Estimating learning benefits from research and development in anaerobic digestion systems for animal waste disposal and energy recovery

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ESTIMATING LEARNING BENEFITS FROM RESEARCH AND DEVELOPMENT IN ANAEROBIC DIGESTION SYSTEMS FOR ANIMAL WASTE DISPOSAL AND ENERGY RECOVERY

by

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A Thesis Submitted to the Faculty of the

DEPARTMENT OF AGRICULTURAL ECONOMICS

In Partial Fulfillment of the Requirements
For the Degree of

MASTER OF SCIENCE

In The Graduate College

THE UNIVERSITY OF ARIZONA

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ACKNOWLEDGMENTS

I wish to express sincere gratitude to my advisor, Dr. Marilyn A. Altobello for her patient guidance and encouragement throughout this study.

I would also like to thank Dr. William E. Martin and Dr. Harry W. Ayer, members of my graduate committee for reading and constructively criticizing this thesis.

Katheryn Bechtold, Steve Jenkins and Dr. James C. Wade contributed invaluable expertise in coercing the computer to compute, for which I am especially grateful.

I would also like to express my appreciation to Mrs. Sharon Calhoun for decoding and typing the several drafts of this cryptically written manuscript and Mrs. Sarah Oordt for professionally typing the final copy of this thesis.

Finally, special thanks go to the faculty of the Department of Agricultural Economics and to fellow graduate students for making this graduate program a positive experience.

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ABSTRACT

This study presents an economic evaluation of anaerobic digestion systems as an alternative energy source, both from the view of the individual firm considering adopting this technology and from that of the public decision maker seeking to estimate the potential net benefits accruing from research and development expenditures in this area.

Parameters of learning functions are estimated for four capacity ranges of animal production units using multiple regression techniques. The estimated relationships indicate that with each doubling of cumulative gross investment, there is a 13-18 percent decrease in the unit cost of gas production.

These equations were used, along with equations representing the real rate of increase in natural gas price, to calculate breakeven points for firms and also the net benefits from adoption of manure/methane systems. Input parameters were varied to consider several states of nature. Results indicate that in most cases, operations with more than 750 head of feeder cattle will attain the breakeven point within the next decade. The greatest proportion of net benefits will accrue to states with large cattle feeding operations.

Externalities were determined to exist as a result of learning and nonmarket pricing of natural gas, and quantitive estimates of these externalities were made.

CHAPTER 1

INTRODUCTION

Statement of the Problem

The problems of solid waste management, escalating energy prices, and corresponding energy shortages have been recognized as significant national issues. This situation has resulted in increased interest in evaluating alternative energy sources.

The year 1973 marked the beginning of a period of energy supply limitations and increasing energy prices. Indications are that this trend of increasing prices will continue into the foreseeable future. In spite of this trend, a 50 percent increase in total energy use in agriculture is expected by the year 2000 (Committee on Agriculture and the Environment, 1974).

Not only has the energy situation become a serious issue, but also the desire for a reduction in environmental pollution and more efficient use of resources other than energy has been indicated by society. This desire is reflected by the fact that as of 1972, over 350 bills with the objective of reducing solid waste have been introduced to Congress, state legislatures, and municipal governments (Bingham and Mulligan, 1972).

Historically, animal manures have been recycled through the soil. The change to intensive livestock production as well as changes in crop patterns and the substitution of chemical fertilizers for manure have reduced the effectiveness of the complementary relationship between crop production and livestock production (Loehr, 1973).

The trend of increasing size and concentration of animal production units has created a situation where there is a separation of feeding operations from feed production. The result of this separation is that intensive livestock production units have been constructed on locations where there generally is insufficient land to spread all the manure produced (Loehr, 1973, and Denewiler, 1977).

One method of handling both the general energy and livestock and poultry manure management problems is to implement disposal systems which incorporate energy conversion technologies. The systems under consideration in this study are those which use anaerobic digestion to biologically degrade livestock and poultry manures. This process results in a fuel gas which is 60-70 percent methane (CH_4) (Fischer, 1978; Jewell, 1976; Lapp, 1974; and Singh, 1974).

Purpose of the Study

The general purpose of this study is to estimate the impact of cumulative gross investment expenditures in anaerobic digestion technology research and development on the cost of producing methane gas from livestock and poultry manures. Anaerobic digestion is evaluated as an alternative energy source, both from the view of the individual firm considering adopting this technology and from that of the public decision maker seeing to estimate the potential net benefits accruing from public research and development expenditures in this area.

The specific objectives are:

1) To examine the trend of research and development expenditures in the area of methane production from anaerobic digestion of livestock and poultry manures.
2) To estimate the parameters of learning functions which relate the cost of producing methane by anaerobic digestion of manures to cumulative gross investment in anaerobic digestion research and development, as well as other variables.
3) To use these estimated learning functions to calculate potential net benefits accruing to various size firms adopting anaerobic digestion facilities given varying rates of discount, increases in natural gas price and gross investment over time.
4) To determine the regional distribution of net benefits potentially accruing from research and development expenditures in anaerobic digestion technology.
5) To investigate the possibility of externalities accruing from learning and those resulting from nonmarket pricing of energy.

CHAPTER 2

LITERATURE REVIEW

The review of the literature is divided into two general categories. The first is a synthesis of technical literature describing the engineering and biochemical aspects of methane generating disposal systems. The second is a review of literature which develops the economic theory of learning and applying the concepts of learning and externalities in economic analyses.

Technical Literature

Anaerobic digestion has long been recognized as a practical process for stabilizing sewerage, as well as a potential source of methane gas. The first case of methane production from anaerobic digestion was reported by Donald Cameron, who in 1895 built the first municipal-sized septic tank in Exiter, England. Only recently, however, has methane generation from anaerobic digestion been seriously considered as a significant source of energy.

The process of anaerobic digestion is carried out by a "small group of spirillae" (Hoenig and Russ, 1974, p. 1). These microbes or bacteria are of two general types. The first group converts a substrate of methane into short chain fatty acids, ammonia (NH_3) and carbon dioxide (CO_2). The second group converts fatty acids into methane (Smith, 1977 and Ecotope Group, 1975). The resulting gas consists of approximately 54-70 percent methane, 27-45 percent carbon dioxide, small amounts of hydrogen, nitrogen, carbon monoxide, oxygen, and hydrogen sulfide (Ecotope Group, 1975; Hoenig and Russ, 1974; and Johnson 1972). The gas has a calorific value of 600 Btu per cubic foot as compared to approximately 1,000 Btu per cubic foot for natural gas (Smith, 1977, and Johnson, 1972).

A major factor in determining output of methane from anaerobic digestion is the physical design of the digester. In practice, the simplest anaerobic digester would consist of an oxygen-free tank containing bacteria and a manure slurry. There is, however, a wide range of variation in digester design.

Reactor design ranges from the simple plug-flow with no mixing to a variety of completely mixed reactors (Jewell et al., 1976 and Morris et al., 1975). Several schemes have been developed to recycle materials from the slurry, and others to separate the acid-forming and methane-forming bacteria in a stage-wise operation (Ashare et al., 1977).

Besides reactor design, there are a number of environmental and operational factors which affect the quantity and quality of gas production from anaerobic digestion. Briefly, these factors are:

1) Temperature: Microbial activity increases between temperatures of 32° and 140°F. Maximum gas production is attained between temperatures of 90° and 95°F (32°-35°C). A digester's methane-producing bacteria can be upset by a change of ±2°F (1°C) (Lapp et al., 1974). Therefore it is essential to maintain the contents of the digester or slurry at a constant temperature.

2) pH: The pH of the slurry must be maintained between 6.6 and 7.6. Gas production will not occur below 6.2 (Ashare et al., 1977).

3) Nutrient Availability: In order to maintain satisfactory methane production, the nutrient level must remain proportional to the synthesis of new microbial cells. The use of animal manures for digestion seldom results in a lack of nutrients (Jewell, 1976). However, the type of manure, in addition to manure storage practices, can affect methane production.

   The volatile solids of manure are often used as an indication of its digestibility. Volatile solids content is the percentage of total solids drive off by combustion at a temperature of 600°C for one hour (Ecotope Group, 1975). The volatile solids in manure are generally reduced with storage, and this then reduces the digestibility (Lapp et al., 1975).

4) Presence of Toxic Materials and Oxygen: The presence of toxic materials in the slurry must be minimized for effective digestion. Basic types of toxic materials are alkali cations, alkaline cations, ammonia sulfide, heavy metals, and several organic materials (Ashare et al., 1977). Also, the level of oxygen must be kept at a minimum in order for anaerobic bacteria to survive.

5) Retention Time: Retention time refers to the amount of time material remains in the digester and is generally measured in terms of liquid flow or rate at which solids leave and enter. For gas production to occur, there is a minimum required retention time,

which is related to the rate of reproduction of the bacteria (Pfeffer, 1974). Beyond this minimum, the longer the digestible material is retained, the greater the proportion digested. Related to retention time is loading rate, which is the amount of waste added per day, technically measured in volatile solids added per day. It may be noted that there is an inverse relationship between retention time and loading rate (Ashare et al., 1977, and Jewell et al., 1976).

Factors 1) through 5) above can be altered by digester design and management practices and should change as learning about anaerobic waste disposal systems accumulates.

Acccrding to Jewell et al. (1978), there are several areas in which anaerobic fermentation can be rapidly improved as it applies to digestion of agricultural residues. The three general areas are:

1) Development of simplified digester systems for small-scale operations.
2) Identification of "high-rate multiple by-product reactors." One example of this would be a thermophilic reactor which could utilize the gas to float the fibers to attain an internal liquid-solid separation.

Another improved technique recently investigated by Jewell et al. (1978) has resulted in the highest yield of methane observed from organic matter such as cow manure. This technique involves separation of the active bacteria from the flow so they remain in the reactor. This "attached film expanded bed process" consists of a filter composed of inert particles to which the microbes naturally attach, creating a film. The unit normally is run with an upflow which slightly expands the bed and helps distribute the flow around the microorganisms.

3) Expansion of current information available regarding the impact of substrate composition, viscosity, nutrients, toxic materials, and microbiology. Hollaender et al. (1973) concurs, emphasizing that substantial advances can be made through investigation of microbial biochemical and genetic mechanisms of the methane-forming bacteria.

Other areas which could have an impact on the adoption and associated feasibility of anaerobic digestion waste disposal systems are development of safe and more efficient methods of collection, scrubbing, storing and utilizing digester gas, further analysis of the effluent, and an assessment of its use as fertilizer (Lapp et al., 1975).

Economic Theory of Learning and Some Applications

In a path-breaking paper, K. T. Arrow (1962) initiates the integration of learning and economic theory. His basic hypothesis is that technological change in general can be ascribed to experience, and that the activity of production gives rise to problems for which responses are made over time. Two major empirical generalizations underlie Arrow's hypothesis. The first is that "learning is a product of experience", and the second that learning associated with repetition of essentially the same problem is subject to sharply diminishing returns.

Arrow develops the argument that learning derived from present investment will benefit future investors, "but this benefit is not paid for by the market" (Arrow, 1962, p. 168). This situation creates a divergence between social and private costs or, in the case of learning, a positive externality may occur with investment. If this externality goes unrecognized, there may be a problem of underinvestment from a social point of view (Arrow, 1962 and Rausser et al., 1972).

The generally accepted functional form used to describe the learning process is:

$$Y = aX^b \tag{2.1}$$

where X is a surrogate for accumulated experience, Y is a measure of learning and a and b are parameters. If the measure of learning is represented by a cost, it is theoretically expected that b will be negative. This implies that, as accumulated experience increases, the cost will decrease. It can be shown that the percent slope (S) of an exponential functional form is:

$$S = 2^b \cdot 100. \tag{2.2}$$

If the percent slope is equal to 75, then a doubling in X will decrease Y by 25 percent.

There have been several attempts to empirically estimate exponential learning functions. Alchian (1963) estimated learning functions for production line processes, where unit cost was the measure of learning. Empirical estimations which expanded the application to include technological change were conducted by Rausser (1972) in a study of desalting plants and by Slane (1974) in a study of anaerobic digestion systems. Several different indexes of accumulated experience have been used in the past: cumulative gross investment (Arrow 1962), cumulative industrial output (Bardhan 1971), and time (Fellner 1969). In the research done by Wells (1971), Rausser et al. (1972), and Slane (1974) cumulative capacity was used as a proxy for accumulated experience.

In evaluating the external learning benefits in both the studies of desalting plants and methane generation operations, the present value of all cost reductions to future plants in year m when learning occurs was subtracted from the present value of future cost reductions in year m with no benefits from learning. The value of this externality was used to determine appropriate subsidies which would in turn influence the rate of adoption of the technology (Willis et al., 1977, and Slane, (1974).

The study of anaerobic digestion systems and learning (Slane, 1974) was undertaken to evaluate poultry waste disposal systems. The study consisted of an economic analysis of adopting a methane-generating waste treatment stage by three different scale hypothetical egg-producing operations in Massachusetts, and included the estimation of a learning function for methane-generating waste treatment systems. One conclusion from this study was that with each doubling in cumulative capacity, the capital costs of the system were reduced approximately 25 percent. It was also concluded that a public transfer in the range of $42,000 to $90,000 would likely be required to induce poultrymen to include a methane-generating system in their operations. The external learning benefits were estimated to be in excess of this value.

There are two major shortcomings in Slane's analysis. First, there is an inherent weakness in the use of cumulative capacity as proxy for experience since many "cost reductions will be attributed to non-methane generating research and development, such as improved pumps, new digester technology, microbiology, and new displacement technology" (Slane 1974, p. 54). This understatement of cost reductions will tend to overstate the value of external learning benefits. A second shortcoming of Slane's analysis is his assumption that information flows at the same rate and accuracy throughout all systems.

