Opportunities for Energy Conservation through Biotechnology

**J. K. Young
E. A. Griffin
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November 1984

**Prepared for the U.S. Department of Energy
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Dear Recipients:

RE: Opportunities for Energy Conservation through Biotechnology, Pacific Northwest Laboratory, Richland, Washington, January 1979

Please make the following changes in your copy of the subject report:

PAGE

vii	paragraph 4, line 5; "or about 115 quads" should read "or about 1.15 quads"
3.18	paragraph 1, line 2; 8.9 quads should be changed to 6.7 quads
3.18	paragraph 1, line 3; reference (U.S. DOE 1983) should read (OTA 1983)
3.19	paragraph 4, line 4; 1-3 butanediol should be changed to n-butanol
3.20	Fig 3.2, reference to 2.3 butanediol should say n-butanol
3.21	Fig 3.3, reference to 1, 3 butanediol should read n-butanol
3.22	Table 3.11, heading of last column; should read 10^{12} instead of 10^{15}
3.24	Table 3.12, column 1; reference to 2, 3 butanediol should read n-butanol
3.24	Table 3.12, Footnote (b); should read "produced as a byproduct in n-butanol production"
3.24	Table 3.12, Footnote (n); should be deleted

Sincerely,

Joan K. Young

Joan K. Young
Research Engineer
Technology Performance Analysis Section

JKY:krp

OPPORTUNITIES FOR ENERGY
CONSERVATION THROUGH BIOTECHNOLOGY

J. K. Young
E. A. Griffin
J. A. Russell

November 1984

Prepared for
the U.S. Department of Energy
Energy Conversion and Utilization
Technologies Division
under Contract OE-AC06-76RLO 1830

Pacific Northwest Laboratory
Richland, Washington 99352

PREFACE

The Energy Conversion and Utilization Technologies (ECUT) Program of the U.S. Department of Energy supports the long-term, high-risk, generic, applied research and exploratory development necessary to ensure the availability of an advanced technology base that will 1) substantially increase the efficiency of energy conversion and utilization systems, and 2) promote the use of noncritical fuels. The ECUT Program seeks to accomplish these goals as follows:

1. conduct applied research and exploratory development activities that address specific problems associated with efficiency limits and multi-fuel use;
2. research and develop processes and materials that improve the efficiency and the alternative fuel use capabilities of energy conversion devices, components, and systems;
3. monitor advances in basic scientific research and evaluate them for applicability to energy conservation;
4. establish the feasibility of innovative revolutionary concepts that significantly reduce energy consumption; and
5. conduct exploratory development of novel and innovative conservation concepts.

Biotechnology shows considerable promise for saving energy and conserving petroleum resources. The United States is at the forefront of the basic science of genetics and molecular biology. However there is the question of whether this scientific base is adequate and whether it can be effectively translated into energy saving processes. The ECUT Program is therefore evaluating the energy conservation potential for bioprocessing and trying to determine the appropriate federal role in this area.

Two ECUT studies are being conducted to evaluate bioprocessing as a means of saving energy and using alternative fuels. This report describes a study conducted by the ECUT Systems Analysis Project to identify emerging biotechnologies and provide quantitative estimates of energy savings in various end-use sectors including fuels, chemicals, mining, pollution control, food processing,

and agriculture. This work is also intended to provide background and focus for a second, more extensive ECUT study being conducted by the National Academy of Sciences (NAS). The NAS study concentrates on evaluating the potential of using industrial bioprocessing methods, with emphasis on the production of bulk or commodity chemicals. The processes currently used to produce these high volume products consume large amounts of energy and use critical petroleum feedstocks. Bioprocessing offers the possibility of using less energy-intensive processes and alternative feedstocks such as biomass. The NAS study is addressing the following important technical questions:

- What improvements, if any, can be expected in energy conservation due to the emergence of biotechnology?
- How might these improvements manifest themselves?
- Quantitatively, how significant might these be?
- What course of action should be taken to exploit such opportunities?
- How should such an energy conservation-related use of biotechnological developments fit in with some broader biotechnology policy of the U.S.?
- What is the appropriate federal role in developing biotechnology?

David L. Brenchley, Manager
ECUT System Analysis Project

EXECUTIVE SUMMARY

This study was conducted by the Pacific Northwest Laboratory (PNL) under contract to the Energy Conversion and Utilization Technologies (ECUT) Program of the U.S. Department of Energy (DOE). The purpose is to identify and quantify potential energy savings available through the development and application of biotechnologies. This information is required in support of ECUT research planning efforts as an aid in identifying promising areas needing further consideration and development. It is also intended as background information for a companion ECUT study being conducted by the National Academy of Science to evaluate the use of bioprocessing methods to conserve energy.

Several studies have been conducted recently to assess the status and implications of the development of biotechnology. The Office of Technology Assessment (OTA) considered institutional, economic, and scientific problems and barriers.^(a) The National Science Foundation sponsored a study to examine regulatory needs for this new and expanding technology.^(b) Somewhat in contrast to these studies, this report covers principally the technical issues.

It should be emphasized that the practicality of many developments in biotechnology is not evaluated solely on the basis of energy considerations. Bioprocesses must often compete with well-established coal, petroleum, and natural gas technologies. A complete evaluation of the technical, economical, and ecological impacts of the large-scale applications discussed in this report is not possible within the scope of this study. Instead, this report assesses the potential of biotechnology to save energy so that research into all aspects of implementation will be stimulated for those industries with significant energy savings potential.

