CRC

# FUEL GAS DEVELOPMENTS

Donald L. Wise

CRC PRESS

# Fuel Gas Developments



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## CRC Series in Bioenergy Systems

Series Editor-in-Chief

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**CRC Press, Inc.**
**Boca Raton, Florida**

**Library of Congress Cataloging in Publication Data**
Main entry under title:

Fuel gas developments.

(CRC series in bioenergy systems)
Bibliography: p.
Includes index.
1. Gas as fuel. 2. Biomass energy. I. Wise, D. L.
(Donald Lee), 1937- II. Series.
TP345.F83 1983 665.7'76 82-18507
ISBN 0-8493-6092-7
ISBN 0-8493-6090-0 (Series)

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Direct all inquiries to CRC Press, Inc., 2000 Corporate Blvd., N.W., Boca Raton, Florida, 33431.



International Standard Book Number 0-8493-6092-7
International Standard Book Number 0-8493-6090-0 (Series)

Library of Congress Card Number 82-18507
Printed in the United States

# CRC SERIES IN BIOENERGY SYSTEMS

Editor-in-Chief
**Donald L. Wise, Ph.D.**

## Fuel Gas Systems

Potential of biomass. Biogas digester design. Use of the upflow anaerobic sludge blanket process in wastewater treatment. Methane from crop-grown biomass. Methane production from agriculture residues by anaerobic digestion in batch and continuous culture. An integrated approach to the anaerobic digestion process. Comparative anaerobic digestion of secondary organic residues. Generation of electric power from biogas. Assessment of secondary agricultural residues: part I; resources available and evaluation for energy recovery. Assessment of secondary agricultural residues: part II, engineering and economic analysis for conversion to methane and/or alcohol fuels.

## Fuel Gas Developments

Methane from farm wastes and energy recovery. Characteristics of bacteria in thermophilic digesters and effect of antibiotics on methane production. Autohydrolysis for increasing methane yields for lignocellulosic materials. Bioconversion of classified municipal solid wastes: state-of-the-art review and recent advances. Biomethanation of biomass pyrolysis gases. Bioconversion of industrial residues to methane gas. Utilization of biomass digester effluents as soil conditioners and feeds. Operational experience from the Kaplan industries anaerobic digester. Feasibility study for anaerobic digestion of agriculture crop residues to fuel gas.

## Liquid Fuel Systems

Biomass fuel and chemical perspectives. Crop residue availability for fuel. Alcohol production from cassava. Immobilization technology in alcohol fuels production. A strategy for biomass utilization. Production of ethanol from cellulosic residues by chemical/biochemical methods. Production of alcohol and organic acids with anaerobic bacteria. Ethanol production from cellulosic feedstocks. Technology and economics of ethanol production via fermentation. Ethanol-methane comparative study of agricultural crop residues.

## Liquid Fuel Developments

Production of ethanol from biomass using anaerobic thermophilic bacteria. Screening for cellulolytic mutants. Enzymatic hydrolysis of cellulose to fermentable sugars. Process biotechnology for the conversion of biomass into liquid fuels. Flow reactor for acid hydrolysis or pretreatment of cellulosic biomass. Production of ethanol and chemicals from wood by the Georgia Tech process. Liquid fuels and chemicals from cellulosic residues by acid hydrolysis. Alkane liquid fuels production from biomass. Integration of production of corn-derived fuels with animal feed production.

## Bioconversion Systems

Fuels and chemicals from biomass: a role for gene-splicing technology. Lactic acid production by pure and mixed bacterial cultures. Conversion of lignin to useful chemical products. Chemicals from microalgae. Forage crops as chemical feedstocks. Biomass conversion into chemicals using wet oxidation. Technology and economics of chemicals from wood. An integrated anaerobic digestion system for the production of energy and livestock feed based on aquatic biomass production on sand using seawater spray. Liquid fuel production from biomass in the developing countries — an agricultural and economic perspective. Part I: introduction and background. Part II: the tropical environment and the availability of suitable land. Part III: agricultural properties of energy crops. Part IV: economic analysis of liquid fuel options and summary and conclusions.