An attempt will be made in this study to extend the analysis in order to deal with these two problems. The use of cumulative gross investment in anaerobic systems will replace cumulative capacity as a proxy for experience and should compensate for overstatements associated with the first problem. The rate at which information flows through the system will be estimated using the various lag techniques explained in Chapter 4. This study will also extensively expand the data base used in Slane's study and estimate a learning function for both livestock and poultry anaerobic waste disposal systems.

CHAPTER 3

THEORETICAL FRAMEWORK

This chapter consists of four sections. The first two sections develop decision frameworks for individual firms considering adopting anaerobic digestion systems and for policy-makers concerned with allocating public funds for research and development in this area. The second two sections review the theoretical concepts related to externalities accruing from learning and those caused by a nonmarket price for natural gas.

For the purpose of developing the theoretical framework necessary for this study, it is assumed that the learning relationship is of the generally accepted functional form: $Y = aX^b$, where Y is the measure of learning, in this case unit gas cost, X is the surrogate for accumulated experience, in this case cumulative gross investment in research and development of anaerobic digestion systems, and a and b are parameters.

Calculation of the Present Value of Net Benefits: Private Decision Maker

In this analysis, cumulative gross investment in anaerobic digestion technology, measured in real dollars, is defined as X, and is assumed to be a function of time:

$$X = f(t). \tag{3.1}$$

This relationship may be substituted into the learning function as follows:

$$Y = a[f(t)]^b \tag{3.2}$$

where Y represents the cost of producing a unit of gas by anaerobic digestion (in real dollars).

If it is next assumed that the price at which a unit of gas can be purchased or sold is the current price of natural gas received by a utility, and that this price of natural gas is increasing at a real continuous positive rate, an equation can be developed to reflect the price of natural gas as a function of time:

$$PNG_t = PNG_0 e^{rt} \tag{3.3}$$

where PNG_t = price of a unit of natural gas (in real dollars) in time t; PNG_0 = current price of a unit of natural gas (in real dollars); r = real rate of increase in the unit price of natural gas.

Equating the right-hand sides of (3.2) and (3.3) will yield a point in time, t_b, at which the cost of generating gas by anaerobic digestion is equal to the price paid for gas purchased from a utility company:

$$PNG_0e^{rt} = a[f(t)]^b. \qquad (3.4)$$

This relationship is illustrated in Figure 3.1 for a situation in which $r > 0$ and $b < 0$.

In this case, it is assumed that the firm is restricted to one of two options:

a) if $PNG_t \geq Y_t$ then the firm will produce gas;

b) if $PNG_t < Y_t$ then the firm will not produce gas.

At any point in time where $PNG_t \geq Y_t$, the net benefit of producing a unit of gas may be defined as the difference between the cost of producing a unit of gas and the price paid for a unit of gas purchased from a utility company.

If the life of a gas plant is N years, and the firm begins producing gas at the point in time at which $PNG_0e^{rt} = a[f(t)]^b$, or t_b, the undiscounted value of net benefits can be represented by area ABC in Figure 3.2. The present value of total net benefits (B) can be calculated by multiplying the annual per unit net benefits by the amount of gas produced that year and discounting the resulting value, as follows:

$$B = G \sum_{t=t_b}^{t_b+N-1} (1+\alpha)^{-(t+1)} \cdot \int_t^{t+1} (PNG_0e^{rt} - a[f(t)]^b)dt \qquad (3.5)$$

where α = rate of discount; G = units of gas produced per year.

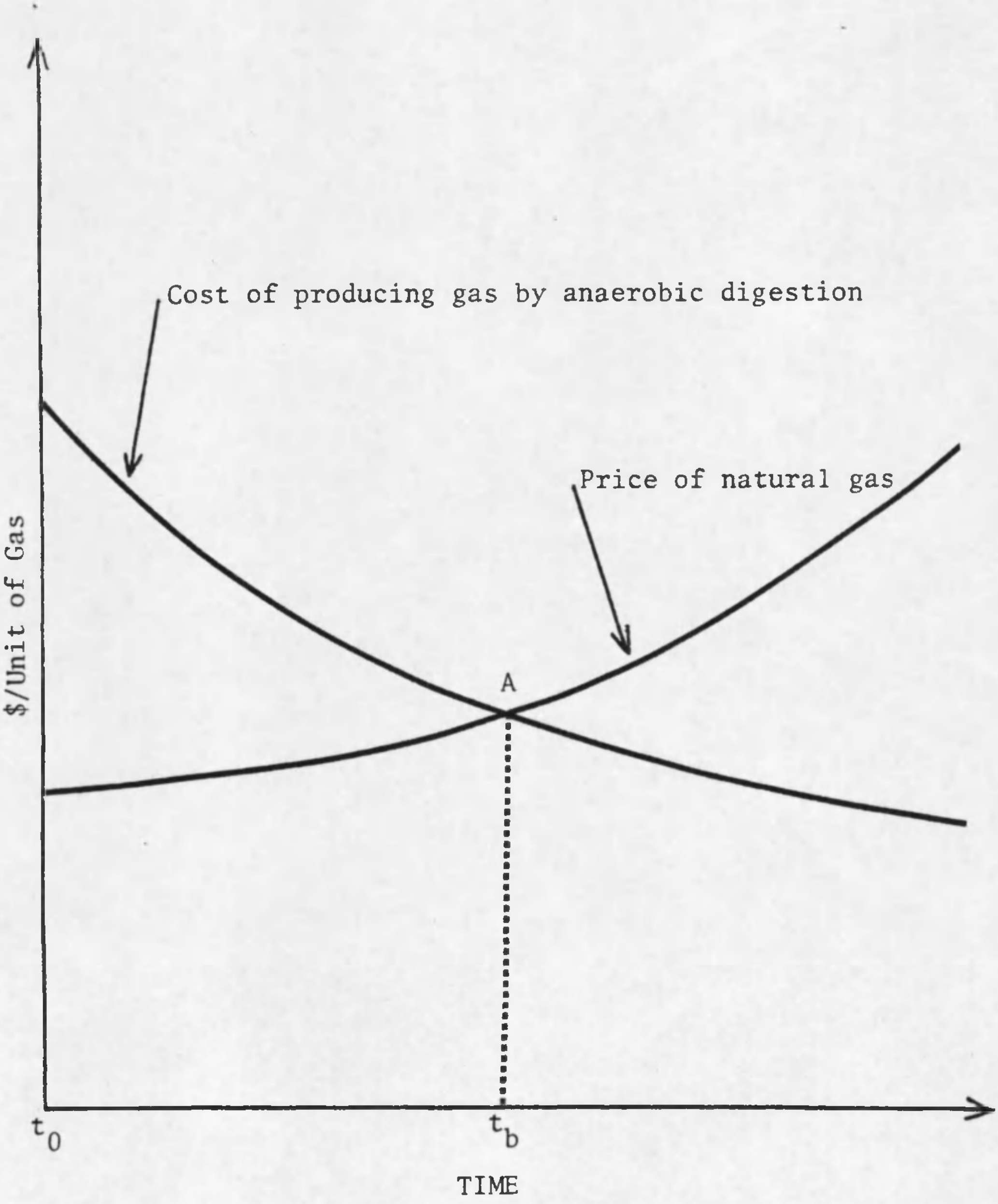

Figure 3.1. The Breakeven Point, t_b, Where $PNG_0 = e^{rt} - a[f(t)]^b = 0$.

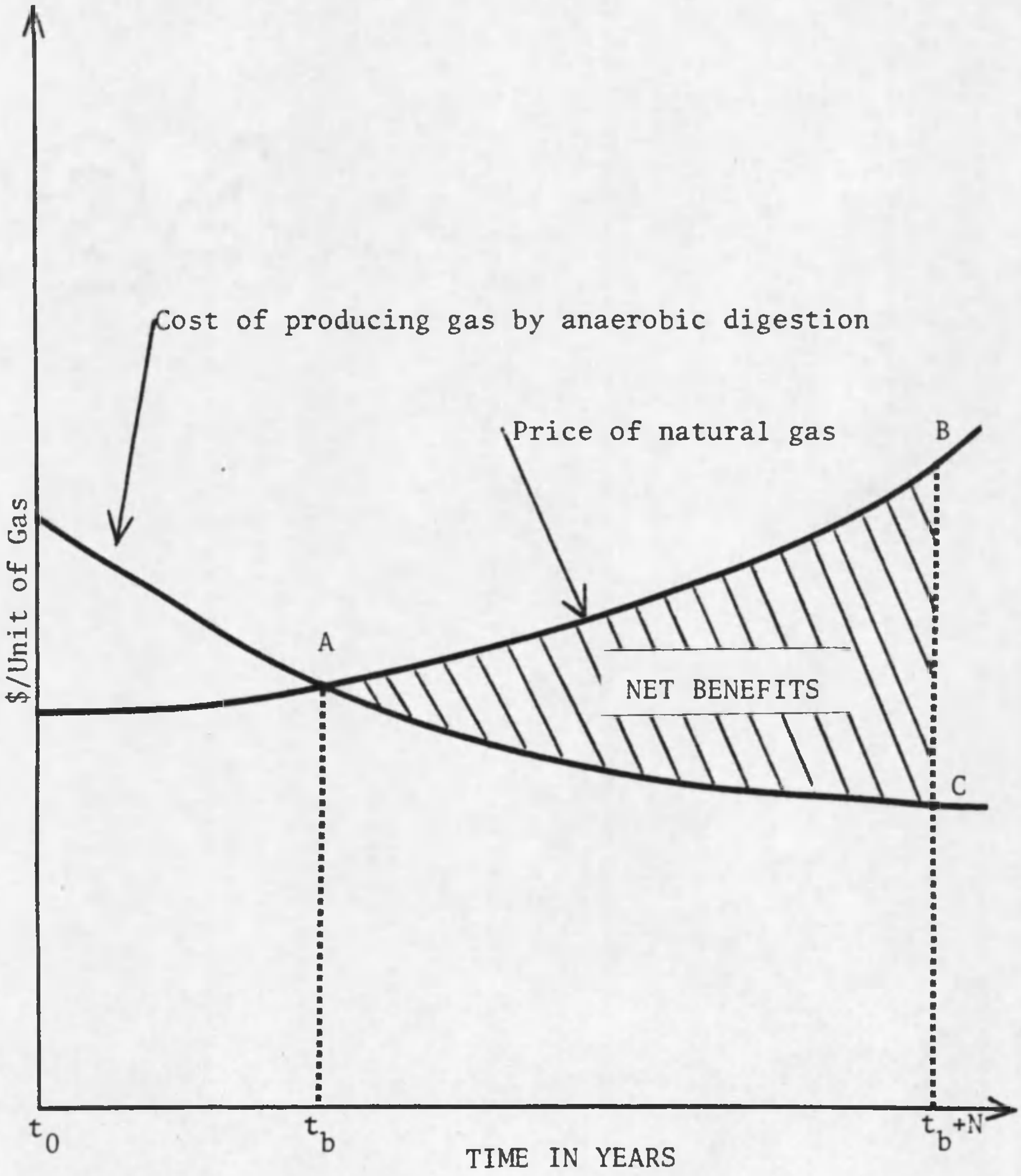

Figure 3.2. Net Benefits per Unit of Gas Produced Annually Beginning at the Breakeven Point and Continuing for N Years.

The present value of net benefits represents the gain which would accumulate to an individual firm choosing to allocate its resources to the adoption of a methane generation waste disposal system. This analysis does not imply that the firm should produce gass since the opportunity costs of alternative uses of the firm's resources have not been considered.

Calculation of the Present Value of Net Benefits Under a Limited Time Frame: The Aggregate Situation

In this section a method will be developed to determine the minimum fixed aggregate annual gas production required such that the present value of gross investment over a prescribed period of time is equal to the present value of the net benefits from aggregate gas production over the same period of time. Expressed mathematically:

$$G_a = \frac{PVX_H}{B_H} \tag{3.6}$$

where PVX_H = present value of gross investment over the prescribed planning period of H years; B_H = present value of net benefits from producing a unit of gas annually during the prescribed planning period of H years; G_a = fixed aggregate annual gas production.

It is assumed that cumulative gross investment from the beginning of the prescribed planning period (t_{h0}) until the end of the period $(t_{h0} + H)$ can be expressed as a function of time:

$$X_1 = g(t) \tag{3.7}$$

where X_1 = cumulative gross investment in real dollars from t_{h0} to t_{h0+H}. The present value of aggregate gross investment (PVX_H) over the planning period of H years may then be expressed as follows:

$$PVX_H = \sum_{t=t_{h0}}^{t_{h0+H-1}} (1+\alpha)^{-(t+1)} \cdot \int_t^{t+1} g(t)dt. \tag{3.8}$$

The present value of the aggregate net benefits (B_a), is computed in a manner similar to that expressed by equation (3.5):

$$B_a = G_a \sum_{t=t_b}^{t_{b0+H-1}} (1+\alpha)^{-(t+1)} \cdot \int_t^{t+1} (PNG_0 e^{rt} - a[f(t)]^b)dt \tag{3.9}$$

where $B_a = B_H \cdot G_a$.

When the right-hand sides of equations (3.8) and (3.9) are equated, the system may be solved for G_a:

$$G_a = \frac{\displaystyle\sum_{t=t_{h0}}^{t_{h0+H-1}} (1+\alpha)^{-(t+1)} \cdot \int_t^{t+1} g(t)dt}{\displaystyle\sum_{t=t_b}^{t_{h0+H-1}} (1+\alpha)^{-(t+1)} \cdot \int_t^{t+1} (PNG_0 e^{rt} - a[f(t)]^b)dt}. \tag{3.10}$$

When (3.10) is solved, G_a represents the minimum fixed agregate annual units of gas production required for the condition expressed by equation (3.6) to hold.

