uses" (U.S. EPA 2004, page 1-3). Because effluent cannot be applied to cropland year round, a storage system for effluent is required (U.S. EPA 2004).

Biogas Handling and Usage

In all four systems, biogas produced is trapped and removed through a gas handling system. Handling systems require piping, gas pump or blower, gas meter, pressure regulator, and condensate drains (U.S. EPA 2004). Pulling a slight vacuum on the collection pipe removes the trapped biogas. The gas meter monitors the flow rate while the regulator controls the flow. As the warm biogas travels through the piping it cools. This cooling causes condensation of water vapor in the biogas, which is then removed by condensate drains. Besides required equipment, a gas scrubber may be necessary. The scrubber strips the biogas of corrosive compounds such as hydrogen sulfide (U.S. EPA 2004).

Biogas recovered is a mixture primarily of methane and carbon dioxide. The methane has a heating value between 600 and 800 Btu/ft^3 (U.S. EPA 2004). An internal combustion engine can be used to generate electricity from the methane. In addition to the electricity, the by-product heat from the internal combustion engine may be captured and used on-farm.

Benefits of Anaerobic Digesters

Multiple benefits are associated with the use of an anaerobic digester. Digesters are beneficial in areas where there is concern about air and surface and ground water pollution (Lusk 1991; Lusk 1995). Runoff from livestock operations using anaerobic digesters is considered safe for rivers and streams (*U.S. Water News Online*). Anaerobic digesters also help reduce greenhouse gas emissions such as carbon dioxide, allowing livestock operations to comply with environmental regulations (Legrand; Chynoweth et al.; Chynoweth, Owens, and Legrand; Maeng, Lund, and Hvelplund; Parsons 2004; U.S. EPA 2002). The anaerobic digester's cover aids in reducing overflow in situations of heavy rainfall by diverting the rain (U.S. EPA 2002; U.S. EPA 2004).

Odor Reduction

Research shows conventional and fixed film anaerobic digesters are a cheaper alternative to reduce odors from livestock waste than chemical odor-reducing additives which have proven to be very expensive (Persson et al.; Parsons 2004; Ernst et al.; Powers et al.). On a swine operation, waste treated by the anaerobic digester showed a reduction in the offensiveness of the odors on humans (Welsh et al.). The temperature at which anaerobic digesters operate is linked to odor reduction. Anaerobic digestion at a temperature of 95°F controlled odors more effectively than digestion at 77°F, though both temperatures would fall in the mesophilic range (Welsh et al.). In addition to temperature, length of time at which livestock waste is retained and consumed in the anaerobic digester can help reduce harmful odors (Welsh et al.). Another problem related to odors, flies, is reduced when using an anaerobic digester (Persson et al.).

Compost, Bedding, and Fertilizer

Solid material produced by the anaerobic digester, called digestate, can be utilized for bedding and compost (Mehta). In some cases, digestate, however, must be transported off-farm and outside a particular region, due to insufficient quantities of agricultural land to use it (Masud et al.). Digestate can be marketed and sold as fiber, generating additional revenues for the livestock operation (Ernst at al.). Additionally, anaerobic digesters produce effluent, which has value as a fertilizer for cropland (U.S. EPA 2004; *U.S. Water News Online*).

Biogas Production

Recent literature cites weight differences among dairy cattle breeds as affecting biogas production. The two most common dairy cattle breeds are Jersey and Holstein. A Jersey cow weighs around 1,000 lbs (1 AU), whereas a Holstein cow weighs around 1,400 lbs (1.4 AU). Hansen reports 44 ft^3 of biogas production based on a 1,000-pound animal. Jones, Nye, and Dale reported an average biogas production of 28.4 ft^3 per 1,300-pound animal. Fulhage, Sievers, and Fischer report a biogas production level of 26.5 ft^3 per 1,400-pound animal. The Agricultural Biogas Casebook shows an average of 74.8 ft^3 of biogas per 1,400-pound animal of biogas on eight dairies (Kramer). Despite the variation, dairies have the possibility of producing large quantities of biogas, which can be harnessed for its energy potential.

Electricity Generation

Anaerobic digesters are a conversion technology, allowing livestock waste to be changed into multiple varieties of energy (Chynoweth et al.; Chynoweth, Owens, and Legrand; Persson et al.; *U.S. Water News Online*). These energy forms range from heat, steam, hydrogen for fuel cells to electricity (Chynoweth et al.; Chynoweth, Owens, and Legrand; Durand et al.). The electricity may be utilized for many on-farm uses. These uses include such items as barn/home lighting, heating milking parlor, water boilers, pasteurizing milk for creamery, heating plant greenhouses, refrigeration equipment, and cooking/lighting (U.S. EPA 2004; Mehta). Though a livestock operation’s electricity consumption levels may remain unchanged or increase, anaerobic digesters provide potential cost savings (U.S. EPA 2004). Anaerobic digestion is cost competitive when compared to conventional waste management practices (U.S. EPA 2002).

Livestock operations using anaerobic digesters may be considered a small energy provider or an independent power producer (IPP). Three distinctions separate IPPs from regular utilities (*The Wall Street Transcripts*). First, IPPs are not regulated in the same manner as a regular utility. Reduced regulations lower barriers on IPPs return rates and profitability. Second, IPPs are usually only involved in electricity generation, not transmission, and distribution. Third, IPPs are a small component of the U.S. energy market (*The Wall Street Transcripts*). In 1999, about half of all the new energy capacity constructed in the U.S. came from IPPs, while IPPs themselves only comprised approximately 9% of the market (*The Wall Street Transcripts*).

When a livestock operation with an anaerobic digester enters into an agreement with a utility provider, the utility mandates equipment necessary to allow electricity transmission from the generator to the power grid. The equipment usually includes the placement of a transformer on-site at the anaerobic digester's generator facility. The utility is responsible for transmission and distribution of the electricity to consumers. Terms of the contract include return rates. In 2003, the passage of a California law allowed meters to sell excess electricity to the grid, which is known as net metering (Parsons 2004). Net metering allows the excess electricity produced by an anaerobic digester to be sold to the grid and/or used on-farm, thus offsetting utility bills (Durand et al.). Besides California, other states also allow net metering.

Economic Feasibility and Implications of Anaerobic Digesters

Beginning in the late 1970's to early 1980's, anaerobic digesters and biogas production have been utilized for energy production in Europe. Some studies show that economies of scale may exist in anaerobic digester technology, which would suggest as digester size increases, costs are lowered (Fischer et al.; Stewart). Parsons (1986) found anaerobic digestion of dairy waste to be "not economic."

Other potential benefits from anaerobic digesters, however, were not included in early studies. These benefits include a decrease in fossil fuel use and increases in employment, incomes, and state finances (Maeng, Lund, and Hvelplund). Since the 1980's, anaerobic digestion technology has undergone technological improvements and adoption in Europe to help lower carbon dioxide and other greenhouse gas emissions (Maeng, Lund, and Hvelplund; Raven). Because of the biogas plants, the emissions of carbon dioxide from Denmark were reduced by 0.1% and total greenhouse gas emissions decreased 0.3% in 1996 (Maeng, Lund, and Hvelplund). In addition, over a 13-year period from 1984 to 1997, the operating and capital costs per cubic meter of biogas production decreased (Maeng, Lund, and Hvelplund). Maeng, Lund, and Hvelplund noted that Danish biogas plants are socio-economically feasible because of their positive contributions to reducing pollution.

Although the U.S. has provided funding for research into new renewable sources of energy, including anaerobic digestion, progress has been slow. Economic implications of anaerobic digestion technology in the U.S. are varied in scope, context, and results. Coppinger, Baylon, and Lenart determined using an anaerobic digester is cost efficient, especially if owned and operated by the owner. Anderson discussed impacts of technological and institutional changes on economic feasibility. His conclusion was that to spur adoption and feasibility, the anaerobic digester's fixed costs must decrease while efficiency must increase. Fischer et al. concluded that an anaerobic digester on a 3200 hog swine operation would yield a positive net present value (NPV) and a profitable benefit/cost ratio.

Durand et al. concluded that among types of anaerobic digesters a thermophilic system impacted profitability more positively than a mesophilic system. They concluded that operations using an anaerobic digester should not recover the by-product heat. Recovering heat required additional equipment; therefore, more costs will be incurred by the anaerobic digester owner. Durand et al. recommends converting energy produced into electricity through combustion. Lusk (1991) found that a psychrophilic anaerobic digester had a greater NPV, payback period, and internal rate of return than did a mesophilic digester. In agreement with Durand et al., Lusk (1991) discovered a mesophilic anaerobic digester produced a lower NPV.

Engler et al. found that for a 400-cow dairy using an anaerobic digester, the expected annual costs were greater than the benefits in electricity cost savings. Several factors, however, were attributed to the poor performance of the anaerobic digester on the dairy studied, including a low feed rate of waste to the digester and reductions in the number of milking cows (Engler et al.). In addition, the dairy was not selling excess electricity to the utility. Electricity was not sold because of degraded connections and generator inefficiency. More recently, Mehta concluded that larger sized dairies, if allowed to sellback excess electricity flexibly, may earn positive profits from energy sales. Some costs were non-quantified in Mehta's work, such as odors, pests, and costs of complying with environmental regulations.

In most studies, the primary livestock operations of interest were either dairies or confined hog operations. Coppinger, Baylon, Lenart, along with Anderson, analyze anaerobic digesters on 100-cow dairies. Engler et al. studied a 400-cow dairy using an anaerobic digester in Texas. Mehta expanded on these studies by looking at 60-cow, 200-cow, and 400-cow dairies. Livestock operations have undergone tremendous expansion in the numbers of confined animals over the past few decades. Peebles and Reinemann found that although the numbers of dairies may be declining, the size of dairy herds has increased in the past twenty years. Most of the studies involving anaerobic digestion don't capture this information, as there are many dairies with herd sizes larger than 400 cows.

Schwart et al. developed a capital budgeting model of an anaerobic digester system for dairy waste management. The capital budget section of the analysis performed by Schwart et al. is constructed based on details outlined by Barry et al. Schwart et al. tested the model on two anaerobic digester types: plug-flow and covered lagoon. Findings show that all of the plug-flow anaerobic digesters and three out of five covered lagoon anaerobic digesters had negative returns. In addition, Schwart et al. concludes that increasing electricity generation and revenues are not enough to generate positive net returns.

One reason cited for using anaerobic digestion technology is pollution abatement, such as air and water quality control (Coppinger, Baylon, and Lenart; Maeng, Lund, and Hvelplund; Raven). However, these impacts were deemed non-quantifiable (Coppinger, Baylon, and Lenart; Welsh et al.; Engler et al.; Mehta). There is agreement that the costs of pollution abatement are difficult to measure. In addition, the costs of compliance with state and federal environmental regulations were not included. These costs of compliance include such items as pollution permits, creating, filing, and updating nutrient management plans, environmental testing of air and water in and near livestock operations, and the costs of environmental fines.

CHAPTER IV

DATA COLLECTION

When this research began, no known anaerobic digester was being used to process dairy waste in Texas. Necessary data, therefore, were obtained by touring eleven anaerobic digester facilities outside of Texas, which had been in operation for at least one year. Two anaerobic digesters in Texas are known, one which has since stopped and one that has started operating near the completion of this study. One Texas dairy constructed and operated an anaerobic digester in 1998 (Engler et al.). This dairy has since ceased operations (Engler et al.). A second dairy recently constructed an anaerobic digester, with the aid of state and federal funding, to help curb excess phosphates from polluting Lake Waco (Shlachter). Relevant data from this dairy's anaerobic digester was non-existent at the time of data collection because digester operations began in late spring 2005 (Shlachter). Data were collected between mid-November 2004 and mid-January 2005.

An owner/operator, henceforth owner, was interviewed at each facility. The procedure employed to collect information was an informal face-to-face interview. The interviews were designed to gather data on six aspects: A) operations; B) installation; C) electricity generation; D) biogas production; E) effluent waste and digestate; and F) additional information. A complete listing of the questions asked is provided in Appendix A. Not all owners provided information for all the questions.

Interview Questions

Anaerobic Digester Operations

The first question, A.1, asked for the capacity of the anaerobic digester in terms of waste input. Question A.2 inquired if the anaerobic digester was operating at full capacity. Question A.3 was concerned with the animal species, number, and weight of the animals that the anaerobic digester serves. Finally, in question A.4 owners provided estimates of total livestock waste produced. This estimate could be reported as a daily, monthly, or yearly amount in pounds, tons, or gallons, depending on the owner's records.

Anaerobic Digester Installation

In question B.1, the owner identified their anaerobic digester type from five choices plug-flow, vertical, multiple tanks, fixed film, and covered lagoon. Next, the owner identified the category of cover their anaerobic digester used rigid, soft-top, or another design. Why the owner installed an anaerobic digester was the subject of question B.3. Available reasons were to comply with state/federal waste management system regulations, environmental concerns (i.e. excess nutrients, odors, etc.), earn extra revenue from selling electricity and by-products, or other. The owner could select all answers that applied.

Questions B.4-B.10 obtained anaerobic digester installation cost and financing information. Items included were grants/subsidies, installation financing, anaerobic digester installation inventory and costs, labor requirements, insurance costs and type, training costs, and operating financing. In question B.11, the owner provided cash inflows and outflows of the anaerobic digester in the form of a quarterly operating budget.

Electricity Generation

Question C.1 asked if electricity from the anaerobic digester is currently sold to a utility. The next three questions pertained to what was the access rule to the electrical grid, is there a net metering agreement with the utility, and the terms of the net metering agreement. Next, owners were asked if they are required to purchase from and sell electricity to the same utility. Questions C.6-C.8 obtained information on the current buying price of electricity from the grid, selling price of electricity ($/kWh), and if they expected either of these prices to change in the near future.

In question C.9, the daily electrical production levels from the anaerobic digester in kilowatt-hours (kWh) was obtained. Next, owners provided the maximum and continuous output of their electrical generator size in kWh. Owners were then asked if their generator was operated continuously or intermittently. How the generator is powered, gas powered reciprocating, gas turbine, steam turbine, steam reciprocating, or other are the subjects of question C.12. Finally, the owner provided information concerning necessary additional components required by the utility before accepting the owner's electricity, along with the components' costs.

Biogas Production

First, the owner provided an estimate of their biogas production. Biogas storage methods comprised the second question. Questions D.3 and D.4 asked if the biogas gas was scrubbed of impurities before it was used, along with the cost of the scrubber.

Finally, the owner selected the use of the by-product heat from converting biogas to electricity from four choices; warm the anaerobic digester, heat wash water, heat buildings, or other. The owner could select all choices that apply.

Effluent Water and Digestate

These two by-products are of special importance in relation to environmental impacts from contamination of air and water sources by livestock waste. Question E.1 asked the owner to describe what they did with their effluent. Questions E.2 and E.3 were concerned with effluent testing and associated costs. In question E.4, owners estimated how costs associated with effluent have changed from costs before using the anaerobic digester.

The next two questions asked the owners to identify nitrogen and phosphorus handling methods, and whether using the anaerobic digester allows them to comply with environmental regulations on nitrogen and phosphorus levels. Question E.7 inquired if the owner separates their liquid and solid digestate. In questions E.8 and E.9, owners provided information on how the two forms of digestate are disposed. In question E.10, the owner identified if livestock waste odor is still a concern after the anaerobic digester was installed. The owner could answer question E.10 with four selections yes, somewhat, no, or uncertain.

Additional Information

Finally, owners were asked to share additional information about the anaerobic digester or its operation that they felt was relevant in Section F. In addition, sketches of the owner's set-up and layout of their anaerobic digester were obtained in the interview.

Table 4.1. Description of the Anaerobic Digester Facilities Toured

Facility	State	County	Animal Species	Number Of Animals	Animal Units[2]
CA1	California	Tulare	Dairy	2,200	3,080
CA2	California	Tulare	Swine	4,000	275
CA3	California	San Joaquin	Dairy	3,500	4,900
CA4	California	Merced	Dairy	5,081	7,113
CA5	California	Marin	Dairy	580	812
CA6[1]	California	San Bernardino	Dairy	11,720	16,408
CA7	California	San Bernardino	Dairy	1,990	2,786
MN1	Minnesota	Isanti	Dairy	1,000	1,400
WA1	Washington	Whatcom	Dairy	1,000	1,400
			Swine	50	3
WI1	Wisconsin	Calumet	Dairy	1,700	2,380
WI2	Wisconsin	Calumet	Dairy	3,600	5,040

[1] CA6 is operated by a utility provider and services 11,720 head from several local dairies.

[2] Animal units (AU) are calculated by multiplying the number of dairy cattle by 1.4 (U.S. EPA 1995). For swine, the AU calculations are from Schwart et al.

Description of the Anaerobic Digester Facilities

The eleven anaerobic digester facilities toured were located in four states in different regions of the U.S. (Table 4.1). Seven facilities located in California are denoted as CA1 to CA7. One anaerobic digester facility is located in northern Washington (WA1) and another in central Minnesota (MN1). Two anaerobic digester facilities are located in Wisconsin, denoted as WI1 and WI2. Information on location, animal species, and numbers at the anaerobic digester facilities is provided in Table 4.1. Most of the anaerobic digesters were located on dairies, which range in size from 580 to 5,081 head. Facility CA2 services a 4,000 head swine operation. The WA1 facility services both a swine and a dairy operation.

Interview Responses

Anaerobic Digester Operations

A variety of anaerobic digester sizes and capacities are represented by the facilities visited (Table 4.2). CA5 reported the smallest anaerobic digester capacity at 2,139 ft^3, while the largest capacity digester is 5,912,022 ft^3 at CA4. Based on the responses provided, the average anaerobic digester size is 1,254,640 ft^3. Along with variability in anaerobic digester capacities, there is variability in total number of animal units (AU) served by the digester (Table 4.1). The smallest total number of animals is at CA5, with 580 head or 812 AU, while the largest number is at CA6, with 11,720 or 16,408 AU. CA2, a swine operation, has AU. The average AU is 4,400 AU.

Only two facilities, CA1 and CA2, estimated livestock waste production levels in terms of manure production. CA1 provided percentage values of moisture content of their manure. CA1 reported 20% of total manure as dry, 80% wet, and a total manure production of approximately 100 lbs per animal per day. CA1's approximate dry manure level is 20 lbs/animal/day with wet waste at 80 lbs/animal/day.

CA2 is a 4,000 head confined swine operation reporting a manure production level of 1 ton/day, or 2,000 lbs/day, at 80% wet and 20% dry. According to linear interpolation of data furnished by the University of Minnesota Extension Service, a 105 lb hog should produce an estimated 6.8 pounds of manure daily (Schmitt and Rehm; Midwest Plan Service). This would result in CA2 actually producing around 27,200 lbs of manure daily. Using CA2's reported moisture percentages, 5,440 lbs of manure, around 2.4 tons, should be dry and 21,760 lbs should be wet, around 9.7 tons.

Table 4.2. Type and Capacity of Anaerobic Digester Facilities

Facility	Type of Anaerobic Digester	Reported Capacity	Capacity Converted To Cubic Feet
CA1	Covered Lagoon	990,000 ft^3	990,000
CA2	Covered Lagoon	6,000,000 gal	802,083
CA3	Covered Lagoon	2,240,000 ft^3	2,240,000
CA4	Covered Lagoon	44,225,000 gal	5,591,022
CA5	Covered Lagoon	16,000gal	2,139
CA6	Plug-Flow	225 wet tons	7,520
CA7	Plug-Flow	76,440 ft^3	76,440
MN1	Plug-Flow	N/A	N/A
WA1	Plug-Flow	45,000 gal	6,016
WI1	Plug-Flow	N/A	N/A
WI2	Plug-Flow	N/A	N/A

N/A is not available.
Facility codes are defined in Table 4.1.

Anaerobic Digester Installation

The interviews revealed two types of anaerobic digesters are being used, covered lagoon and plug-flow. CA1, CA2, CA3, CA4, and CA5 utilize a covered lagoon. Covered lagoons are used primarily because of the anaerobic digester facilities locations being in central and southern California where there is a warmer climate than the other facilities. The remaining facilities use plug-flow anaerobic digesters. Four plug-flow facilities are located in the northern U.S. including Washington, Minnesota, and two in Wisconsin. Two plug-flow facilities are located in California, CA6 and CA7. Although sited in warm urban Southern California, CA6 is a plug-flow anaerobic digester owned and operated by a utility provider. CA6 possibly constructed a plug-flow anaerobic digester for safety reasons. CA7 is a plug-flow facility located in the Mojave Desert, a region that experiences cold temperatures. The covered lagoon anaerobic digesters have soft tops while the plug-flow types have rigid tops, usually made of concrete.

Table 4.3. Rationale to Construct an Anaerobic Digester

Rationale[1]	Number of Responses
Comply with state/federal livestock waste management system regulations	1
Environmental concerns (i.e. excess nutrients, odors, etc.)	3
Earn extra revenue from selling electricity and by-products	5
Other	1

[1] Respondents could select all applicable answers. Not all respondents answered this question.

Responses to why the owner constructed their anaerobic digester are provided in Table 4.3. Five owners said an anaerobic digester was built so they could earn extra revenues from electricity generation and/or by-products. Two owners said environmental concerns played a role in their decision to use an on-farm anaerobic digester. One owner answered the reason for building the anaerobic digester was to comply with state/federal regulations on livestock waste management. One facility, CA5, responded to this question by selecting “other.” CA5 explains they utilize their anaerobic digester to promote an “environmentally friendly” image when marketing their dairy products locally.

Seven of the eleven facilities received a grant/subsidy for installing an anaerobic digester (Table 4.4). The smallest grant was $67,900 received by CA5, whereas, the largest grant was $650,000 received by CA3. The average grant is $264,676 and the median is $210,000. Federal, state, and local utilities all provided grant funding to help finance the anaerobic digesters. The average length of grant was 2 years.

Only two operations provided information on financing their anaerobic digester. CA2 reported $90,000 was financed entirely from owner’s equity. WA1 reported $1,128,000 was financed.

Table 4.4. Grants/Subsidies Received to Construct Anaerobic Digester

Facility	Amount Of Grant/Subsidy	Grantor	Length Of Grant
CA1	N/A	N/A	N/A
CA2	N/A	N/A	N/A
CA3	$650,000	Federal/Local Utility	2 years
CA4	$600,000	N/A	N/A
CA5	$67,900	State	N/A
	$87,361	Federal/State	N/A
CA6	N/A	N/A	N/A
CA7	$262,000	State	N/A
	$260,000	Federal	N/A
MN1	$127,500	N/A	N/A
WA1	$272,000	Federal	1 year
	$160,000	State	3 years
WI1	$160,000	N/A	N/A
WI2	N/A	N/A	N/A
Average	$264,676	--	2 years
Median	$210,000	--	2 years

N/A is not available.
Facility codes are defined in Table 4.1.

Installation costs differed among the anaerobic digester facilities. All facilities had common elements such as engine, electrical generator, concrete, and piping. Some facilities had equipment the other operations did not possess. For example, CA5 had a hot water distribution system, while no other facility reported such a system. The installation costs of the anaerobic digester facilities are given in Table 4.5.

Two owners provided labor costs specifically for their anaerobic digester. CA2 estimated 22.5 man-hours per quarter for labor at a reported $10 per hour wage, or an estimated $900 annually. CA3 estimated 0.5 man-hours per day for labor at an $18 per hour wage, or $3,287 annually. No owner had insurance on their anaerobic digester or related equipment. One owner, WA1, said training costs associated with their anaerobic digester were minimal but could not provide an estimate.