(a) Office of Technology Assessments (OTA). 1984. Commercial Biotechnology - An International Analysis. U.S. Government Printing Office, Washington, D.C.

(b) Arthur D. Little, Inc. 1984. Study of Federal Biotechnology Policy Issues. BOA NO. PRA-8400692, National Science Foundation, Washington, D.C.

APPROACH

Since this is an initial ECUT assessment of energy conservation opportunities for biotechnology, a broad scope was deemed important. While this survey investigates many different possibilities, they basically occur in two categories: 1) biomass conversion, and 2) genetic engineering of materials. Biomass conversion deals with processes that use renewable feedstocks to replace fossil-based fuels and chemicals. Genetic engineering is the use of biologically-engineered enzymes and organisms to reduce process energy requirements.

The main interest of this work was to establish the feasibility of using biotechnology to save energy. This was accomplished by examining the potential energy consumption of current and emerging biotechnology applications within promising industries and comparing it with the fossil energy consumption of the conventional technologies. Then estimates were pooled for the industry and extrapolated to a nation-wide basis, based on current energy consumption levels. This in turn provided a basis for determining the relative importance of these technologies for saving energy.

Fossil energy savings from biomass conversion and genetic engineering developments were estimated for fuels production, chemical feedstock production, mining, pollution control, agriculture, and the food industry. In many cases, quantitative estimates could not be made due to lack of data, but a discussion of the potential for fossil fuel energy savings was still included.

Data for calculations were obtained from various literature sources. Most information on biotechnology is widely scattered; in addition, most of the available literature does not emphasize energy consumption. As a result, an extensive literature review was required before appropriate data could be obtained and evaluated. A peer review process was then used to evaluate the data selected for analysis. Several reviewers were utilized because of the large number of technologies and industries evaluated in this report.

FINDINGS

Estimated energy savings from specific applications of these technologies are discussed on an industry-by-industry basis below. Savings are expressed in quadrillion Btu (quads, equal to 10^{15} Btu) on an annual basis. Energy savings for biomass conversion processes include the fossil feedstock energy replaced by biomass derivatives.

Fuels

- Using wastes, residues, and surplus crops currently available, about 3.1 quads could be replaced by biomass-derived fuels. This represents up to 1% of the current liquid fuel consumption and 16% of the gaseous fuels consumption in the U.S. in 1982.
- Based on PNL calculations, replacing the 26.9 quads of liquid fuels and the 17.9 quads of gaseous fuels used in 1982 with biomass-derived methanol, ethanol, or SNG would require significantly larger quantities of land than are currently available.

Chemicals

- Using available supplies of biomass, a potential fossil-feedstock energy saving of over 2.1 quads is possible for the synthesis of existing organic chemical feedstocks and nitrogenous fertilizer. However, process energy requirements exceed conventional requirements by 160%, or about ~~1.5~~^{1.15} quads, due to problems such as diluted products.
- Genetic engineering of biocatalysts and the development of the corresponding scaled-up bioreactions systems could significantly reduce the energy requirements in both the conventional and biomass-based chemicals industry scenarios. However, a biomass-based industry would make use of a renewable feedstock, while the conventional industry uses petroleum feedstock.

Mining

- Approximately 20%, or 0.014 quads of the energy currently used for metal mining could be saved if bacterially-assisted in-situ recovery methods were utilized.

- Bioaccumulation techniques for the recovery of gold and silver from waste streams could potentially save the 0.002 quads currently required for mining these precious metals.

Pollution Control

- Utilization of microbial desulfurization of coal, anaerobic digestion of sewage, and deep-shaft aeration of industrial organic waste for pollution control could save at least 0.71 quads or 33% of the total energy estimated to be currently used for this purpose.

Food Processing

- Two food processing industries that have a potential for energy savings through biotechnology are fruit processing and meat packing. During the fruit pulping operation, up to 50% of the energy required, or 0.23 trillion Btu, could be saved by using enzymatic liquefaction methods. Using enzyme-based cleaners, the meat packing industry could save 0.38 trillion Btu.

Agriculture

- Utilization of genetic engineering to increase the disease- and pest-resistance of plants would reduce the consumption of agrichemicals and fuels used to grow crops. A 10% reduction is estimated, with a calculated savings of about 0.2 quads per year.

CONCLUSIONS AND RECOMMENDATIONS

The quantitative estimates obtained for this study substantiate the premise that biotechnology offers a substantial potential for energy savings. Additional conclusions and the resulting recommendations are described below.

- Genetic engineering and bioprocessing developments provide industry with the potential to save energy and substitute for fossil fuel.
However, substantial technical barriers to implementing these processes in certain industries exist.

Recommendation:

PNL therefore recommends that the energy savings opportunities described in this report be used as a basis for prioritizing research to eliminate the technical barriers to large-scale applications of biotechnologies.

- Land requirements for biomass growth limit the large-scale replacement of fossil fuels with biomass-derived fuels. Land requirements could be reduced with genetic engineering to improve current yields of biomass and to increase current glucose to cellulose conversion rates.

Genetic engineering of biocatalysts and bioreactors could allow biomass conversion technologies to approach theoretical yields of glucose from cellulose. Current biomass yields could be potentially improved by using genetic engineering developments to increase photosynthetic efficiencies, promote biological nitrogen fixation, improve the water retention of soil, and/or increase disease- and pest-resistance.

Recommendation:

Therefore, a balanced program to improve biomass yields and conversion technologies should be implemented and supported.