It should be noted that if equation (3.6) holds for a situation, this does not imply a Pareto optimal rate of gross investment or gas production. A necessary condition for Pareto optimality, under capital constraints, requires that the ratios of marginal benefits and marginal costs of alternative projects be equal:

$$\frac{MB_1}{MC_1} = \frac{MB_2}{MC_2} = \ldots = \frac{MB_n}{MC_n} \qquad (3.11)$$

where MB_k = marginal benefit accruing from project k and MC_k = marginal cost of project k ($k = 1, 2, \ldots, n$).

In this study it is impossible to determine the value of marginal benefits and marginal costs unless a model is developed which defines a relationship between cumulative gross investment in research and development in anaerobic systems and the rate of adoption. The marginal costs and marginal benefits of alternative projects are also unknown.

Learning Externalities

As mentioned in Chapter 2, the externality caused by learning is equal to the difference between the present value of the benefits from learning and the present value of the benefits under a circumstance in which no learning occurs.

Assume a number of years, H, for which the learning externality is to be estimated. The equation for the present value of the net benefits that occurs with no learning (B_{NL}) is:

$$B_{NL} = G_{NL} \sum_{t=t_b}^{t_{h0+H-1}} (1 + \alpha)^{-(t+1)} \cdot \int_t^{t+1} (PNG_0 e^{rt} - Y_{NL})dt \qquad (3.12)$$

where G_{NL} = fixed aggregate annual gas production when no learning occurs; Y_{NL} = uint cost of gas produced from anaerobic digestion systems with no learning, assumed to be constant over time; t_{bNL} = the point in time at which $PNG_0 e^{rt} = a[f(t)]^b$ with no learning.

Equation (3.9) can be used to represent the present value of net benefits from the adoption of anaerobic digestion systems when learning occurs. Hence the present value of the learning externality, B_{LE}, may be derived by subtracting the right-hand side of (3.12) from that of (3.9):

$$\begin{aligned} B_{LE} = \{G_a \sum_{t=t_b}^{t_{h0+H-1}} (1 + \alpha)^{-(t+1)} \cdot \int_t^{t+1} (PNG_0 e^{rt} - a[f(t)]^b)dt\} \\ - \{G_{NL} \sum_{t=t_{bNL}}^{t_{h0+H-1}} (1 + \alpha)^{-(t+1)} \cdot \int_t^{t+1} (PNG_0 e^{rt} - Y_{NL})dt\}. \end{aligned} \qquad (3.13)$$

In this study, problems arise in the calculation of the external benefits from learning because of the lack of a relationship between gross investment and the rate of adoption of anaerobic digestion systems. This problem will be discussed in greater detail in Chapter 5.

Externalities Resulting from a Nonmarket Price for Natural Gas

The method for evaluating the present value of an externality caused by a nonmarket price for natural gas is essentially identical to that in the previous analysis. The value of the externality (B_{ME}) will be equal to the difference between the present value of the benefits that will occur if an aanaerobic system is adopted using the market price for natural gas as a decision criterion, and those that will occur using a nonmarket price of natural gas as a decision criterion.

For the sake of clarification, it is assumed that the free market price for natural gas at t_{h0}, (PNG_{M0}) is greater than the nonmarket price of natural gas at t_{h0}, (PNG_{N0}). It is also assumed that the evaluation of the externality will be restricted to a planning period of H years.

In a procedure similar to that used in the previous section is followed, then the equation for the present value of the externality (B_{ME}) is:

$$B_{ME} = \{G_M \sum_{t=t_{bM}}^{t_{h0+H-1}} (1 + \alpha)^{-(t+1)} \cdot \int_t^{t+1} (PNG_{M0}e^{rt} - a[f(t)]^b)dt\}$$

$$- \{G_N \sum_{t=t_{bN}}^{t_{h0+H-1}} (1 + \alpha)^{-(t+1)} \cdot \int_t^{t+1} (PNG_{N0}e^{rt} - a[f(t)]^b)dt\}$$

where t_{bM} = the point in time at which $PNG_{M0}e^{rt} = a[f(t)]^b$ under free market conditions; G_M = aggregate annual gas production from anaerobic digestion systems under free market natural gas pricing conditions;

t_{bN} = the point in time at which $PNG_{N0}e^{rt} = a[f(t)]^b$ under nonmarket natural gas pricing conditions; G_N = aggregate annual gas production from anaerobic digestion systems under nonmarket pricing conditions.

When decisions whether or not to adopt anaerobic digestion technology are made using the nonmarket price for natural gas, and when the nonmarket price is lower than the market price, there will tend to be underinvestment in anaerobic digestion systems.

CHAPTER 4

EMPIRICAL ESTIMATION OF THE LEARNING FUNCTIONS

The first part of this chapter reviews the data sources and outlines the collection procedures followed in obtaining data required to empirically estimate the learning functions. A discussion of the functional forms and variables used in the regression analysis will follow. Finally, the empirical estimation of the learning functions and the associated statistical tests will be presented.

Data Sources and Collection Procedure: Gross Investment

As explained in Chapter 2, cumulative gross investment in research and development in anaerobic digestion systems which recover methane will be used as a surrogate for experience.

There are limited publications which review the amounts of funding for anaerobic digestion waste disposal systems. However, lists of funded projects with abstracts are available from Smithsonian Information Service, Congressional Hearings, United States Department of Agriculture, various National Science Foundation publications, program/project status reports from the U.S. Environmental Protection Agency, Energy Research and Development Administration and the U.S. Department of Energy. There are no sources known which accurately summarize gross investment in anaerobic digestion system research and development over any substantial length of time. The format of the research directories used is such that total funds are listed along with duration and the starting date of the research or development project.

Abstracts of the projects and researchers involved were used to determine if a particular project was related to the study of anaerobic digestion systems. Other investment data were attained by correspondence with individual researchers, sponsors, and firms involved with the study of anaerobic systems. The vast majority of the research and investment is currently sponsored by Federal and State governments; however, the need to contact individuals and firms arose when attempting to determine research spending through the 60's and to determine investment made by private firms.

There were three major problems encountered in the collection of gross investment data. The first problem was simply to get a complete picture of investment levels. In 1971 there was a marked increase in the availability of data from government publications, therefore there is a high degree of confidence in the completeness of this gross investment data from 1971 on. Prior to 1971, the data are more scarce. The potential to underestimate the level of gross investment becomes apparent. The problem was compensated for by the use of the report, "The Anaerobic Digestion of Livestock Wastes to Produce Methane: 1946-June 1975, A Bibliography with Abstracts", by G. Shaddock and J. Moore (1975). The bibliography was used as a cross-check to see if there was funding data recorded for the respective publications. If data were not already attained from one of the various sources, an attempt was made to contact the researchers involved by phone or letter.

The second problem in estimating cumulative gross investment levels became evident when it was necessary to subjectively determine the emphasis of a particular investment. In most cases, either from the abstract or from having read articles which had evolved from a particular project, it was relatively easy to determine intuitively if the spending in question could potentially have had an impact on learning in anaerobic digestion systems. Unfortunately, many projects have multiple objectives. In these cases, whether or not to include all or part of the spending in the compilation of cumulative gross investment data was a subjective decision based on experience.

In order to estimate quarterly spending, the total funds alloted for a project were divided by the number of quarters over the project's duration. This assumption that a project's spending is distributed equally through time is relatively arbitrary.

To summarize, the data gathered to calculate cumulative gross investment in livestock and poultry methane-generating disposal systems represent virtually all the spending made by the U.S. Department of Agriculture, the Agriculture Experiment Stations, the U.S. Environmental Protection Agency, the National Science Foundation, and the Energy Research and Development Agency/U.S. Department of Energy, over the past decade. The data also represent a major portion of the gross investment made by state governments, miscellaneous agencies and foundations, private firms and the aggregate gross investment made prior to 1967.

Data Sources and Collection Procedure: Gas Cost and Other Variables

In this study gas cost was used as an index of accumulated learning. Gas cost must be standardized from the various sources to reflect cost per unit, in this case $\$/10^6$Btu.

All the cost data were derived from individual studies or projects which involved some type of feasibility analysis. Data were available from thirty-four different feasibility studies or actual plant operations. Of these thirty-four sources, twenty-two had detailed enough information to estimate unit cost of the systems evaluated. In order for a cost estimate of methane generation disposal systems to be standardized to a unit cost, the study must have contained enough information to estimate the net annual production of gas in 10^6Btu. In some cases this figure was given. In most cases the annual production was easily derived. For example, a study may have estimated annual production in terms of cubic feet of gas. This value was then simply converted into a value reflecting the annual 10^6Btu of gas production. More complicated conversions were necessary when the annual 10^6Btu production had to be estimated from the capacity of the anaerobic digester system under evaluation. Typically, capacity is defined in terms of tons of manure or volatile solids added to the reactor per day or in terms of number of animals served by the anaerobic waste disposal system. Table 4.1 contains the rate of manure production from various animals and the corresponding gas conversions which were used in estimating annual 10^6Btu production in the above cases.

A crucial factor in the estimation of unit gas cost is the ability to calculate annual costs. Here again, in many cases an average annual cost was estimated in the cost study. Normally this annual cost was determined by amortizing the capital cost, using a percentage of capital cost to represent repairs, a percentage to represent taxes, and adding an estimation of the particular systems operating expenses. There are several variables represented in the calculation of annual cost; interest rate on capital, rate of repairs, rate of taxation, labor wage rate, and energy cost. The impact of these variables was compensated for by categorizing three types of cost studies so that dummy variables could be utilized in the OLS estimation.

With the knowledge of annual costs and net annual production at hand, a cost in terms of $\$/10^6$Btu can be estimated. These unit gas costs were then inflated to 1977 dollars using the total fixed nonresidential, gross private domestic investment price index.

One calculation, derived from an article by Rosenberg (1951), of unit costs required the conversion of British pounds to U.S. dollars. The conversion was made by inflating the British unit cost estimate to 1977 British pounds using the United Kingdom's wholesale price index for building material; then converting the pounds into dollars using the average 1977 exchange rate.

Table 4.1. Characteristics of Livestock and Poultry Manure of Primary Importance in this Study

Investigator	Source of Waste	Weight of Animal (lbs)	Raw Waste (lb/day/10^3 lb Animal)	Total Solids (lb/day/10^3 lb Animal)	Total Solids (% Raw Manure)	Volatile Solids (lb/day/10^3 lb Animal)	Volatile Solids (% Total Solids)	Gas Production (ft^3/lb V.S.)	Gas Produced (ft^3/10^3 lb Animal)	Gas Production (ft^3/lb raw waste)
Morris et al. (1975)	Dairy		85	10.6		8.7		4.7	40.7	
	Beef		58	7.4		5.9		6.7	39.9	
	Swine		50	7.2		5.9		7.3	43.1	
	Poultry		59	17.4		12.9		8.3	110.9	
Johnson et al. (1972)	Garbage									1.35
	Manure									1.11
	Cow Manure									0.71
Kispert et al. (1975)	Municipal Waste							7.4		
Biogas of Colo. (1977)	Feeder Cattle							3.54[a]		
Infeadi and Brown (1975)	Dairy	1,200	82		12.7		82.5		42-60	
	Beef	900	60		11.6		85.0		32-36	
	Swine	140	65		9.2		80.0		29-100	
Loehr (1973)	Poultry	4-5			23		74-79	9.9		
Pfeffer (1974)	Municipal Waste				52					2.06[a]
	Sludge				3		2.1	3.95[a]		
Ashware et al. (1977)	Cattle (environmental feedlot)			9.0[b]	15		80			
Costigane et al. (1974)	Hogs	100							80	
	Cattle	1,000							50	
	Poultry	5							80	
Taignaides et al. (1963)	Swine	50							63	
	Poultry	80							42	
	Dairy	71							80	

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[a] 1000 Btu per ft^3; others are approximately 600 Btu per ft^3

[b] (lb/day/animal)

There are operational and environmental factors which may have an impact on cost, that can be varied by managerial and design practices, and are expected to change with accumulated learning. Principally, there are four other variables that may influence cost but are not influenced by learning. These variables are the scale of the livestock or poultry operation, the ambient temperature of the operating location, the Btu value per cubic foot of product gas, and peculiarities associated with different types of cost studies.

The scale of an operation was standardized in number of tons of volatile solids added to the anaerobic waste disposal system per day. The average annual ambient temperature (C°) of the location of an anaerobic system was supplied by the cost study or was estimated. Three categories were defined to account for the peculiarities of different types of studies. The three categories were: cost studies which use only secondary sources ("paper" studies), cost studies which use actual lab or pilot plant data along with data available in secondary sources, and cost studies which evaluate actual full-scale operations. A summary of the relevant data is contained in Appendix 1.

Specification of Functional Forms and Variables Used to Estimate the Unit Cost Equations

Two functional forms were used to express the relationship between the dependent variable, Y_i, (unit cost), k explanatory variables, $X_{1i}, \ldots, X_{ki}$ and the disturbance term u_i.

The first is a linear relationship where:

$$Y_i = a + b_1X_{1i} + \ldots + b_kX_{ki} + u_i \quad (i = 1, 2, \ldots, m). \qquad (4.1)$$

In the second specification, the dependent and explanatory variables are related exponentially:

$$Y_i = aX_{1i}^{b_1} \cdot X_{2i}^{b_2} \cdot \ldots \cdot X_{k_i}^{b_k} \cdot \exp(u_i) \quad (i = 1, 2, \ldots, m) \qquad (4.2a)$$

or

$$\ell nY_i = \ell na + b_1\ell nX_{1i} + b_2\ell nX_{2i} + \ldots + b_k\ell nX_{ki} + u_i \qquad (4.2b)$$

$$(i = 1, 2, \ldots ,m).$$

It is assumed that the X_i and u_i are independent, that u_i has a mean of zero and u_i is independently distributed with an unknown variance σ^2 (Beals, 1972).