Table 4.5. Anaerobic Digester Installation Costs in Dollars

Item	CA1	CA2	CA3	CA4	CA5
Planning/Engineering	0	0	69,811	0	0
Site Prep	0	0	0	350,000	0
Piping & Scrubber	0	1,400	35,000	190,000	0
Concrete	45,000	800	10,000	500,000	0
Construction Labor	0	3,000	0	0	0
Construction Mgmt.	0	0	0	0	0
Facility	0	0	0	0	0
Mixing	0	0	0	0	0
Engine & Generator	130,000	60,000	150,000	240,000	0
Engine Bldg	0	0	50,000	0	0
Separator	60,000	0	107,373	0	0
Cover & Lining	25,000	25,000	265,974	320,000	0
Ponds	0	10,000	0	0	0
Meters	0	0	1,978	0	0
Spark Arrester	0	0	3,000	0	0
Lagoon	0	0	176,000	0	0
Effluent Lagoon	0	0	90,000	0	0
Gas Network	0	0	21,413	0	0
Heating System	0	0	0	0	7,605
Conversion Costs	0	0	0	0	175,000
Hot Water Distribution	0	0	0	0	11,500
Electrical Intercept	0	0	0	90,000	0
Asphalt	0	0	0	135,000	0
Controls & Cooling	0	0	0	0	0
Collection Pit	0	0	0	0	0
Anaerobic Digester System	0	0	0	0	0
Process Equipment & Install	0	0	0	0	0
Startup Test & Train	0	0	0	0	0
Contractor Bond	0	0	0	0	0
Shipping	0	0	0	0	0
Meserator Pump	0	0	0	0	0
Additional Components	0	0	0	0	257
Miscellaneous	5,587	0	5,000	0	142,000
Total	265,587	100,200	985,549	1,825,000	336,362

Facility codes are defined in Table 4.1.

Table 4.5 Continued

Item	**WA1**	**MN1**	**WI1**	**WI2**
Planning/Engineering	68,163	44,400	0	0
Site Prep	0	0	0	0
Piping & Scrubber	0	2,331	0	0
Concrete	0	0	0	0
Construction Labor	0	0	0	0
Construction Mgmt.	79,792	0	0	0
Facility	0	138,861	0	921,888
Mixing	29,640	35,964	0	0
Engine & Generator	282,788	117,660	75,445	501,288
Engine Bldg	55,921	18,204	0	52,871
Separator	0	0	53,457	0
Cover & Lining	0	0	0	0
Ponds	0	0	0	0
Meters	0	2,220	0	0
Spark Arrester	0	0	0	0
Lagoon	0	0	0	0
Effluent Lagoon	0	0	0	0
Gas Network	0	0	0	0
Heating System	0	0	25,000	0
Conversion Costs	0	0	0	0
Hot Water Distribution	0	0	0	0
Electrical Intercept	0	0	0	0
Asphalt	0	0	0	0
Controls & Cooling	0	0	74,019	0
Collection Pit	15,024	0	0	0
Anaerobic Digester System	525,899	0	0	0
Process Equipment & Install	33,523	0	0	0
Startup Test & Train	15,387	0	0	0
Contractor Bond	14,790	0	0	0
Shipping	8,060	0	0	0
Meserator Pump	60,000	0	0	0
Additional Components	0	34,410	0	0
Miscellaneous	0	0	465,261	0
Total	1,188,987	394,050	693,182	1,476,047

Facility codes defined in Table 4.1.

Electricity Generation

Eight facilities reported generating electricity which is sold to utilities. One facility, CA7, reported that they were not generating electricity to be sold at the time of the interview, although they expected to sell electricity in the future. Two owners did not provide information on if they sold electricity. A utility establishes grid access rules before they accept the electricity generated by the anaerobic digesters. Grid access rules require the installation of extra but necessary equipment such as an induction system, dual meters, paneling, more wiring, ground banks, utility testing, and system protection.

The California anaerobic digester owners are taking advantage of net metering agreements between themselves and the utility. One respondent, CA2, provided information on their agreement's components. CA2's agreement allows the electricity generated to provide total offset of electrical use on their main meter and 60% on their sub-meters. CA2 is only billed for the electricity consumed during each billing period.

All owners, except one, stated they had to buy from and sell electricity to the same utility. CA5 provided information in the form of a published evaluation report by the California Energy Commission (Marsh and LaMendola). CA5's selling price varied over a three-month period during the summer of 2004. For CA5, the average June selling price was $0.1112 per kWh, $0.0986 per kWh for July, and $0.0951 for August (Marsh and LaMendola). CA2 did not provide a selling price, but using data they provided, a sale price can be calculated based on their revenue and electricity production levels. CA2 reported yearly electricity sales revenues of $43,800 or $119.92 per day, and an electricity production level of 1,620 kW per day. CA2's selling price is estimated by dividing reported daily electricity sales by their daily production. CA2's calculated selling price is $0.074/kWh. MN1 reported a selling price of $0.033/kWh. Both WI1 and WI2 reported a selling price at $0.0433/kWh. WA1 reported a buying price of $0.0575/kWh and a selling price of $0.05/kWh. Most owners expected both their buying and selling prices to change, though they were unsure of how they will change.

One highly varied response among owners was in terms of electricity production. Electricity produced depends on a number of factors such as methane production potential of the anaerobic digester, generator size, and anaerobic digester capacity. CA2 estimated their daily electrical production at 1,620 kW. CA4 estimated their annual electricity production level at 2,500,000 kW, which translates into a daily production level of 6,845 kW. CA5 estimated daily average electricity production at 628 kW (Marsh and LaMendola). CA7 estimated their daily electrical production level at 3,119 kW. WA1 stated their estimated electrical production level at 7,200 kW per day.

CA2 and CA5 have the smallest generators at 75 kW, while the largest generator was 500 kW at CA6 (Table 4.6). Average generator size is 212 kW, with a mode of 300kW. Because generators do not run at their designed output levels, responses on generator output and rated capacity can estimate the capacity ratio (CR), which is actual generator output divided by rated capacity. The lowest CR is 53.47% at CA3, whereas the highest CR is 95.06% at CA4 (Table 4.6). The estimated CR of CA5 is 76.12% using calculations based on the response the generator operates only 11 hours per day. The average generator CR is 79.28% and the median is 80.56% (Table 4.6). All owners replied that their electrical generator was a gas-powered reciprocating engine/generator.

Table 4.6. Electrical Generator Capacity

Facility	Generator Rated Capacity (kW)	Generator Actual Capacity (kW)	Generator Capacity Ratio[1] (%)
CA1	150	N/A	N/A
CA2	75	67.50	90.00%
CA3	160	85.56	53.47%
CA4	300	285.19	95.06%
CA5[2]	75	57.09	76.12%
CA6	500	380.00	76.00%
CA7	200	170.00	85.00%
MN1	135	N/A	N/A
WA1	300	N/A	N/A
WI1	135	N/A	N/A
WI2	300	N/A	N/A
Mean	212	192.19	79.28%
Median	160	170.00	80.56%
Mode	300	--	--
Minimum	75	57.09	53.47%
Maximum	500	380.00	95.06%

[1] Generator Capacity Ratio: (Actual Capacity/Rated Capacity) * 100%
[2] CA5 operates the generator only for 11 hours per day.
N/A is not available.
Facility codes are defined in Table 4.1.

Biogas Production

Four of the eleven owners provided biogas production levels. CA2 estimated daily biogas production at 34,020 ft^3. CA4 estimated daily biogas production at 288,000 ft^3 with around 130,000 ft^3 used by the generator daily. At CA4, biogas not utilized by the generator is flared off. CA5 estimated daily biogas production levels at 14,789 ft^3 (Marsh and LaMendola). CA7 reported monthly biogas production to be 387,400 ft^3.

No owner reported storing biogas. CA2 and WA1 said biogas is used continuously and not stored. CA5's biogas is used continuously when the generator is on but is flared off when the generator is off (Marsh and LaMendola). Two owners, CA3 and CA6, use scrubbers to purify the biogas, though they were unsure of cost. CA6 uses a scrubber because of the anaerobic digester's urban location. The remaining owners reported not using scrubbers.

Along with biogas production, another by-product of the anaerobic digester's generator is heat. Heat can be captured and utilized for different farm functions. CA2 makes use of their heat to warm the swine nursery barns. CA3 and CA5 use the heat to warm water for washing dairy equipment and cows. CA4 captures heat for usage in a processing plant they also operate, reducing yearly propane expenses at the plant. CA5 uses heat to warm the anaerobic digester, allowing the digester to operate in the psychrophilic temperature range for increased biogas production (Marsh and LaMendola). CA6 applies by-product heat to warm water in a desalinization plant. CA7 recaptures heat to help maintain and warm their anaerobic digester. WA1 uses heat to warm the anaerobic digester and to heat wash water and buildings.

Effluent Water and Digestate

In addition to heat, two other by-products of anaerobic digesters are effluent water and digestate. Owners stated that their effluent was used for irrigating nearby crop fields, to flush waste from livestock alleyways and feeding pens, or recycled as water to be heated for use in the anaerobic digester. CA2 reported that every two to three years, they incur environmental testing expenses on their effluent of $75 per test. Regarding nitrogen and phosphorus, owners said these nutrients are handled with the effluent used for irrigation and fertilizer application. WA1 said that with the solid digestate leaving the site they were compliant with regulations on levels of nitrogen and phosphorus.

Table 4.7. Odor Problems/Concerns with Using the Anaerobic Digester

Facility	Response	Level Of Concern
CA1	Uncertain	1
CA2	No	2
CA3	Somewhat	3
CA4	Yes	4
CA5	No	2
CA6	Yes	4
CA7	No	2
MN1	N/A	N/A
WA1	No	2
WI1	N/A	N/A
WI2	N/A	N/A
Mean		2.5
Median		2
Mode		2

N/A is not available.
Facility codes described in Table 4.1.

All owners except CA2 separated the effluent water from solid digestate. The solid digestate has multiple uses. CA3 used their solid digestate for bedding. CA6 composted their solid digestate. CA7 and WA1 distributed solid digestate on pasture and cropland. WA1 utilized solid digestate for bedding. In addition, WA1, along with WI1, sold digestate as fiber for use as a soil amender.

Owners were asked to identify an odor concern level associated with using an anaerobic digester by selecting from four responses; yes there's still a concern, somewhat of a concern, no concern, or uncertain if a concern still exists. One owner responded uncertain, four replied no concern, two stated yes, and the remaining four did not respond (Table 4.7). Responses were converted into a 4-point Likert scale model, with yes=4, somewhat=3, no concern=2, and uncertain=1. The average response was

2.5, somewhere between no concern and somewhat concerned. Both the median and mode responses were 2 or no concern.

Additional Information

No owner provided additional information about their anaerobic digester other than sketches of their facility layout. The four layouts of the anaerobic digester facilities provided are presented in Figures B.2 to B.5 in Appendix B.

CHAPTER V

MODEL DEVELOPMENT

Two decision models, denoted as the anaerobic digester (AD) and the standard lagoon (SL) models, employing modified capital budgeting and simulation, are developed to achieve the objectives outlined in Chapter I. The analysis treats waste management as an independent enterprise associated with the dairy. The models' foundation is the Schwart et al. model. Simulations are performed within Microsoft Excel using Simetar, an add-in for Excel developed by the Agricultural Food and Policy Center at Texas A&M University's Department of Agricultural Economics (Richardson). Both models assume the perspective of an individual dairy owner and not that of society. In addition, both models assume new construction of either an anaerobic digester or a lagoon for waste management.

The AD Model

Dairies without anaerobic digesters employ the use of pits or lagoons for waste management (Miner, Humenik, and Overcash). A lagoon's only use is in waste management; it has no alternative use. Revenue generated from selling the waste as fertilizer does not cover the expenses of operating and maintaining the lagoon and collecting and transporting waste for fertilizer use. In addition, biogas is not captured for electricity generation and sale; it is lost to the atmosphere. The construction of an anaerobic digester results in additional investment and expenses for the dairy. There is, however, a potential to generate revenues by selling electricity and fiber, along with cost savings from capturing by-product heat and reduced environmental fines.

A dairy's initial investment, along with estimated revenues, expenses, and cost savings, are used by the AD model to estimate the average expected net present value, E(NPV), of an anaerobic digester facility. The E(NPV) for an anaerobic digester facility is analyzed over a 10-year planning horizon and represents net returns to farm management and land from the digester operation. E(NPV) is calculated as:

$$(1) \qquad E(NPV) = \sum_{i=1}^{100} \{-I_0 + \sum_{n=1}^{10} [ER_{ni} + FS_{ni} + G_{ni} + RHE_{ni} -$$

$$EC_{ni} - ME_{ni} - OC_{ni} - FC_{ni} - T_{ni}]\left(\frac{1}{1+d}\right)^n + SV_{10}\}$$

where:

I_0	is initial investment as the down payment in year 0 (assumed to be 2004);
ER_{ni}	is revenues generated from electricity sales;
FS_{ni}	is revenues generated from selling digestate (fiber);
G_{ni}	is grants or subsidies received;
RHE_{ni}	is reduced heating expenses;
EC_{ni}	is costs of environmental non-compliance;
ME_{ni}	is waste collection, loading, transport, and land application expenses;
OC_{ni}	is operating costs;
FC_{ni}	is financing costs;
T_{ni}	is income taxes;
d	is the real discount rate;
SV_{10}	is the salvage value of the digester and equipment in year 10;
i	represents the iteration number; and
n	represents the year of the 10-year planning horizon.

One hundred iterations of the model were performed by Simetar when simulating E(NPV). Each iteration represents a 10-year period. The 100 iterations were utilized to create a cumulative distribution function (CDF) and probability distribution function (PDF) of E(NPV).

Initial Investment

Recall, there are four types of anaerobic digesters, with covered lagoon or plug-flow digesters as the two main types used by dairies. A pre-existing lagoon can be modified into covered lagoon digesters by deepening and/or widening the lagoon to accommodate more waste and adding a cover. Examples of converting pre-existing dairy waste lagoons into anaerobic digesters are found in warm regions of the U.S. (Lusk 1991).

Plug-flow digesters require additional physical capital over covered lagoon digesters. An example of additional equipment required is internal piping to carry hot water necessary to maintain the digester's operating temperature. Such piping is not necessary with a covered lagoon digester. A plug-flow digester is usually built in cool to cold regions of the U.S. Recently, a plug-flow anaerobic digester was built on a dairy in Central Texas in the NBR watershed[1], denoted as TXD (Shlachter). The anaerobic digester was constructed by TXD for environmental reasons, despite its warm location. TXD's digester is designed to help with phosphorus abatement in the NBR watershed and to promote an environmentally friendly image to surrounding residents and downstream Waco citizens (Shlachter).

In the AD model, it is assumed a plug-flow type anaerobic digester is built and operated on a dairy because of environmental reasons stated by TXD. Initial investment costs are calculated for a 1,400 AU (1,000 cows) dairy. This dairy size is selected because it is similar in size to TXD.

---

[1] The NBR watershed includes Bosque, Erath, and Hamilton counties in Central Texas.

From the interviews it was noted initial investment costs are related to the number of livestock serviced and anaerobic digester type. The interviews reported 33 items as initial investment costs on their anaerobic digesters. Items included are engines, electrical generators, cover, piping, separators, pumps, electrical meters, scrubbers, and concrete. Investment costs among the facilities interviewed ranged from $100,200 at CA1 to $1,825,000 at CA4.

Ordinary least squares (OLS) is used to estimate total investment costs as a function of the numbers of animal units (AU_0), number of animal units squared (AU_0^2), and digester type (DT_0). AU is squared in the investment equation because a U-shaped investment curve may be present due to economies of scale (Mehta; Schwart et al.). In the equation, DT_0 is a qualitative variable taking a value of zero for a covered lagoon type and one for a plug-flow type digester. Data for the OLS equation are from nine of the eleven interviews. The estimated investment equation is:

$$\begin{aligned} IN_0 &= 233{,}787.611 - 89.491AU_0 + 0.045AU_0^2 + 541{,}955.425DT_0 \\ &\quad (239{,}124.394)\,(181.813) \qquad (0.025) \qquad (210{,}425.109) \end{aligned} \tag{2}$$

where numbers in parentheses below the estimated coefficients are standard errors.

The estimated coefficients for DT_0 and AU_0^2 are statistically significant at the 7% and 15% levels. Estimated coefficients for the intercept and AU_0 are not statistically significant at the 1%, 5%, and 10% levels. As expected, the signs on the estimated coefficients of AU_0 and AU_0^2 are negative and positive. An F-test is performed to determine if the estimated coefficients of AU_0 and AU_0^2 are jointly statistically different from zero. The results of the F-test show the estimated coefficients to be jointly statistically different from zero, at the 1% significance level.

By taking the partial derivative of IN_0 with respect to AU_0 and solving for AU_0, the minimum cost occurs at 1001 AU, or 715 dairy cows. Initial investment costs increase as AU increases for AU greater than 1001. There are dairies in the NBR watershed with herds much larger than 1001 AU (Adhikari et al.; Smith). In 2004, dairies in this region had at least 1,120 AU or 800 cows, though some dairies had up to 1,680 AU, or 1,200 cows (Smith). Most dairies installing and operating an anaerobic digester will encounter increasing initial investment costs as herd size increases.

The initial investment costs for a plug-flow digester are $541,955.43 more than covered lagoon digesters. The adjusted R^2 for the equation is 0.78, which shows a reasonable fit. By using the equation, initial investment costs can be estimated for either type of anaerobic digester based on animal units. However, care should be used when interpreting the equations because of the small degrees of freedom. It is felt that the flexibility of the equation and expense of obtaining additional data outweigh the statistical concerns for this study.

The interviews revealed a certain percentage of initial investment was paid for by the anaerobic owner. Because of the large amount of investment required to construct and operate a digester, a down payment is required from the owner by the financing institution. It is assumed that of the owner's estimated initial investment, the down payment is 20% and is shown as I_o in equation (1) (United States Small Business Administration).

Electricity Revenues

Data collected from the interviews of the digester owners is used to calculate electricity revenues (ER_{ni}). The equation used is:

(3) $$ER_{ni} = \left(EGS * OT * EP * EGCR_{ni}\right) * days / year$$

where EGS is the electrical generator size in kW, OT is the daily operating time of the electrical generator in hours, EP is the selling price of electricity in \$/kWh, $EGCR_{ni}$ is the electrical generator capacity ratio, and days/year is the number of days per year the generator is operated. EGS, OT, and EP are based on the interview data.

EGS is linked with the amount of biogas produced by the dairy's herd. To calculate EGS, a formula linking EGS as a function of herd size in AU, biogas production, and energy potential of the biogas is used. Biogas production levels vary depending on cattle breed, weight, and nutrition (Hansen; Jones, Nye, and Dale; Fulhage, Sievers, and Fischer; Kramer). Literature was used to estimate the average biogas production levels for a 1,400 lb dairy cow, which is 65.153 ft^3/cow (Hansen; Jones, Nye, and Dale; Fulhage, Sievers, and Fischer; Kramer). Hansen reports a daily biogas production level of 44 ft^3/cow, with an energy potential of 26,000 BTU or 590.91 BTU/ft^3 of biogas. A 55kW gas-powered reciprocating engine/generator requires 670,230 BTU/hour to operate, or 0.0000821 kWh/BTU (Stirling Power, LLC). Using these values, the calculation of EGS is:

(4) $$EGS = [(\#cows) * (ft^3 biogas / cow) * (BTU / ft^3 biogas) * (kWh / BTU)] / 24h.$$

The base scenario of the AD model assumes the anaerobic digester operates on a 1,400 AU dairy; therefore the EGS needed is 132kW.

All but one facility reported continuous use of their generator. However, repairs and maintenance to the digester and its components may be necessary, which would change the *OT*; therefore, it is assumed the electrical generator is not in use 2% of the time. This assumption allows *OT* to be 23.52 hours/day. In addition, it is assumed in the AD model, the generator will operate for 365 days/year.

The expected electricity-selling price in Texas is assumed to be \$0.08/kWh, the price to be received by TXD. *EGS* will be variable in the scenarios as different levels of AU are examined and thus, *EGS* will change accordingly. *OT* is fixed for all scenarios, while scenarios examine the effects of changing *EP*.

To obtain the electrical generator capacity ratio, data provided by six of the eleven owners is used. For each anaerobic digester the generator capacity ratio is calculated as:

$$(5) \qquad EGCR_j = \left(\frac{Electrical\ Generator\ Actual\ Capacity}{Electrical\ Generator\ Rated\ Capacity}\right) \ for\ j = 1,\ldots,6.$$

To allow random variables of $EGCR_{ni}$ and ER_{ni} to be generated for use in the AD model, a distribution of the generator capacity ratios was created. Because there are six observations of generator efficiency, a truncated empirical distribution was created to estimate the true parameters for the distribution (Richardson, Ch. 16, p. 8). The distribution has four components, with $EGCR_j$ representing sorted values of the six generator efficiencies, $p(EGCR_j)$ or the cumulative probabilities for the six generator efficiencies, and *Min* and *Max*, represent the distribution's truncated ends. The expected value of the distribution of EGE_{ni} is 0.8053.

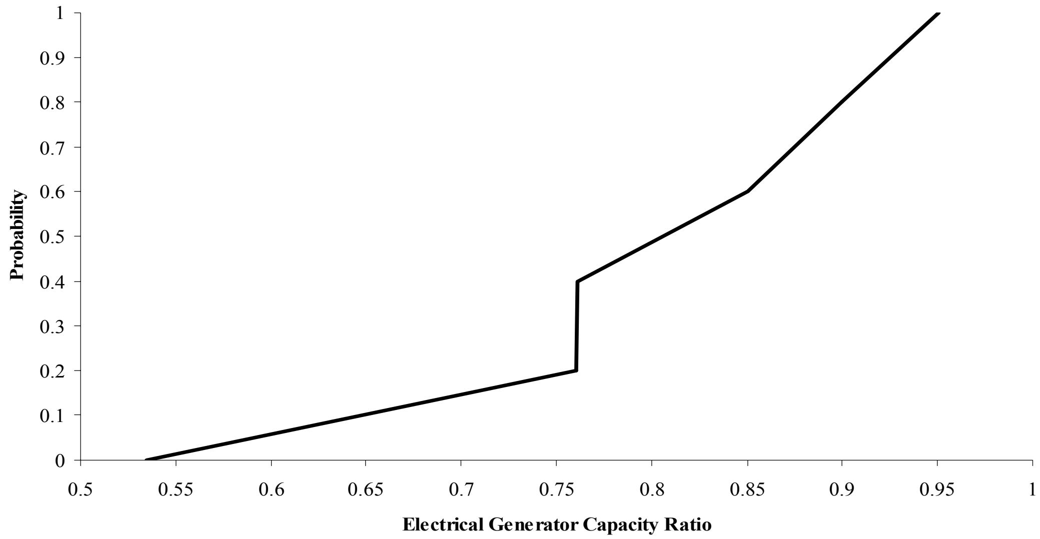

Figure 5.1. Cumulative Distribution Function of the Electrical Generator Capacity Ratios

A graph of the cumulative distribution function (CDF) of the owner's electrical generator capacity ratios is shown in Figure 5.1. In Figure 5.1, the nearly vertical portion of the CDF is due to the proximity of two capacity ratios from CA5 at 0.7607 and CA6 at 0.76. In the AD model, $EGCR_{ni}$ varies by each year and iteration, n and i. Therefore, ER_{ni} is stochastic, varying by n and i as well.