- Chemicals production is potentially a more attractive use of current biomass supplies, since the dollar value added is greater for chemicals than fuels.

The OTA study concluded that commodity chemicals will not be produced by U.S. industry for at least twenty years because of the industry's complex infrastructure, reliance on petroleum feedstocks, and low profit margin. However, the information developed in this project suggests that technical issues, such as high process energy requirements, inhibit chemicals production from biomass.

Recommendation:

The technology to design stable biocatalysts in immobilized bioreactor systems should be developed. This would provide more effective catalysts for bioprocessing, which would in turn lead to lower process energy requirements. This could be the key step in the development of a competitive biomass-based chemicals industry.

- Genetic engineering advances that affect more energy-intensive sectors of the economy (such as fuels and chemicals) will also affect pollution control, metals mining and recovery, food processing, and agriculture.

Several industrial-specific factors must be considered to effectively exploit the energy saving opportunities provided by genetic engineering R&D:

- a) The implementation of biological methods to reduce energy requirements for pollution control could become more desirable in the future due to stricter regulations; however, the most important consideration for industry will be compliance with standards.
- b) Mining of deep deposits is expected to increase, but the geologic and mineralogic limitations that currently inhibit the applicability of bacterially-assisted "in-situ" methods must be addressed.
- c) For food processing, particular attention should be paid to enzymatic methods.
- d) Many of the genetic engineering opportunities for improved biomass yields also apply to agriculture, but public acceptance may limit their utilization.

ACKNOWLEDGMENTS

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CONTENTS

PREFACE	iii
EXECUTIVE SUMMARY	v
ACKNOWLEDGMENTS	xi
1.0 INTRODUCTION	1.1
2.0 BIOMASS CONVERSION AND GENETIC ENGINEERING TECHNOLOGIES	2.1
2.1 BIOMASS CONVERSION TECHNOLOGIES	2.1
2.1.1 Current Availability of Biomass	2.1
2.1.2 Potential for Future Production	2.2
2.2 TECHNOLOGIES FROM GENETIC ENGINEERING	2.3
3.0 BIOMASS CONVERSION APPLICATIONS	3.1
3.1 FUELS FROM BIOMASS	3.1
3.1.1 Determination of Energy-Efficient Methods for Producing Fuels from Biomass	3.4
3.1.2 Current Potential Energy Savings from Bio-derived Fuels	3.12
3.1.3 Research Needs for Fuels Production	3.16
3.2 BIOMASS AS A CHEMICAL FEEDSTOCK	3.16
3.2.1 Structure of Biomass-Based Chemicals Industry	3.19
3.2.2 Comparison of Energy Consumption for Chemicals	3.22
3.2.3 Research Needs for Biomass as a Feedstock for Chemicals	3.23
4.0 APPLICATIONS FROM GENETIC ENGINEERING	4.1
4.1 FUELS PRODUCTION	4.1
4.1.1 Current Limitations to Large-Scale Fuels Substitution	4.1
4.1.2 Potential Impact of Genetic Engineering	4.2

4.2	CHEMICALS PRODUCTION	4.6
4.2.1	Advantages of Bioprocessing	4.7
4.2.2	Limitations to Implementation of Bioprocesses	4.8
4.3	METALS MINING AND RECOVERY	4.9
4.3.1	Bacterially-Assisted Recovery Methods	4.9
4.3.2	Energy Savings from Biotechnology	4.12
4.3.3	Research Needs for Metals Mining and Recovery	4.13
4.4	POLLUTION CONTROL	4.14
4.4.1	Possibilities for Biotechnological Pollution Control	4.15
4.4.2	Energy Savings Impact of Available Biotechnology	4.18
4.4.3	Future Developments In Pollution Control	4.20
4.5	FOOD INDUSTRY	4.22
4.5.1	Potential Biotechnological Developments	4.23
4.5.2	Potential Energy Savings from Biotechnology	4.24
4.5.3	Research Needs for Foods Production	4.25
4.6	AGRICULTURE	4.25
4.6.1	Energy Use for Conventional Methods	4.26
4.6.2	Energy Savings Potential of Biotechnology	4.27
5.0	SUMMARY OF ENERGY SAVINGS FROM BIOTECHNOLOGY	5.1
5.1	BIOMASS CONVERSION TECHNOLOGIES	5.1
5.1.1	Fuels Production	5.1
5.1.2	Chemicals Production	5.1
5.2	GENETIC ENGINEERING	5.2
5.2.1	Fuels Production	5.2
5.2.2	Chemicals Production	5.2

5.2.3 Metals Mining and Recovery	5.3
5.2.4 Pollution Control	5.3
5.2.5 Foods	5.3
5.2.6 Agriculture	5.4
REFERENCES	R.1
APPENDIX A - PROCESS DETAILS OF LIQUID AND GASEOUS FUELS PRODUCTION	A.1
APPENDIX B - BIOMASS PRODUCTION REQUIREMENTS FOR LIQUID AND GASEOUS FUEL	B.1

FIGURES

3.1	Structure of Organic Chemicals Industry	3.17
3.2	Biomass-Based Organic Chemicals Industry	3.20
3.3	Synthesis Routes to Major Chemical Intermediates	3.21
4.1	Potential Availability of Biomass to Provide Liquid Fuel from Methanol	4.3
4.2	Potential Availability of Biomass to Provide Liquid Fuel from Ethanol	4.4
4.3	Potential Availability of Biomass to Provide Gaseous Fuel from SNG	4.5