The intercept a, coefficients $b_1, \ldots, b_k$, and the parameters of the u distribution were estimated by ordinary least-squares (OLS) regression analysis.

As explained in Chapter 2, to calculate future net benefits it is necessary to estimate a relationship between cumulative gross investment and time. This relationship is then substituted into the unit cost function. To estimate the relationship between cumulative gross investment and time, the parameters of both the linear and squared functional forms were estimated using ordinary least squares.

Before an explanation of the individual variables used in specifying the unit cost functions is undertaken, the reasons for and methods of determining the lags associated with cumulative gross investment in anaerobic digestion systems are presented.

It is reasonable to expect that there will be some period of time between when learning resulting from investment is disseminated to other researchers and operations and is assimilated into the research work or plant operation. In the work conducted by Slane (1974), it was assumed that the gains from learning spread uniformly and at an equal rate from system to system.

Instead of using a fixed lag, a lag time was empirically estimated for each cost estimate. It was assumed that the lag time was directly associated with the date of the latest references used by a researcher or operator and the date of publication. For example, an author may have published a feasibility study on 6/76, but his most current references were dated 1/75, 12/74 and 6/74. This implies a time period of approximately six quarters from the time the information was available and when it was assimilated. Fortunately, it was possible to reasonably estimate this lag for all projects. Appendix A contains the dates used in estimating the lag. The resulting lag times ranged from one to three years. Actual plants had the longest lag times.

In addition to the lag explained above, another lag used in estimating the unit gas cost function was the lag just described plus two additional quarters.

The following is a list of the variables used in specifying and estimating the unit gas cost function:

Y_1 is the unit gas cost in 1977 dollars per 10^6Btu of gas produced.

Y_2 is the natural log of Y_1.

X_{1t-n} is the cumulative gross investment in thousands of 1977 dollars made for research and development in anaerobic waste disposal systems incorporating methane recovery in $t - n$, where n represents the number of years associated with the difference between when learning occurred and when it became available. (This lag was explained in greater detail earlier in this section).

X_{2t-n} is the natural log of X_{1t-n}.

$X_{2t-n/1/2}$ is the natural log of the thousands of 1977 dollars spent on cumulative gross investment in $t - n - 1/2$ (a lag of $n + 1/2$ years).

X_{3t-n} is the natural log of $1.33X_{1t-n}$ (explained in the last section).

S_1 is tons of volatile solids added to the digester per day.

S_2 is the natural log of S_1.

T_1 is the average annual temperature (C°) in the location of the intended or actual anaerobic waste disposal system.

T_2 is the natural log of T_1.

D_1 is a dummy variable associated with cost studies which evaluated actual operations.

D_2 is a dummy variable associated with cost studies which used data from lab or pilot plants as well as secondary data for the evaluation of specific anaerobic systems.

B_1 is the Btu value of the product gas per cubic foot.

B_2 is the natural log of B_1.

Characteristics of Capacity Ranges

Familiarity with anaerobic digestion systems indicates that a system which could be adopted for a 75,000 head cattle feedlot would differ significantly from one on a farm with 100 dairy cows. The difference in the design and management of the systems is so great that it was decided to make estimations of unit cost functions for four different capacity ranges. The capacity ranges were defined in terms of tons of volatile solids processed by the anaerobic waste disposal system per day. Using the information supplied in Table 4.1, these values can be converted to size ranges which are defined in terms of number of head of a particular animal. The results of these conversions are found in Table 4.2.

When the capacity ranges are characterized by the number of feeder cattle handled by the systems, it is realized that the type of feedlot will affect the production of volatile solids per day. In Table 4.2 the capacity ranges are estimated for two types of feedlots, an environmental feedlot and a concrete floor feedlot. The environmental feedlot is one where the urine and manure fall through a grating into a pit where manure can be collected daily (Ashare et al., 1977). The typical feedlot considered by Bio-Gas of Colorado, Inc., (1977) has a concrete floor where manure is scraped from the pens.

The Empirically Estimated Unit Cost Functions

The unit cost functions estimated by OLS methods are summarized in Tables 4.3 through 4.7.

Capacity Range I

Equation 4.3.2 indicates that for Capacity Range I a linear function has limited explanatory value, since the coefficient of determination is only 0.376, when the independent variables are X_{1t-n}, S_1, and T_1. An exponential function estimated using the natural log of the same variables (equation 4.4.1) has much higher coefficient of determination of 0.755. The estimated coefficient of T_2 is found to be not significant at the .25 level using the student t-test. By

Table 4.2. Animal Equivalents of Each Capacity Range

Capacity Range	Volatile Solids (Tons V.S./Day)	Number Cattle (Env. Feedlot)[1]	Number Cattle Concrete Floor[2]	Number Dairy Cows[3]	Number hogs[4]	Number Poultry[5]
I	0.022-0.30	7-100	8-110	4-62	77-1,100	931-13,300
II	0.31-0.94	100-300	110-330	63-188	1,100-3,300	13,300-39,900
III	0.75-8.5	240-2,700	260-3,000	150-1,700	2,640-29,700	31,900-359,100
IV	21-487.5	6,700-156,000	7,400-172,000	4,187-97,500	73,700-1,720,000	891,100-20,748,000

[1] Ashware et al. (1977)

[2] Bio-Gas of Colorado (1977)

[3] Jewell et al. (1976)

[4] Ifeadi et al. (1975)

[5] Slane (1974)

Table 4.3. Sample Results for the OLS Estimation of the Linear Unit Cost Functions: Capacity Ranges I through IV.

				Explanatory Variables										
Equation	Capacity Range	Dependent Variable	Constant	X_{1t-n}	S_1	T_1	D_1	D_2	B_1	R^2	F-Statistic	$\hat{\sigma}_u$	D-W	Number of Observations
4.3.1	I	Y_1	37.53* (4.31)	-0.0034** (2.42)						0.328	5.875**	15.14	1.868	11
4.3.2	I	Y_1	64.76** (1.99)	-0.0014 (.754)	-70.54 (1.14)	-3.01 (0.728)				0.376	3.01	0.657	1.860	11
4.3.3	II	Y_1	13.66* (4.33)	-0.00074 (1.64)						0.158	4.95	4.95	1.498	10
4.3.4	II	Y_1	26.37** (2.54)	-0.0014** (3.64)	0.440 (0.08)	-1.29 (1.66)	7.03** (3.63)	-1.55 (0.645)		0.797	8.05**	2.43	3.89	10
4.3.5	III	Y_1	18.1* (7.08)	-0.0024* (4.97)						0.683	24.7*	3.17	1.43	12
4.3.6	IV	Y_1	4.86* (6.50)	-0.00034* (3.24)						0.421	10.44*	1.5	1.31	14
4.3.7	IV	Y_1	4.03** (2.15)	-0.00019 (1.17)	-0.0051 (1.26)		2.42** (2.33)	-0.84 (0.66)	0.00017 (0.0065)	0.604	4.30**	1.24	1.92	14

Note: Number in parenthesis is the absolute value of the t-statistic.

*Indicates significance at the 1% level.

**Indicates significance at the 5% level.

Table 4.4. Sample Results for the OLS Estimation of the Exponential Unit Cost Functions: Capacity Range I

			Explanatory Variables										
Equation	Dependent Variable	Constant	X_{2t-n}	$X_{2t-n-1/2}$	X_{3t-n}	S_2	T_2	R^2	F-Statistic	$\hat{\sigma}_u$	D-W	Number of Observations	Percent Slope
4.4.1	Y_2	3.08 (1.08)	-0.263** (2.57)			-0.618* (3.11)	-0.177 (0.17)	0.755	11.3**	0.400	1.82	11	83
4.4.2	Y_2	3.52* (3.85)	-0.264** (2.78)			-0.595* (4.43)		0.785	19.3*	0.375	1.79	11	83
4.4.3	Y_2	3.58* (3.76)		-0.278** (2.72)		-0.590* (4.34)		0.781	18.8*	0.378	1.76	11	82
4.4.4	Y_2	3.60* (3.83)			-0.264** (2.78)	-0.594* (4.34)		0.785	19.26*	0.375	1.79	11	83

Note: Number in parenthesis is the absolute value of the t- statistic.

*Indicates significance at the 1% level.

**Indicates significance at the 5% level.

Table 4.5. Sample Results for the OLS Estimation of the Exponential Unit Cost Functions: Capacity Range II

Equation	Dependent Variable	Constant	Explanatory Variables							R^2	F-Statistic	$\hat{\sigma}_u$	D-W	Number of Observations	Percent Slope S
			X_{2t-n}	$X_{2t-n-1/2}$	X_{3t-n}	T_2	S_2	D_1	D_2						
4.5.1	Y_2	8.43* (4.79)	-0.230* (3.01)			-1.97** (2.25)	-0.127 (0.28)			0.510	4.82**	0.427	1.84	12	85
4.5.2	Y_2	3.76* (5.60)	-0.192** (2.48)					0.183 (0.71)	-0.506* (2.01)	0.616	5.80**	0.319	2.195	10	87
4.5.3	Y_2	3.94* (6.58)	-0.205** (2.83)						-0.577** (2.58)	0.643	9.10**	0.317	2.31	10	87
4.5.4	Y_2	4.07* (5.23)	-0.241** (2.59)							0.389	6.73**	0.415	2.08	10	85
4.5.5	Y_2	3.97* (6.58)		-0.214** (2.85)					-0.571**	0.645	9.19**	0.316	2.33	10	86
4.5.6	Y_2	4.00* (6.48)			-0.205** (2.83)				-0.577** (2.58)	0.643	9.106**	0.317	2.31	10	87

Note: Number in parenthesis is the absolute value of the t-statistic.

*Indicates significance at the 1% level.

**Indicates significance at the 5% level.

Table 4.6. Sample Results for the OLS Estimation of the Exponential Unit Cost Functions: Capacity Range III

Equation	Dependent Variable	Constant	Explanatory Variables				R^2	F-Statistic	$\hat{\sigma}_u$	D-W	Number of Observations	Percent Slope S
			X_{2t-n}	$X_{2t-n-1/2}$	S_2	T_2						
4.6.1	Y_2	8.48** (2.72)	-0.304** (2.49)		-0.641** (2.88)	-1.82 (1.42)	0.675	8.619**	0.464	1.64	12	81
4.6.2	Y_2	4.26* (4.24)	-0.287** (2.23)		-0.626** (2.66)		0.639	10.72*	0.489	1.24	12	82
4.6.3	Y_2	9.80* (15.88)	-1.08** (2.98)				0.418	8.89*	0.974	1.43	12	47
4.6.4	Y_2	3.67* (4.40)		-0.472** (3.16)			0.450	19.38*	0.660	1.38	12	72
4.6.5	Y_2	4.41* (4.39)		-0.316** (2.38)	-0.609** (2.64)		0.656	11.48*	0.477	1.25	12	80

Note: Number in the parenthesis is the absolute value of the t-statistic.

*Indicates significance at the 1% level.

**Indicates significance at the 5% level.

Table 4.7. Sample Results for the OLS Estimation of the Exponential Unit Cost Functions: Capacity Range IV

			Explanatory Variables												
Equation	Dependent Variable	Constant	X_{2t-n}	$X_{2t-n-1/2}$	X_{3t-n}	S_2	B_2	D_1	D_2	R^2	F-statistic	σ_u	D-W	Number of Observations	Percent Slope S
4.7.1	Y_2	5.15 (1.35)	-0.213** (2.19)			-0.418** (2.21)	1.44** (2.11)	0.255 (.80)	-0.35 (1.12)	0.643	4.89**	0.352	2.48	14	86
4.7.2	Y_2	-3.61 (1.08)	-0.288* (5.22)			-0.274 (1.80)	1.21** (2.04)			0.675	10.01*	0.335	2.80	14	82
4.7.3	Y_2	0.182 (0.064)	-0.280* (8.00)				0.435 (0.98)			0.609	11.13*	0.367	2.54	14	82
4.7.4	Y_2	3.10* (4.69)	-0.252* (4.24)			-0.048 (0.40)				0.581	10.03*	0.381	2.10	14	84
4.7.5	Y_2	2.92* (6.41)	-0.258* (4.62)							0.611	21.39*	0.367	2.19	14	84
4.7.6	Y_2	2.90* (6.38)		-0.261* (4.59)						0.607	21.12*	0.369	2.17	14	83
4.7.7	Y_2	2.99* (6.36)			-0.258* (4.62)					0.611	21.39*	0.367	2.19	14	84

Note: Number in parenthesis is the absolute value of the t-statistic.

*Indicates significance at the 1% level.

**Indicates significance at the 5% level.

dropping T_2, the R^2 is raised to 0.785 from 0.755 and the F-test for the equation 4.4.2 finds the equation significant at the 1 percent level. The t-statistic for the estimated parameters in equation 4.4.2 indicates that they are all significant, at least at the 2.5 percent level.

Recalling from Chapter 2, the percent slope of an equation of the form aX^b is $2^b \cdot 100$, in the case of equation 4.4.2 the percent slope is 83. This percent slope implies that for every doubling in cumulative gross investment there is a decrease of 17 percent in the cost per 10^6Btu of gas produced.

If $X_{2t-n-1/2}$ is used along with S_2 to estimate the unit cost (equation 4.4.3), it will be noted that the significance of parameters is weakened. Thus it was decided that equation 4.4.2 would be used in the analysis.