# SERIES PREFACE

This series on Bioenergy Systems grew out of the editor's work on projects sponsored by the Biomass Energy Systems Branch (formerly the Fuels from Biomass Branch) of the U.S. Department of Energy and the editor's professional acquaintance with other workers holding subcontracts from the Solar Energy Research Institute, an organization in Golden, Colorado, totally funded by the U.S. Department of Energy. The U.S. Department of Energy organized the workers holding grants or contracts in biomass into several groups, including one on gaseous fuel production via anaerobic digestion and one on liquid fuel (primarily alcohol) production; the editor was involved with several projects in both groups. The leading workers in these biomass/bioconversion areas of the solar energy field agreed to prepare overviews of their projects for this series of texts. Additionally, workers from around the world were invited to prepare descriptive summaries of their activities in the area of gaseous and liquid fuels production, as well as organic chemicals, from agricultural residues and crop-grown biomass.

This series is a sequel to the two volumes the editor recently had published by CRC Press, Inc. (1981) entitled *"Fuel Gas Production from Biomass"*. These earlier texts described largely the status of methane fermentation and are believed to be the first collected set of reports in which is described all the technical activities in the area of anaerobic digestion with the specific objective of optimizing fuel gas production. It is interesting to note that much of the developmental activities reported on in these earlier texts described the methane fermentation of animal manures — this is simply because manure, as the most readily available and fermentable substrate, was the first to receive attention. Now that some animal manure to fuel gas systems are becoming commercial, research and development attention is being directed towards agricultural residues, especially stover and straws. With these substrates, present attention is focused not only on methane fermentation but on liquid fuel production and even bioconversion to more highly valued organic chemicals. There are an array of readily available organic substrates, but they require a better understanding of processing technology before economic bioconversion to fuels and organic chemicals may be practiced.

In a similar manner as with the earlier texts, these present texts describe the continued efforts in this newly emerging energy recovery field. The major input/output aspects of the bioconversion field are emphasized in this present series of texts. One major aspect of the series on bioenergy systems with respect to inputs of feedstock is to include work on all primary and secondary agricultural residues from which energy is being recovered; this includes biomass grown as an energy crop, i.e., crop-grown biomass. Another major aspect of this series is with respect to product from the bioconversion of biomass. The product from energy recovery is expanded in this present series to include gaseous fuel, liquid fuel, and organic chemicals. Thus, the intention is to include work on all aspects of biomass/bioconversion. Specifically, the projects and work described in this series are those dealing with cellulose, lignin, and fermentable industrial residues with the goal of the programs discussed being energy recovery in the form of gaseous fuel (methane), liquid fuel (most often, alcohol), and organic chemicals.

In addition to representing almost all of the work in the biomass/bioconversion solar energy area sponsored by the U.S. Department of Energy, this series has an international authorship of chapters. These volumes include a broad range of current work ranging from fundamental analysis and research work at the laboratory bench through discussion of engineering pilot plants and field demonstration units. Most of the work reported, due to the overall status of this emerging field, is seen to be strongly dedicated to what is appropriately termed development. In all cases these contributed chapters are designed to be largely tutorial in nature with the objective of providing the reader with an overall sense of direction, rather than being alternatives to publications in standard archival journals. It is to be noted that the editor requested from the experts working in this area to contribute chapters on their own work by describing in readable fashion the overall objectives, status, and especially the impact of their work. To the end of providing further insight into the socioeconomic impact of the potential results of all this biomass/bioconversion work, chapters have been included on technological assessment and economic analysis. On this basis, this series is intended to provide a reference and planning guide for the many industrial executives, plant managers, and state and local government officials who are now or certainly will be dealing with the demands of energy recovery. With this background, it will be useful to discuss the major areas included in this series on Bioenergy Systems.

In this series primary agricultural residues are defined as the waste material remaining following harvesting of grain, principally straw, as well as forest residues. Discussion of the location, amounts, and developmental programs underway for energy recovery from these primary residues form the basis for a major portion of this series. On the other hand, secondary agricultural residues are defined herein as that waste material remaining after some formal processing of an agricultural crop has taken place. On this basis, municipal solid waste may be considered as combined secondary agricultural residues. However, a less complex, single component secondary agricultural residue such as whey may be used as an example for discussion. Whey is the secondary agricultural residue that remains after the processing of milk to cheese. Continuing with this example, it may be shown that the whey from a typical modern cheese processing plant, if bioconverted to a gaseous or liquid fuel, may provide replacement of a substantial portion of the cheese plant's present petroleum derived fuel oil requirements.