Finally, assuming that electricity is sold does not keep the dairy from using the electricity. In this case, the electricity sold represents a cost savings. Assuming all electricity is sold is conservative as the price of electricity sold to the dairy will most likely be less than the price if bought.

Fiber Sales

Digestate, or fiber, from the digester can be utilized as a soil amender, bedding, or fertilizer either on or off-farm. If used off-farm then fiber is sold, generating extra revenue. If used on-farm fiber represents a cost savings as its substitute is no longer purchased. In the AD model, it is assumed fiber is not sold or used; therefore, FS_{ni} enters the model as zero. This assumption is made because ten of the eleven owners interviewed reported not selling fiber. Scenarios are examined that assume fiber is sold.

For the scenario assuming fiber sales, the estimated revenues from fiber sales, FS_{ni}, is calculated using data from the interviews and previous research. WA1 and WI2 both reported annual fiber sales of $41,000. To utilize this amount, the fiber savings is divided the total number of AU serviced by the digesters. Fiber sales values of $29.22 per AU per year are obtained for WA1 and $8.13 per AU per year for WI2.

Mattucks and Moser estimated fiber sales from anaerobic digesters on five Midwest dairies between 1999 and 2002. Their estimates were adjusted to 2004 dollars using the Consumer Price Index (Sahr). The estimated sales were converted to annual fiber sales per AU. The lowest annual fiber sales per AU were $8.40 on a 1,400 AU dairy, while the largest was $32.64 on a 980 AU dairy. WA1's fiber sales per AU per year are within the range of values from Mattucks and Moser. The average annual fiber sales per AU, using WA1 and WI2's values and Mattucks and Moser's study, are $19.14/AU. When fiber is assumed to be sold from the farm, it is assumed that 1% of fiber sales must cover advertising and selling expenses incurred by the owner. In the AD model, the formula to calculate FS_{ni} utilizes the average annual fiber sales per AU calculated from Mattucks and Moser's study. The equation for FS_{ni} is:

$$(6) \qquad FS_{ni} = (\$19.14 * \text{AU} * 0.99).$$

FS_{ni} does not vary by n or i.

Grants / Subsidies

Agencies funding anaerobic digesters usually provide either grants or subsidies. Of those owners receiving a grant, the smallest grant received was \$67,900 by CA5 (Table 4.4). The largest grant was received by CA3, who reported a two-year grant of \$650,000. The median grant was \$210,000 while the average was \$264,676 (Table 4.4). According to the interviews the maximum length of time over which a grant was received was two years. In the base scenario of the AD model, G_{ni} is assumed to be zero for each year of the 10-year planning horizon in the AD model. As with fiber sales, sensitivity analysis on the grant amounts received is performed.

Reduced Heating Expenses

Anaerobic digesters produce by-product heat during the conversion of biogas to electricity. The heat can be captured and utilized elsewhere, such as warming water to help the anaerobic digester maintain its designed operating temperature. Using heat for farm, personal, or anaerobic digester use allows dairy owners to save money on hot water and propane expenses. In the AD model, heating expenses were not included because the interview data did not provide amounts spent on hot water and propane annually by the owners. However, one interview coupled with previous studies provided estimates on the value of reduced heating expenses, RHE_{ni}.

One of the eleven anaerobic digester owners interviewed, CA5, reported their average heat savings. CA5 estimated heat savings at \$6,000/year or a yearly cost savings or \$7.39/AU (Marsh and LaMendola). Mattucks and Moser's estimated heat savings for digesters on five Midwest dairies between 1999 and 2002. The heat savings per AU estimates from Mattucks and Moser were adjusted to 2004 dollars using the CPI and used to calculate annual heat savings per AU. Annual heat savings per AU from Mattucks and Moser vary from a minimum of \$5.94/AU to a maximum of \$22.84/AU.

CA5's heat savings is within the range of Mattucks and Moser's estimates. CA5's digester is located is in a warmer region of the U.S., California, and is a different type, covered lagoon, than the Midwest dairies from Mattucks and Moser's study. However, CA5's heat is utilized by the dairy's creamery. CA5's heat savings per AU were included in the values calculated from Mattucks and Moser to arrive at an average annual heat savings estimate of \$13.03 per AU. Though Texas is considered to have a warm climate, there is a possibility for cool winters which would require heat for milking or other dairy operations. Hot water and propane expenses will vary from dairy to dairy. However, in the base scenario of the AD model, it is assumed that the anaerobic digester owner captures and uses the by-product heat and receives the estimated average annual heat savings per AU. Scenarios are examined that assume receiving zero savings, along with the minimum and maximum heat savings. The calculation for RHE_{ni} is:

$$(7) \qquad RHE_{ni} = (\$13.03 * AU).$$

RHE_{ni} is a fixed cost savings that does not vary by year or iteration, n or i.

Costs of Environmental Non-Compliance

Dairies are more apt to be compliant with state environmental regulations after installing an anaerobic digester. In the AD model, it is assumed environmental fines are no longer incurred. Therefore, the costs of environmental non-compliance, EC_{ni}, in the AD model are assumed to be zero and do not vary by year or iteration, n or i.

Waste Collection, Loading, Transportation, and Application Expenses

Without the construction and operation of an anaerobic digester, livestock waste is primarily stored in lagoons for fertilizer use. Digesters process the livestock waste and separate the solid material, the digestate, or fiber, from the liquid material or effluent. The effluent is usually stored for on-farm use.

The effluent separated from the digester through fiber production can be stored on-farm, as is the case of facilities CA1, CA2, CA7, and WA1. If fiber is used by the owner as a soil amender or fertilizer then there are costs incurred to load, transport, and apply the fiber to land. Effluent is assumed to be loaded, transported, and applied on nearby land for on-farm use; therefore these costs are also incurred. WI2 reported selling their effluent occasionally but there was no specification on amount sold or price.

The costs of collecting, loading, transporting, and applying the dairy waste to land is denoted as ME_{ni}. None of the digester owners knew their livestock waste and effluent collection, loading, transportation, and land application costs. WA1 reported decreases in land application costs of their effluent, though unsure of the amount.

Previous research was utilized to help determine ME_{ni}. Adhikari et al. reported the livestock waste collection and storage costs along with loading, transportation, and application costs for 225, 400, and 1,200 cow dairies in the NBR watershed. For the 400-cow dairy (560 AU) total costs were $16,900, which is $30.18/AU or $39.45 when adjusted to 2004 dollars using the CPI. For a 1,200-cow dairy (1,680 AU), livestock waste collection and storage costs were \$19,800 and loading, transportation, and application costs were \$9,100 (Adhikari et al.). Total costs were \$28,900, or \$17.20/AU. When adjusted to 2004 dollars, total costs are \$22.49/AU. Adhikari et al.'s values show that as AU increases, livestock waste expenses per AU decrease. Unfortunately, only two values are not enough to estimate such a function.

In the AD model, the value of ME_{ni} is assumed to be \$22.49/AU, which is Adhikari et al.'s estimate for a 1,680 AU dairy. The formula to enter ME_{ni} into the AD model is:

$$(8) \qquad ME_{ni} = (\$22.49 * AU).$$

ME_{ni} enters the AD model as an expense and does not vary by year or iteration, *n* or *i*.

Operating Costs

The formula for determining operating costs, OC_{ni}, is:

$$(9) \qquad OC_{ni} = (LA_n + RMC_n + MC_n + D_n)$$

where LA_n are labor expenses, RMC_n are repair and maintenance costs, MC_n are testing and monitoring costs of the effluent from their digester for possible pollutants, and D_n is depreciation. Each component of OC_{ni}, except MC_n, is entered into the AD model as a constant; they do not vary by year or iteration, *n* or *i*.

Only two of the eleven anaerobic digester owners reported their labor expenses. CA2 reported 22.5 man-hours expended in labor on their digester per quarter, or 90 hours annually. At a reported wage rate of \$10/hour, CA2's labor expenses are \$900/year. CA3 reported 0.5 man-hours in labor per day every day, or 182.5 hours annually. At a reported wage rate of \$18/hour, CA3's labor expenses are \$3,287/year.

These two estimates were converted to a labor expense per AU. CA2's labor expense is \$3.27/AU and CA3's labor expense is \$0.67/AU. In the AD model it is assumed that the labor charge is \$2.00/AU, which is between the CA2 and CA3's figures. The formula to calculate the total annual labor expense is:

(10) $$LA_{ni} = (\$2.00 * AU).$$

Repairs and maintenance costs vary from 1% to 5% of initial investment (Lusk 1991; Mukhtar). RMC_n is assumed to be 3% of initial investment in each year of the AD model. One facility, CA2, reported effluent testing and monitoring expenditures, MC_n, or \$75 every two years. In the AD model, MC_n is \$75 every second year and zero the other years. MC_n does not vary by iteration. D_n is calculated using the straight-line method over the 10-year planning horizon; therefore it is 10% of the initial investment.

Financing Costs

Financing costs, FC_{ni}, are the principal and interest payments on funds borrowed to construct the digester. Because the down payment is 20%, the amount financed for the anaerobic digester is 80% of the estimated initial investment. The down payment enters into the AD model as $-I_0$, to allow the down payment to be recovered. In the AD model, it is assumed the loan is amortized over the 10-year planning horizon, similar to Schwart et al. The loan interest rate is assumed to be a real interest rate of 4.6% (United States Office of Management and Budget).

Income Taxes

Income taxes, T_{ni}, are calculated as a percentage of taxable income as follows:

(11) $$T_{ni} = ([ER_{ni} + FS_n + G_n + RHE_{ni} - EC_{ni} - ME_n - OC_n - IP_n] * TR)$$

where IP_n is interest payment, TR is the tax rate, and all other variables are as previously defined. The tax rate used is 28%, as used by Schwart et al. Because of the stochastic nature of ER_{ni}, T_{ni} becomes stochastic as well, varying by year and iteration, n and i.

Discount Rate

The AD model uses 2004 dollars; therefore, a real discount rate is necessary. Different studies have assumed different nominal and real discount rates. Engler et al. used a rate of 2.5%, Masud et al. used a rate of 3.5%, and Schwart et al. used a rate of 4.5%, while Lusk (1991) used a rate of 7%. The discount rate assumed for the model is 2.8%. This was suggested by the 2004 real discount rate forecast published by the United States Office of Management and Budget based on the interest rate of a treasury bond with a 10-year maturity date (United States Office of Management and Budget).

Salvage Value

SV_{10} represents the expected value of the digester and related equipment at the end of the 10-year period. In the model, salvage value is assumed to be zero.

The SL Model

The E(NPV) for a standard lagoon is analyzed over a 10-year planning horizon and represents net returns to management and land. Equation (1) is used in the SL model; however, some of the component variables are changed. Results from the SL model are used to compare with results from the AD model.

Variables Set Equal to Zero

Because of differences between a standard lagoon and an anaerobic digester, several variables are set equal to zero in the SL model. Because there is no biogas captured and used to generate and sell electricity, ER_{ni}=\$0. Without a digester, fiber is not produced or sold for revenue; therefore FS_{ni}=\$0. In addition, grants for standard lagoons are usually not received, so G_{ni}=\$0. Without biogas capture and conversion, by-product heat is not produced; therefore heating expenses are not reduced and RHE_{ni}=\$0.

Initial Investment

OLS was utilized to estimate the standard lagoon's initial investment, with total investment costs as a function of AU_0 and AU_0^2. Equation (12) differs from equation (2) in the AD model in there is no qualitative variable for anaerobic digester type. This is because there are no types of lagoons. Interview data was used to create the investment equation, with all costs related to the anaerobic digester and related equipment was removed. The estimated initial investment equation is:

$$\begin{array}{ll} (12) & IN_0 = 56{,}682.772 + 61.078AU_0 - 0.003AU_0^2 \\ & \quad (140{,}588.627)\ (104.031)\quad (0.014) \end{array}$$

where the numbers in parentheses are the standard errors of the coefficients.

The estimated coefficients for the intercept, AU_0 , and AU_0^2 are not statistically significant at the 1%, 5%, or 10% levels. As expected, the signs on the estimated coefficients of AU_0 and AU_0^2 are positive and negative. An F-test was performed to determine if the estimated coefficient of AU_0^2 is statistically different from zero. The results of the F-test show the estimated coefficient of AU_0^2 to not be statistically different from zero, at the 1%, 5%, or 10% levels. Therefore, AU_0^2 is removed from equation (12) and the new estimated initial investment equation is:

$$\begin{array}{ll} (13) & IN_0 = 81{,}806.591 + 37.411AU_0 \\ & \quad (83{,}966.907)\ (24.441) \end{array}$$

By removing AU^2, there is an improvement in adjusted R^2 from 0.004 in equation (12) to 0.161 in equation (13).

By using equation (13), initial investment costs were estimated for a lagoon, showing each additional AU increases investment by \$37.41. However, care should be used when interpreting equation (13) because of the small degrees of freedom. As before, it is felt that the flexibility of the equation and expense of obtaining additional data outweigh the statistical concerns for this study. Similar to the AD model, it is assumed that 20% of the owner's initial investment is the down payment, I_o, with the remaining 80% borrowed and financed (United States Small Business Administration).

Costs of Environmental Non-Compliance

By using a standard lagoon, pollutants, odors, and excess nutrients from waste will enter the environment. This may cause dairies to be noncompliant with state and federal environmental regulations. The costs of environmental non-compliance, EC_{ni}, are included in the standard lagoon model.

A record of fines for dairies in the NBR watershed that have violated state environmental regulations was provided by the Texas Commission on Environmental Quality (TCEQ). Violations include improper wastewater storage capacity and negligence. Negligence includes illegal dumping of wastewater from lagoons and storage facilities. Data provided by TCEQ details 52 violations and fine amounts during the period from June 1998 to November 2004, denoted as F_k. The fines were adjusted using the Consumer Price Index to 2004 dollars (Sahr). The minimum adjusted fine is \$850 with the maximum adjusted fine is \$24,195 and a range of \$23,345.

A truncated empirical distribution, E_f, of F_{ni} is assumed (Richardson, Ch.16, p. 8). The distribution of E_f utilizes three components, with EF_k representing the sorted values of the fines (k is fines 1 through 52), $p(EF_k)$ or the cumulative probabilities for the fines, and *Min* represents the distribution's lower truncated end. In E_f, *Min* is zero because a negative fine cannot be received. The expected value of the distribution is \$4,569. The distribution gives a random fine for each year and iteration, F_{ni}.

However, not all dairies in the NBR watershed are fined each year. Data from the United States Department of Agriculture's Agricultural Marketing Service give the total number of dairies per month in the NBR watershed from June 1998 to November 2004. The fine data and monthly numbers of dairies were used to determine the monthly probability of receiving a fine in the NBR (Appendix C). The average monthly probability is multiplied by 12 to obtain the yearly probability of a dairy in the NBR watershed receiving a fine, $p(F)$. A $p(F)$ of 0.0525 is obtained. The equation for EC_{ni} is:

$$(14) \qquad EC_{ni} = (F_{ni} * p(F)).$$

In the SL model, EC_{ni} is a stochastic cost, varying by year and iteration, n and i. Due to EC_{ni}, the E(NPV) of a standard lagoon becomes stochastic.

A graph of the probability distribution function (PDF) of the environmental fines incurred by the dairies in the NBR from June 1998 to November 2004 is provided in Figure 5.2. The probability of a dairy in the NBR watershed received a fine less than the average was greater than a dairy that received a fine greater than average. Therefore, the environmental fine data is skewed to the right.

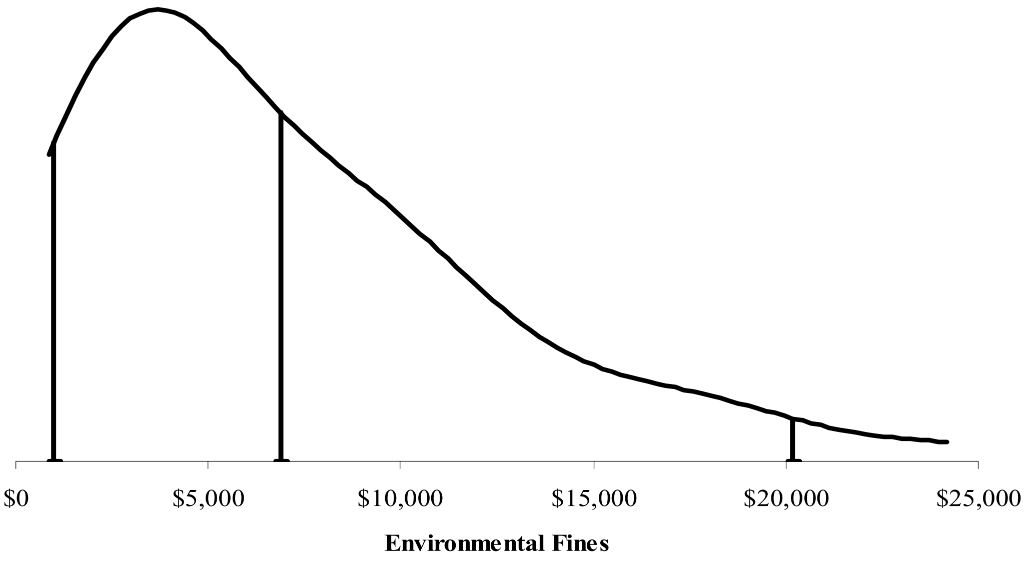

Figure 5.2. Probability Distribution Function of Environmental Fines Incurred by Dairies in the NBR Watershed from June 1998 to November 2004 (in 2004 Dollars)

Waste Collection, Loading, Transportation, and Application Expenses

Livestock waste must be disposed of or used in some method by a dairy. The dairy still incurs waste collection, loading, transportation, and land application expenses regardless of whether an anaerobic digester or standard lagoon is used for waste management. Waste collection, loading, transportation, and application expenses, ME_{ni}, are included in the standard lagoon model. ME_{ni} enters the SL model using the same calculation as was used in the AD model.

Operating Costs

Repair and maintenance expenses, along with environmental testing and monitoring of the lagoon, are still incurred. Depreciation charges are calculated for a lagoon in the same manner as in the AD model. The only difference in calculating operating costs between the SL model and the AD model is in the repair and maintenance expenses. For the AD model, repair and maintenance expenses were calculated as 3% of initial investment costs. In the SL model, repair and maintenance expenses are set at 1% of initial investment. This is because there is less equipment associated with a lagoon as compared to an anaerobic digester. Thus, operating costs of a lagoon are lower than that of the anaerobic digester.

Financing Costs

A standard lagoon for dairy waste management in of itself is a sizeable investment. Dairies face the possibility of having to borrow funds to construct a standard lagoon. In the SL model, it is assumed funds are borrowed to build the lagoon. There are financing costs associated with the borrowed amount, similar to the AD model. The estimated initial investment, after the down payment, is a loan to the dairy and amortized over the 10-year planning horizon. The loan interest rate is assumed to be a real interest rate of 4.6%, same as in the AD model (United Office of Management and Budget).

Income Taxes

Income taxes in the SL model are calculated same as in the AD model. A dairy generates zero revenues from their lagoon. Because a dairy incurs only expenses for a lagoon, T_{ni} in the SL model becomes positive. This allows for lower income taxes for the dairy.

Discount Rate

The discount rate used in the SL model is 2.8%, as used in the AD model.

Salvage Value

A lagoon is designed only to store waste and has no alternative uses. Similar to the AD model, the salvage value of a standard lagoon is zero, therefore SV_{10}=\$0.

Variables Not Measured by the Models

There are several issues related to human health and the environment which could not be quantified for usage in the models. Previous studies show the link between harmful odors, dust, flies, and pathogens and human health. The value of reducing harmful odors, dust, flies, and pathogens associated with livestock waste by using anaerobic digesters are not included.

Anaerobic digesters help reduce the offensiveness of livestock waste odors on humans, depending on operating temperature and length of time for which waste is retained (Welsh et al.). Harmful odors from swine operations have been shown to decrease residential property values (Hopey; Herriges, Secchi, and Babcock). Odors contain such materials as methane, ammonia, nitrous and nitric oxide, and hydrogen sulfide which can detrimentally effect the environment (NRC; Innes; Miner, Humenik, and Overcash.).

Dust from waste is also a problem because it can cause lung damage and breathing difficulties in humans (National Research Council of the Academies). Flies can transmit diseases and sicknesses to nearby residents. Pathogens can enter a watershed and travel many miles, possibly entering public water supplies and endangering human health (Miner, Humenik, and Overcash; Metcalfe; Parker; Fisher et al.; Krapac et al.). These issues are expected to be reduced with the usage of anaerobic digesters (Lusk 1991; Legrand; Chynoweth, Owens, and Legrand; Maeng, Lund, and Hvelplund; Parsons 2004; U.S. EPA 2002; Welsh et al.). The anaerobic digester's cover prevents release of odors. Because livestock waste is contained inside the anaerobic digester in a wet state, issues of dust are no longer a problem. The anaerobic digester also aids in removing harmful pathogens.

Aside from the study linking harmful odors to decreasing property values, there were no studies found quantifying the economic value of reducing harmful dust, flies, pathogens, and pollutants from agricultural sources. In both models, these variables were not included because there is no direct way to estimate the economic impact of reducing health and environmental concerns related only to livestock waste by using anaerobic digesters.

Besides the inability to quantify these variables, a second reason they are not included is that the models assume an individual dairy perspective. Individual dairies would not be able to capture many of these benefits as the benefits are external to the dairy. Society would experience these benefits. Because individuals adopt new technology and not society, it is important to examine anaerobic digestion technology from the individual's perspective. Society's viewpoint is also important, but that is a separate research issue.

CHAPTER VI

RESULTS AND DISCUSSION

The two decision models, the anaerobic digester (AD) and standard lagoon (SL) models, developed in Chapter V are used to analyze the economic implications of dairy waste management options in the NBR watershed. Results from the two models, along with outcomes from sensitivity analysis, are presented and discussed. The average expected net present value, E(NPV), of an anaerobic digester is calculated over a 10-year timeframe. In addition, distributions of E(NPV) are presented. Recall, E(NPV) represents the returns to management and land.

Empirical Results

The SL Model

The final results from the AD and SL models and sensitivity analysis are presented in Table 6.1. The E(NPV) from the SL model is -\$316,913 (Table 6.1). The only stochastic variable is costs of environmental compliance, which are shown as fines charged to the dairies by state authorities. The range of E(NPV) is small, as given by the 95% confidence interval of -\$320,319 to -\$315,251. The probability of a positive E(NPV) is zero. Because a lagoon is utilized strictly for waste management and with no revenue generating capacity, a negative E(NPV) is expected.