Capacity Range II

When the linear equations 4.3.3 and 4.3.4 for the unit cost function are compared with the exponential equations in Table 4.5 it is found that the parameters related to cumulative gross investment are highly significant with less use of other explanatory variables in the exponential form. For this reason and because of empirical evidence presented in Chapter 2, the exponential form will be considered.

Using the t-test for the parameters in equations 4.5.1 and 4.5.2, it is found that the explanatory variables S_2 and D_1 are not significant at the 25 percent level. It is expected that S_2 might be dropped in this capacity range because the upper limit is only three times the lower limit. In the first capacity range the upper limit is more than fifteen times the lower limit.

The highest R^2 is found when only X_{2t-n} and D_2 are used as explanatory variables (equation 4.5.3). All the parameters in equation 4.5.3 are significant at the 2.5 percent level and the F-test indicates significance of the equation at the 5 percent level. The percent slope related to cumulative gross investment in equation 4.5.3 is 87, which is in the same range as the estimate for the first capacity range.

The use of $X_{2t-n-1/2}$ (equation 4.5.5) does not change the statistical indicators significantly and implies a less conservative estimate of the present slope. Therefore equation 4.5.3 will be used in further analyses.

Capacity Range III

The explanatory ability of the exponential functions in this range tends to be less than the explanatory ability of the simple linear function. The linear equation 4.3.5 has a coefficient of determination of 0.683, while an exponential estimate using X_{2t-n} and S_2 has an R^2 of only 0.639. The F-significance of both equations is at the one percent level.

The previous research, as well as the majority of the estimates made in this study, indicate that the exponential form theoretically best estimates the learning relationship. For this reason the equation

4.6.2 will be used as the estimate of the unit cost function in this capacity range.

Capacity Range IV

Estimations of unit cost functions for Capacity Range IV clearly show that the exponential form (Table 4.7) provides a statistically better fit than the linear estimates (equations 4.3.6 and 4.3.7).

Referring to equation 4.7.5 which uses only cumulative gross capacity as the explanatory variable, a coefficient of determination is found to be 0.611 and the significance of the parameters is at the 1 percent level. The addition of other explanatory variables has little impact on the R^2. The equation using $X_{2t-n-1/2}$ (equation 4.7.6) was found to be statistically weaker than the equation using X_{2t-n}. It was decided that equation 4.7.5 would be used as the representative unit cost function.

A Summary of the Empirically Estimated Learning Functions

In order to determine a learning function for each capacity range, the mean value of all variables, other than the cumulative gross investment, is substituted so that the only fluctuations being considered are those relative to changes in the proxy for learning. The equations for the different capacities are:

Capacity Range I: .02 to .31 tons of VS/day

Mean tons of VS/day = .157

Mean number of cattle from an environmental feedlot = 50

Learning function:

$$\$/10^6\text{Btu} = 101.77(X_{1t-n})^{-0.264}. \tag{4.3}$$

Capacity Range II: .31 to .94 tons of VS/day

Mean tons of VS/day = .61

Mean number of cattle from an environmental feedlot = 195

Learning function:

$$\$/10^6\text{Btu} = 51.19(X_{1t-n})^{-0.205}. \tag{4.4}$$

Capacity Range III: .75 to 8.5 tons of VS/day

Mean tons of VS/day = 2.4

Mean number of cattle from an environmental feedlot = 764

Learning function:

$$\$/10^6\text{Btu} = 40.62(X_{1t-n})^{-0.287}. \tag{4.5}$$

Capacity Range IV: 21 to 487.5 tons of VS/day

Mean tons of VS/day = 178

Mean number of cattle from an environmental feedlot = 56,870

Learning Function:

$$\$/10^6\text{Btu} = 18.46(X_{1t-n})^{-0.258}. \tag{4.6}$$

The Empirically Estimated Rate of Cumulateve Gross Investment

In order to conduct the analysis outlined in Chapter 3, a relationship between cumulative gross investment and time is necessary.

In 1973 there was a marked increase in the rate of spending on research and development in anaerobic digestion and anaerobic digester systems for methane recovery. Using quarterly data from 1973 to mid-1977, the following equations were estimated:

	Corrected R^2	Constant	Coefficient	
$X_1 = 3056.7 + 793.4Q$	.956	.005	.005	(4.7)
$X_1 = 5486.96 + 46.2Q^2$	.995	.005	.005	(4.8)

where X_1 = cumulative gross investment (in thousands of 1977 dollars).

Q = quarter, where first quarter ends 10/73.

Both equations 4.7 and 4.8 have a relatively high R^2 and the significance of the coefficients is the same in both cases. It is generally accepted by standard scientific methods to use the simplest hypothesis to explain the data. Therefore, in the following analysis, the rate of cumulative gross investment will be represented by the linear function.

The Effect of Underestimating Cumulative Gross Investment

Equations 4.4.4, 4.5.6, and 4.4.7 represent unit cost function estimates using X_{3t-n} as one of the explanatory variables. As defined earlier, X_{3t-n} is the natural log of $1.33X_{1t-n}$. Equations were estimated using X_{3t-n} as an explanatory variable to see if an underestimate in the amount of cumulative gross investment would affect the percent slope, S. It was found that even if the actual cumulative gross investment was 33.3 percent greater, the percent slope would remain unchanged. This is an important realization for an analysis which considers future benefits under various cumulative investment rates as this study does.

CHAPTER 5

RESULTS OF ANALYSIS

In this chapter, the estimated learning functions summarized in Chapter 4 will be used to illustrate the application of the decision frameworks outlined in Chapter 3. The chapter will also examine the sensitivity of the breakeven points and net benefits to changes in input parameters. In particular, the effects of changes in the rate of gross investment, the real rate of natural gas price increase and the discount rate will be examined.

The Determination of Breakeven Points for Each Capacity Range: Private Decision Maker

The breakeven point, t_b, was determined for the average firm in each of the capacity ranges. This point, expressed by equation (3.4), represents the intersection of the cost of producing a unit of gas as a function of time (3.2) and the rate of increase in price of natural gas (3.3).

In order to calculate breakeven points, it was necessary to derive a time trend equation from (4.7) to represent lagged cumulative gross investment as a function of time (in years) and substitute this into the learning functions to obtain a relationship between unit gas cost and time. When equation (4.7) is expressed in years, the result is:

$$X_1 = 3057 + 3173t \qquad (5.1)$$

where the first year begins 7/73.

Recalling from Chapter 4, it was determined that there exists a lag ranging from one to three years between cumulative gross investment and the investment's effect on unit gas cost. For this analysis, an average lag of 1.5 years will be assumed. An equation must then be derived for $X_{1t-1.5}$ from equation (5.1). The result is

$$X_{1t-1.5} = 3057 + 3173t \qquad (5.2)$$

where the first year begins 1/75.

This analysis undertaken in this chapter will use 7/77 as the beginning of the period under evaluation. Therefore the last step in obtaining a substitutable equation is to modify equation (5.2) appropriately:

$$X_{1t-1.5} = 11015 + 3173t. \qquad (5.3)$$

Equation (5.3) may now be substituted into equations (4.3) through (4.6) to obtain:

Capacity Range	Learning Function	
I	$Y_1 = 101.77\ (11015 + 3173t)^{-0.264}$	(5.4)
II	$Y_1 = 51.19\ (11015 + 3173t)^{-0.205}$	(5.5)
III	$Y_1 = 40.62\ (11015 + 3173t)^{-0.287}$	(5.6)
IV	$Y_1 = 18.48\ (11015 + 3173t)^{-0.258}.$	(5.7)

For illustrative purposes, values were assumed for two parameters: $PNG_0 = 1.95$, the average price paid for 10^6Btu of natural gas in 1977 in the U. S. (in dollars); $r = 0.04$, real rate of natural gas price increase. Given these assumptions, equation (3.3) may be rewritten as

$$PNG_0 = 1.95e^{0.04t}. \tag{5.8}$$

The right-hand side of (5.1), (5.2), (5.3) and (5.4) was equated with the right-hand side of (5.5) and solved for t. The resulting set of breakeven points, t_b, for each capacity range are summarized in Tables 5.1 through 5.4. These points represent the year in which the cost producing unit of gas from anaerobic digestion is equal to the price paid for the same unit of natural gas purchased from a utility company.

A 70 percent confidence interval for predictions derived from the four learning functions was calculated using the methods outlined by Kelejian and Oates (1974, pp. 111-16). The unit gas cost estimated

Table 5.1. Number of Years from 7/77 Until the Breakeven Point (t_b): Capacity Range I

Price of Natural Gas in 1977 (PNG_0)	Real Rate of Increase of PNG_0 (r)	Aggregate Annual Gross Investment (1977 Dollars)				
		2.1×10^6	3.2×10^6	3.2×10^6	3.2×10^6	4.2×10^6
		Number of Years from 7/77 Until Breakeven (t_b)				
		50 Percent Confidence	85 Percent Confidence	50 Percent Confidence	15 Percent Confidence	50 Percent Confidence
1.50	0.00	100+	100+	100+	100+	100+
1.50	0.02	55.5	76.0	51.0	30.0	48.5
1.50	0.04	31.0	41.0	29.0	18.5	27.5
1.50	0.06	22.0	28.5	20.5	14.0	20.0
1.75	0.00	100+	100+	100+	100+	100+
1.75	0.02	49.5	70.0	45.5	25.5	42.5
1.75	0.04	28.0	38.0	26.0	16.0	24.5
1.75	0.06	20.0	26.5	18.5	12.0	18.0
1.95	0.00	100+	100+	100+	100+	100+
1.95	0.02	45.0	60.5	41.0	25.0	38.5
1.95	0.04	25.5	33.0	24.0	15.0	22.5
1.95	0.06	18.5	23.0	17.0	11.0	16.5

Table 5.2. Number of Years from 7/77 Until the Breakeven Point (t_b): Capacity Range II

		Aggregate Annual Gross Investment (1977 Dollars)				
		2.1×10^6	3.2×10^6	3.2×10^6	3.2×10^6	4.2×10^6
		Number of Years from 7/77 Until Breakeven (t_b)				
Price of Natural Gas in 1977 (PNG_0)	Real Rate of Increase of PNG_0 (r)	50 Percent Confidence	85 Percent Confidence	50 Percent Confidence	15 Percent Confidence	50 Percent Confidence
1.50	0.00	100+	100+	100+	100+	100+
1.50	0.02	55.5	71.0	52.0	34.0	50.0
1.50	0.04	30.5	38.5	30.0	20.0	28.0
1.50	0.06	21.0	26.5	20.5	14.0	19.5
1.75	0.00	100+	100+	100+	100+	100+
1.75	0.02	49.5	65.0	46.0	29.5	43.5
1.75	0.04	27.5	35.0	26.0	17.0	24.5
1.75	0.06	19.0	24.5	18.0	12.0	17.5
1.95	0.00	100+	100+	100+	100+	100+
1.95	0.02	44.5	60.5	41.5	24.5	39.5
1.95	0.04	25.0	35.5	23.5	15.0	22.5
1.95	0.06	17.5	24.5	17.0	11.0	16.0

Table 5.3. Number of Years from 7/77 Until the Breakeven Point (t_b): Capacity Range III

		Aggregate Annual Gross Investment (1977 Dollars)				
		2.1×10^6	3.2×10^6	3.2×10^6	3.2×10^6	4.2×10^6
		Number of Years from 7/77 Until Breakeven (t_h)				
Price of Natural Gas in 1977 (PNG_0)	Real Rate of Increase of PNG_0 (r)	50 Percent Confidence	85 Percent Confidence	50 Percent Confidence	15 Percent Confidence	50 Percent Confidence
1.50	0.00	40.0	100+	26.5	0.5	20.0
1.50	0.02	13.0	33.0	11.0	0.5	9.5
1.50	0.04	8.5	19.0	7.5	0.5	6.5
1.50	0.06	6.5	14.0	5.5	0.0	5.0
1.75	0.00	22.0	100+	14.5	0.0	11.0
1.75	0.02	9.0	27.5	7.5	0.0	6.0
1.75	0.04	6.0	16.5	5.0	0.0	4.5
1.75	0.06	5.0	12.0	4.0	0.0	3.5
1.95	0.00	13.5	100+	9.0	0.0	6.5
1.95	0.02	6.5	23.5	5.0	0.0	4.5
1.95	0.04	4.5	14.5	4.0	0.0	3.5
1.95	0.06	3.5	10.5	3.0	0.0	2.5

Table 5.4. Number of Years from 7/77 Until the Breakeven Point (t_b): Capacity Range IV

		Aggregate Annual Gross Investment (1977 Dollars)				
		2.1×10^6	3.2×10^6	3.2×10^6	3.2×10^6	4.2×10^6
		Number of Years from 7/77 Until Breakeven (t_b)				
Price of Natural Gas in 1977 (PNG_0)	Real Rate of Increase of $PNG_0(r)$	50 Percent Confidence	85 Percent Confidence	50 Percent Confidence	15 Percent Confidence	50 Percent Confidence
1.50	0.00	2.5	27.0	2.0	0.0	1.5
1.50	0.02	1.5	10.0	1.5	0.0	1.0
1.50	0.04	1.0	6.5	1.0	0.0	1.0
1.50	0.06	1.0	5.1	1.0	0.0	0.5
1.75	0.00	0.0	13.0	0.0	0.0	0.0
1.75	0.02	0.0	6.5	0.0	0.0	0.0
1.75	0.04	0.0	4.5	0.0	0.0	0.0
1.75	0.06	0.0	3.5	0.0	0.0	0.0
1.95	0.00	0.0	7.0	0.0	0.0	0.0
1.95	0.02	0.0	4.0	0.0	0.0	0.0
1.95	0.04	0.0	3.0	0.0	0.0	0.0
1.95	0.06	0.0	2.5	0.0	0.0	0.0

by a function which represents the lower boundary of a 70 percent confidence interval has a 15 percent probability that the estimated value will be less than or equal to the actual unit gas cost. The function defining the upper boundary of a 70 percent confidence interval has associated with it an 85 percent probability that the value will be less than, or equal to, the actual unit gas cost.