In a similar manner, as with primary and secondary agricultural residues, bioconversion from a crop grown specifically for energy recovery is considered throughout this series. Often the term biomass is used to imply only crops grown solely for energy conversion, while primary and secondary agricultural residues are placed in a separate category termed, simply, wastes. People working in the area, however, generally classify all fermentable organic substrates together as biomass — recognizing the broad solar energy conversion aspects of all fermentable organic substrates, and this general classification is implied throughout the series. It is to be further noted at this point, with respect to bioconversion processing, that the specific objective is optimum production of a product. For many years the bioconversion field has been oriented to waste stabilization — only recently has attention been directed towards optimizing fuel production and the larger solar energy impact of this area been realized. Thus, the work included in the series is devoted to economic production of some valued product and does not simply include waste disposal. Clearly, commercial systems for any gaseous fuel, liquid fuel, or organic chemical production from biomass will emerge only if the energy balance and costs are economically competitive.

In addition to bioconversion to both gaseous and liquid fuels, the historical background, the basic fundamentals, the present status of development, and the potential for organic chemical production from biomass are also presented. In these portions of the series, contributed chapters depart from conventional methane and alcohol fermentations and deal with production of higher valued organic chemicals. These portions of the series provide the reader with insight into this rapidly emerging new field. It is interesting to note that prior to the development of the petrochemical industry an array of organic chemicals were made via fermentation routes. Moreover, selected fermentable feedstocks, including industrial residues, were often used for bioconversion to organic chemicals — some of these feedstocks are now being regarded again.

In many chapters dealing with gaseous fuel, liquid fuels, and organic chemicals an excellent review is provided of the fundamentals of these bioconversions and biomass. Also presented are the basic principles of the thermodynamics involved and the biochemical pathways understood as basic to product formation. Contributed chapters from workers in the field provide a ready insight to those interested in moving into this field or in capitalizing on developmental results. Also included are discussions on novel fermentations, chemical production by suppressing standard methane fermentation, and a number of other novel endeavors. Current progress on more classical fermentations such as acetone/butanol is also included. The broad question of longer range potential and the application of genetic engineering to produce organic chemicals are addressed. With this introduction, the organization of the series is reviewed, as well as the specific contents of each volume.

This series on Bioenergy Systems has been organized into five major volumes. *Fuel Gas Systems* and *Fuel Gas Developments* deal with fuel gas production from biomass, *Liquid Fuel Systems* and *Liquid Fuel Developments* deal with liquid fuel production from biomass, while *Bioconversion Systems* deals with unconventional processes, organic chemical production from biomass, and a broad overview of the impact of bioenergy systems in lesser developed countries.

*Fuel Gas Systems* and *Fuel Gas Developments* include chapters on both the research and development aspects of fuel gas production via anaerobic digestion. Specifically, *Fuel Gas Systems* tends to include the more practical or developmental aspects of fuel gas production from biomass — chapters deal largely with systems and engineering evaluations of total systems. *Fuel Gas Developments* includes a greater emphasis on current research and engineering topics or programs under development. It is to be noted that the first chapter in *Fuel Gas Systems* is by Dr. Roscoe F. Ward, now with the United Nations, but earlier responsible for carrying out the mission of the U.S. Department of Energy in the production of gaseous fuels, liquid fuels, and organic chemicals from biomass as Branch Chief of Fuels from Biomass. *Fuel Gas Developments* appropriately leads off with a chapter by Professor David A. Stafford, University College, Cardiff, Wales, U.K., who is well known for having initiated the International Symposia on Anaerobic Digestion. Both Dr. Ward and Dr. Stafford appropriately deserve having the lead chapters in each of these two volumes on fuel gas production from biomass.