Table 6.1. Empirical Results from the Anaerobic Digester (AD) and Standard Lagoon (SL) Models for Various Scenarios

Model	AU	EGS[1] (kW)	ESP ($/kWh)	Heat Savings	Fiber Sales	Grants	Down Payment	Discount Rate	E(NPV)	Probability E(NPV)≥ 0	95% Confidence Interval	
											Lower Bound	*Upper Bound*
SL (Base)	1400	--	--	--	--	--	--	2.8%	($316,913)	0.000	($320,319)	($315,251)
AD (Base)	1400	132	$0.08	Average	No	No	20%	2.8%	($370,797)	0.000	($503,993)	($291,719)
AD (No Revenues)	1400	--	--	--	--	--	--	2.8%	($934,315)	0.000	--	--
AD (Full)	1400	132	$0.08	Average	Yes	Yes	20%	2.8%	$16,842	0.570	($116,353)	$95,920
AD (Covered Lagoon)	1400	132	$0.08	Average	No	No	20%	2.8%	$158,898	1.000	$25,702	$237,976
Animal Units (AU)												
AD	700	66	$0.08	Average	No	No	20%	2.8%	($545,722)	0.000	($612,320)	($506,183)
SL	700	--	--	--	--	--	--	2.8%	($217,091)	0.000	($220,498)	($215,430)
AD	2100	197	$0.08	Average	No	No	20%	2.8%	($202,700)	0.000	($402,493)	($84,083)
SL	2100	--	--	--	--	--	--	2.8%	($416,555)	0.000	($419,962)	($414,894)
AD	3360	316	$0.08	Average	No	No	20%	2.8%	$82,668	0.810	($237,001)	$272,456
SL	3360	--	--	--	--	--	--	2.8%	($595,460)	0.000	($598,867)	($593,799)
Electricity-Selling Price (ESP)												
AD	1400	132	$0.00	Average	No	No	20%	2.8%	($821,805)	0.000	--	--
AD	1400	132	$0.0421	Average	No	No	20%	2.8%	($584,121)	0.000	($645,215)	($542,506)
AD	1400	132	$0.12	Average	No	No	20%	2.8%	($145,653)	0.000	($345,446)	($27,036)
Heat Savings												
AD	1400	132	$0.08	Zero	No	No	20%	2.8%	($484,027)	0.000	($617,222)	($404,949)
AD	1400	132	$0.08	Minimum	No	No	20%	2.8%	($432,428)	0.000	($565,623)	($353,350)
AD	1400	132	$0.08	Maximum	No	No	20%	2.8%	($285,576)	0.000	($418,771)	($206,498)
Fiber Sales												
AD	1400	132	$0.08	Average	Yes	No	20%	2.8%	($221,179)	0.000	($354,374)	($142,101)
Down Payment												
AD	1400	132	$0.08	Average	No	No	0%	2.8%	($366,326)	0.000	($499,818)	($287,545)
AD	1400	132	$0.08	Average	No	No	40%	2.8%	($374,971)	0.000	($508,167)	($295,893)
AD	1400	132	$0.08	Average	No	No	60%	2.8%	($379,146)	0.000	($512,341)	($300,068)
AD	1400	132	$0.08	Average	No	No	80%	2.8%	($383,320)	0.000	($516,515)	($304,242)
AD	1400	132	$0.08	Average	No	No	100%	2.8%	($387,494)	0.000	($520,690)	($308,416)
Discount Rate												
AD	1400	132	$0.08	Average	No	No	20%	4.5%	($351,751)	0.000	($474,047)	($279,144)
SL	1400	--	--	--	--	--	--	4.5%	($293,060)	0.000	($296,188)	($291,535)
AD	1400	132	$0.08	Average	No	No	20%	7%	($327,824)	0.000	($436,377)	($263,375)
SL	1400	--	--	--	--	--	--	7%	($263,003)	0.000	($265,780)	($261,649)

[1] EGS is electrical generator size.

Cumulative distribution function (CDF) and probability distribution function (PDF) graphs of E(NPV) from the SL model are presented in Figures 6.1 and 6.2. The centerline in Figure 6.2 represents E(NPV), and the right and left lines representing the upper and lower bounds of the 95% confidence interval. The PDF is skewed, showing a greater probability of an E(NPV) smaller than the mean occurring. Environmental fines incurred between 1998 and 2004 by dairies in the NBR watershed range from $850 to nearly $25,000, with an average fine of approximately $6,886 (Table C.1). The PDF of the environmental fines is skewed to the right (Figure 5.2). In Figure 6.2, the CDF of E(NPV) mirrors that of Figure 5.2. The difference is that being the fines enters the SL model as a cost; therefore, the CDF in Figure 6.2 is skewed to the left.

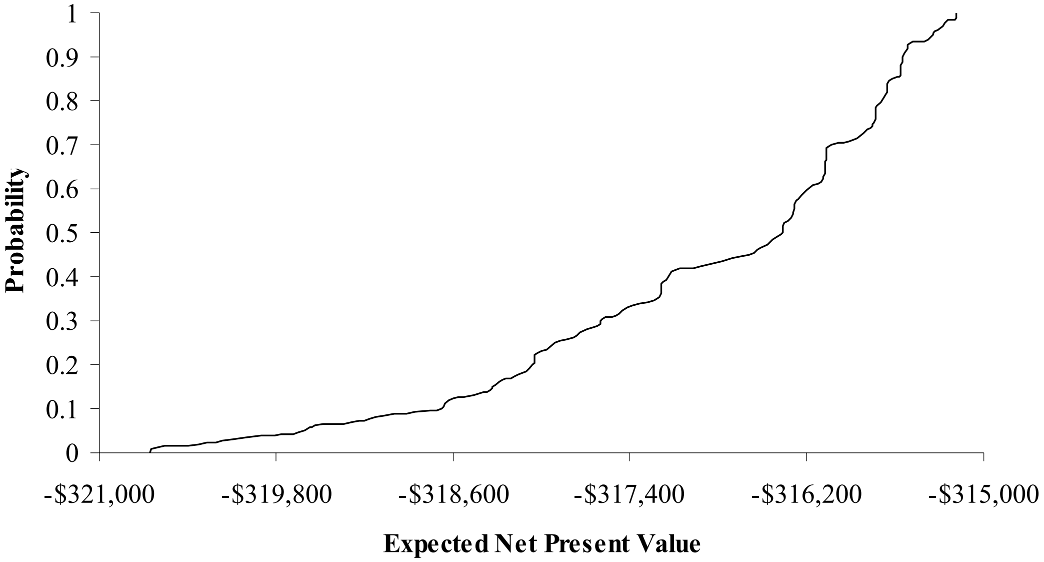

Figure 6.1. Cumulative Distribution Function of Expected Net Present Value from the Standard Lagoon Model

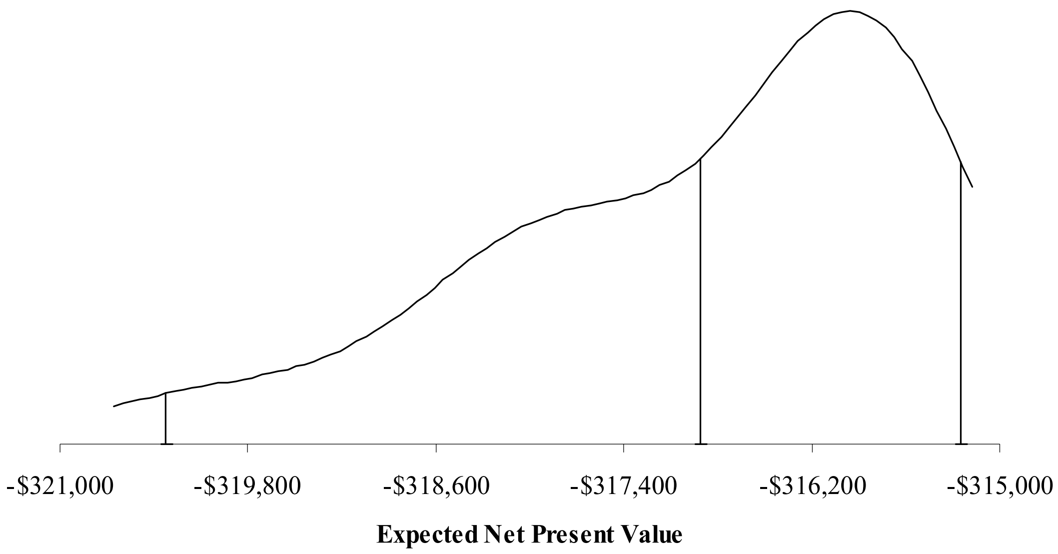

Figure 6.2. Probability Distribution Function of Expected Net Present Value from the Standard Lagoon Model

The AD Model

The E(NPV) associated with the AD model is -$370,797 with a 95% confidence interval of -$503,993 to -$291,719 (Table 6.1). This confidence interval is much larger than the interval associated with the SL model. In the AD model, the electrical generator capacity ratio is stochastic and is used to estimate revenues from selling electricity. Estimating revenues from electricity sales utilizes an empirical distribution of the range of reported electrical generator capacity ratios. This creates a range of possible electricity revenues and E(NPV).

CDF and PDF graphs of the results from the AD model are presented in Figures 6.3 and 6.4. From Figures 6.3 and 6.4, it can be seen that the probability of a positive E(NPV) occurring is zero. In Figure 6.3, the CDF curve is S-shaped but has a short near vertical section between E(NPV) values of -$394,737 and -$392,942. Approximately 20% of possible values of E(NPV) occur in this region.

In Figure 6.3, the nearly vertical section is attributable to the truncated empirical distribution of generator capacity ratios used in the AD model. There are a small number of empirical observations. Two of the reported capacity ratios are in close proximity to one another, approximately 0.76. The probability of obtaining a capacity ratio near 0.76 occurring, therefore, is greater than the other potential values. This causes a higher probability of E(NPV) in this range, thus the near vertical region (Figure 6.3).

In Figure 6.4, the PDF graph is bimodal, with two peaks and E(NPV) in between. The peak to the left of E(NPV) is due to the cluster of possible values of E(NPV) in the near vertical region. However, the area under the peak to the right of E(NPV) shows there is a greater probability of the anaerobic digester's E(NPV) being greater than the mean. The skewness of the PDF to the left in Figure 6.4 mirrors the skewness in electrical generator efficiency (Figure 5.1).

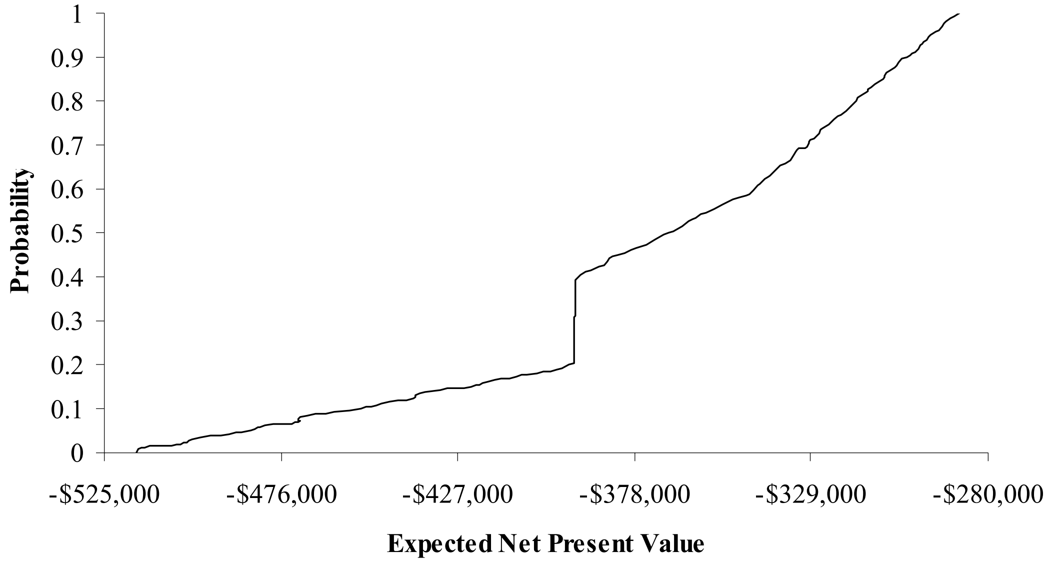

Figure 6.3. Cumulative Distribution Function of Expected Net Present Value from the Anaerobic Digester Model

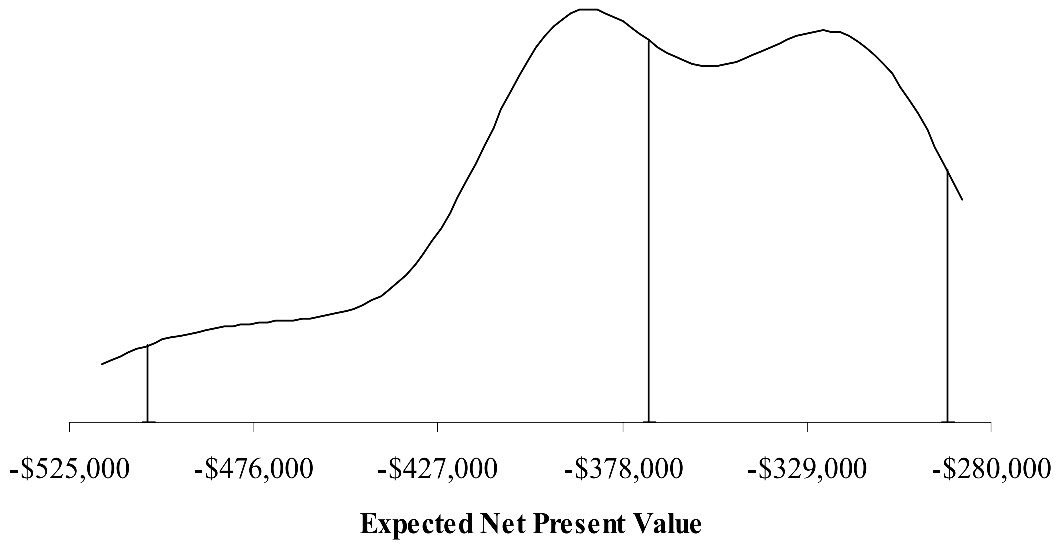

Figure 6.4. Probability Distribution Function of Expected Net Present Value from the Anaerobic Digester Model

Model Comparison

E(NPV) calculated for both models is negative with the probability of a positive E(NPV) occurring being zero in both models as well (Table 6.1). Without electricity sales and heat savings, the E(NPV) of the anaerobic digester is approximately -$934,315 (Table 6.1). This loss is greater than the loss associated with a standard lagoon, which is -$316,913 (Table 6.1). Further, the E(NPV) of the base scenario of the SL model is greater than the E(NPV) from the base scenario of the AD model. This result suggests that a lagoon would be preferred to an anaerobic digester for waste management. This finding is consistent with waste management in the NBR watershed. Currently, lagoons are the standard waste management strategy.

Sensitivity Analysis

Animal Units

The effects of differing numbers of animal units (AU) the anaerobic digester and lagoon services are examined (Table 6.1). Three alternate AU levels analyzed are 700 AU, 2,100 AU, and 3,360 AU. These different AU levels represent various dairy herd sizes found in Texas (Duncan). AU, biogas production, and electrical generator size are linked together in the AD model. Using equation (4) in Chapter V, the electrical generator size for 700 AU is 66kW, at 2,100 AU it is 197kW, and at 3,360 AU it is 316kW (Table 6.1). Electricity revenue is adjusted based on these factors. Altering AU changes the costs of labor and waste collection, loading, and land application in both models. Initial costs are also a function of AU because estimated investment costs are linked with AU in both models. Thus, the down payment, along with the financed costs also changes by AU.

For the AD model, the E(NPV) at 700 AU is -$545,722 with a 95% confidence interval of -$612,320 to -$506,183. The probability of a positive E(NPV) occurring is zero. E(NPV) with 2,100 AU is -$202,700 with a 95% confidence interval of -$402,493 to -$84,083. The probability of obtaining a positive E(NPV) with 2,100 AU is zero. The E(NPV) with 3,360 AU is $82,668 with a 95% confidence interval of -$237,001 to $272,456. The probability of a positive E(NPV) occurring with 3,360 AU is 0.8104.

In the SL model, the E(NPV) at 700 AU is -$217,091 with a 95% confidence interval of -$220,498 to -$215,430. With 2,100 AU, E(NPV) decreases to -$416,555 with a 95% confidence interval of -$419,962 to -$414,894. At the 3,360 AU level, the E(NPV) is -$595,460 with a 95% confidence interval of -$598,867 to -$593,799. The probability of obtaining a positive E(NPV) in the SL model is zero for all of the AU levels examined.

The E(NPV) for a lagoon decreases with larger AU levels. Results from the AD model, however, reveal that the E(NPV) increases as AU levels increase. As AU increases biogas production and electricity generation on the dairy increases. To capture this increased biogas production and convert it to electricity, the owner incurs increased costs. In the AU range examined, revenues increase faster than costs.

CDF's and PDF's comparing the three AU level scenarios in both of the models are given in Figures 6.5 to 6.8. As AU increases, the distribution of E(NPV) shifts to the right in the AD model (Figure 6.5) and to the left in the SL model (Figure 6.6). In addition, the CDF becomes less steep as AU increases in the AD model (Figure 6.5). The vertical line in Figure 6.5 represents an E(NPV) of $0. For all scenarios of AU in the AD model, the CDF curves are S-shaped.

As AU levels increase, the confidence interval around the E(NPV) calculated by the AD model increases (Figure 6.7). Recall, electrical generator size increases as AU levels increase. As electrical generator size increases, with a stochastic electrical generator capacity ratio, the variability in electrical generator output grows larger. A wider range of electricity production, therefore, is possible from the anaerobic digester, which results in the wider ranges of electricity revenues. This causes the confidence intervals to widen and overlap as AU levels increase (Figure 6.7). However, there is no overlap in the confidence intervals for the SL model (Figure 6.8).

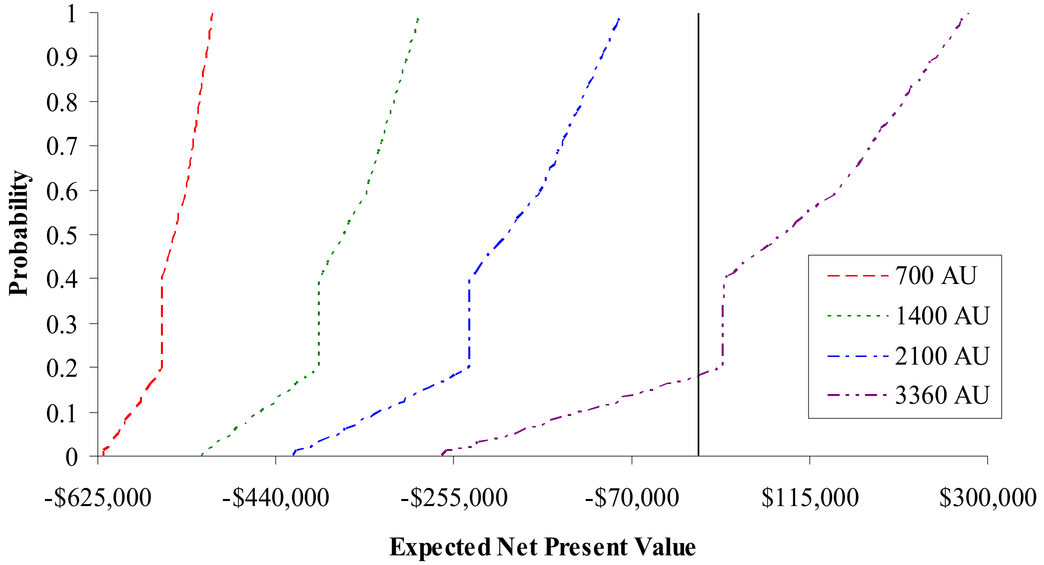

Figure 6.5. Cumulative Distribution Functions of Expected Net Present Value from the Anaerobic Digester Model by Varying Animal Units (AU)

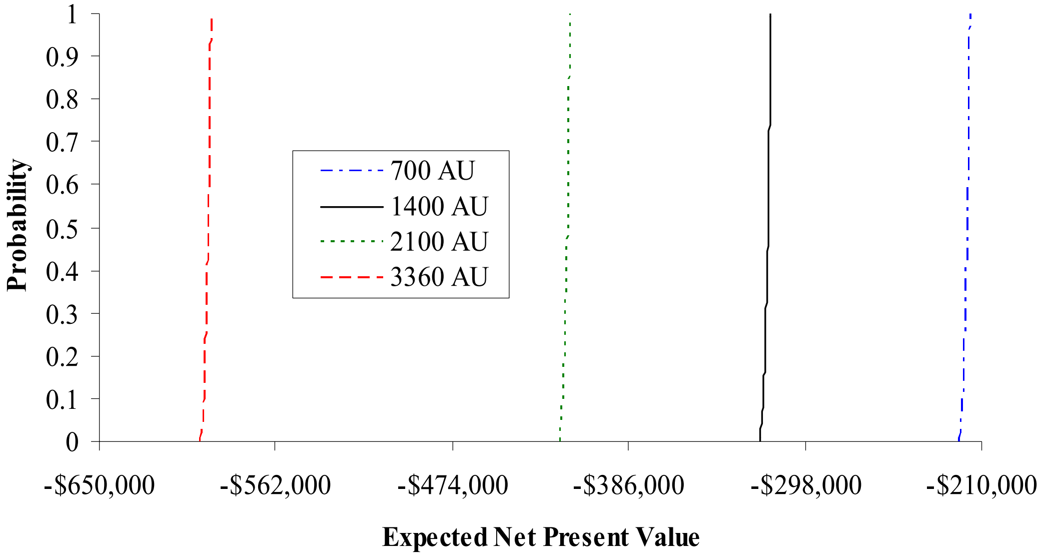

Figure 6.6. Cumulative Distribution Functions of Expected Net Present Value from the Standard Lagoon Model by Varying Animal Units (AU)

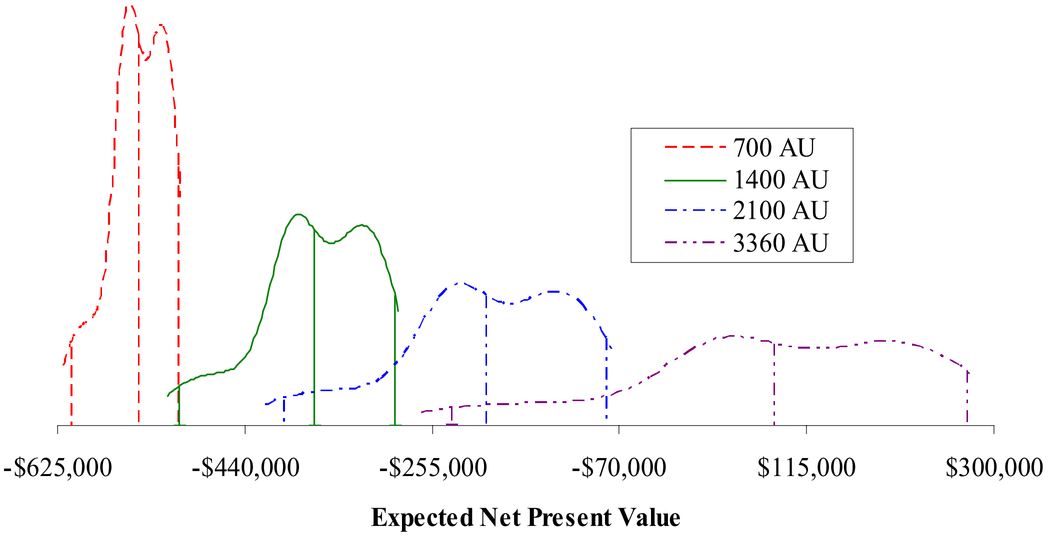

Figure 6.7. Probability Distribution Functions of Expected Net Present Value from the Anaerobic Digester Model by Varying Animal Units (AU)

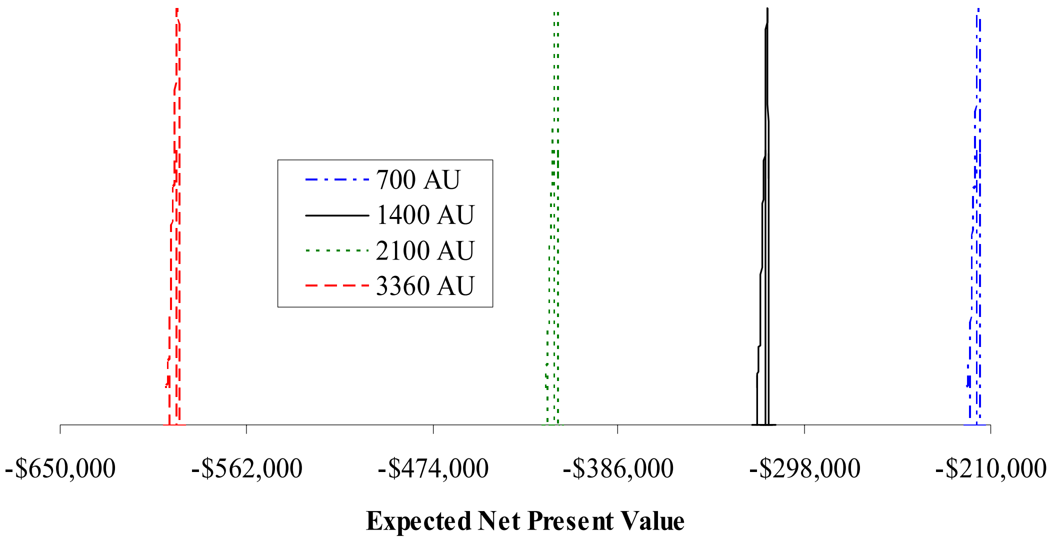

Figure 6.8. Probability Distribution Functions of Expected Net Present Value from the Standard Lagoon Model by Varying Animal Units (AU)

Electricity-Selling Price

The base scenario employs an electricity-selling price of $0.08/kWh, the reported price received in Texas. Three alternative electricity-selling prices are examined. One alternate selling price analyzed is $0.0421/kWh, which is the mean of the selling prices received by MN1, WA1, WI1, and WI2. A second selling price is $0.12/kWh, the price received in California. The third price scenario examines how much electricity revenues add to E(NPV) in the base scenario. In this scenario, selling price is $0.00/kWh, though the benefit of heat savings is still included.