Referring to Tables 5.1 through 5.4, the number of years until the breakeven point, t_b, is estimated with a 15 percent and an 85 percent probability that the breakeven point will occur in or less than the number of years presented in the tables.

Calculation of the Present Value of Net Benefits: Private Decision Maker

The present value of net benefits for the private decision maker can be found using equation (3.5). The net benefits accruing to a firm with a plant that operates twenty years is found by summing the discounted annual net benefits from year t_b until $t_b + 20$. Along with the assumed values for PNG_0 and r, a value must be assumed for α. In this example, α will be 0.07, which is approximately the current discount rate used in cost/benefit analyses conducted by federal agencies. When values for these parameters, an estimated learning function, and t_b are substituted into equation (3.5), the resulting equation for net benefits accruing to the average firm in Capacity Range IV per unit of gas produced annually is:

$$B = G \sum_{t=0}^{19} (1.07)^{-(t+1)} \int_{t}^{t+1} [1.95e^{0.04t} - 18.46(11015 + 3173t)^{-0.258}]dt \quad (5.9)$$

where $G = 1$.

When equation (5.9) is solved for B, the resulting present value of the net benefits per annual 10^6Btu of gas produced by the average firm in Capacity Range IV is \$15.65. When B is calculated for the intermediate capacity ranges, the present value of net benefits is \$4.30 per 10^6Btu of gas produced annual for a firm in Capacity Range II and \$10.62 for a firm in Capacity Range III. (See Tables 5.5 through 5.7 for the present value of net benefits computed using other parameter values.)

Using conversions adopted from Jewell and Morris (1974), one pound of volatile solids from beef cattle manure will result in approximately 4,000 Btu of product gas. Using this information, the total net benefits can now be computed for an average operaton in the three capacity ranges under consideration. The total net benefits are found by multiplying the present value of net benefits from each 10^6Btu of gas produced annually by the number actually produced annually. The results are:

Table 5.5. The Present Value (7/77) of Net Benefits per 10^6 Btu of Annual Gas Production for a Firm With a 20-Year Plant Life Which Starts Production at the Breakeven Point (t_b): Capacity Range II

			Aggregate Annual Gross Investment (1977 Dollars)				
			2.1×10^6	3.2×10^6	3.2×10^6	3.2×10^6	4.2×10^6
			Present Value of Net Benefit ($)				
Price of Natural Gas in 1977 (PNG_0)	Real Rate of Increase of $PNG_0(r)$	Discount Rate (α)	50 Percent Confidence	85 Percent Confidence	50 Percent Confidence	15 Percent Confidence	50 Percent Confidence
1.50	0.02	0.05			0.0		
1.50	0.02	0.07	0.0	0.0	0.0	0.51	0.0
1.50	0.02	0.1			0.0		
1.50	0.04	0.05			7.25		
1.50	0.04	0.07	2.65	0.0	2.75	3.80	2.91
1.50	0.04	0.1			0.67		
1.95	0.02	0.05			0.0		
1.95	0.02	0.07	0.0	0.0	0.0	1.36	0.0
1.95	0.02	0.1			0.0		
1.95	0.04	0.05			9.39		
1.95	0.04	0.07	4.19	3.23	4.30	6.14	4.65
1.95	0.04	0.1			1.95		

Table 5.6. The Present Value (7/77) of Net Benefits per 10^6 Btu of Annual Gas Production for a Firm With a 20-Year Plant Life Which Starts Production at the Breakeven Point (t_b): Capacity Range III

			Aggregate Annual Gross Investment (1977 Dollars)				
			2.1×10^6	3.2×10^6	3.2×10^6	3.2×10^6	4.2×10^6
			Present Value of Net Benefit ($)				
Price of Natural Gas in 1977 (PNG_0)	Real Rate of Increase of PNG_0(r)	Discount Rate (α)	50 Percent Confidence	85 Percent Confidence	50 Percent Confidence	15 Percent Confidence	50 Percent Confidence
1.50	0.02	0.05			3.95		
1.50	0.02	0.07	2.06	0.56	2.41	7.21	2.86
1.50	0.02	0.01			1.10		
1.50	0.04	0.05			9.54		
1.50	0.04	0.07	5.99	1.48	6.42	10.80	6.88
1.50	0.04	0.1			3.54		
1.95	0.02	0.05			7.20		
1.95	0.02	0.07	4.37	1.27	5.12	12.89	5.88
1.95	0.02	0.1			3.06		
1.95	0.04	0.05			14.63		
1.95	0.04	0.07	9.51	6.15	10.62	18.56	11.09
1.95	0.04	0.1			6.64		

Table 5.7. The Present Value (7/77) of Net Benefits per 10^6 Btu of Annual Gas Production for a Firm With a 20-year Plant Life Which Starts Production at the Breakeven Point (t_b): Capacity Range IV

			Aggregate Annual Gross Investment (1977 Dollars)				
			2.1×10^6	3.2×10^6	3.2×10^6	3.2×10^6	4.2×10^6
			Present Value of Net Benefit ($)				
Price of Natural Gas in 1977 (PNG_0)	Real Rate of Increase of PNG_0 (r)	Discount Rate (α)	50 Percent Confidence	85 Percent Confidence	50 Percent Confidence	15 Percent Confidence	50 Percent Confidence
1.50	0.02	0.05			7.36		
1.50	0.02	0.07	5.10	4.22	5.77	10.05	6.24
1.50	0.02	0.1			4.05		
1.50	0.04	0.05			12.40		
1.50	0.04	0.07	8.69	6.67	9.64	13.64	10.07
1.50	0.04	0.1			6.70		
1.95	0.02	0.05			13.46		
1.95	0.02	0.07	10.20	5.28	10.99	15.74	11.57
1.95	0.02	0.1			8.26		
1.95	0.04	0.05			19.47		
1.95	0.04	0.07	14.86	10.56	16.65	20.40	16.23
1.95	0.04	0.1			11.51		

Capacity Range	Mean Annual Gas Production (10^6Btu)	Present Value of Net Benefits
II	1,781	$ 7,659
III	12,140	$ 128,926
IV	519,760	$8,134,244

Substituting the breakeven points found for a 70 percent confidence interval, the corresponding 70 percent confidence interval for the estimated learning functions, and the other previously assumed parameter into equation (3.5) results in a 70 percent confidence interval for the net benefits. Table 5.8 contains the 15 percent confidence and 85 percent confidence present value of net benefits per 10^6Btu produced annually for a twenty year plant life and the present value of the net benefits for the average plant, in three capacity ranges.

The individual decision maker must, of course, consider the benefits and costs associated with alternative uses of the resources required to adopt an anaerobic waste disposal system for methane recovery. The breakeven points for firms in Capacity Ranges I and II are so far in the future that under the assumed values for the parameters PNG_0, r, and α, it is doubtful that anaerobic digestion should be considered in current investment decisions. However, for

Table 5.8. The Present Value of Net Benefits for a Firm With a 20-Year Plant Life, When Annual Aggregate Gross Investment is 3,173,000, (r) is .04, (PNG_0) is 1.95 and (α) is .07

		P.V. of Net Benefits per Annual 10^6Btu of Gas Produced ($)			P.V. of Net Benefits if the Average Annual 10^6Btu of Gas is Produced ($)		
Capacity Range	Average Annual 10^6Btu of Gas Produced	85 Percent Confidence	50 Percent Confidence	15 Percent Confidence	85 Percent Confidence	50 Percent Confidence	15 Percent Confidence
II	1,781	3.23	4.30	6.14	5,752	7,659	10,935
III	12,140	6.15	10.62	17.56	74,661	128,926	213,178
IV	519,760	10.56	15.65	20.40	5,490,000	8,134,244	10,600,000

firms in the two larger capacity ranges, this technology should be considered as an investment alternative under the conditions described.

Calculation of the Present Value of Net Benefits: An Aggregate Situation

As stated in Chapter 3, an objective of this section is to use the present value of the net benefits per 10^6 Btu produced annually to determine the minimum fixed aggregate annual gas product on required such that the present value of gross investment over a prescribed planning period (in this case \$3,173,000 annually over ten years, from 7/77 to 7/87) is equal to the present value of the net benefits of aggregate gas production over the same period of time.

The minimum fixed aggregate annual gas production described above can be calculated by substituting the appropriate values into equation (3.10). The results of substituting the assumed values for PNG_0, r, α, t_b, and the learning function for Range IV (equation 5.7) are:

$$G_a = \frac{\sum_{t=0}^{19} (1.07)^{-(t+1)} \int_t^{t+1} 3{,}173{,}000t\, dt}{\sum_{t=0}^{19} (1.07)^{-(t+1)} \int_t^{t+1} [1.95e^{0.04t} - 18.96(11015+3173t)^{-0.258}]dt} \tag{5.10}$$

$$= \frac{\$15{,}775{,}000}{\$7.11/10^6 \text{Btu of gas produced annually}}$$

$$= 2{,}218{,}700 \quad 10^6 \text{Btu of gas produced annually.}$$

The numerator represents the discounted value of gross investment of $3,173,000 per year in anaerobic digestion systems for ten years, from 7/77 to 7/87. The denominator is the present value of the net benefits from producing 10^6Btu annually for the same ten years. The minimum fixed aggregate 10^6Btu of gas that must be produced annually, G_a, such that the present value of the net benefits is equal to the present value of the gross investment by 7/87, is 2,218,700 10^6Btu (G_a can be calculated for other situations and capacity ranges by dividing the appropriate values from Tables 5.9 and 5.10 into the corresponding value found in Table 5.11).

Since the average operation in Capacity Range IV can produce approximately 519,760 10^6Btu annually, an aggregate production of 2,218,700 10^6Btu annually implies that four to five operations of average size must operate from the breakeven point (t_b) to realize the desired situation. Another way of interpreting this value for aggregate gas production is that the manure from at least 242,000 cattle in an environmental feedlot must be used to produce methane in order for the present value of net benefits to equal the present value of gross investment.

The potential aggregate 10^6Btu gas production from manure for the U. S. and other regions was estimated from 1974 estimates of the available manure (Table 5.12) using conversions presented by Morris et al. (1975). From the values in Table 5.13, it can be shown that

Table 5.9. The Present Value (7/77) of Net Benefits Accruing per 10^6 Btu of Annual Gas Production from the Breakeven Point (t_b) Until the End of the Planning Horizon (7/87): Capacity Range III

Price of Natural Gas in 1977 (PNG_0)	Real Rate of Increase of PNG_0(r)	Discount Rate (α)	Aggregate Annual Gross Investment (1977 Dollars)				
			2.1×10^6	3.2×10^6	3.2×10^6	3.2×10^6	4.2×10^6
			Present Value of Net Benefit ($)				
			50 Percent Confidence	85 Percent Confidence	50 Percent Confidence	15 Percent Confidence	50 Percent Confidence
1.50	0.02	0.05			0.0		
1.50	0.02	0.07	0.0	0.0	0.0	3.24	0.02
1.50	0.02	0.1			0.0		
1.50	0.04	0.05			0.29		
1.50	0.04	0.07	0.07	0.0	0.23	4.39	0.46
1.50	0.04	0.1			0.17		
1.95	0.02	0.05			2.27		
1.95	0.02	0.07	0.36	0.0	2.15	6.78	1.15
1.95	0.02	0.1			2.04		
1.95	0.04	0.05			2.22		
1.95	0.04	0.07	1.42	0.0	1.92	8.27	2.44
1.95	0.04	0.1			1.52		

Table 5.10. The Present Value (7/77) of Net Benefits Accruing per 10^6 Btu of Annual Gas Production from the Breakeven Point (t_b) Until the End of the Planning Horizon (7/87): Capacity Range IV

			Aggregate Annual Gross Investment (1977 Dollars)				
			2.1×10^6	3.2×10^6	3.2×10^6	3.2×10^6	4.2×10^6
			Present Value of Net Benefit($)				
Price of Natural Gas in 1977 (PNG_0)	Real Rate of Increase of PNG_0 (r)	Discount Rate (α)	50 Percent Confidence	85 Percent Confidence	50 Percent Confidence	15 Percent Confidence	50 Percent Confidence
1.50	0.02	0.05			2.45		
1.50	0.02	0.07	1.66	0.0	2.19	5.54	2.46
1.50	0.02	0.1			1.84		
1.50	0.04	0.05			3.76		
1.50	0.04	0.07	2.82	0.36	3.34	6.60	3.60
1.50	0.04	0.1			2.79		
1.95	0.02	0.05			6.20		
1.95	0.02	0.07	5.16	1.03	5.61	9.78	5.96
1.95	0.02	0.1			4.85		
1.95	0.04	0.05			7.90		
1.95	0.04	0.07	6.65	2.36	7.11	10.48	7.46
1.95	0.04	0.1			6.08		

Table 5.11. The Present Value of Fixed Aggregate Gross Investment Cver a Ten Year Period

Discount Rate (α)	Annual Aggregate Gross Investment (1977 $/Year)	Present Value of Ten Years of Aggregate Gross Investment ($)
0.05	2.1×10^6	12.75×10^6
0.05	3.2×10^6	19.26×10^6
0.05	4.2×10^6	25.61×10^6
0.07	2.1×10^6	10.44×10^6
0.07	3.2×10^6	15.78×10^6
0.07	4.2×10^6	20.98×10^6
0.1	2.1×10^6	7.74×10^6
0.1	3.2×10^6	11.69×10^6
0.1	4.2×10^6	15.65×10^6

Table 5.12. Recoverable Manure from Livestock and Poultry, 1974

	Total (tons)	Recoverable Manure				
		Less than Capacity Range I	Capacity Range I	Capacity Range II	Capacity Range III	Capacity Range IV
		Percent of Total				
United States						
Beef Cattle	1,897,000	0.7	47.1	21.2	31.0	-
Dairy Cattle	20,358,000	2.4	48.8	35.2	13.6	-
Feeder Cattle	16,000,000	-	14.0	11.8	15.1	59.1
Hogs	5,538,000	6.3	77.2	16.5	-	-
Poultry	3,259,000	5.5	15.5	27.0	52.0	-
Feedlot Region						
(AZ, CA, CO, KS, NE, NM, OK, TX)						
Beef Cattle	753,000	0.5	43.3	27.0	29.2	-
Dairy Cattle	2,587,152	2.9	17.5	30.7	51.8	-
Feeder Cattle	9,624,403	-	4.5	4.8	10.4	80.3
Hogs	696,239	19.0	67.0	13.0	-	-
Poultry	731,462	2.0	7.5	13.3	77.2	-
ARIZONA						
Beef Cattle	17,956	0.1	10.4	25.1	64.4	-
Dairy Cattle	160,144	1.7	2.4	9.1	86.8	-
Feeder Cattle	638,450	-	-	0.1	2.8	97.1
Hogs	8,512	2.0	20.6	77.4	-	-
Poultry	13,301	3.2	19.8	11.1	65.9	-

Sources: Van Dyne and Gilbertson (1978) and USDA (1978).