As noted, *Fuel Gas Systems* and *Fuel Gas Developments* are devoted to gaseous fuel production via anaerobic fermentation. Excellent fundamental chapters are included in both volumes, as well as examples of practical research and development programs around the world. To single out for comment any one of these chapters in *Fuel Gas Systems* and *Fuel Gas Developments* dealing with fuel gas production from biomass would not be fair to any of the others. It is appropriate to point out, however, that the team leaders responsible for the experimental research and development work presented here are believed to be the foremost workers in the field of methane fermentation in the world. Each of these chapters represents more than a simple presentation of one research and/or development project — they each represent a continued and devoted effort to advance an entire field. Concluding chapters in each of these two volumes are given on the economic feasibility for fuel gas production from agricultural residues of various types. These economic analyses and technical assessments from authors at Dynatech were carried out for the Solar Energy Research Institute (SERI) of the U.S. Department of Energy. It is appropriate here to thank Mr. Dan Jantzen, now with the U.S. Agency for International Development, Katmandu, Nepal, who was Program Manager at SERI and responsible for coordinating projects in the area of fuel gas production from biomass via anaerobic fermentation.

Included in *Fuel Gas Systems* is a two-part assessment of secondary agricultural residues, indicating the broad array of potential sources for initiating energy recovery systems. In keeping with environmental concerns about removal of primary crop residues from the land for purposes of energy recovery, an assessment of this potential problem is also included. To conclude *Fuel Gas Developments* on a practical and economic note, and in keeping with the theme of this entire series, a comparative study of converting agricultural crop residues to either gaseous or liquid fuels is presented.

*Liquid Fuel Systems* and *Liquid Fuel Developments* are devoted to liquid fuel production. Here the organization of *Liquid Fuel Systems,* is to place together chapters on complete systems, i.e., processes under development or undergoing economic assessment. The organization of *Liquid Fuel Developments,* is to include those chapters dealing with more specific research problems. On the other hand, these are really two complete volumes on liquid fuel production from biomass. It is meaningful to note that chapters in these two volumes are largely from groups funded by the U.S. Department of Energy, where the major effort on alcohol from cellulose is being conducted. One novel project on alkane fuel from biomass is also described. The chapters on experimental alcohol fuel development include basic work at the University of Georgia, Rutgers University, U.S. Army Natick R&D Laboratory, University of Connecticut, and General Electric. More process development oriented research is presented from Lehigh University (the workers most recently at the University of Pennsylvania), Dartmouth College, Georgia Institute of Technology, University of Arkansas, and New York University. Because the effort on alcohol fuel from cellulose has had major U.S. Department of Energy funding, it is seen that most of the chapters describing experimental programs are from workers in the U.S. On the other hand, work in Brazil and Scotland is presented. It is also interesting to note that the technical assessments and economic evaluations included have been carried out with a world-wide perspective.

It is meaningful to note that the lead chapter in *Liquid Fuel Systems,* is by Prof. H. R. Bungay, now with Rensselaer Polytechnic Institute who was responsible for initially organizing the U.S. Department of Energy programs in the area of liquid fuels and organic chemicals from biomass.

*Bioconversion Systems* is devoted to unconventional systems, production of organic chemicals from biomass, and a perspective of bioenergy systems to lesser developed countries. Perhaps because of the newness of this area of investigation, the chapters range from a very thought-provoking one on the potential for genetic engineering, to one as practical as the conversion of lignin to useful chemical products. Several chapters on chemicals from a variety of biomass feedstocks are included as is a very useful economic assessment. A culminating chapter to this entire series is on integrating a crop-grown biomass system with an on-farm anaerobic digestion system. This chapter is presented to show how the future of fuels and organic chemicals may evolve. Finally, to provide a broad evaluation of the impact of biomass to liquid fuel in developing countries, a comprehensive series of four chapters is presented.

Hopefully, all the work described in this series in Bioenergy Systems will inspire those now working in the field and will encourage those who are now beginning to investigate this field.

Collecting and organizing the work reported in this series has been a very meaningful experience for the editor. Especially heartwarming have been the working with old friends and meeting with new friends. The detailed work of organizing and corresponding with sometimes tardy authors, the helpful and time consuming work of making the chapters as readable as possible, and the communication with our publisher have been done by Joyce E. Perkins, Ph.D. Dr. Perkins also brought a joy to her work that made her sometimes tedious tasks more pleasant and in this manner assisted the editor immeasureably. We are all very appreciative of her expertise as an English scholar and her executive talents.