E(NPV) of the AD model at $0.0421/kWh is -$584,121 with a 95% confidence interval of -$654,215 to -$542,506 (Table 6.1). The E(NPV) of the AD model at $0.12/kWh is -$145,653, with a 95% confidence interval of -$345,446 to -$27,036. At the prices of $0.0421/kWh and $0.12/kWh, the probability of obtaining a positive E(NPV) is zero. With no electricity revenues, the AD model becomes deterministic and the E(NPV) is -$821,805.

As expected, results show as selling price increases, E(NPV) increases. In addition, the distribution of E(NPV) shifts right (Figures 6.9 and 6.10). As selling price increases, the confidence intervals also widen in size, for the same reasons as the confidence intervals in the previous AU scenarios widened. There is overlap in the confidence intervals at $0.08/kWh and $0.12/kWh, but not between $0.0421/kWh and $0.08/kWh. To obtain an E(NPV) of zero, the electricity-selling price must be approximately $0.146/kWh. This selling price is approximately 82.5% higher than the current price of $0.08/kWh in Texas.

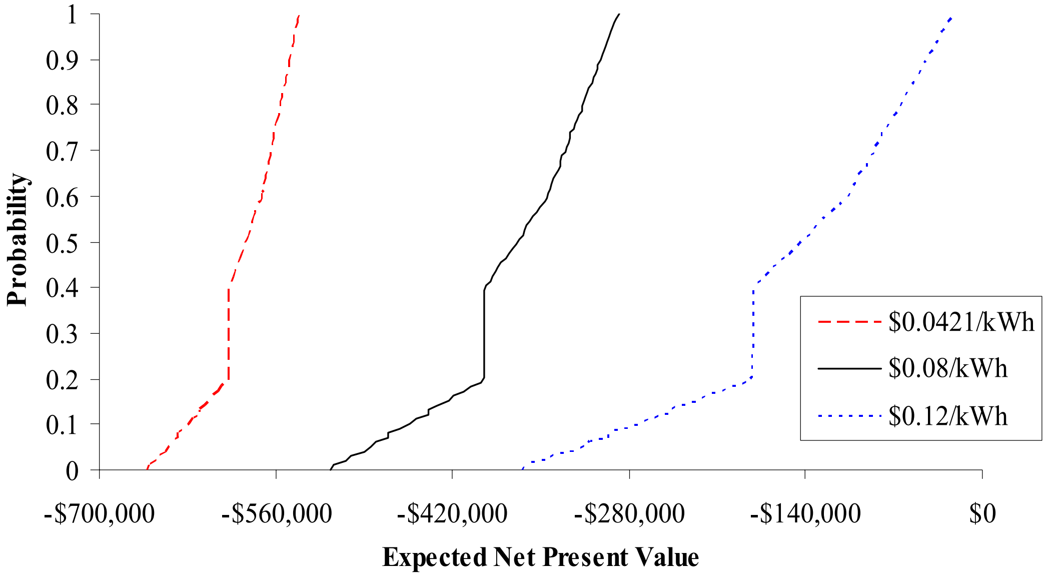

Figure 6.9. Cumulative Distribution Functions of Expected Net Present Value from the Anaerobic Digester Model by Varying Electricity-Selling Price ($/kWh)

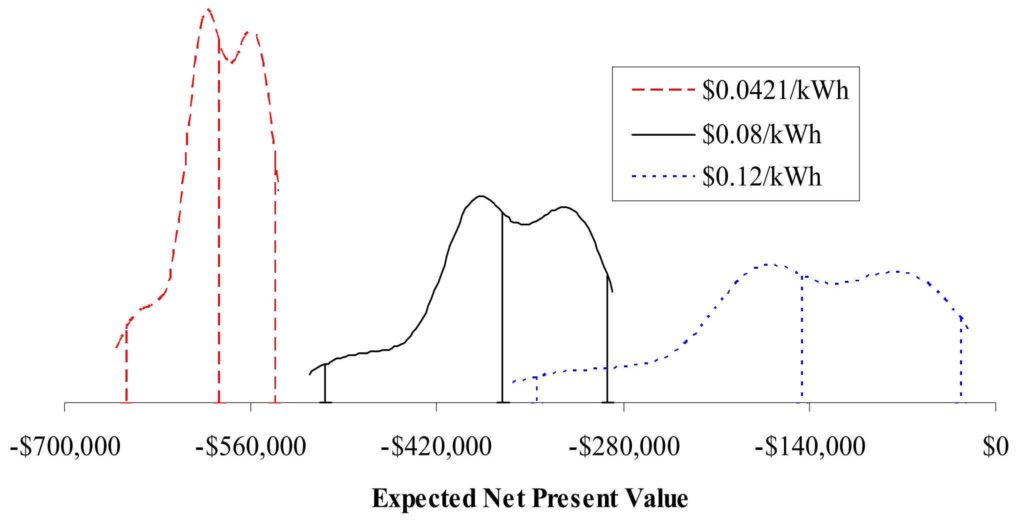

Figure 6.10. Probability Distribution Functions of Expected Net Present Value from the Anaerobic Digester Model by Varying Electricity-Selling Price ($/kWh)

Heat Savings

Potential savings on heating and propane expenses are included in the AD model's base scenario. Anaerobic digester owners may choose not to capture by-product heat and let it dissipate into the atmosphere. The base scenario of the AD model utilized average heat and propane savings. Scenarios examine the effect on E(NPV) of receiving zero, the minimum, and the maximum heat and propane savings per AU, as described in Chapter V.

The E(NPV) of the AD model with zero savings on heating and propane expenses is -$484,027 with a 95% confidence interval of -$617,222 to -$404,949 (Table 6.1). At the minimum amount of heat savings the E(NPV) is -$432,428 with a 95% confidence interval of -$565,623 to -$353,350, while at the maximum heat savings, E(NPV) is -$285,576 with a 95% confidence interval of -$418,771 to -$206,498. As in the base scenario, the probability of obtaining a positive E(NPV) is zero at the three levels of heat savings.

By capturing the by-product heat from the anaerobic digester for on-farm use, the E(NPV) of the digester increases. The shifts in the distributions of E(NPV) of the AD model with the various amounts of heat savings per AU are shown in Figure 6.11. PDF graphs of the results of the heat savings scenarios are presented in Figure 6.12.

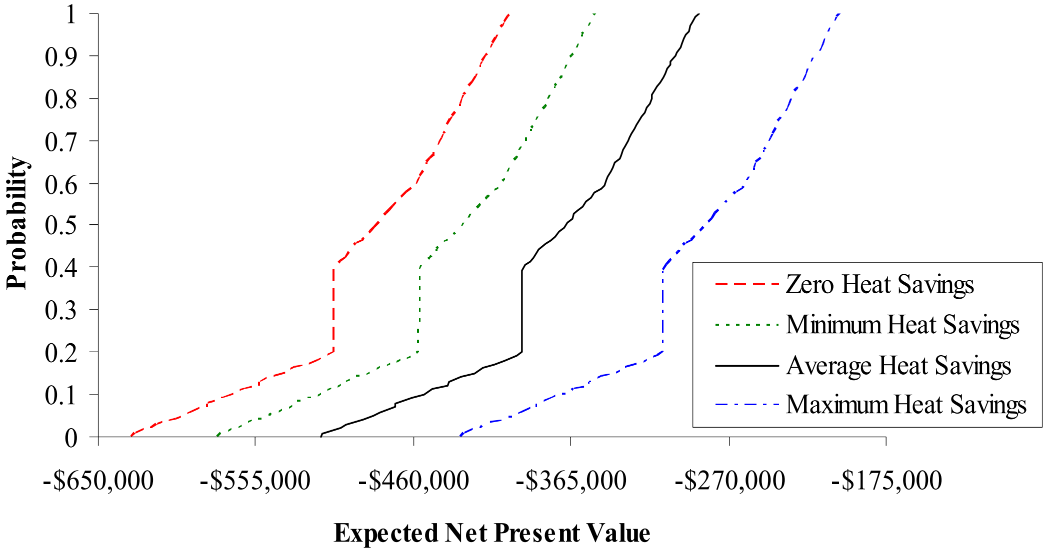

Figure 6.11. Cumulative Distribution Functions of Expected Net Present Value from the Anaerobic Digester Model with Differing Heat Savings

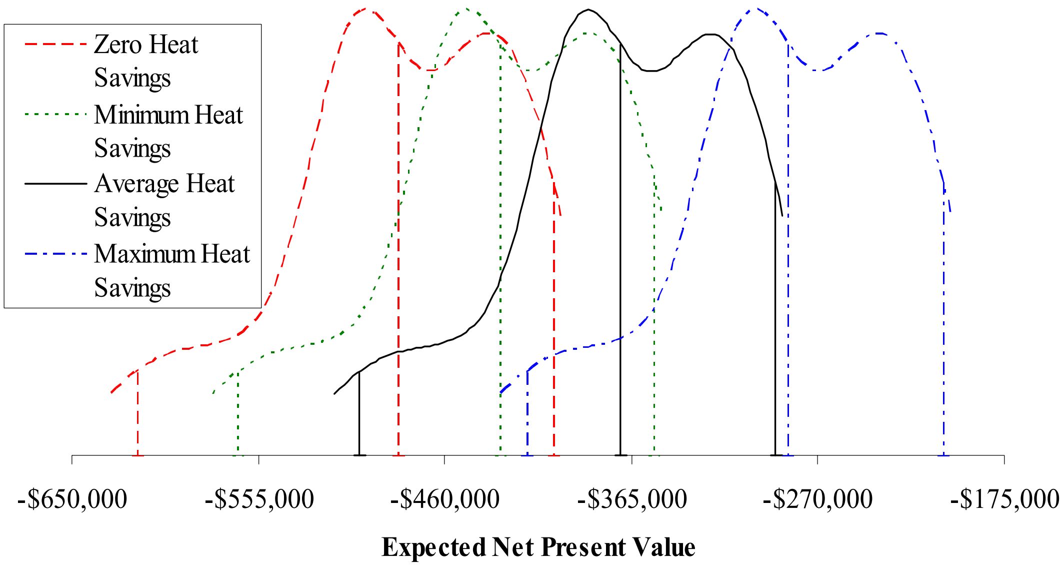

Figure 6.12. Probability Distribution Functions of Expected Net Present Value from the Anaerobic Digester Model with Differing Heat Savings

Fiber Sales

Fiber is assumed not to be sold in the base scenario of the AD model. An anaerobic digester owner, however, may be able to sell fiber. E(NPV) of the AD model with fiber sales included is -$221,179 with a 95% confidence of -$354,374 to -$142,101 (Table 6.1). Similar to the base scenario, the probability of a positive E(NPV) occurring is still zero. As expected, selling fiber increases E(NPV) in comparison to E(NPV) when fiber is not sold. The E(NPV) when fiber is sold is approximately 40% larger than the E(NPV) of the AD model or a difference of approximately $149,618. The shift in the CDF of E(NPV) of the AD model with and without fiber sales is shown in Figure 6.13. The PDFs of these results are presented in Figure 6.14.

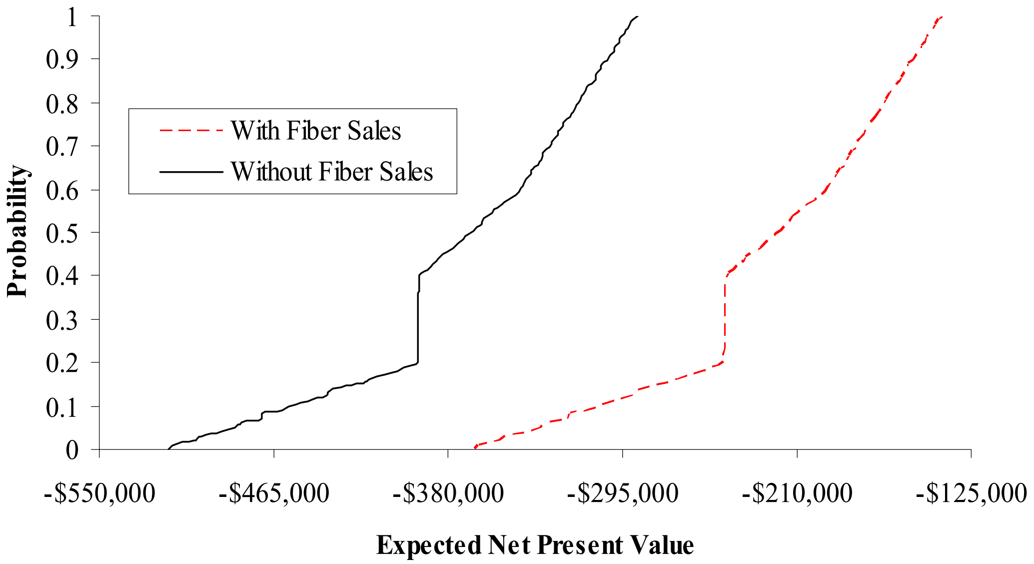

Figure 6.13. Cumulative Distribution Functions of Expected Net Present Value from the Anaerobic Digester Model with and without Fiber Sales

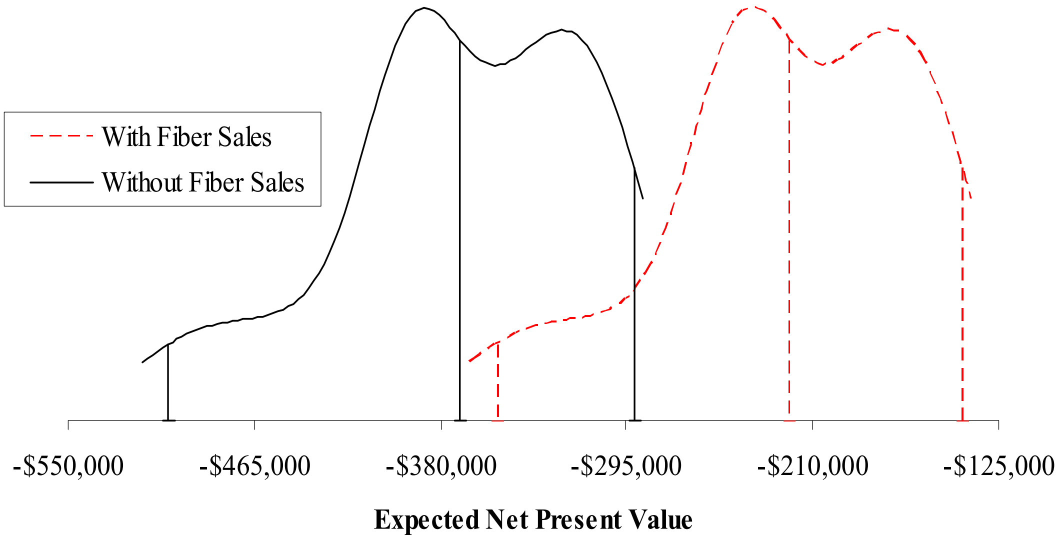

Figure 6.14. Probability Distribution Functions of Expected Net Present Value from the Anaerobic Digester Model with and without Fiber Sales

Grants/Subsidies

A scenario was developed to test the effects of receiving grants for the anaerobic digester. Grants were added for only the first two years of the 10-year budget in the AD model. E(NPV) was then simulated to determine what grant produces an E(NPV) of $0. A grant of $268,363 per year for the first two years or a total of $536,726 is necessary to obtain an E(NPV) of zero. The probability of obtaining a positive E(NPV) is 0.5043.

Financing Costs

Changes in financing costs are performed by changing the percentage of down payment on initial investment. By changing the down payment, financing costs also change. In the base scenario of both models, 20% of initial investment is the amount of the down payment on the digester. Sensitivity analysis examines the effect of changing the down payment percentage to 0%, 40%, 60%, 80%, and 100%.

E(NPV) for the base scenario of both models and the other four down payment percentages are given in Table 6.1 with CDF's given in Figures 6.15 and 6.16. The probability of a positive E(NPV) occurring is zero at all down payment levels in both models. As down payment increases, E(NPV) decreases, shown in the leftward shifts of the CDF curves in both models (Figures 6.15 and 6.16). E(NPV) decreases because the down payment increases the initial outlays by the owner of the anaerobic digester. Similar results are noted for a standard lagoon. Although financing costs are still incurred, they decrease as down payment increases relative to the initial outlays.

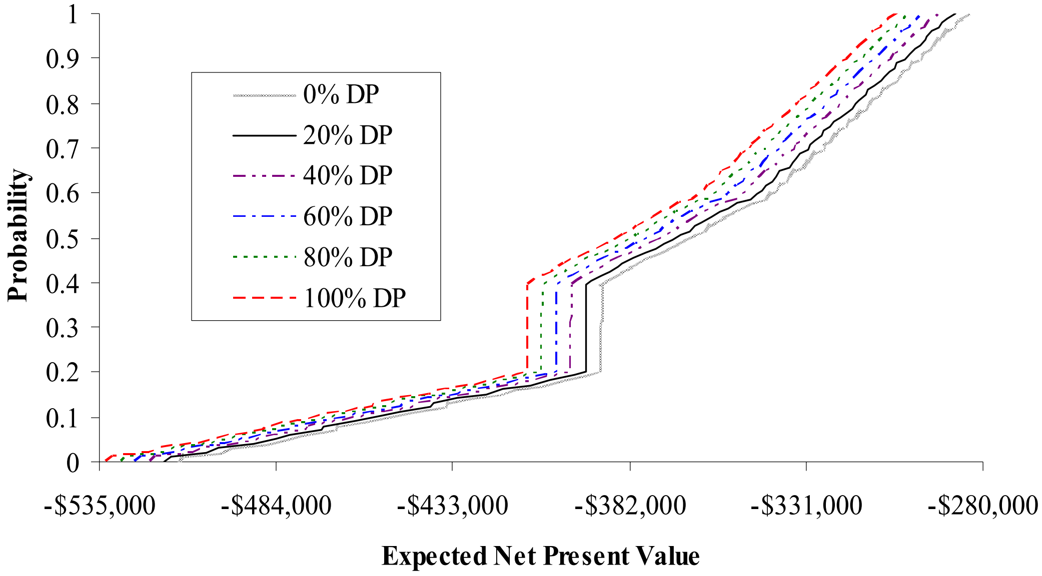

Figure 6.15. Cumulative Distribution Functions of Expected Net Present Value from the Anaerobic Digester Model by Varying Down Payment (DP)

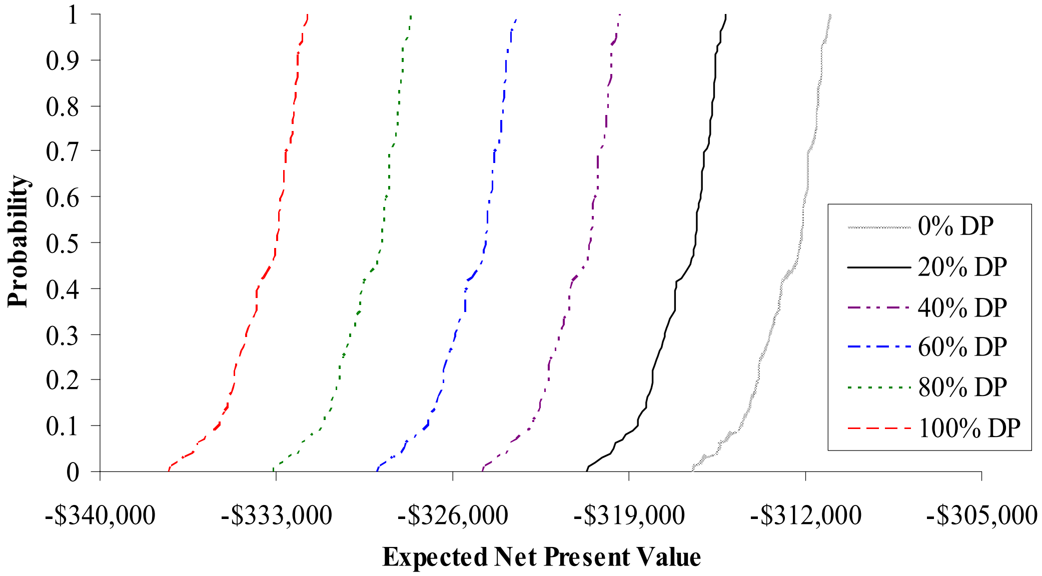

Figure 6.16. Cumulative Distribution Functions of Expected Net Present Value from the Standard Lagoon Model by Varying Down Payment (DP)

Discount Rate

The discount rate in the base scenario is 2.8%. This rate is adjusted to test its effects on E(NPV). Different discount rates examined are 4.5% as used by Schwart et al. and 7% as used by Lusk (1991). The E(NPV) in the AD model is -$351,751 at a discount rate of 4.5% and -$327,824 at a rate of 7% (Table 6.1). The E(NPV) in the SL model is -$293,060 at a discount rate of 4.5% and -$263,003 at 7% (Table 6.1). These results show that as discount rate increases the E(NPV) in both models increases.