TABLES

3.1	Quantity and Types of Energy Consumed in 1982, by Sector	3.2
3.2	Estimated 1982 Energy Use By Type and by Industry in Quads	3.3
3.3	Total Quantities of Liquid or Gaseous Fuels Consumed in 1982	3.4
3.4	Process Energy Balances for Ethanol Production from Starch Hydrolysis	3.6
3.5	Process Energy Balance for Ethanol from Cellulose	3.8
3.6	Process Energy Analysis for Methanol from Wood Residue	3.9
3.7	Energy Balance for Wood Gasification	3.10
3.8	Available Biomass Sources and Energy Values, 1980	3.12
3.9	Amount of Fuel that Could be Produced from Biomass	3.13
3.10	Energy Consumption Pattern for the Chemicals Industry	3.18
3.11	Energy Consumption of Primary Chemicals in Conventional Scenario, 1983	3.22
3.12	Energy Consumption for Biologically-Based Chemicals	3.24
4.1	Land Requirements for Biomass Production to Meet the 1982 Fuel Demand	4.2
4.2	Process Energy Required per Ton Product	4.10
4.3	Energy Consumption in Metal Production (10^{12} Btu), 1980	4.11
4.4	Pollution Control Energy by Consumer and by Pollutant Type	4.15
4.5	Energy Requirements for Four Biodegradation Techniques	4.18
4.6	Energy Balance for Anaerobic Digestion of Sewage Sludge	4.19
4.7	Potential Energy Savings for Microbial Desulfurization	4.19
4.8	Series of Calculations to Determine Potential Energy Savings for Deep-Shaft Aeration of Organic Wastes	4.21
4.9	Top Five Food Industry Energy Consuming Groups in 1980	4.22
4.10	Energy Use in Farm Production 1974-1990	4.25

4.11 Analysis of <u>Spirulina</u> Algae and Other Protein Sources.....	4.29
5.1 Total Energy Savings Estimate for Biological Pollution Control, 1982	5.3

1.0 INTRODUCTION

This report establishes the feasibility of using biotechnology to reduce domestic reliance on fossil fuels. Biotechnology is defined in this study as the use of biological materials to meet the technological needs of mankind. Biotechnological developments include new and improved biomass conversion methods and technologies resulting from the genetic engineering of cells. In biomass conversion processes, energy and materials are obtained from available renewable feedstocks such as wood, grain, and fiber (biomass) using chemical, enzymatic, or thermal methods. Developments from genetic engineering include plants, microorganisms, or enzymes that can be used to produce valuable products or degrade host substances.

Major areas that are expected to be affected by future developments in biotechnology include fuels, chemicals, mining, pollution control, food processing, and agriculture. Major biotechnological applications for these industries are summarized as follows:

- Fuels - synthetic natural gas, ethanol, methanol, and other liquid fuels obtained from renewable resources
- Chemicals - organic chemicals and polymers and nitrogenous fertilizers produced from biofeedstocks and biosynthesis
- Mining - bacterial leaching and biotransformations used to concentrate metals
- Pollution control - degradation of pollutants and conversion of waste products using biotechnological methods
- Foods - processing improvements using biotechnological methods
- Agriculture - use of genetic engineering to produce more vigorous plants, improve nitrogen fixation, and develop algal protein for food.

Biotechnological processes can improve energy efficiency in two ways:

- by utilizing biomass conversion technologies to manufacture renewable feedstocks and fuels to replace fossil-based derivatives,

- by developing biologically-engineered enzymes and organisms that reduce process energy requirements.

Energy-saving biotechnologies are identified to provide a framework for evaluating the relative merit of various R&D strategies. Only those biotechnologies with significant energy-savings potential are reviewed. When possible, energy consumption is determined for both the conventional and the biologically-assisted scenarios so that the energy-savings potential can be quantitatively estimated.

It should be emphasized that the practicality of many developments in biotechnology is not evaluated solely on the basis of energy considerations. Bioprocesses must often compete with well-established coal, petroleum, and natural gas technologies. A complete evaluation of the technical, economical, and ecological impacts of the large-scale applications discussed in this report is not possible within the scope of this study. Instead, this report assesses the potential of biotechnology to save energy so that research into all aspects of implementation will be stimulated for those industries with significant energy savings potential.

The types of biotechnological developments with the potential for energy conservation are described in Section 2.0. These include biomass conversion technologies and technologies from genetic engineering. Section 3.0 discusses the two major applications of biomass conversion technologies--fuels production and chemicals from biomass feedstocks. Section 4.0 discusses the applications of genetic engineering developments for fuels, chemicals, metal mining, pollution control, food processing, and agriculture. The same format is used to discuss each application for both Sections 3.0 and 4.0. First, the current energy consumption for conventional methods is determined for each application and compared with the energy used by the biotechnological methods. Then, the energy savings from biotechnology is estimated. If the potential large-scale energy savings are not currently feasible due to technical barriers, research needs are identified. The results of each section are summarized in Section 5.0.

2.0 BIOMASS CONVERSION AND GENETIC ENGINEERING TECHNOLOGIES

The two biological materials with the greatest potential for energy conservation are biomass and genetically-engineered microorganisms. Improved biomass conversion technologies and advanced techniques for the genetic manipulation of microorganisms will provide industry with potentially viable alternatives to conventional production methods. The potential for these technologies to save energy will be a key determinant in their implementation.