**Donald L. Wise, Ph.D.**
Editor

# PREFACE

The lead chapter in this volume is by Dr. D. A. Stafford of the U.K., initiator of the International Symposia on Anaerobic Digestion. Continuing chapters in this volume are devoted to describing specific development programs in the area of fuel gas production from biomass. Thus, V. H. Varel of the U.S. Department of Agriculture presents a very meaningful review of the microbiological aspects of digester performance. Perry McCarty and his colleagues at Stanford University, describe continued efforts on pretreatment to increase methane production from biomass digestion. In a very skillfully done chapter Adam Ng and his colleagues tell of their work at UCLA using municipal solid waste as the feedstock. The novel "biomethanation" of biomass gasifier product gases (CO, $CO_2$, and $H_2$) to methane via a gaseous methane fermentation is described by C. A. Tracy and E. Ashare, while the practical aspects of industrial residue digestion is described by D. D. Jech and J. A. Brautigam of Olympic Associates. Roscoe Ward of the United Nations warns of the problems associated with over-confidence in using biomass digester effluents as soil conditioners and feeds while Coppinger and Richter of Anaerobic Energy Systems, Inc., discuss some of their experiences with a commerical manure-to-fuel gas system at large environmental beef cattle feedlots. The volume appropriately concludes with an assessment, by West and her colleagues at Dynatech, of the economic potential for fuel gas production from agricultural crop residues. Together with *Fuel Gas Systems* this volume represents the status of fuel gas production from biomass around the world and provides insight into future usefulness.

# THE EDITOR

**Donald L. Wise, Ph.D.,** is Vice President of Dynatech R/D Company, Cambridge, Mass. Dr. Wise received his B.S. (magna cum laude), M.S., and Ph.D. degrees in chemical engineering at the University of Pittsburgh. Dr. Wise is a specialist in process and biochemical engineering as well as advanced biomaterials development. At Dynatech he has managed a series of programs to develop processes for production of fuel gas, liquid fuels, and organic chemicals from municipal solid waste, an array of agricultural residues, and a wide variety of crop-grown biomass, especially aquatic biomass. Dr. Wise has also been primarily responsible for the initiation of development work on peat to gaseous fuel, liquid fuels, and organic chemicals, and he also originated work on the bioconversion of coal gasifier product gases to these products. This work of Dr. Wise has been carried out from laboratory experiments to pilot-scale operation to full-scale demonstration.

Dr. Wise has worked in the area of biotechnology research and development for two decades and has approximately fifty publications in the field. As Associate Editor of *Solar Energy,* the journal of the International Solar Energy Society, he is responsible for the review of manuscripts in the biomass/bioconversion area. Dr. Wise is also on the Editorial Board of *Resources and Conservation,* an international journal published by Elsevier, Amsterdam. He is an officer of the Biotechnology and Chemicals Sciences Division of the American Society for Solar Energy, a section of the International Solar Energy Society.

Recently Dr. Wise initiated a program to establish the engineering feasibility of converting large-scale combined agricultural residues to fuel gas by the action of microorganisms. Earlier, feasibility study work directed by Dr. Wise on the "controlled landfilling" of municipal solid waste for enhanced methane recovery led to several demonstration projects at landfill sites around the U.S. He initiated the program at Dynatech on organic chemical production from biomass sponsored by the U.S. Department of Energy. Dr. Wise also initiated a unique program for syngas fermentation, i.e., the fermentation of CO, $CO_2$, and $H_2$ to methane and also organic chemicals. Dr. Wise was also responsible for an economic assessment of fuel gas production from animal residues for the U.S. Department of Energy and earlier coordinated the work in this area. The development of a peat biogasification process was initiated by Dr. Wise. He has also probed the economics and impact of large-scale aquatic biomass farming.

Prior to this work, Dr. Wise initiated a program at Dynatech for the production of fuel gas from solid waste by anaerobic digestion. The experimental laboratory feasibility study was carried out by Dr. Wise. Continuing with the success of this experimental program, Dr. Wise organized a broad interdisciplinary team to carry out the computer-based economic analysis of a 1000 ton/day plant servicing a population of 400,000 for bioconversion of solid waste. Dr. Wise has supervised a pilot plant for the conversion of up to 100 lb/day of solid waste to fuel gas.