Full AD Model

From the interviews, it is found that the most common rationale to construct an anaerobic digester was for revenue generation. A scenario was constructed to test the effects on E(NPV) in the AD model when revenues from electricity and fiber sales, maximum heat savings per AU, and the average grant are all included. This scenario is denoted as the full AD model. The E(NPV) is $16,842 with a 95% confidence interval of -$116,668 to $95,920 (Table 6.1). The probability of obtaining a positive E(NPV) is 0.57. A CDF and PDF of the results are presented in Figures 6.17 and 6.18. The CDF is similar to the base scenario of the AD model in that an S-shape is visible with a near vertical section. In addition, the PDF is similar to the base scenario of the AD model with both a bimodal appearance and skewed to the left.

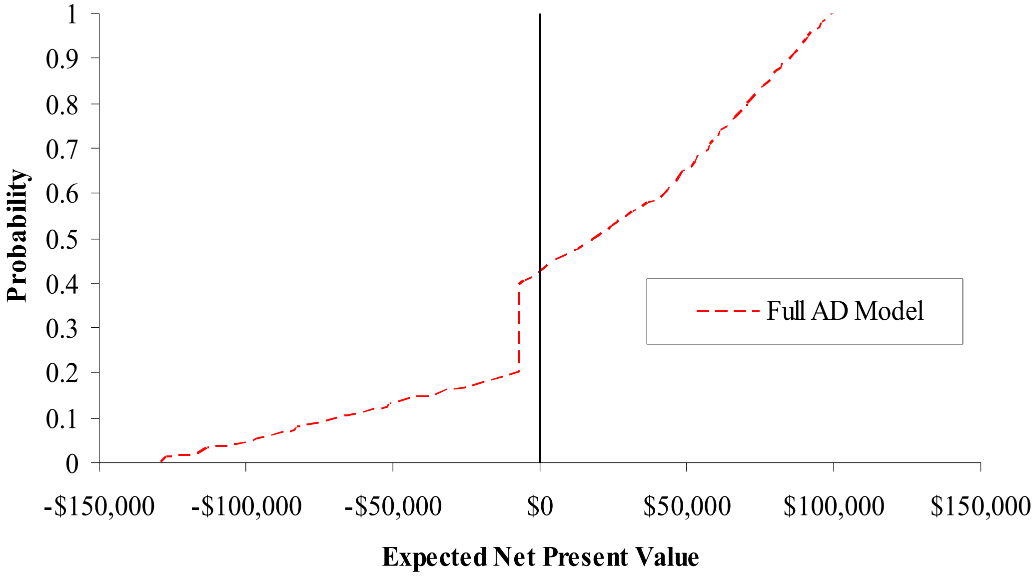

Figure 6.17. Cumulative Distribution Function of Expected Net Present Value from the Full Anaerobic Digester Model

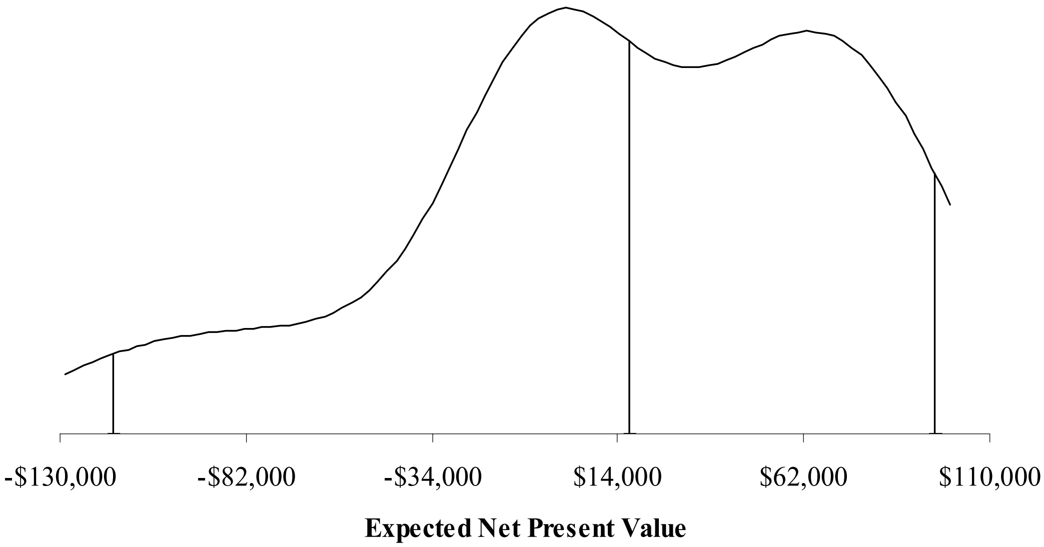

Figure 6.18. Probability Distribution Function of Expected Net Present Value from the Full Anaerobic Digester Model

Breakeven Electricity-Selling Price

This scenario determines at what electricity-selling price is E(NPV) the same for the AD and SL models. All other factors remain as they are in the base scenario. Recall, the E(NPV) of the base scenario of the AD model is -$370,797 and the E(NPV) of the SL model is -$316,913 (Table 6.1). For the two models to produce an equal E(NPV), the electricity-selling price must be increased from the price used in the base scenario. At an electricity-selling price of $0.0896/kWh, the E(NPV) between the models is equal; therefore, this price is the breakeven electricity-selling price.

With an electricity-selling price at the breakeven price or less, the lagoon is preferred to an anaerobic digester for dairy waste management. The breakeven electricity-selling price is approximately 12% greater than that of the current selling price in Texas of $0.08/kWh. However, this breakeven electricity-selling price will depend on AU level, heat savings, fiber sales, and grants/subsidies received.

Covered Lagoon Anaerobic Digesters

The base scenario of the AD model examined a dairy constructing a new plug-flow anaerobic digester for dairy waste management. This scenario examines the effect of operating a covered lagoon anaerobic digester. Recall, in equation (2) in Chapter V, a qualitative variable was used to distinguish between anaerobic digester types, with one representing a plug-flow digester and zero representing a covered lagoon digester. To perform this scenario, a zero is input into equation (2) for anaerobic digester type and E(NPV) is simulated. All other factors remain as they are in the base scenario.

The E(NPV) from this scenario is $158,898, with a 95% confidence interval of $25,702 to $237,976 (Figures 6.19 and 6.20). The E(NPV) from this scenario is greater than the base scenarios of both the AD and SL models. These results show that covered lagoon anaerobic digesters may be more feasible than plug-flow digesters as a dairy waste management strategy. Analysis shows that below the electricity-selling price of $0.0518/kWh, the E(NPV) of a covered lagoon anaerobic digester is negative. This electricity-selling price is approximately 35% lower than the current electricity-selling price in Texas. The covered lagoon anaerobic digester with zero electricity sales has a greater E(NPV) than that of a standard lagoon. Further analysis shows that the breakeven electricity-selling price between the covered lagoon and plug-flow anaerobic digester is $0.1741/kWh.

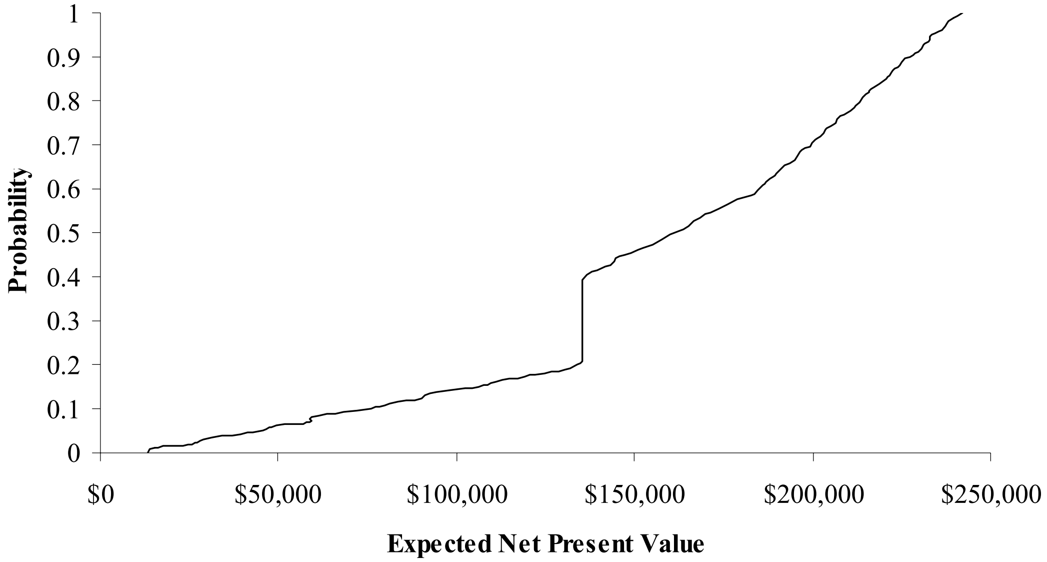

Figure 6.19. Cumulative Distribution Function of Expected Net Present Value of the AD Model Using a Covered Lagoon Anaerobic Digester

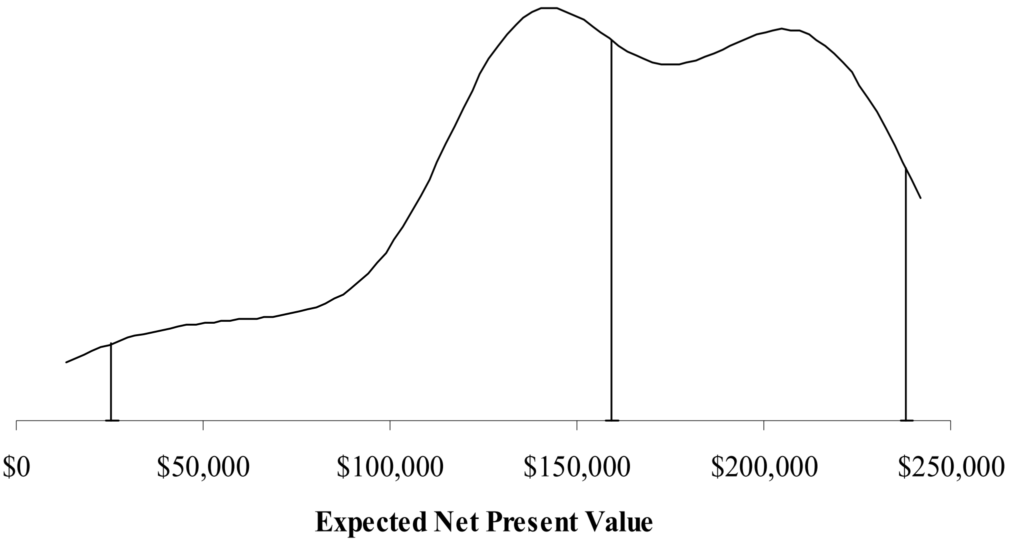

Figure 6.20. Probability Distribution Function of Expected Net Present Value of the AD Model Using a Covered Lagoon Anaerobic Digester

Operating Pre-existing Lagoons

All results up to this point examine new construction of either an anaerobic digester or a standard lagoon. Most dairies are currently operating with lagoons; therefore, this scenario examines the effect of operating a pre-existing lagoon using the AD model. In this scenario, initial investment and financing costs are sunk costs because the lagoon is already built and has no alternative use. The E(NPV) from this scenario is -$176,092. The pre-existing lagoon's E(NPV) is higher than the E(NPV) of a newly constructed anaerobic digester from the results of the base scenario of the AD model. This difference over ten years helps explain why dairies may not install new anaerobic digesters for waste management.

Summary

Empirical results show anaerobic digesters should not be utilized for waste management unless the dairy can capture the digester's revenue generating benefits. These benefits include selling electricity and fiber and capturing by-product heat to reduce propane and hot water expenses. Results from the sensitivity analysis show as the number of AU increases, the E(NPV) also increases, suggesting plug-flow anaerobic digesters may be more feasible on larger dairies. The electricity-selling price is critical to the economic feasibility of the anaerobic digester. Results show that the breakeven electricity-selling price is approximately 12% greater than the reported price currently received in Texas. Below the breakeven selling price, lagoons are preferable to plug-flow anaerobic digesters for waste management. Analysis also shows an electricity-selling price approximately 82.5% greater than the Texas selling price is required to obtain a positive E(NPV). Results also show that capturing the by-product heat from the conversion of biogas to electricity for dairy usage provides a cost savings and increases the E(NPV) of the plug-flow anaerobic digester.

Findings suggest covered lagoon anaerobic digesters are more feasible than lagoons for waste management. The E(NPV) of a covered lagoon anaerobic digester is greater than that of both a plug-flow digester and a lagoon. In addition, the E(NPV) of a covered lagoon anaerobic digester is greater than that of a lagoon with zero electricity sales. The breakeven electricity-selling price between a covered lagoon and plug-flow anaerobic digester is approximately 218% greater than the Texas selling price. Further, the E(NPV) of a pre-existing lagoon is greater than the E(NPV) from the base scenario of the AD model.

CHAPTER VII

CONCLUSIONS, IMPLICATIONS, LIMITATIONS, AND FURTHER RESEARCH

The findings of past research on the economic feasibility of anaerobic digestion technology are contradictory. Some studies concluded it to be too expensive for implementation in the U.S. because the technology is too inefficient and costly (Anderson; Parsons 1986; Engler et al.; Durand et al.; Lusk 1991). Other studies found anaerobic digestion technology to be economically viable. Coppinger, Baylon, and Lenart, for example, concluded that farmer owned and operated anaerobic digesters were cost effective if farmers finance the facility themselves. Fisher et al. found that anaerobic digesters were feasible for swine operations; however, they may be even more beneficial for dairy waste management.

Recent changes in institutional factors are changing the way anaerobic digesters are perceived. Critical changes include: 1) recognizing an anaerobic digester's environmental benefits; 2) improved digester efficiency; 3) new regulations including green electricity requirements and allowing for electricity generated by on-farm digesters to be sold to utilities; and 4) government and utility subsidization of digesters (Anderson; Welsh et al.; Persson et al.; Ernst et al.; Powers et al.; Lusk 1991; Legrand; Chynoweth, Owens, and Legrand; Maeng, Lund, and Hvelplund; Parsons 2004; U.S. EPA 2002; U.S. EPA 2004; Coppinger, Baylon, and Lenart; Raven; Center for Resource Solutions; *U.S. Water News Online*). One improvement in biogas generation efficiency is through increasing the anaerobic digester's operating temperature. Higher temperatures allow for increased biogas production and electricity generation (Wohlt et al.). One regulatory change is that state and federal governments have implemented new policies calling for the creation and usage of "green" energy, or electricity produced from renewable sources (Center for Resource Solutions). In addition, state and federal governments are investing millions of dollars in employing new technologies and approaches to help reduce livestock waste pollution without increasing the farmer's costs (*U.S. Water News Online*). Biomass, which includes anaerobic digestion technology, is considered a source of green energy (Center for Resource Solutions).

The objective of this research was to determine the economic implications of using anaerobic digesters for dairy waste management within the North Bosque River (NBR) watershed in Texas. Dairies in the NBR watershed face increasing pressure to manage livestock waste and maintain an "environmentally friendly" operation. A standard lagoon is the most common waste management system in the NBR watershed. Lagoons are open-air earthen pits that store livestock waste in liquid to semi-solid form to be used later as crop fertilizer and do not possess all the environmental benefits of an anaerobic digester.

Environmental benefits of anaerobic digestion technology include reducing air and water pollution from excess nutrients, harmful odors, greenhouse gases, flies, and health concerns associated with livestock waste. In addition, anaerobic digesters are designed to capture biogas produced by livestock waste and convert it to electricity, along with transforming the waste into fiber. Both the electricity and fiber can be sold for revenue. Given the environmental benefits and revenue potential of anaerobic digesters, the economic implications of this technology on Texas dairies are important.

The perspective of this study is that of an individual dairy owner. An individual owner would not be able to capture many of the environmental benefits that society would experience. The adoption of new technologies occurs at the individual level. For an individual to adopt new technology, they must realize positive net benefits. As such, the models developed for this study analyze dairy waste management at the individual level. Two models, an anaerobic digester (AD) model and a standard lagoon (SL) model, are constructed to compare the expected net present value, E(NPV), of the two types of waste management systems.

The base scenario of the AD model examines a plug-flow type digester servicing a 1,400 AU dairy where electricity is sold, by-product heat is captured to reduce heating expenses, fiber is not sold for revenue, and no grants are received. Reduced heating expenses are calculated using literature and are included in the base scenario as average heat savings per animal unit (AU). The SL model examines the costs of utilizing a lagoon for livestock waste management. A standard lagoon has little capacity to generate revenues. Sensitivity analysis is conducted on both models.

Conclusions

For a Texas dairy, installing a standard lagoon is preferred to a plug-flow anaerobic digester if no revenues from fiber and electricity sales are generated and cost savings on heating are not captured. A lagoon is preferred as plug-flow anaerobic digesters have additional costs associated with them and the individual would capture few environmental benefits. Dairies, however, have options available to improve the cash flow of plug-flow anaerobic digesters and cover the additional expenses associated with a digester. Options include selling electricity and capturing savings on hot water and propane expenses by using by-product heat from the plug-flow anaerobic digester. By generating these revenues and capturing the savings, the E(NPV) of the plug-flow anaerobic digester still does not exceed that of a standard lagoon. An additional revenue option for dairies is selling fiber produced by the anaerobic digester. Selling fiber increases the E(NPV) of a plug-flow anaerobic digester to above that for a standard lagoon. Plug-flow anaerobic digesters are a potentially economic feasible choice for dairy waste management. Further, as expected, subsidization of plug-flow anaerobic digesters increases the economic feasibility to the individual owner.

Although environmental benefits are not captured in both models, the models do account for environmental cash costs dairy owners may incur. The SL model includes potential fines associated with non-compliance for waste management in the NBR watershed. Anaerobic digesters, in general, do not incur these fines. Considering potential fines increases the economic feasibility of anaerobic digesters relative to standard lagoons.

Sensitivity analysis was conducted by varying key variables in both models to determine their effect on E(NPV). Results suggest larger dairies, as represented by increasing AU levels in both models, stand the best chance of obtaining a positive E(NPV) from a plug-flow anaerobic digester. Even though initial costs and expenses adjust accordingly, larger AU levels result in increased biogas production and electrical generation, and therefore, increased potential electricity revenues and heat savings. These results support the conclusions of Mehta, who found larger dairies could earn profits from electricity sales from anaerobic digester operations.

Constructing and operating a plug-flow anaerobic digester requires a large input of capital from the dairy operation. Anderson noted if fixed costs could be lowered, an anaerobic digester's profitability could increase. An option to lower the individual owner's fixed costs is to provide grants and/or subsidies for the construction of the plug-flow anaerobic digester. European nations, such as the Netherlands, have subsidized anaerobic digestion technology as a way to increase renewable energy sources (Parsons 1986; Maeng, Lund, and Hvelplund; Raven). Although the anaerobic digester's costs, from society's viewpoint are the same if a grant is received, to the individual these costs decrease. By including the revenue generating and cost saving variables, in addition to receiving a grant or subsidy, the E(NPV) of a plug-flow anaerobic digester may become positive. Society may want to subsidize anaerobic digester construction because many benefits are external to the dairy.

A dairy could construct and operate a covered lagoon anaerobic digester instead of using a plug-flow digester. Covered lagoon anaerobic digesters function well in warm climates such as the NBR watershed, are a common digester type used on dairies, and have some of the same environmental benefits as plug-flow digesters (U.S. EPA 2004). In addition, covered lagoon anaerobic digesters require a lower input of capital than that required for a plug-flow digester. Findings show that the E(NPV) of a covered lagoon anaerobic digester is greater than that of both a standard lagoon and a plug-flow digester. These results suggest covered lagoon anaerobic digesters are a feasible dairy waste management strategy.

Both models are designed for the construction and operation of a new plug-flow anaerobic digester or lagoon for dairy waste management. However, there are dairies that are currently using a pre-existing lagoon for waste management. The E(NPV) of a pre-existing lagoon is little over double the E(NPV) of the anaerobic digester in the base scenario of the AD model. Given this finding, a grant or subsidy would be necessary for the base scenario anaerobic digester to have a greater E(NPV) than the pre-existing lagoon.

At the current electricity-selling price in Texas of $0.08/kWh, a lagoon would be preferred to a plug-flow anaerobic digester for dairy waste management. At this price, the E(NPV) of the lagoon exceeds the E(NPV) of the anaerobic digester. The Texas electricity-selling price is less than both the breakeven price of $0.0896/kWh and the price of $0.146/kWh necessary to produce a positive E(NPV). At the Texas electricity-selling price, using covered lagoon anaerobic digesters would generate a positive E(NPV).

Adjusting financing costs on a plug-flow anaerobic digester is examined by varying the percentage of down payment. As down payment rate increases, the E(NPV) of the anaerobic digester and a lagoon decreases. Between the option of zero down payment and 100% down payment, the difference in E(NPV) of an anaerobic digester is approximately 5.4%. The difference in E(NPV) of a lagoon between zero and 100% down payment is approximately 6.2%.

At the current electricity-selling price, a covered lagoon anaerobic digester would be preferred to both a plug-flow digester and a lagoon for dairy waste management. The electricity-selling price necessary for the plug-flow anaerobic digester to breakeven with a covered lagoon digester is $0.1741/kWh. In addition, if a dairy operates a covered lagoon anaerobic digester, but chooses not to sell electricity, the E(NPV) from the digester exceeds that of a lagoon.

Implications for the North Bosque River Watershed

A plug-flow anaerobic digester has a negative E(NPV), even with selling electricity and the heating expense savings. At the current electricity-selling price in Texas, the E(NPV) of constructing and operating a plug-flow anaerobic digester is less than that of constructing a lagoon. This implies plug-flow anaerobic digesters are not a feasible livestock waste management strategy than lagoons for new dairy operations. However, if the dairy can maximize the savings they receive on hot water and propane expenses by capturing the by-product heat from the anaerobic digester, and sell fiber, the E(NPV) of the plug-flow anaerobic digester increases. This finding suggests the plug-flow anaerobic digester would be preferred to the lagoon for waste management (Table 6.1).

The E(NPV) of a covered lagoon anaerobic digester is greater than the E(NPV) of both a plug-flow digester and a lagoon. This result suggests that it may be more economically feasible for a dairy in the NBR watershed to construct and operate a covered lagoon anaerobic digester than a plug-flow digester or a lagoon. Given that the E(NPV) of a covered lagoon anaerobic digester exceeds that of a lagoon, subsidization would not be required to aid in the construction and operation of covered lagoon digesters for waste management.

For dairies, the E(NPV) of their pre-existing lagoon exceeds the E(NPV) of a plug-flow anaerobic digester. As of December 2004, there were 120 dairies in the NBR watershed (Table C.1). From the results, for dairies to convert a pre-existing lagoon to an anaerobic digester, subsidization is required. Recall, the base scenario of the AD model is a plug-flow type anaerobic digester. It may be more economically feasible for a dairy in the NBR watershed to take their pre-existing lagoon and convert it to a covered lagoon type anaerobic digester.