2.1 BIOMASS CONVERSION TECHNOLOGIES

Although biomass can be burned directly to provide process and space heat or steam, it can also serve as the raw material for synthesizing organic fuels and chemicals. As discussed below, large-scale implementation of biomass conversion technologies is currently limited by biomass feedstock supply. However, with proper agricultural management and improvements to photosynthetic efficiencies, biomass can ensure a continuous renewable supply of essential raw materials in the future.

2.1.1 Current Availability of Biomass

Total annual biomass production on timberland or cropland in the United States is about 3.5 billion tons/year, not including unproductive or reserved forestland, pasture and rangeland, swampland, or industrial and urban areas. At 8000 Btu/lb, this is about 56 quads of thermal energy (one quad is equal to 10^{15} Btu) or 75% of current domestic energy use. The most that can be reasonably expected to be used is about 1.4 billion tons/year of wood and wood wastes and 550 million tons/year of agricultural residues. The inclusion of an estimated 160 million tons/year of municipal solid wastes and 6.2 million tons per year of surplus crops brings the maximum amount of biomass available to 2.1 billion tons. Only 20% of this is estimated to be economically available, which reduces the amount of biomass available for energy production to 420 million tons/year or about 7.0 quads/year of thermal energy. If all 7.0 quads of biomass are processed into fuels and chemicals, only 30% of the original heat content, or 2.1 quads/year, is available, due to conversion losses (Goldstein 1981).

About 2.8 quads of the current supply of biomass were consumed for energy in 1982. Of that amount, 0.02 quads were converted to alcohol fuel or methane and the remainder was burned directly (Haggin and Krieger 1983). The DOE and other sources project that about 5 quads/year of biomass will be available by the year 2000 (Klass 1983, Science 1979).

2.1.2 Potential for Future Production

The development of plants with photosynthetic efficiencies much greater than the current values of under 1% would vastly increase the production of biomass. The theoretical maximum photosynthetic yield of plants has been estimated at around 100 tons/acre-year (Bassham 1977), but many experts feel that even 50 tons/acre-year is optimistic. At about 5000 Btu/lb and 50 tons/acre-year, the 482 million acres of land available for intensive agriculture in the year 2000 could produce 240 quads/year by burning biomass directly (two to three times the estimated energy consumption for the year 2000) (Shen and Turnhollow 1983).

Assuming current thermodynamic efficiencies, conversion of biomass to liquid or gaseous fuels significantly decreases the amount of energy originally available in the biomass resource. At least one-half to two-thirds of the energy content of the biomass is lost during the conversion process. However, conversion of the maximum amount of biomass potentially available from agricultural land in the year 2000 would result in at least 80 quads of liquid or gaseous fuel. This is about 80% of the projected demand for primary energy in the year 2000.

Ecological impacts and imbalances of large-scale biomass production must also be considered. For example, a biomass energy plantation would be vulnerable to crop failures and fire. Sustained agricultural production also causes depletion of soil nutrients and excessive topsoil erosion. In addition, biomass not only competes with the production of food, but with many other materials. An integrated energy plantation providing food and materials, in addition to energy feedstock, would be a possible alternative. Considerable R&D and drastic changes in the nation's eating habits would probably be required to realize the advantages of large-scale fuel production from

biomass. Despite these facts, many argue that biomass fuels are desirable because they can be sustained indefinitely and they employ unskilled workers.

2.2 TECHNOLOGIES FROM GENETIC ENGINEERING

Genetic engineering involves manipulating the genetic material (DNA) of a living cell so that the cell can produce valuable metabolites or perform completely new or enhanced functions.

Genetic alterations can be induced by either recombinant DNA or nonrecombinant DNA methods. In recombinant DNA methods, genes from separate sources are isolated and then spliced together chemically into a functional unit. Nonrecombinant techniques used by genetic engineers in conjunction with gene-splicing technologies include:

- Induced mutations - a chemical or physical agent is used to interfere with normal cellular processes.
- Cell fusion - two cell types are fused together into a single unit. Monoclonal antibodies and tissue culturing (protoplast fusions) are two cell fusion approaches.
- Conjugation (plasmids) - a one-way transfer of DNA between bacteria during cellular contact.
- Transduction - DNA is transferred between bacteria using a transmitting agent such as a virus.

Genetic engineering will result in a variety of microbes and plants with traits that can be used to conserve energy. Some of the practical applications of genetically-engineered microorganisms are as follows:

- microbial production of fuels and chemicals from biomass
- manufacture of enzymes to catalyze chemical reactions
- bacterially-assisted leaching or accumulation of metals
- microbial degradation of pollutants
- production of enzymes for food processing

Genetic engineering of plants can also enhance normal cellular functions such as photosynthesis, resulting in more vigorous plants and higher crop productions.

Currently, the implementation of genetically-engineered materials is limited not only by technical and economic constraints, but also by public acceptance. For example, a bacterium was recently developed that increased the frost-resistance of plants. The bacterium has not been tested under actual field conditions because of public resistance to its release into the environment.

3.0 BIOMASS CONVERSION APPLICATIONS

The following sections discuss the energy-savings impact of biomass conversion technologies on the production of fuels and the use of biomass as a chemical feedstock. Fuels production from biomass is discussed in the beginning sections. The fermentation processes for ethanol production and the gasification processes for methanol and synthesis gas are included.