At the present time, Dr. Wise is involved in the production of higher valued products from the bioconversion of biomass including the production of pentanol, a high octane booster for gasoline, as well as selected organic chemicals. He is also currently working on the utilization of biomass lignin with the objective of developing a commercial process for production of a BTX type liquid fuel.

A meaningful portion of these programs that Dr. Wise initiated and has been carrying out is his meeting with experts across the U.S. and around the world to become familiar with both current and practical aspects of fuels and organic chemicals from biomass.

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Chapter 1

# METHANE FROM FARM WASTES AND ENERGY RECOVERY

**D. A. Stafford**

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## I. INTRODUCTION

The use of farm wastes as an energy source is now coming into its own because of the energy crisis and because of the recognition that these wastes contain useful organic materials that can be converted into liquid and gaseous fuels. The residues produced after bioconversion can also be used as good quality organic fertilizers and as potential protein food supplements for feeding to animals. There is the considerable and added advantage that dangerous pathogens, such as Salmonellae, which affect animals and man, and plant pathogens, such as the potato root eel worm, are very quickly destroyed within these bioconversion systems. The processes in mind are basically anaerobic digestion systems of which there are a number of basic types. Although it is very difficult to describe the types in definitive terms, it is true to say that for the digestion of wet manures there are four basic ones. These are the plug flow digester, the contact digester, the anaerobic filter digester, and variously fed digesters like the hydraulic digester developed in University College, Cardiff.[1] There are the dry bioconvertors for converting plant materials, such as those developed at the University of Cornell, U.S.[2] As the cost of energy rises, the production of methane in biogas by microbial systems might ensure that, at least at a local level, certain industries and farming enterprises may be self-sufficient with respect to energy, and partially self-sufficient with respect to fertilizer and protein. Whatever the contribution to the national energy needs, that contribution could have a greater effect as time goes on. Certainly, in many developed countries, the net increase in energy costs could be 10% above inflation over the next 5 or 10 years. The design of various digester systems has been the subject of a number of publications[3-5] and in order to turn the knowledge of digester design into a viable process for the end user, the production of methane from specific waste arisings would have to be studied in pilot plant systems or even full-scale systems to determine the digestability of the various wastes. This has been particularly true for farm wastes, although much data now has been accrued from the digestion of pig wastes and cattle wastes and, to a lesser extent, from chicken wastes.[6,7] In the past, farmers would have regarded the slurries produced on the farm as a necessary evil and not as a potential energy source. However, this tendency in thinking is changing, more rapidly in some countries and less rapidly in others. In countries like China and India there is a tremendous increase in the use of anaerobic digester systems as there is also in Korea.[8,9] One of the more difficult aspects of treating farm wastes, particularly in Western Europe and in the U.S., has been that of handling and storage of the effluents. This is particularly so with the increase in intensive farming and also with the increase in water pollution legislation. The average pig farm (in the U.K.) of about 5000 pigs (350 sows and followers) would produce the same kind of waste, in terms of the organic loading, as the waste from about 10,000 people in a small town. If there is enough land area on or near the farm, many of these slurries will be spread on the land, perhaps after storage in large lagoon systems. Unfortunately, many farmers don't have this facility and often they will use bedding material and straw to absorb urine and liquid wastes and at the same time increase the problem of handling. With respect to pig slurry, this waste is normally collected in channels under slats under the pig houses, which will flow slowly to a large collecting pit from where it will be pumped into a digester. Alternatively, it can be collected from the pit into large tankers and taken to the site of a central digester (Figure 1).