One option that could possibly be employed in the NBR watershed is based on one of the anaerobic digesters interviewed, CA6. CA6 is an anaerobic digester owned and operated by a utility located in a region of southern California home to several dairies (Table 4.1). CA6 services the dairies within their region for waste management. Livestock waste is transported to the facility and treated in the plug-flow anaerobic digester. Electricity generated is distributed and sold to local consumers with by-product heat used by a nearby water desalinization plant.

Combining CA6’s business plan with the result that larger facilities are more profitable, it is reasonable to recommend the study of the construction and operation of a plug-flow anaerobic digester facility in a central location in the NBR watershed. Such an anaerobic digester would have waste transported from the dairies in the watershed to the facility for treatment. The positive environmental benefits of an anaerobic digester would be realized for the watershed.

The City of Waco has already taken a stand in an effort to help keep their public water supply clean through litigation with several dairies upstream (Shlachter). The City of Waco has incurred legal costs associated in their lawsuits with the upstream dairies. Implementing and using an anaerobic digester to treat dairy waste may allow for the reduction in associated air and water pollution that the city is fighting for. The City of Waco may want to investigate paying out the grants required to support anaerobic digesters in place of the costs associated with their legal efforts. The costs to the city in subsidizing anaerobic digestion technology may be much cheaper than the costs of litigation, especially if it is with all 120 dairies.

Another alternative is the City of Waco supports anaerobic digester implementation through sponsorship and promotion of the technology for the upstream dairies in the NBR watershed. Through increased knowledge of anaerobic digesters, there may be an increase in the rate of adoption of the technology. Over time, society would benefit from the reduced air and water pollution associated with dairy waste. In addition, the dairies in the NBR watershed would benefit from a potential additional revenue source and remaining in compliance with local, state, and federal environmental regulations.

Limitations

There are data limitations to be noted. Because of time and expense constraints, only eleven anaerobic digester facilities currently in operation were interviewed for data collection. The facilities interviewed comprise only a small portion of the total anaerobic digester facilities in the U.S. Anaerobic digester facilities exist in various parts of the country outside the regions visited for this research. There were 19 anaerobic digesters in the Great Lakes region alone in the fall of 2002 (Kramer). It was estimated at least 40 anaerobic digesters were in operation in 2003, with another 30 in the planning stages (U.S. EPA 2004). In addition, there were gaps in the data, especially in regards to labor, heating expenses, fiber revenues, and costs of waste loading, transport, and land application. Due to the gaps in the data, the literature is used to help quantify these variables.

The E(NPV) calculated by both models represents the returns to management and land. The amount of time required to manage the anaerobic digester exceeds that of a lagoon. The time an owner spends in managing the anaerobic digester is not quantified in this study. Management time necessary may help explain why few anaerobic digesters are currently being used. This time may be better spent elsewhere on the dairy.

In this study, the environmental benefits of anaerobic digesters are discussed at the societal level. However, the models approached the feasibility of anaerobic digesters from the individual's perspective. There is a limitation in that environmental benefits to the individual were not quantified.

Further Research

Both the AD and SL models each had one stochastic variable. Inclusion of more risk components will most likely increase the confidence intervals of E(NPV). Further study on the risk components is necessary.

An opportunity to expand on this study exists in quantifying the environmental benefits associated with utilizing anaerobic digesters. Recall, some Ohio residents noted increases in medical issues and expenses due to their proximity to the open-air lagoons storing livestock waste from a confined hog operation (Lee). The Ohio residents' beliefs have never been scientifically correlated to the hog lagoons. However, one study attempted to quantify the benefits of reduced air and water pollution on human health and the environment. Herriges, Secchi, and Babcock indirectly measured these benefits and costs in terms of housing property values in relation to the property's proximity to livestock operations. As the property's distance from the livestock operation increased, so did its value (Herriges, Secchi, and Babcock). As environmental benefit variables are quantified, this only serves to enhance the economic feasibility of anaerobic digestion technology.

Another prospect for further research is to examine the interaction of a dairy with an anaerobic digester and the utility in terms of contracts. For example, a dairy may know at what price level electricity must be sold at to earn a profit. Then the dairy can negotiate a contract for this selling price as a guaranteed selling price with a utility. In addition, time spent by an anaerobic digester owner managing the contract and all relations with the utility could be measured. In addition, dairies with an anaerobic digester that is selling electricity are considered an independent power producer (IPP) (*The Wall Street Transcripts*). The interaction of the dairy as an IPP and the utility, in terms of contracts, could be studied, similar to the study of IPP-Utility interactions by Geerli, Niioka, and Yokoyama. Issues of asymmetric information, asymmetric negotiation costs, and a changing regulatory environment provide an excellent chance to use and advance contract theory.

An additional aspect for further research is the societal impact of anaerobic digesters in their function as a renewable energy source. However, the benefits from the electricity produced by an anaerobic digester are only realized if they reduce the electricity generated from non-renewable sources. European studies, especially Maeng et al. and Raven, show a possible positive socioeconomic benefit of anaerobic digesters is that they reduce dependence on non-renewable energy sources, such as coal and oil. The U.S. is just now in the first stages of adoption and subsidization of anaerobic digestion technology. Given time and further subsidization, multiple anaerobic digesters may have an impact on society through their environmental benefits and provisions of renewable energy.

REFERENCES

Adhikari, M., K.P. Paudel, N.R. Martin Jr., and W.M. Gauthier. "Economics of Dairy Waste Use as a Fertilizer in Central Texas." *Waste Management* 25(2005): 1069-1074.

Anderson, J.L. "Economic Assessment of Anaerobic Digestion Systems for Dairy Waste Disposal and Energy Recovery: Effect of Selected Institutional and Technological Changes." *Energy and Conservation* 8(1982): 131-146.

Barry, P., P. Ellinger, J. Hopkin, and C. Baker. *Financial Management in Agriculture*, Sixth Edition, Danville, IL: Interstate Publishers, Inc. 2000.

Biogas Works. "Introduction to Anaerobic Digestion." 2000. Available at: http://www.biogasworks.com/Index.

Center for Resource Solutions. 2005. "Green-E: Renewable Electricity Certification Program." Available at: http://www.green-e.org.

Centner, T.J. "Evolving Policies to Regulate Pollution from Animal Feeding Operations." *Environmental Management* 28(2001): 599-609.

Chandrasena, R.I.I. "The Cost of Agriculturally Based Greenhouse Gas Offsets in the Texas High Plains." MS Thesis, Texas A&M University, December 2003.

Chynoweth, D.P., C.E. Turick, J.M. Owens, and D.E. Jerger. "Biochemical Methane Potential of Biomass and Waste Feedstocks." *Biomass and Bioenergy* 5(1993): 95-111.

Chynoweth, D.P., J.M. Owens, and R. Legrand. "Renewable Methane from Anaerobic Digestion of Biomass." *Renewable Energy* 22(2001): 1-8.

Coggins, M. "Byl Dairy Reaches Settlement with Waco." *Stephenville Empire-Tribune*, 23 September 2004. Available at: http://www.empiretribune.com/.

Coppinger, E., D. Baylon, and J. Lenart. "Economic and Operational Experience of Full-scale Anaerobic Dairy Manure Digester." *Biogas and Alcohol Fuels Production*, J. Golstein, ed., pp. 220-233. Emmaus, PA: The JG Press, 1980.

Correll, D.L. "The Role of Phosphorus in the Eutrophication of Receiving Waters: A Review." *Journal of Environmental Quality* 27(1998): 261-266.

Datta, P.S., D.L. Deb, and S.K. Tyagi. "Assessment of Ground Water Contamination from Fertilizers in the Delhi Area based on ^{18}O, NO$^{-}_{3}$, and K^{+} Composition." *Journal of Contaminant Hydrology* 27(1997): 249-262.

Duncan, A.R. "Probability of Economic Success for Netherlands Dairy Farmers Moving Operations to the United States." MS Thesis, Texas A&M University, 2004.

Durand, J.H., J.R. Fischer, E.L. Ianotti, and J.B. Miles. "Development of an Economic System Model to Optimize the Performance of a Swine Waste Digestion System." *Biomass* 14(1987): 219-244.

Edwards, A.C., H. Twist, and G.A. Codd. "Assessing the Impact of Terrestrially Derived Phosphorus on Flowing Water Systems." *Journal of Environmental Quality* 29(2000): 117-124.

Engler, C.R., E.R. Jordan, M.J. McFarland, and R.D. Lacewell. "Economics and Environmental Impact of Biogas Production as a Manure Management Strategy." Presented to Southwestern Economics Association, Corpus Christi, TX, March 1998.

Ernst, M., J. Rodecker, E. Luvaga, T. Alexander, and J. Miranowski. "Viability of Methane Production by Anaerobic Digestion on Iowa Swine Farms." 1999 Swine Research Report, ASLR1693, Department of Economics, Iowa State University: Ames, IA, January 2000.

Filip, D.S. and E.J. Middlebrooks. "Eutrophication Potential of Dairy Cattle Waste Runoff." *Water Research* 10(1976): 89-93.

Fischer, J.R., D.D. Osburn, N.F. Meador, and C.D. Fulhage. "Economics of a Swine Manure Anaerobic Digester." *Transactions of the American Society of Agricultural Engineers* 24(1981): 1306-1310.

Fisher, D.S., J.L. Steiner, D.M. Endale, J.A. Stuedemann, H.H. Schomberg, A.J. Franzluebbers, and S.R. Wilkinson. "The Relationship of Land Use Practices to Surface Water Quality in the Upper Oconee Watershed of Georgia." *Forest Ecology and Management* 128(2000): 39-48.

Fleming, R.A., B.A. Babcock, and E. Wang. "Resource or Waste? The Economics of Swine Manure Storage and Management." *Review of Agricultural Economics* 20(1998): 96-113.

Fulhage, C, D. Sievers, and J. Fischer. "Generating Methane Gas from Manure." Fact Sheet G1881, University of Missouri Extension, Columbia, MO, October 1993.

Galloway, J.N. and E.B. Cowling. “Reactive Nitrogen and the World: 200 Years of Change.” *AMBIO: A Journal of the Human Environment* 31(2002): 64-71.

Geerli, S. Niioka, and R. Yokoyama. “Electricity Pricing and Load Dispatching in Deregulated Electricity Market.” *International Journal of Electrical Power & Energy Systems* 25(2003): 491-498.

GHD, Inc. 2005. “Basic Anaerobic Digester System Diagram.” Available at: http://www.ghdinc.net/products.aspx.

Hansel, J. “Manure In, Energy Out: Plug-Flow Digesters Becoming More Popular.” *Lincoln Journal Star*, 25 August 1999. Available at: http://www.biogasworks.com/News/Plug-Flow%20Digesters.htm.

Hansen, R. W. "Methane Generation from Livestock Wastes.” Farm & Ranch Series: Equipment # 5.002*,* Colorado State University Cooperative Extension, Fort Collins, CO, January 2003.

Herriges, J., S. Secchi, and B.A. Babcock. “Living with Hogs in Iowa: The Impact of Livestock Facilities on Rural Residential Property Values.” Center for Rural Development, Iowa State University, Ames, IA, August 2003.

Hopey, D. “Hog Heaven? Study Finds Large Hog Farms Lower Property Values.” *Pittsburgh Post-Gazette*, 7 June 2003. Available at: http://www.post-gazette.com/pg/03158/189643.stm.

Hudak, P.F. “Regional Trends in Nitrate Content of Texas Ground Water.” *Journal of Hydrology* 228(2000): 37-47.

Hudak, P.F. and S. Blanchard. “Land Use and Ground Water Quality in the Trinity Group Outcrop of North-Central Texas.” *Environment International* 23(1997): 507-517.

Innes, R. “The Economics of Livestock Waste and Its Regulation.” *American Journal of Agricultural Economics* 82(2000): 97-117.

Jones, D, J. Nye, and A. Dale. “Methane Generation from Livestock Waste.” Purdue University Cooperative Extension, West Lafayette, IN, September 1980.

King, T. “At a Minnesota Dairy, Holsteins Are in the Energy Business.” *Christian Science Monitor*, 21 November 2002. Available at: http://www.csmonitor.com/2002/1121/p17s01-sten.html.

Kramer, J. *Agricultural Biogas Casebook Prepared for Great Lakes Regional Biomass Energy Program, Council of Great Lakes Governors***.** Resource Strategies, Inc., Madison, WI, September 2002.

Krapac, I.G., W.S. Dey, W.R. Roy, C.A. Smyth, E. Storment, S.L. Sargent, and J.D. Steele. "Impacts of Swine Manure Pits on Groundwater Quality." *Environmental Pollution* 120(2002): 475-492.

Leatham, D.J., J.F. Schmucker, R.D. Lacewell, R.B. Schwart, A.C. Lovell, and G. Allen. "Impact of Texas Water Quality Laws on Dairy Income and Viability." *Journal of Dairy Science* 75(1992): 2846-2856.

Lee, J. "Neighbors of Vast Hog Farms Say Foul Air Endangers Their Health." *New York Times*, 8 May 2003. Available at: http://www.nytimes.com/2003/05/11/health/11HOGS.html.

Legrand, R. "Methane from Biomass Systems Analysis and CO_2 Abatement Potential." *Biomass and Bioenergy* 5(1993): 301-316.

Letson, D., and N. Gollehon. "Confined Animal Production and the Manure Problem." *Choices* 11(1996):18-22.

Lusk, P.D. *Anaerobic Digestion of Livestock Manures: A Current Opportunities Casebook*. Washington DC: U.S. Department Of Energy, Regional Biomass Energy Program, August 1995.

Lusk, P.D. "Comparative Economic Analysis: Anaerobic Digester Case Study." *Bioresource Technology* 36(1991): 223-228.

Maeng, H., H. Lund, and F. Hvelplund. "Biogas Plants in Denmark: Technological and Economic Developments." *Applied Energy* 64(1999): 195-206.

Marsh M.L.H. and T. LaMendola. "PIER Report: Dairy Power Production Program Dairy Methane Digester System 90-Day Evaluation Report, Blakes Landing Dairy (Straus)." Western United Resource Development, Inc., Modesto, CA, October 2004.

Masud, S.M., R.D. Lacewell, B. Schwart, G. Allen, and A. Lovell. "Feasibility of Large Scale Alternatives for Dairy Waste Recycling and Treatment: Erath County Region of Texas." Texas Agricultural Experiment Station, College Station, TX, October 1991.

Mattucks, R.P. and M.A. Moser. 2005. “Anaerobic Digesters at Dairies in Cold Climates.” Available at: http://64.225.36.90/images/PDF/RCMColdClimateDigesters062503.pdf.

Mehta, A. “The Economics and Feasibility of Electricity Generation Using Manure Digesters on Small and Mid-size Dairy Farms.” Department of Agricultural and Applied Economics, University of Wisconsin-Madison, 2002.

Metcalfe, M. “State Legislation Regulating Animal Manure Management.” *Review of Agricultural Economics* 22(2000): 519-532.

Midwest Plan Service. *Livestock Waste Facilities Handbook*. Ames, IA: Midwest Plan Service, Iowa State University, 1985.

Miner, J.R., F.J. Humenik, and M.R. Overcash. *Managing Livestock Wastes to Preserve Environmental Quality*. Ames, IA: Iowa State University Press, 2000.

Morse, D. “Impact of Environmental Regulations on Cattle Production.” *Journal of Animal Science* 74(1996): 3103-3111.

Mukhtar, S. Personal communication. September 12, 2005.

National Research Council of the National Academies. *Air Emissions from Animal Feeding Operations: Current Knowledge, Future Needs*. Washington DC: National Academies Press, 2003.

Nolan, B.T., B.C. Ruddy, K.J. Hitt, and D.R. Helsel. “Risk of Nitrate in Ground Waters of the United States—A National Perspective.” *Environmental Science & Technology* 31(1997): 2229-2236.

Oenema, O., P.C.M. Boers, M.M. van Eerdt, B. Fraters, H.G. van der Meer, C.W.J. Roest, J.J. Schroder, and W.J. Willems. “Leaching of Nitrate from Agriculture to Ground Water: The Effect of Policies and Measures in the Netherlands.” *Environmental Pollution* 102(1998): 471-478.

Osei, E., P.W. Gassman, R.D Jones, S.J. Pratt, L.M. Hauck, L.J. Beran, W.D. Rosenthal, and J.R. Williams. “Economic and Environmental Impacts of Alternative Practices on Dairy Farms in an Agricultural Watershed.” *Journal of Soil and Water Conservation* 55(2000): 466-472.

Parker, D. “Controlling Agricultural Nonpoint Water Pollution: Costs of Implementing the Maryland Water Quality Improvement Act of 1998.” *Agricultural Economics* 24(2000): 23-31.

Parsons, C. “Cows Put Out the Power.” *Western Dairy Business*, 14 August 2004, 12-18.

Parsons, D.J. “The Economics of the Treatment of Dairy Cow Slurry by Anaerobic Digestion.” *Journal of Agricultural Engineering Research* 35(1986): 259-276.

Peebles, R.W. and D.J. Reinemann. “Demand-side Management/Energy Conservation Potential for Wisconsin Dairy Farms.” Paper presented at the International Winter Meeting of the American Society of Agricultural Engineers, Atlanta GA, December 1994.

Persson, S.P.E., H.D. Bartlett, A.E. Branding, and R.W. Regan. “Agricultural Anaerobic Digesters: Design and Operation.” College of Agriculture Agricultural Experiment Station, Bulletin 827, Pennsylvania State University: State College, PA, November 1979.

Powers, W.J., H.H. Van Horn, A.C. Wilkie, C.J. Wilcox, and R.A. Nordstedt. “Effects of Anaerobic Digestion and Additives to Effluent or Cattle Feed on Odor and Odorant Concentrations.” *Journal of Animal Science* 77(1999): 1412-1421.

Raven, R.P.J.M. “Implementation of Manure Digestion and Co-combustion in the Dutch Electricity Regime: A Multi-level Analysis of Market Implementation in the Netherlands.” *Energy Policy* 32(2004): 29-39.

Rejesus, R.M. and R.H. Hornbaker. “Economic and Environmental Evaluation of Alternative Pollution-Reducing Nitrogen Management Practices in Central Illinois.” *Agriculture, Ecosystems, and Environment* 75(1999): 41-53.

Richardson, J.W. *Simulation for Applied Risk Management with an Introduction to the Excel Simulation Add-In: Simetar©*. College Station TX: Texas A&M University, Department of Agricultural Economics, 2004.

Rivard, C. and D. Boone. “The Anaerobic Digestion Process.” *Second Biomass Conference of the Americas; August 21-24, 1995, Portland Oregon*. Golden CO: National Renewable Energy Laboratory, 1995, pp. 785-790.

Rodecap, J. “Phosphorus, Algae in Water, Human Health Linked.” *Water Watch*, Iowa State University Extension Bulletin, No. 86, June 2000.

Sahr, R. “Inflation Conversion Factors for Dollars 1665 to 2015.” 2005. Available at: http://oregonstate.edu/dept/pol_sci/fac/sahr/sahr.htm.

Schmitt, M. and G. Rehm. “Fertilizing Cropland with Swine Manure.” 2002. Available at: http://www.extension.umn.edu/distribution/cropsystems/DC5879.html.

Schwart, R., R. Jackson, B. Herbst, R. Whitney, R. Lacewell, and J. Mjelde. "Methane Generation: Final Report to the State Energy Conservation Office." Department of Agricultural Economics, Texas A&M University, June 30, 2005.

Sharpley, A.N., T. Daniel, T. Sims, J. Lemunyon, R. Stevens, and R. Parry. "Agricultural Phosphorous and Eutrophication." United States Department of Agriculture, Agricultural Research Service, ARS-149, 1999.

Shlachter, B. "Manure Dispute Lands in Waco Judge's Hands." *Fort Worth Star-Telegram*, 30 January 2005. Available at: http://www.dfw.com/mld/startelegram.

Smith, R. "Burdensome Rules, Misunderstanding Threaten Erath County Dairy Industry." *Farm Press*, 18 November 2004. Available at: http://www.keepmedia.com/pubs/SouthwestFarmPress/2004/11/18/652901?extID=10026.

Stewart, D.J. "Energy Crops to Methane." Paper presented at the First International Symposium on Anaerobic Digestion, University College, Cardiff, Wales, England, September 1979.

Stirling Power, LLC. 2005. "Turning Waste into Power." Available at: http://www.iinet.com/~grott/index.htm.

Texas Commission on Environmental Quality (TCEQ). 2005. Available at: http://www.tceq.state.tx.us/.

Texas Dairy Review. 2004. "Milk Agencies to Aid Dairies in Waco Suit." Available at: http://www.texasdairy.com.

Toxic Texas. 2004. "Erath County's Booming Dairy Industry Pollutes Texas' Waterways." Available at: http://www.txpeer.org/toxictour/erath.html.

United States Department of Agriculture, Agricultural Marketing Service, Dairy Programs. 2005. "Federal Order 126: Monthly Milk Marketing Data (TXT)." Available at: http://www.dallasma.com/mcd26.html.

United States Environmental Protection Agency. "A Manual for Developing Biogas Systems at Commercial Farms in the United States." *AgSTAR Handbook*, Washington DC: United States Environmental Protection Agency, 2004.

United States Environmental Protection Agency. "CERCLA and EPCRA Release Reporting Requirements." Washington DC, 1998.

United States Environmental Protection Agency. "Guide Manual on NPDES Regulations for Concentrated Animal Feeding Operations." Washington DC, 1995.

United States Environmental Protection Agency, Office of Air and Radiation. "Managing Manure with Biogas Recovery Systems, Improved Performance at Competitive Costs: The AgSTAR Program." Washington DC, 2002.

United States Office of Management and Budget. "Discount Rates for Cost-Effectiveness Analysis of Federal Programs." *Federal Register* 26 Feb. 2004: 8991-8992.

United States Small Business Administration. 2005. "Borrowing Money." Available at: http://www.sbaonline.sba.gov/managing/financing/borrowing.html.

U.S. Water News Online. "One Manure Pile at a Time, Farmers Help River's Comeback." November 2005. Available at: http://www.uswaternews.com/archives/arcpolicy/5onexmanu11.html.

Vukina, T. "The Relationship between Contracting and Livestock Waste Pollution." *Review of Agricultural Economics* 25(2003): 66-88.

Wall Street Transcripts, The. "Independent Power Producers." Analyst Interview: Ali Agha, 21 June 1999. Available at: http://www.twst.com/pdf/GAX820.pdf.

Welsh, F.W., D.D. Schulte, E.J. Kroeker, and H.M. Lapp. "The Effect of Anaerobic Digestion upon Swine Manure Odors." *Canadian Agricultural Engineering* 19(1977): 122-126.

Westenbarger, D.A. and D. Letson. "Livestock and Poultry Waste-Control Costs." *Choices* 10(1995):27-30.

Wohlt, J.E., R.A. Frobish, C.L. Davis, M.P. Bryant, and R.I. Mackie. "Thermophilic Methane Production from Dairy Cattle Waste." *Biological Wastes* 32(1990): 193-207.

Zhang, W.L., Z.X. Tian, N. Zhang, and X.Q. Li. "Nitrate Pollution of Ground Water in Northern China." *Agriculture, Ecosystems, and Environment* 59(1996): 223-231.