First, existing processes for producing ethanol from biomass are evaluated to determine the process with the most efficient net energy balance. The processes to produce methanol and SNG by gasification of wood are also presented. Then the scenario in which currently available supplies of biomass are used to replace fossil fuels is discussed. Research needs for fuels production using biomass conversion are identified as a result of this discussion.

The last section discusses the use of biomass as a feedstock for organic chemicals and for manufacturing nitrogenous fertilizers. First, the structure of the bulk chemicals industry is presented along with the necessary modification of that structure to incorporate large-scale production of chemicals from biomass feedstocks. Second, the current consumption of fossil energy by the conventional chemicals industry is compared with a biomass-based industry. Third, the energy-savings impact of using biomass-derived chemical feedstocks is evaluated. Finally, research needs are identified that will improve the technical feasibility of a biomass-based chemicals industry.

3.1 FUELS FROM BIOMASS

In 1982, the U.S. consumed a total of 72×10^{15} Btu, or 72 quads, of primary energy. About 7 quads of this total energy were consumed by industry, 26 quads by commercial and residential heating, and 19 quads by all forms of transportation. The types of energy consumed by each major user are listed in Table 3.1.

As shown, the transportation sector uses petroleum products almost exclusively (primarily in the forms of gasoline and diesel fuels), while electricity is the largest source of energy for commercial and residential purposes. The industrial sector consumes fossil energy for use as chemical feedstocks as well

TABLE 3.1. Quantity and Types of Energy Consumed in 1982, by Sector
(in Quads) (a)

Sector	Coal	Natural Gas	Petroleum	Electricity ^(b,c,d)	Other	Total
Industry ^(e)	2.60	6.91	7.85	8.66	1.17	27.19
Commercial and Residential	0.21	7.50	2.49	15.50	0	25.70
Transportation	--	0.61	18.42	0.13	0	19.16
Total	2.81	15.02	28.76	24.29	1.17	72.05

(a) Source: DOE (1983)

(b) 10,400 Btu/kwh.

(c) 55% generated from coal, 14% from natural gas, 6% from petroleum, 12% from nuclear, and 14% from hydro and biomass as indicated in source cited in footnote (a).

(d) Includes electrical losses from transmission and generation as well as electricity actually consumed.

(e) 82% of energy used for fuel, 18% for feedstock.

as for fuel. It has been estimated that 82%, or 22.34 quads, of the total energy consumption in 1982 for all industries was for fuel and 18%, or 4.85 quads, was for feedstock (Holtberg, et al. 1983). An approximate breakdown for the type of energy consumed by industry is shown in Table 3.2. The fuel total includes electrical energy.

Approximately 44.8 quads of energy consumed in 1982 were in a liquid or gaseous form, as shown in Table 3.3. This includes the petroleum and natural gas used to generate electricity, but excludes the natural gas and petroleum used as feedstock by the industrial sector. Approximately 26.9 quads were consumed as liquid fuel and 17.9 quads as gaseous fuel.

Biomass-based fuels are evaluated in this report as substitutes for currently used liquid and gaseous fuels. In this assessment, ethanol is produced by fermentation of grain or cellulose, and methanol is manufactured from biomass gasification to replace currently used liquid fuels. Low-to-medium Btu gas from anaerobic digestion or gasification replaces natural gas.

TABLE 3.2. Estimated 1982 Energy Use by Type and by Industry in Quads^(a)

Sector	Electricity ^(c)	Natural Gas		Petroleum		Coal		Other	Fuel Total ^(d)
		Total	Fuel Only	Total	Fuel Only	Total	Fuel Only		
Chemicals	1.59	1.87	1.32	1.71	1.16	0.32	0.32	0.15	4.54
Petroleum	0.40	2.40	2.40	2.67	--	--	--	0.08	2.88
Primary Metals	1.50	0.64	0.64	0.15	0.15	1.36	0.29	0.10	2.68
Paper	0.87	0.37	0.37	0.28	0.28	0.23	0.23	0.05	1.80
Stone, Clay, and Glass	0.30	0.39	0.39	0.04	0.04	0.29	0.29	0.12	1.15
Food	0.50	0.44	0.44	0.09	0.09	0.12	0.12	0.11	1.27
Textiles	0.27	0.08	0.08	0.03	0.03	0.02	0.02	0.04	0.45
Fabricated Metals	0.25	0.14	0.14	0.02	0.02	--	--	0.06	0.48
Machinery	0.32	0.11	0.11	0.02	0.02	0.02	0.02	0.05	0.53
Transportation Equipment	0.31	0.10	0.10	0.03	0.03	0.04	0.04	0.03	0.52
Other Manufac- turing Ind.	1.05	0.27	0.27	0.09	0.09	0.07	0.07	0.38	1.86
Nonmanufactur- ing Ind.	1.27	0.09	0.09	2.73	2.73	0.10	0.10	--	4.18
									22.34

(a) Holtberg, et al. 1983 and DOE 1983.

(b) Holtberg et al. 1983 lists the following splits for all industry:

8% of industrial natural gas used for feedstock

59% of industrial coal used for feedstock

59% of petroleum used for feedstock.

For this table, natural gas feedstock was assumed to be consumed in the chemicals industry, coal feedstock was assumed to be consumed in the primary metals industry, and petroleum feedstock was assumed to be consumed in both the chemicals and the petroleum industries.

(c) Includes losses from generation and transmission of electrical power.

(d) Includes totals for actual fuel use only (feedstock use has been removed).