Poultry wastes are usually handled as a solid since they are fairly high in solid matter (Table 1) and various mechanisms have been devised for the handling of this relatively solid material.[6] Cattle wastes are particularly difficult since they are often contaminated with straw and this has to be scraped from a solid floor. In large cattle feed lots in the U.S., and to a lesser extent in Europe, the cattle are kept on slats and the slurry is much easier to handle. It is also becoming more important that less manure goes on the land as fresh manure because of the possibility of agricultural run-off, which is a very common form of point source

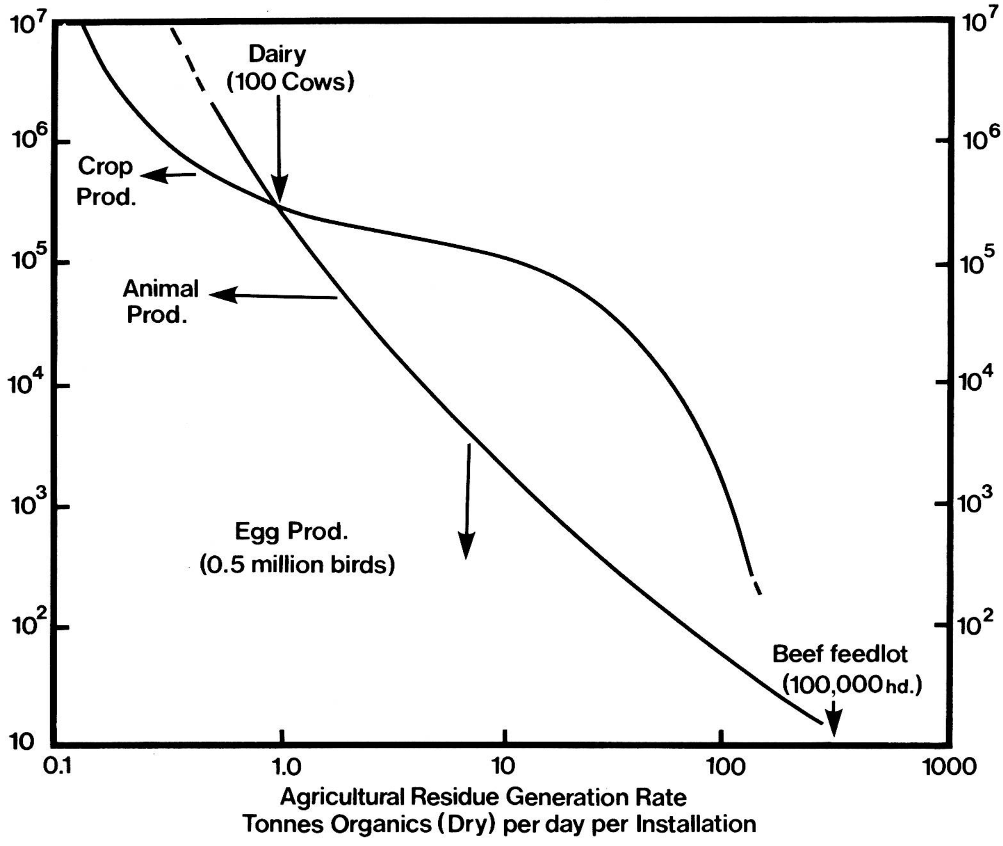


FIGURE 1. Relation of the number of farming operations, size of operation, and sustainable organic residue production rate to the potential for methane generation and its associated value.

pollution for rivers and for lakes.[10] Thus the environmental pressure to improve treatment by whatever means is just as strong as the pressure to produce energy and other potential spin-offs. For the various production figures of manures from farm animals see Table 1. It has been shown that these organic residues produced from the farm in the U.S. could be used to produce about $30 billion worth of energy every year.[11] It is a useful exercise to show the relationship between the number of farming operations, the size of those operations, and the sustainable organic residue that could be produced from these systems and their associated value (Figure 2). Thus there are several million farms in the U.S. that have the potential to generate between 0.5 and 3 tonnes of material every day from this particular type of residue. This would generate the equivalent energy value of between $1000 and $8000 per annum (1980 prices). It is important, however, that the type of digester that is supplied to the farmer is such that the pay-back time is no more than 4 or 5 years. It is no use having a very complicated and fail-safe automatic digester system if it is going to cost so much the farmer will take a long time to pay it off. Unfortunately, many of these digester designs have been taken from fairly conventional public health engineering books and have usually been built to a much larger scale than is necessary for the particular waste. Very expensive equipment has been installed to mix, heat, and control the various feeds. What has developed in the last 2 or 3 years, however, are newer types of design, which are much cheaper to install and operate. Such systems, including the plug flow type of anaerobic digester system, have been used successfully on pilot and full-scale in the U.S., in Scandanavia, and in the U.K.