APPENDIX A

METHANE GENERATION AND USE INTERVIEW QUESTIONS

A. *DIGESTER OPERATIONS*

1. What is the capacity of the digester in regards to the waste input?

2. Are you currently operating the digester at full capacity? (Please check one box.)
   - ☐ Yes
   - ☐ No

3. What species, number, and weight of animals does the digester serve? (Please check all that apply.)

   ☐ Dairy
   Number:
   Weight:

   ☐ Beef cattle
   Number:
   Weight:

   ☐ Swine
   Number:
   Weight:

   ☐ Other, please identify species:
   Number:
   Weight:

4. How much waste is produced by your operation (in pounds, tons, or gallons)? (Please select choice most appropriate for your record keeping)

   ☐ Daily ____

   ☐ Monthly ____

   ☐ Yearly ____

B. *DIGESTER INSTALLATION*

1. What type of methane digester are you using? (Please check boxes)
    - ☐ Plug flow
    - ☐ Vertical
    - ☐ Multiple Tank
    - ☐ Fixed Film
    - ☐ Covered Lagoon

2. What type of installation is the digester? (Please check box.)
    - ☐ Rigid
    - ☐ Soft-top
    - ☐ Other, please identify:

3. Why was the facility and system installed? (Please check all that apply.)
    - ☐ Comply with state/federal requirements to have a waste management system
    - ☐ Environmental concerns (i.e. nitrate & phosphate level, odors, flies, etc.)
    - ☐ Earn revenues for current operation by selling electricity and by-products
    - ☐ Other. If selected, please explain:

4. Please list all subsidies you received and the length of time for the subsidy:

Agency / Grantor	**Dollars**	**Length Of Time**

5. Installation financial information:

Installation Financing	
	Amount
Total Needed	
Down Payment	
Net Financed	
Number of Periods	
APR	

6. Digester Installation Inventory & Costs:

Item	**Cost**	**Economic Life (In Years)**	**Salvage Value**
Planning & Engineering			
Site Preparation			
Lining			
Piping			
Concrete			
Construction Labor			
Digester Facility			
Digester Mix Tank & Waste Collection Facilities			
Engine & Generator			
Engine Building			
OTHER			

7. Labor Requirements to run entire methane operation. Rate is in number of man-hours

Quarter	**Hours**	**Rate**	**Total**
Jan-Mar			
Apr-Jun			
Jul-Sep			
Oct-Dec			
YEARLY			

8. What is the type and cost of insurance you have on the digester?

9. What is the training costs associated with the use of the digester?

10. Operating financial information:

Operating Funds:	
	Amount
Total Needed	
Down Payment	
Net Financed	
Number of Years	
APR	

11. Quarterly Operating Budget (Please provide figures based on your records. Number should be reflective of the digester operation **ONLY**)

Item	**Jan-Mar**	**Apr-Jun**	**Jul-Sep**	**Oct-Dec**	**Annual**
From previous period					
Inflows	▨	▨	▨	▨	▨
Electricity					
Amenders/Bedding/Nutrients					
Digester Services					
OTHER					
Total Inflows & Carryover					
	▨	▨	▨	▨	▨
Outflows					
Labor					
Repair/Maintenance					
Insurance					
Interest On Note(s)					
Transportation Of Spent Digestate					
Utilities					
OTHER					
Total Outflows					
Net					

C. *ELECTRICITY GENERATION*

1. Are you currently generating electricity that is sold to a utility or another entity? (Please check one box.)
   - ☐ Yes
   - ☐ No

2. If there is electricity generated and sold, what is the grid access rule?

3. Is there a net metering agreement between the utility provide and yourself? (Please check one box.)
   - ☐ Yes, please answer question #4
   - ☐ No, please answer question #5

4. What are the components of the net metering agreement?

5. Are you required to buy from and sell electricity to the same utility? (Please check one box.)
   - ☐ Yes
   - ☐ No

6. What is the current buy price (in $/KWH) you pay for electricity from grid?

7. What is the current sell price (in $/KWH) you receive for electricity sold?

8. Will the buy or sell price you receive change in the future? How will it change?

9. How much electricity (in KWH) do you produce daily?

10. What is your electricity generator size in terms of maximum and continuous output (in KWH)?

11. How is the electricity generator operated? (Please check one box.)
    - ☐ Continuously
    - ☐ Intermittently

12. How is the generator powered? (Please check one box.)
    - ☐ Gas powered reciprocating
    - ☐ Gas turbine
    - ☐ Steam turbine
    - ☐ Steam reciprocating
    - ☐ Other. If selected, please specify:

13. Were there additional components (i.e. transformer, etc.) you had to purchase to meet the needs of the utility company before they would accept your electricity? What were the costs?

D. *METHANE PRODUCTION*

1. How much gas do you produce? (Please select choice most appropriate to your knowledge of your records)

☐ Daily ____

☐ Monthly ____

☐ Yearly ____

2. How is the methane stored?

3. Is the gas scrubbed of impurities before it is used? (Please check one box.)
☐ Yes, please answer question #4
☐ No, skip to question #5

4. If answered yes to #4, what was the cost of the scrubber?

5. How is the by-product heat used? (Please check boxes that applies.)
☐ Warm digester
☐ Heating wash water
☐ Heating buildings
☐ Other. If selected, please specify:

E. *EFFLUENT WATER & DIGESTATE*

1. What happens to the effluent water?

2. Do you incur any testing expenses on the effluent? (Please check one box.)
   - ☐ Yes, please answer question #3
   - ☐ No

3. If so, then how much?

4. What is the change in your costs associated with effluent water from before using the digester to now?

5. How do you handle nitrogen and phosphorus?

6. Does using the digester make you compliant with regulations on nitrogen and phosphorus levels? How?

7. Do you currently separate the liquid and solid digestate? (Please check one box.)
   - ☐ Yes
   - ☐ No

8. How will the LIQUID digestate be disposed of?

9. How will the SOLID digestate be disposed of? (Please check boxes that applies.)
   - ☐ Bedding
   - ☐ Sold as soil amender
   - ☐ Distributed on pastureland or cropland
   - ☐ Other. If selected, please specify:

10. Are there still odor problems/concerns even with using the digester? (Please check box.)
    - ☐ Yes
    - ☐ Somewhat
    - ☐ No
    - ☐ Uncertain

F. *ADDITIONAL INFORMATION*

1. Is there additional information that you would like to share?

2. Using the back of this sheet of paper, please provide a sketch of the current set-up of your digester

APPENDIX B

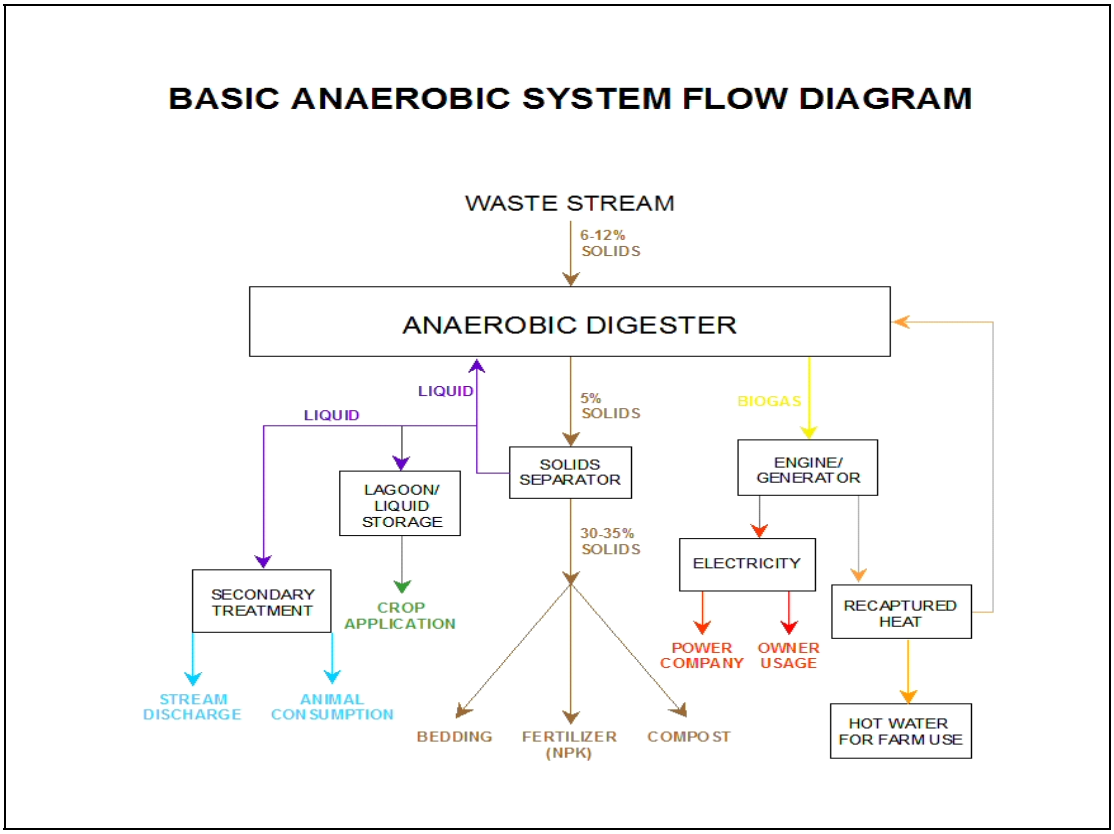

Figure B.1. Anaerobic digestion process (GHD, Inc.)

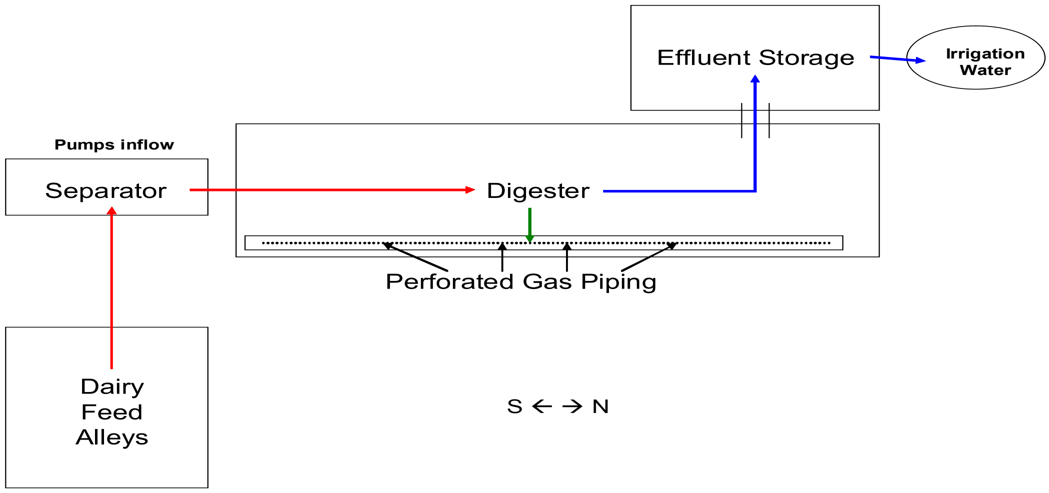

Figure B.2. Anaerobic digester at facility CA1

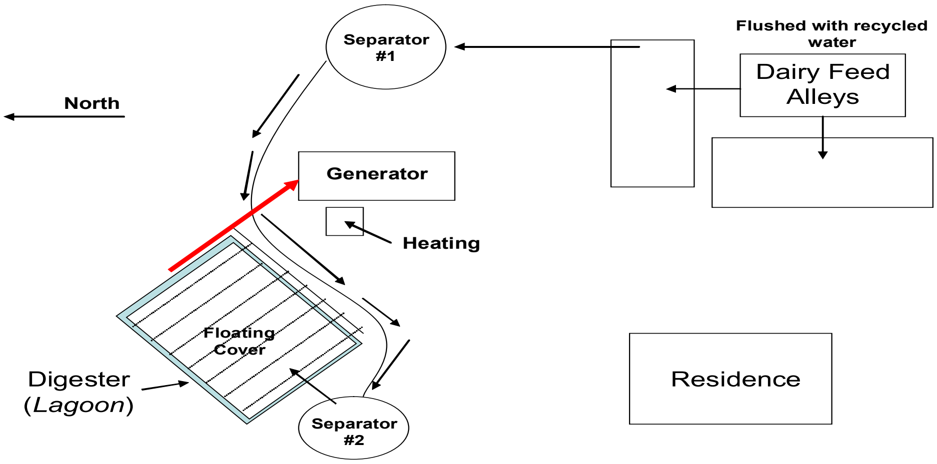

Figure B.3. Anaerobic digester at facility CA5

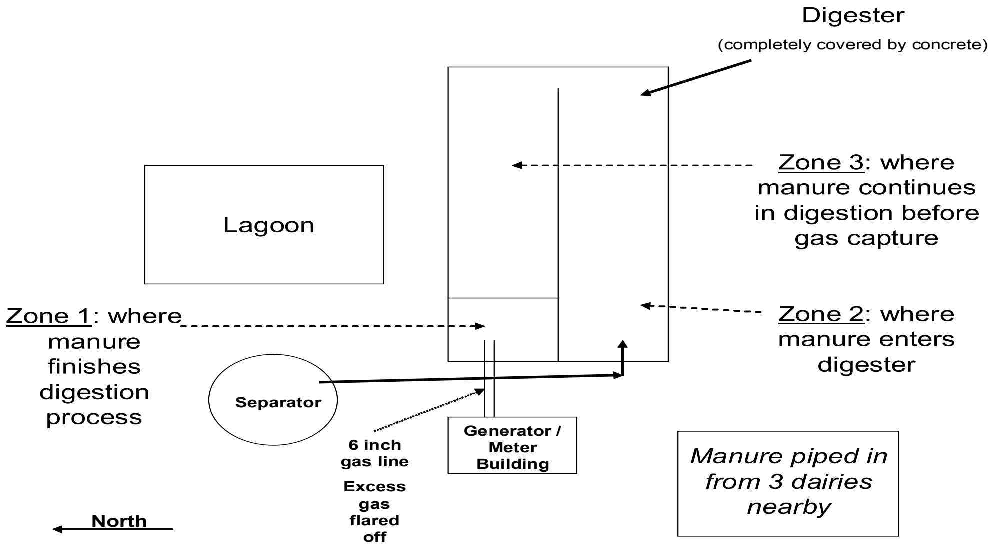

Figure B.4. Anaerobic digester at facility WA1

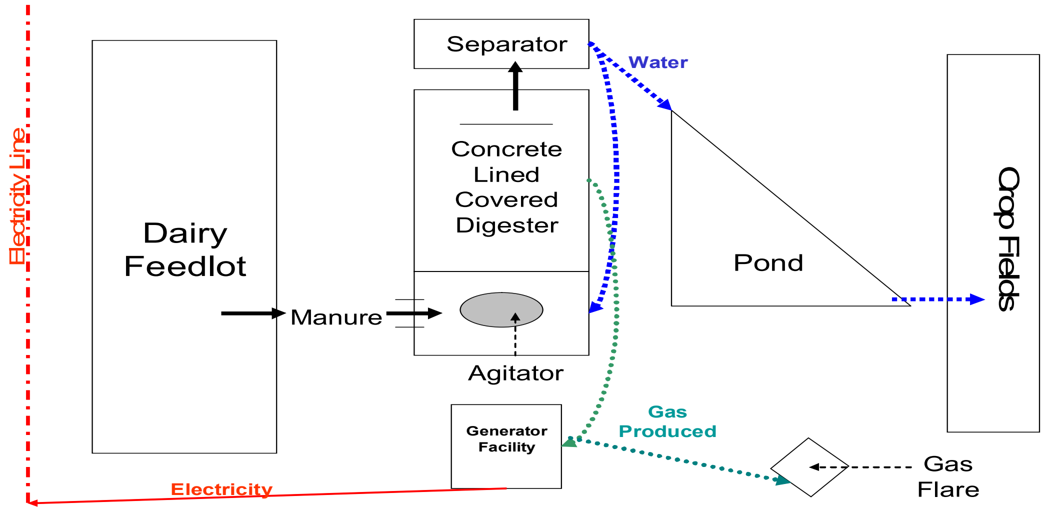

Figure B.5. Anaerobic digester at facility CA7

APPENDIX C

Table C.1. Number of Dairies, Number of Fines, and the Monthly Probability of Receiving a Fine in the NBR Watershed from June 1998 to November 2004

Month	Year	Number of Dairies by County			Total Number of Dairies	Total Number of Fines	Probability of Receiving a Fine
		Bosque	*Erath*	*Hamilton*			
June	1998	4	153	30	187	3	0.016
July	1998	4	152	27	183	2	0.011
August	1998	3	152	27	182	2	0.011
September	1998	3	153	27	183	0	0.000
October	1998	3	154	27	184	3	0.016
November	1998	3	151	28	182	0	0.000
December	1998	3	150	28	181	3	0.017
January	1999	0	150	28	178	1	0.006
February	1999	0	152	28	180	0	0.000
March	1999	0	151	27	178	0	0.000
April	1999	0	149	28	177	0	0.000
May	1999	0	144	28	172	1	0.006
June	1999	0	147	26	173	2	0.012
July	1999	0	149	25	174	2	0.011
August	1999	0	151	25	176	1	0.006
September	1999	0	152	24	176	0	0.000
October	1999	0	150	23	173	0	0.000
November	1999	0	146	22	168	1	0.006
December	1999	0	147	21	168	0	0.000
January	2000	0	146	21	167	0	0.000
February	2000	0	148	20	168	3	0.018
March	2000	0	148	20	168	1	0.006
April	2000	0	145	20	165	0	0.000
May	2000	0	145	20	165	1	0.006
June	2000	0	144	19	163	0	0.000
July	2000	0	142	18	160	0	0.000
August	2000	0	143	18	161	2	0.012
September	2000	0	143	19	162	0	0.000
October	2000	0	144	18	162	0	0.000
November	2000	0	142	17	159	0	0.000
December	2000	0	139	17	156	0	0.000
January	2001	0	136	18	154	0	0.000
February	2001	0	138	18	156	1	0.006
March	2001	0	136	18	154	0	0.000
April	2001	0	138	18	156	0	0.000
May	2001	0	136	18	154	0	0.000
June	2001	0	134	18	152	0	0.000
July	2001	0	134	17	151	0	0.000

Probability of receiving fine: (Total Number of Fines / Total Number of Dairies).

Table C.1 Continued

Month	Year	Number of Dairies by County			Total Number of Dairies	Total Number of Fines	Probability of Receiving a Fine
		Bosque	*Erath*	*Hamilton*			
August	2001	0	131	17	148	0	0.000
September	2001	0	131	17	148	0	0.000
October	2001	0	131	17	148	0	0.000
November	2001	0	130	17	147	2	0.014
December	2001	0	132	17	149	0	0.000
January	2002	0	128	18	146	2	0.014
February	2002	0	128	18	146	1	0.007
March	2002	0	129	17	146	0	0.000
April	2002	0	128	18	146	0	0.000
May	2002	0	126	17	143	1	0.007
June	2002	0	127	16	143	1	0.007
July	2002	0	123	16	139	3	0.022
August	2002	0	117	16	133	2	0.015
September	2002	0	118	16	134	1	0.007
October	2002	0	114	16	130	0	0.000
November	2002	0	114	15	129	0	0.000
December	2002	0	113	15	128	1	0.008
January	2003	0	113	15	128	1	0.008
February	2003	0	114	15	129	0	0.000
March	2003	0	112	15	127	1	0.008
April	2003	0	112	15	127	0	0.000
May	2003	0	113	16	129	1	0.008
June	2003	0	114	16	130	0	0.000
July	2003	0	116	14	130	3	0.023
August	2003	0	106	15	121	1	0.008
September	2003	0	110	14	124	0	0.000
October	2003	0	114	15	129	0	0.000
November	2003	0	112	15	127	1	0.008
December	2003	0	110	14	124	0	0.000
January	2004	0	109	14	123	1	0.008
February	2004	0	112	15	127	0	0.000
March	2004	0	112	14	126	0	0.000
April	2004	0	113	14	127	0	0.000
May	2004	0	114	14	128	0	0.000
June	2004	0	111	14	125	0	0.000
July	2004	0	113	15	128	0	0.000
August	2004	0	101	15	116	0	0.000
September	2004	0	99	15	114	0	0.000
October	2004	0	98	15	113	0	0.000
November	2004	0	96	15	111	1	0.009
December	2004	0	94	15	109	0	0.000

Sources: Number of dairies: USDA-Agricultural Marketing Service, Dairy Programs
Number of fines: Texas Commission on Environmental Quality (TCEQ)

APPENDIX D

Table D.1. Results from the Anaerobic Digester (AD) and Standard Lagoon (SL) Models for Various Scenarios[1]

Model	E(NPV)	Probability E(NPV)≥ 0	95% Confidence Interval	
			Lower Bound	Upper Bound
SL (Base)	($345,942)	0.000	($349,346)	($344,279)
AD (Base)	($188,816)	0.000	($344,751)	($98,878)
AD (No Elec. Sell)	($768,498)	0.000	--	--
AD (Full)	$76,267	0.877	($69,688)	$166,206
Animal Units (AU)				
AD	($372,301)	0.000	($445,268)	($327,331)
SL	($248,272)	0.000	($251,679)	($246,611)
AD	($5,332)	0.521	($224,235)	$129,575
SL	($443,612)	0.000	($447,019)	($441,951)
AD	$324,939	0.955	($25,305)	$540,791
SL	($619,417)	0.000	($622,824)	($617,756)
Electricity-Selling Price (ESP)				
AD	($655,268)	0.000	--	--
AD	($409,798)	0.000	($486,596)	($362,468)
AD	$44,409	0.628	($173,493)	$179,317)
Heat Savings				
AD	($302,046)	0.000	($447,981)	($212,108)
Fiber Sales				
AD	($112,551)	0.000	($258,485)	($22,612)
Down Payment				
AD	($185,602)	0.000	($331,537)	($95,663)
AD	($192,031)	0.000	($337,966)	($102,093)
AD	($195,246)	0.000	($341,181)	($105,308)
AD	($198,461)	0.000	($344,396)	($108,522)
AD	($201,676)	0.000	($347,610)	($111,737)
Discount Rate				
AD	($182,066)	0.000	($316,059)	($99,487)
SL	($320,220)	0.000	($323,348)	($318,695)
AD	($173,621)	0.000	($292,557)	($100,321)
SL	($287,809)	0.000	($290,586)	($286,455)

[1] Preliminary results were calculated using a different method of converting number of animals to AU at each digester facility visited and using an electrical generator efficiency value of 0.85.

VITA

Name: Randy Scott Jackson, Jr.

Address: Department of Agricultural Economics
Texas A&M University
2124 TAMU
College Station, TX, 77843-2124

Education: A.S., North Central Texas College, 1998, Gainesville, TX

B.S., Animal Industries, Tarleton State University, 2000, Stephenville, TX

Certificate in International Agriculture and Resource Management, Department of Agricultural Economics, Texas A&M University, 2003

M.S., Agricultural Economics, Texas A&M University, 2006, College Station, TX

Publications: Schwart, R.B., R.S. Jackson, B. Herbst, R. Whitney, R.D. Lacewell, and J.W. Mjelde. “Methane Generation.” Department of Agricultural Economics, Texas A&M University, 2005.

Ng, D., R.S. Jackson, and K. McCulloch. “Valuing Strategic Alliances in the Pharmaceutical / Biotechnology Industry.” Paper presented to the American Agricultural Economics Association Meetings, Providence RI, July 2005.