TABLE 3.3. Total Quantities of Liquid or Gaseous
Fuels Consumed in 1982

<u>Sector</u>	<u>Liquid (quads)</u>	<u>Gas (quads)</u>
Residential and Commercial	3.4	9.7
Industry	5.1	7.6
Transportation	<u>18.4</u>	<u>0.6</u>
Total	26.9	17.9

3.1.1 Determination of Energy-Efficient Methods for Producing Fuels from Biomass

These first sections address the question of whether the production of fuels from various processes requires more energy than is present in the product.

Methods for fuel production that consume more energy for processing than the products contain are defined in this study to have a net energy loss; those methods that require less energy for processing than the products contain are defined to have a net energy gain. In some of the processes evaluated, feedstock or byproducts are used to supply part of the process energy as well as the energy for conversion to separate products. For these cases, the amount of feedstock energy not converted to products was calculated and included in the processing energy.

The processes for ethanol production evaluated include ethanol from hydrolysis of starch and ethanol from hydrolysis of cellulosic wastes. Calculating net energy gain to determine the relative process energy-efficiency of ethanol production is possible, because the conversion ratio of feedstock energy to ethanol output should be nearly the same for the fermentation process studied. There are several limitations to a net energy analysis, however. Net energy calculations cannot be used to compare processes with different feedstock conversion efficiencies; a total energy balance must be used. In addition, a net energy loss should not be a basis for disregarding biomass-derived fuels, since it does not focus attention on the major advantage of biomass fuels: biomass conversion processes transform renewable feedstocks into desirable substitutes for fossil fuels.

Other processes discussed include methanol and SNG production from wood gasification. Energy balances for thermochemical conversion of biomass to liquid fuels were not available so it is discussed qualitatively. Production of methane from anaerobic digestion is discussed in the section on pollution control. Details for each of these processes are provided in Appendix A.

Ethanol Production from Starch Hydrolysis

When ethanol is produced from a source of starch such as grain, the materials equation looks something like this (David et al. 1978):

The DDG can be a valuable byproduct since it is a high-protein animal feed. The carbon dioxide also can be recovered for beverage use or for making dry ice.

The energy balance for ethanol fermentation depends upon the processing technique. The conventional processing technique used by most beverage alcohol distillers was evaluated for energy consumption for ethanol production, as well as newer processes by ACR, Katzen, and Chemapec.

Although the figures for the Chemapec process shown in Table 3.4 are tentative, it appears to be one of the most energy-efficient processes for producing ethanol from starch hydrolysis. However, the newer processes featuring energy-saving innovations are also net energy producers. Energy balances indicate that the conventional technology requires more energy to produce the alcohol than is obtained from the products.

Full plant design details for the Chemapec process were not available; however, it can be described generally. The energy-savings innovations for the Chemapec process include 1) the separation of the starch portion of grain from nonfermentable materials before fermentation is begun, 2) fermentation done on

TABLE 3.4. Process Energy Balances for Ethanol Production from Starch Hydrolysis
(10^3 Btu/gal EtOH)

Process	Energy In			Energy Out			Net Energy
	Agricultural Energy ^(a)	Process Energy	Total ^(b)	Ethanol	DDG ^(c)	Total	
Conventional ^(d)	47	139	186	84	50	134	-52
ACR ^(e)	47	66	113	84	55 (est)	139	26
Katzen Associates ^(f)	47	55	102	84	50	134	32
Chemapec ^(g)	47	45	92	84	50	134	42

- (a) The energy required for fertilizers, farm fuel use, and transportation is included.
- (b) This value does not include the feedstock energy of corn because corn is not directly used as fuel. The sources of energy are coal for steam production and electricity.
- (c) The energy of DDG is fully counted as output energy since it could be burned, but it is more economical to sell as animal feed.
- (d) Based on David et al. (1978), Smith and McCullough (1980), and Chambers et al. (1979).
- (e) Based on Chambers, et al. (1979), Smith and McCullough (1980), and ACR Company (1980). The energy for capital equipment included in ACR's estimates is excluded for consistency and the heating value of DDG is upgraded to reflect a completely dry product.
- (f) Based on Smith and McCullough (1980); Chambers, et al. (1979); and Paul (1980).
- (g) Based on Smith and McCullough (1980). This estimate assumes both thermal compression and methane recovery are used in plant design.

a continuous basis with continuous vacuum evaporation of the fermentation mixture, and 3) production of methane from anaerobic digestion of process waste streams used to fuel the plant boiler.

Ethanol Production from Hydrolysis of Cellulosic Wastes

Ethanol can be produced from cellulose, as well as from starch, since both polymers are made up of fermentable glucose units. There are much larger quantities of cellulosic wastes available than there are starch wastes (Sarbolouki and Moacanin 1980). In addition, use of cellulose does not divert food crops for fuel production.

The production of ethanol requires separating pure cellulose from the rest of the biomass components, including hemicelluloses and lignins, before the feedstock is available for saccharification and fermentation. The cellulose feedstock typically is then either attacked with heat and dilute acid in several steps (D'Alessio and Blaunstein 1980, Paul 1980), or it is finely ground and enzymatically attacked (Paul, 1980; Emert, et al. 1980).^(a)

Energy balances (see Table 3.5) indicate that current technologies for cellulosic waste hydrolysis require more process energy than the products contain, if the feedstock used for fuel rather than ethanol production is included in the process energy. The Gulf process, for example, requires only 51×10^3 Btu per gallon of ethanol for process energy utilities and diesel fuel. However, an additional 80×10^3 Btu per gallon of ethanol for process energy is supplied from byproducts. Although some of these technologies can be made self-sufficient with respect to fossil fuel consumption, their net energy balance is still negative.