Table 5.13. Potential Gross Annual Gas Production from Recoverable Livestock and Poultry Manure, 1974.

	Potential Gross Annual Gas Production					
	Total	Less Than Capacity Range I	Capacity Range I	Capacity Range II	Capacity Range III	Capacity Range IV
			10^9 Btu			
United States						
Beef Cattle	8,783	61	4,137	1,871	2,723	-
Dairy Cattle	128,430	3,082	62,674	45,207	17,466	-
Feeder Cattle	74,080	-	10,371	8,741	11,186	43,781
Hogs	39,764	2,505	30,698	6,561	-	-
Poultry	24,051	1,323	3,768	6,494	12,506	-
Livestock and Poultry	275,116 (100)[a]	6,971 (3)[a]	111,608 (40)[a]	68,874 (25)[a]	43,881 (16)[a]	43,781 (16)[a]
Feedlot Region						
(AZ, CA, CO, KS, NE, NM, OK, TX)						
Beef Cattle	3,490	17	1,511	942	1,019	-
Dairy Cattle	16,589	480	2,902	5,091	8,590	-
Feeder Cattle	44,782	-	2,005	2,139	4,857	35,782
Hogs	4,999	949	3,349	650	-	-
Poultry	5,398	108	405	718	4,167	-
Livestock and Poultry	75,683 (100)[b] (27.5)[d]	1,556 (2)[b] (22.3)[d]	10,172 (13)[b] (9.1)[d]	9,540 (13)[b] (13.8)[d]	18,633 (25)[b] (42.5)[d]	35,782 (47)[b] (81.7)[d]

Table 5.13, continued

	Potential Gross Annual Gas Production					
	Total	Less Than Capacity Range I	Capacity Range I	Capacity Range II	Capacity Range III	Capacity Range IV
	10^9 Btu					
Arizona						
Beef Cattle	83	0.1	8.6	20.9	53.5	-
Dairy Cattle	1,027	17.5	24.6	93.4	891	-
Feeder Cattle	2,956	-	-	3.0	82.8	2,870
Hogs	61	0.1	12.6	47.3	-	-
Poultry	98	3.1	19.4	10.9	64.7	-
Livestock and Poultry	4,225 (100)[c] (1.8)[d]	22 (-)[c] (-)[d]	65 (2)[c] (-)[d]	176 (4)[c] (0.3)[d]	1,092 (26)[c] (2.5)[d]	2,870 (68)[c] (6.6)[d]

Sources: Van Dyne and Gilbertson (1978); USDA (1978); and Morris et al. (1975).

[a] Number in parenthesis is percent of total U.S. potential production.

[b] Number in parenthesis is percent of total Feedlot Region potential production.

[c] Number in parenthesis is percent of total Arizona potential production.

[d] Number in parenthesis is percent of U.S. potential production in the Capacity Range indicated.

2,218,700 10^6Btu represents only about five percent of the total potential gas production from manure in the U.S. for Capacity Range IV.

At the present time, there is only one producing operation which is in Capacity Range IV. This operation is run by Thermonetics, Incorporated, and is located in Guymon, Oklahoma. The annual capacity is approximately 584,000 10^6Btu (Meckert, 1978). Approximately three more operations of this capacity should have been producing as of 7/77 to recover an annual aggregate gross investment of $3,173,000 by 7/87. The number of operations needed to recover this investment will increase because of a decreasing number of production years between start-up and the hypothetical planning horizona.

Considering the aggregate situation under a ten year planning horizon, a 15 percent and 85 percent confidence prediction can be made regarding the amount of methane which need be produced to recover an annual gross investment of $3,173,000 from 7/77 to 7/87. If only Capacity Range IV is considered, the results can be calculated as explained earlier in this Chapter, and are given in Table 5.14.

These results can be interpreted to mean that a policy maker is 85 percent sure that if 731,336 head from an environmental feedlot of average size in Capacity Range IV or if 15.3 percent of the nation's annual potential 10^6Btu gas production is actually produced, then the investment of $3,173,000 a year will be recovered or exceeded by 7/87 under the given assumptions.

Table 5.14. The Aggregate Situation: A 70 Percent Confidence Interval

	Confidence	
Capacity Range IV	15 Percent	85 Percent
Minimum fixed aggregate annual 10^6 Btu of gas production (G_a)	1,505,000	6,684,000
Minimum number of average size operations required	3	13
Minimum number of cattle from an average size environmental feedlot	164,698	731.336

To fully analyze this problem involving aggregate investment, a relationship between cumulative gross investment and the rate of adoption of anaerobic systems must be estimated. For example, if 731,336 head of cattle in environmental feedlots of average size in Capacity Range IV are producing gas, the cumulative gross investment may be much greater than $3,173,000 annually. In fact, a casual estimate using data from a conversation with G. W. Meckert (1978) indicates that $3,173,000 of gross investment could optimistically support only about two or three operations of 100,000 head capacity in operations similar to that of Thermonetics in Guymon, Oklahoma.

Regional Distribution of Net Benefits and Other Considerations

From estimates of the available manure and potential 10^6Btu of gas production in different regions and among the different capacity ranges (Tables 5.12 and 5.13), it is immediately obvious that since the Feedlot Region contributes 81.7 percent of the potential methane production from Capacity Range IV, over the next decade the majority of benefits derived from gross investment in anaerobic digestion research and development will accrue to this region. Arizona will receive a relatively large proportion of the benefits because its potential contribution to annual methane production from manure wastes is 6.6 percent of the U.S. total, which represents 59 percent of the State's annual potential production.

A region was considered which has no potential gas production in Capacity Range IV; a situation which represents most of the U.S. When aggregate annual gross investment is $3,173,000, PNG_0 is $1.95, r is 0.04 and α is 0.03, the present value of the net benefits per annual 10^6Btu produced for operations in Capacity Range III is $1.92. In other words, approximately 8,089,750 10^6Btu must be produced annually from th breakeven point until the end of the ten year horizon so that the present value of net benefits will equal the present value of gross investment. This amount of annual production is equivalent to 666 operations with a capacity of 2.39 tons of volatile solids per day or with a capacity of approximately 764 beef cattle from an environmental feedlot. Six hundred sixty-six operations at this capacity is also equivalent to 508,824 cattle in an environmental feedlot producing manure to be used for methane production, or about twice as many as needed when considering the large Capacity Range IV.

Waste from 508,824 cattle in Capacity Range III operations represents approximately 18.4 percent of the nation's potential production of gas from manure in Capacity Range III. It should be noted that 42.6 percent of the potential production from Range III is located in the Feedlot Region. This distribution of potential production again implies the feedlot states will receive a relatively greater proportion of the potential benefits from anaerobic digestion technology research and development.

Learning Externalities

As stated in Chapter 2, a complete analysis of externalities resulting from learning in this study is impossible, simply because it is imperative to have a function which relates the rate of adoption to gross investment. A partial analysis can be undertaken if an aggregate production is assumed from the breakeven point, and it is further assumed that the aggregate production is the same whether or not learning has had an effect on unit gas cost.

In this case, it will be assumed that a plant is built at the breakeven point which produces 500,000 10^6Btu of gas annually for its twenty year plant life. This assumption is reasonable because a plant similar to this description is currently operating in Guymon, Oklahoma. The substitution of these assumptions, along with the other previously assumed values for PNG_0, t and α, into equation (3.13) will yield an estimate of the net benefits from learning. This substitution for Capacity Range IV is:

$$B_{LE} = [5000,000 \sum_{t=0}^{19} (1.07)^{-(t+1)} \int_t^{t+1} [1.95e^{0.04t}$$

$$- 18.46(11015 + 3173t)^{-0.258} dt]]$$

$$- [500,000 \sum_{t=0}^{19} (1.07)^{-(t+1)} \int_t^{t+1} (1.95e^{0.04t} - 1.67) dt] \tag{5.11}$$

$$= (500,000)\ (15.65) - (500,000)\ (11.34) = 2,155,000.$$

The present value of net benefits with learning is $15.65 per 10^6Btu produced annually. With an annual production of 500,000 10^6Btu, the present value of the total net benefits with learning is $7,825,000. The present value of the benefits without learning is only $11.34 per 10^6Btu produced annually. When the production is 500,000 10^6Btu annually the present value of he net benefits is $5,067,000. If the aggregate production remains constant at 500,000 10^6Btu annually for the twenty year life of the plant, the difference in the present values of the net benefits is $2,155,000.

Estimation of the value of this externality should be undertaken with considerable care. For example, if 500,000 10^6Btu are produced annually by one operation, the entire amount $2,155,000 cannot be considered a positive externality to the operation. If the operator's investment represents one-third of one year's gross investment, one-third of the externality will be due to his investment and hence may not be considered and externality to him of no one else produces. However, the 66.7 percent of the $2,155,000 of net benefits is the result of investment other than his own and represents a positive externality to the producer.

Externalities Resulting from a Nonmarket Price for Natural Gas

Natural gas prices in the U.S. are regulated. The price per Btu of natural gas generally is less than the price per Btu of other sources of energy. For example, in 1976 the average residential price paid for one million Btu was $1.98 for natural gas, $10.11 for electricty and $3.01 for fuel oil (American Gas Association, 1977, p. 118). If one assumes that market pressures as well as federal energy policy would tend to cause prices of all fuels to converge toward a common value based on the fuel's Btu content, then it might be concluded that the regulated price of natural gas is less than the free market price.

For purposes of analysis, assume that the free market price of natural gas in 1977 is estimated to be $1.95 per million Btu and the actual price for which it is bought and sold is $1.50 (the average price paid by the Mountain States--Arizona, New Mexico, Colorado, Montana, Nevada, Idaho, Wyoming and Utah). If a firm uses the higher free market price for natural gas to determine the breakeven point, it will tend to engage in the production of methane sooner than if it uses the actual price to determine the breakeven point.

The externality which could be realized, as explained in Chapter II, is equal to the present value of the net benefits accumulated over a planning period under the situation where PNG_{M0} is $1.95 gas minus the present value of the net benefit under the situation where PNG_{N0} is $1.50.

The present value of the externality per 10^6 Btu annually produced can be calculated if it is assumed that the aggregate annual production is the same under the free market and nonmarket conditions and that the rate of increase in natural gas price is the same under free market and nonmarket conditions. Substituting the previously assumed vaules for r and α (0.04 and 0.07 respectively), and the estimated learning function (5.7) into equation (3.14), the result is:

$$B_{ME}[\sum_{t=0}^{19}(1.07)^{-(t+1)}\int_{t}^{t+1}(1.95e^{0.04t} - 18.46(11015 + 3173t)^{-0.258})dt]$$

$$- [\sum_{t=1}^{10}(1.07)^{-(t+1)}\int_{t}^{t+1}(1.50e^{0.04t} - 18.46(11015 + 3173t)^{-0.258}dt]. \qquad (5.12)$$

Extracting values from Table 5.10, the resulting net benefits gained by the average firm in Capacity Range IV over a ten year period from 7/77 until 7/87 under free market and nonmarket prices are as follows:

1) If PNG_{MO} = \$1.95, then the present value of net benefits per 10^6 Btu = \$7.11.
2) If PNG_{NO} = \$1.50, then the present value of net benefits per 10^6 Btu = \$3.34.

The difference between the two values is \$3.37 per 10^6Btu of production capacity. Under nonmarket natural gas pricing conditions this represents an externality of \$1,751,600 for the average operation in Capacity Range IV. If the individual producer bases his decisions on the nonmarket price for natural gas at \$1.50 he will tend to underinvest an anaerobic digestion technology because there is no mechanism for internalizing the external benefits.

An increase in the price of natural gas from \$1.50 to \$.195 per 10^6Btu represents a price increase of 30 percent; however, the increase in the net benefits from \$3.34 to \$7.11 per 10^6 Btu of capacity represents an increase in net benefits of approximately 100 percent for the example above.

To estimate a more meaningful value for this externality, it is necessary to have estimates of the free market natural gas price, the free market and nonmarket rates of increase in natural gas prices, and a relationship between gross investment and the rate of adoption of anaerobic digestion systems for methane recovery.