**Table 1**
**ESTIMATED MANURE AND DIGESTER GAS PRODUCTION FROM ANIMAL WASTES**

| Manure production | Cattle | Swine | Poultry |
|---|---|---|---|
| Total solids (g/day) | 4500 | 780 | 45 |
| Volatile solids (g/day) | 3600 | 624 | 36 |
| Digester efficiency (% of VS) | 10—50 | 50 | 20—60 |
| $CH_4$ production ($m^3$/kg VS added) | 0.1—1.0 | 0.1—0.8 | 0.1—0.9 |

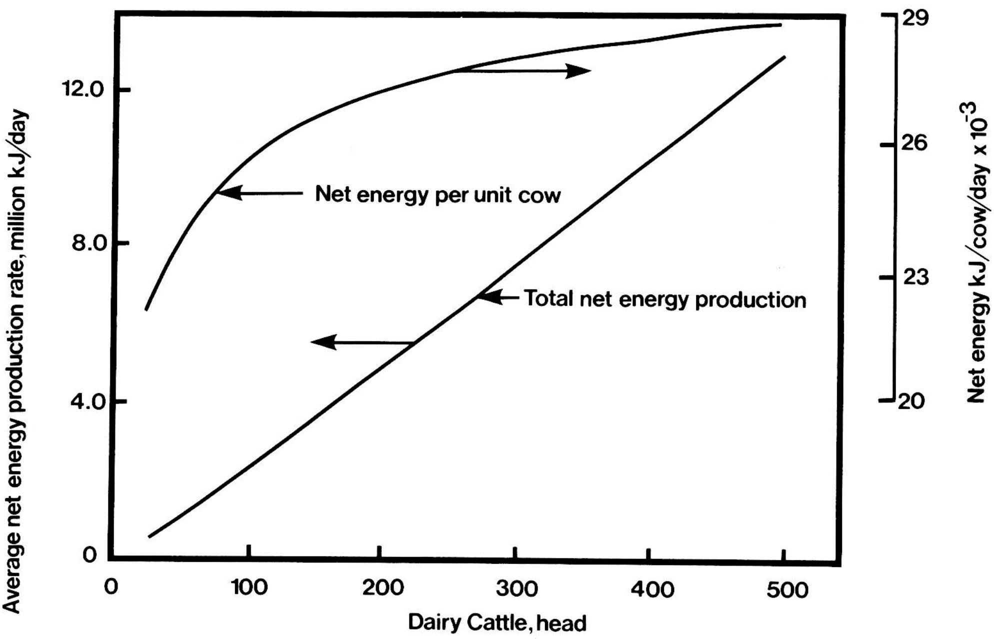


FIGURE 2. The effects of plug flow reactor scale-up on net energy production from cattle waste conversion.

## II. THE PLUG FLOW DIGESTER SYSTEMS

It has been shown at pilot plant level[1,11] that plug flow reactors are successfully able to treat the manures from dairy cows and pigs. A summary of the analyses of the manures fed to the type of plug flow system are shown in Table 2. What is of great interest is that the percentage of total solids destroyed was between 75% and 96% with a feed of between 10 and 12% total solids. The net energy production from these plug flow anaerobic systems is shown in Figure 2. A similar but very large plug flow system has been shown to work effectively in Denmark. Figure 3 shows a 400-$m^3$ reactor that processes the waste from a dairy cattle unit and produces sufficient biogas to generate a 40 kWh generator set. In the U.K., the plug flow system at University College, Cardiff (Figures 4 and 5), has demonstrated the feasibility of producing energy, not only from farm wastes, but also from plant material. In this latter case also, an evaluation is being made of the treatability of pig waste by using plug flow systems with plant material added and especially grown for bioconversion to biogas as an extra digester feed with the pig wastes. A cultivated field which produced a mixture of forage pea and Italian rye grass was ensiled at the end of the summer period and fed to the digester during the winter months. The digester was heated with a gas boiler and kept to a temperature of 24°C ± 2°C and gas yields monitored as shown in Figure 6. It