Sensitivity Analysis

Changes in Breakeven Points and Net Benefits Resulting from Changes in the Rate of Gross Investment

It can be observed from Tables 5.2-5.5 that an increase in the rate of gross investment will shorten the time involved before the breakeven point is attained. Under conditions previously assumed, an increase in the rate gross investment of 33 percent will decrease the number of years until the breakeven point; 1.4 years for Capacity Range I, 1.1 years for Capacity Range II, and 0.5 years for Capacity Range III.

A more useful way to look at the effect of changing the rate of gross investment is to examine the impact of different gross investment rates on net benefits. Using Tables 5.5 through 5.8 the effect of changes in gross investment on net benefits can be determined. The assumed values for PNG_0, r, and α are substituted into equation (3.5).

If the gross investment rate is reduced by 33 percent to \$2,100,000, then the present value of net benefits per 10^6 Btu produced annually is reduced by approximately 3 percent for Capacity Range I, 12 percent for Capacity Range II, and 5 percent for Capacity Range IV. When the gross investment rate is increased 33 percent to \$4,220,000, the present value of net benefits is increased by approximately 8 percent for Capacity Range II, 5 percent for Capacity Range III, and 4 percent for Capacity Range IV. The percentage change in net benefits will be greater when the real rate of increase in natural gas price is reduced.

Changes in Breakeven Points and Net Benefits Resulting from Changes in the Rate of Increase in Natural Gas Prices

Tables 5.1, 5.2, 5.3, and 5.4 summarize the effects of varying real rates of increase in natural gas prices on the number of years until the breakeven point under the different situations. It is obvious from these tables that the rate of increase in natural gas price has a substantial impact on the time at which breakeven occurs, because it is assumed that the price of natural gas increases exponentially. This is especially the case in the smaller capacity ranges. The present value of net benefits for a plant with a twenty year life under various rates of increase in natural gas price are found in Tables 5.5 to 5.8.

Using equation (3.5) and the usual assumed values for PNG_0 and α, it can be shown that a decrease in the real rate of natural gas price increase rate from 4 percent to 2 percent (a decrease of 50 percent) will reduce net benefits per 10^6 Btu produced annually from $15.65 to $10.99, a reduction of 30 percent, for the average firm in Capacity Range IV.

Changes in Breakeven Points and Net Benefits Resulting from Changes in the Discount Rate

Variations in the discount rate will have no effect on the occurrence of the breakeven points. The breakeven point is determined solely by the intersection of the learning function and the expression for increases in the price of natural gas over time. Varying the discount rate will, however, have a significant effect on the present value of net benefits. The relationship is an inverse one. When the discount rate is increased the present value of net benefits is decreased. The greater the length of time until the breakeven point, evident in the smaller capacity ranges, the greater the discount rate will change net benefits in relative terms. The impact of variations in discount rate are summarized in Tables 5.5, 5.6, 5.7, 5.9 and 5.10.

CHAPTER 6

SUMMARY AND CONCLUSIONS

This study presents an economic assessment of the adoption and potential of anaerobic digestion for the disposal of livestock and poultry wastes and the recovery of methane.

The first objective of this study was to estimate the parameters learning functions which relate the unit gas cost of producing methane by the anaerobic digestion of animal manures to cumulative gross investment in anaerobic disposal systems.

Multiple regression was utilized to estimate this relationship. It was found that other than cumulative gross investment, the variable representing the capacity of the operation was highly significant. The data were categorized into four capacity ranges in order to compensate for some of the variation associated with capacity.

The conclusion from the estimations was that there is an inverse relationship between the amount of cumulative gross investment and unit gas costs. These relationships indicate that for each doubling in aggregate cumulative gross investment for operations with a capacity of .02 to .31 tons of volatile solids per day, there could be a decrease in unit cost of 17 percent; for operations with a capacity of .31 to .94 tons of volatile solids per day, there could be a decrease of 13 percent; for operations with a daily capacity of .85 to 8.5 tons of volatile solids, the decrease could be 18 percent, and for operations with a daily capacity of 21 to 487.5 tons of bolatile solids, there could be a decrease of 16 percent.

An examination of the trends in research and development expenditures in the area of methane production from anaerobic digestion revealed that an estimation of a relationship between cumulative gross investment and time could be made, which indicates that annual gross investment since mid-1973 has been approximately $3,173,000 per year in 1977 dollars.

The aforementioned estimated equations were used in estimating breakeven points and net benefits accruing from the adoption of anaerobic digestion systems for waste disposal under a variety of situations.

The breakeven points were determined using the simple criteria that if $PNG_t < Y_t$ then the firm would not produce gas, but if $PNG_t \geq Y_t$ then the firm would produce gas. Breakeven points for a typical situation where real gross investment is $3,173,000 annually and PNG_0 is $1.95, increasing at a real rate of 4 percent, are presented in Table 6.1.

Under the previous situation with a discount rate of 0.07, the present value of the net benefits per 10^6Btu annually produced by a plant with a twenty year life which starts gas production at the breakeven point are summarized in Table 6.2.

Table 6.1. The Year of Breakeven When PNG_0 = \$1.95 and $r = 0.04$

Daily Capacity (Tons of V.S./Day)	Year of Breakeven 85 percent Confidence	 50 percent Confidence	 15 percent Confidence
.16	2003	2001	1999
.61	2002	2001	1999
2.39	1982	1981	1980
178.0	1977	1977	1977

Table 6.2. The Present Value of Net Benefits per 10^6Btu of Gas Produced When PNG_0 = \$1.95, $r = 0.04$ and $\alpha = 0.07$

Daily Capacity (Tons of V.S./Day)	Present Value of Net Benefits/10^6Btu (annually produced) 50 percent Confidence	 85 percent Confidence
.61	\$ 4.30	\$ 3.23
2.39	\$10.62	\$ 6.15
178.0	\$15.65	\$10.56

The analysis of an aggregate situation estimated, under the assumptions defined above, that the present value of ten years of gross investment of \$3,173,000 will be equal to the present value of a ten year stream of net benefits if approximately 5 percent of the potential production of methane is produced by operations with an average capacity of 178 tons of volatile solids a day. It was concluded that in the next decade the majority of the real benefits from the adoption of anaerobic digestion systems to recover methane will be distributed among individuals in the region which includes Arizona, New Mexico, Colorado, California, Texas, Oklahoma, Kansas and Nebraska. Regions which have no potential for operations in Capacity Range IV would need to produce more than three times as much methane from operations with an average daily capacity of 2.39 volatile solids to recover a gross investment of $3,173,000 annually by the end of ten years, planning period from 7/77 to 7/87.

Externalities will occur through learning and through the lack of a true market price for natural gas. This study investigated the methods of estimating these externalities. However, in both cases, it was not possible to place an especially meaningful value on the externalities.

The inability to determine meaningful externality estimates results from the lack of an estimated equation relating gross investment in anaerobic digestion systems and the rate of adoption of these systems. The inability to accurately calculate externalities resulting from nonmarket prices for natural gas occurred because there was no estimate of the true market price for natural gas or true market and nonmarket rates if increase in natural gas price.

It is therefore recommended that future studies be undertaken to estimate the true market price of natural gas and the relationship between gross investment and the rate of adoption systems. With this added information, policy alternatives could be suggested to internalize the externalities which occur.

An estimated relationship between gross investment and rate of adoption is also necessary to determine a significant approximation of marginal benefits associated with gross investment in anaerobic systems. The marginal benefits from gross investment in anaerobic systems and the marginal benefits from gross investment in other similar energy conversion techniques should be calculated in future studies and compared to determine the proper allocation of investment from an aggregate standpoint.

Besides extending this analysis in the areas mentioned above, there are basically two other areas in which shortcomings are evident. Both of these involve data collection procedures.

The first involves problems associated with the collection of gross investment data. These are reviewed in detail in Chapter 4 and will not be repeated here. However, examination of the problems in collecting gross investment data indicate that if such problems significantly affect the data, this study most probably will have underestimated the level of spending. To consider the effect of an underestimation, inflated gross investment data was used to estimate the learning functions as reported in the last section of Chapter 4. The analysis indicated that even if gross investment was 33.3 percent greater than the collected data indicate, this would have virtually no effect on the parameters estimated for gross investment. An underestimation would have an impact on the breakeven points and the net benefits calculation. If gross investment was greater than estimated, the breakeven points would occur earlier and net benefits would be greater. A more in-depth look at the sensitivity of the calculations to gross investment is found in Chapter 5.

The other limitation in this study is that the unit gas cost data are mostly derived from estimates made by engineers or economists using experimental data and secondary sources. Few estimates are from actual operating plants. The dummy variables were included in this study to help compensate for some of the inconsistencies between studies. In order to gain greater confidence in the unit gas cost data, the procedures used by the researchers undertaking future cost studies generally need to be more detailed and more data needs to be collected from actual full-scale operations.

The final recommendation is that future farm management studies be done which not only consider the potential role of anaerobic digestion systems for waste disposal, the recovery of energy and the recovery of by-products, but also realize an incorporate the impact of learning on anaerobic technology.

APPENDIX A

SUMMARY OF RELEVANT DATA

Investigator	Source of Waste	Number of Head	Cattle Equivalence	Volatile Solids/Day (tons)	Date of Sources[2]	$\$/10^6$ Btu (1977 Dollars) Y_1	Btu Value of Product Gas B_1
Ferguson and Wisely (1934)	Mun. Sludge	-	24,000	75.0[3,4]	1934	8.68[5]	600[6]
Rosenberg (1952)	Confined Cows	165	240	0.75[4]	1951	21.99[5]	600
Fry and Merrill (1973)	Hog	-	38	0.12[4]	1956	33.99[5]	580
Loehr (1973)	Confined Cattle	10,000	12,780	40.0[4]	1967	4.64[5]	600
Christopher (1971)	Mun. Refuse	-	155,760	488.0[4]	1968	3.75	1,000
						4.74	
						3.18	
Pfeffer (1974)	Sludge and Refuse		23,000	72.0[4]	1970	3.13[5]	600
Singh (1974)	Cows	7		0.02[4]	1971	67.16[5]	600
Slane (1974)	Poultry	20,000	150	0.47[4]	1972	9.67	600
		40,000	300	0.94[4]		8.01	
		60,000	600	1.88[4]		6.38	
Costigane et al. (1974)	Hogs	100	9	0.028[4]	9/74	27.66	600
		200	18	0.056[4]		20.13	
		500	70	0.14[4]		12.58	
		1,000	89	0.28[4]		9.81	
		2,000	180	0.56[4]		7.42	
		5,000	450	1.4[4]		5.28	
		1,000	900	2.8[4]		4.28	
	Beef Cattle	85	137	0.43[4]	9/74	12.58	600
		1,000	960	3.0[4]		3.52	

Investigator	Source of Waste	Number of Head	Cattle Equivalence	Volatile Solids/Day (tons)	Date of Sources^2	$\$/10^6$ Btu (1977 Dollars) Y_1	Btu Value of Product Gas B_1
Ecotope Group (1975)	Beef and Dairy	350	482	1.51	Early 1974	9.90^5	600
		350	482	1.51			
Schmid (1975)	Concrete feedlot	35,000	6,709	21.0	Early 1974	3.42	600
	Confined feedlot	35,000	23,483	75.0		.81	
Harper and Seckler (1975)	Cattle	100	86	$.27^4$	Mid 1974	11.31^5	500
		100,000	87,500	274.0^4		6.31^5	
Hassen et al. (1975)	Poultry	50,000	377	1.2^4	Early 1974	3.64	600
Kispert (1975)	Munip. Waste	500,000	132,912	416.0^4	Mid 1974	2.67	980
Morris et al. (1975)	Dairy	100	160	.5	Early 1975	11.08^7	600
Ifeadi et. al. (1975)	Cattle	32	27	.085	2/75	31.60	600
		320	270	.85		6.99	
		3,200	2,700	8.5		2.24	
		32,000	27,000	85.0		1.31	
Fischer et al. (1978)	Hogs	360	99	.31	4/75	5.41^5	600
Jewell et al. (1976)	Dairy	40	67	.21	1975	6.38	600
		40	67	.21		7.55	
		100	160	.5		4.27	
		100	160	.5		3.77	
	Beef	1,000	950	2.45		1.44	
		1,000	950	2.95		1.28	

Investigator	Source of Waste	Number of Head	Cattle Equivalence	Volatile Solids/Day (tons)	Date of Sources[2]	$\$/10^6$ Btu (1977 Dollars) Y_1	Btu Value of Product Gas B_1
Ashare et al. (1977)	Concrete Feedlot	10,000	4,025	12.6	Mid 1976	13.84	1,000
	Environmental Feedlot	10,000	10,000	31.3		2.71[8]	
		30,000	30,000	94.0		2.08[8]	
		60,000	60,000	188.0		1.86[8]	
		100,000	100,000	313.0		1.43[8]	
Bio-Gas of Colo. (1977)	Dirt Feedlot	50,000	46,970	147.0	Early 1976	1.59[9]	850
Meckert (1978)	Dirt Feedlot	105,000	103,518	324.0	1/78	1.94	1,000

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[1] Cattle equivalence determined from volatile solids using conversions adopted from Ashare et al. (1977) - See Table 4.1.

[2] Date of sources is estimated using the author's reference list.

[3] Assumed volatile solid value.

[4] Estimated from data supplied by the author or conversions in Table 4.1.

[5] Estimated from data supplied by the author, conversions in Table 4.1, or standard energy conversions.

[6] Assumed Btu value.

[7] Lowest of several estimated $\$/10^6$ Btu values.

[8] $150/ton credit for feed.

[9] This value is an average of four unit costs in values associated with $70.50/ton credit for feed and

(1) corp. ownership with 20-year - 9% interest financing

(2) corp. ownership with 20-year - 5% interest financing

(3) corp. ownership with 39-year - 9% interest financing

(4) corp. ownership with 39-year - 5% interest financing.

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