Methanol Production from Wood

The production of methanol from wood is based on gasification, shift reaction, and the catalytically-controlled combination of the resulting CO and H₂ gases. Major research efforts include the design of catalysts for the shift

(a) Information was also obtained from a Natick Research Laboratory internal document Enzymatic Hydrolysis of Cellulosic Wastes to Glucose, 1975, by L. A. Spano, J. Medeiros, and M. Mandels.

TABLE 3.5. Process Energy Balance for Ethanol from Cellulose (10^3 Btu/gal EtOH)

Process	Energy In			Energy Out			Net Energy
	Collection and Transportation	Processing	Total	Ethanol	Animal Feed	Total	
Acid Hydrolysis ^(a) of Agricultural Residues	8 ^(b)	57 (hydrolysis) 69 (fermentation and drying)	134 ^(c)	84	--	84	-50
Acid Hydrolysis ^(d) of Wood	10 ^(e)	126	136	84	--	84	-52
Enzymatic Hydrolysis of Agricultural Wastes (Gulf Process) ^(f)	8 ^(b)	132 ⁽ⁱ⁾	140 ^(b)	84	41	125	-15
Enzymatic Hydrolysis of Wheat Straw ^(g) (Wilke Process)	8 ^(b)	158 (hydrolysis) 14 (fermentation) 98 (concentration)	278	84	--	84	-194
Enzymatic Hydrolysis ^(h) of Wood	--	--	--	--	--	--	(negative)

(a) Based on data in Smith and McCullough (1980) and D'Alessio and Blaustein (1980).

(b) Agricultural energy to produce residues is not included, since they are byproducts of food crops.

(c) Process residue is burned to produce steam and heating value of agricultural waste not included since residues are not currently being used as fuel.

(d) Based on Smith and McCullough (1980) (estimates for corn) and Pimentel, et al. (1981).

(e) This value is higher than for agricultural residues because most wood wastes are thinly scattered over a large area.

(f) Based on Emert, et al. 1980. Authors suggested that their process would be suitable for agricultural wastes as well as for pulp and municipal solid waste.

(g) Based on information in Paul 1980 and Biomass Digest 1983.

(h) Paul 1980.

(i) Includes process energy supplied by feedstock as well as from fossil fuels and electricity.

reaction and for the methanol production. Catalysts that show resistance to poisoning or clogging with char and that have greater activity and longer life are being developed (Mudge, et al. 1983).

Producing methanol from gasification of wood shows promise and uses less energy than converting the wood to ethanol. A design by Chem Systems claims to require 2200 kW/1000 dry tons wood, over and above the recoverable energy supplied by the wood feedstock (D'Alessio and Blaunstein 1980). Since details about this system were unavailable, however, the process energy used in the energy balance (see Table 3.6) was based on data obtained from a pilot plant designed and operated by PNL (Mudge, et al. 1983; Mudge, et al. 1981).

Methanol production shows a slight net energy gain. The process energy is nearly all supplied by wood and byproduct char. In this process, char is not counted under "energy out" as a byproduct, although all the other energy balances list byproduct energy as an output credit. This is because the char is recycled, so its energy value is included as a credit in the process energy. The value obtained for net energy is not affected by counting char against process energy rather than as a byproduct.

TABLE 3.6. Process Energy Analysis for Methanol from Wood Residues^(a)

<u>Item</u>	<u>Energy, 10³ Btu/gal methanol</u>
Collection and chipping	5.4
Transportation, 6 mi	.6
Process energy ^(b)	<u>57.6</u>
Total energy in	63.6
Methanol	<u>64.8</u>
Total energy out	64.8
Net positive energy	1.2

(a) Based on a 2000 dry ton/day plant producing 1000 ton/day methanol

(b) Energy value of raw wood input not contained in product energy + electrical energy + diesel fuel energy.

Gasification of Wood

Except for the catalysts, the production of fuel gas by wood gasification is similar to the production of methanol and uses an equivalent amount of energy. Currently, wood gasification technology is limited and slow (Mudge, et al. 1983). The state-of-the-art procedure uses a fluidized bed gasifier and a catalyst designed to promote formation of the desired products.

An energy balance, shown in Table 3.7, has been calculated for a new gasification process developed at PNL (Mudge, et al. 1983). This pilot plant operates on sawdust at 10 atm and 1382°F with added steam, and uses a specially designed trimetallic catalyst. Processing energy includes utilities requirements and wood used for heating rather than feedstock.

Using the best technology, gasifying biomass has become economical if a collected supply and a local market are available. An earlier energy balance on the same process extrapolated to a 2000 ton/day gasification plant gives a net energy gain of 2.1×10^3 Btu/lb of wood (Mudge 1981) based on the same assumptions; process energy remained unchanged but product yields were improved.

TABLE 3.7. Energy Balance for Wood Gasification^(a)

<u>Item</u>	<u>Energy, 10^3 Btu/lb Wood Feedstock</u>
Collection and chipping	0.27
Transportation, 6 mi	0.03
Process energy	<u>3.10</u>
Total energy in	3.40
Char, 10% yield	1.32
Gas	<u>5.90</u>
Total energy out	7.22
Net positive energy	3.82

(a) Excludes the heating value of the feedstock, but includes the energy content of the char.

Thermochemical Conversion of Biomass to Liquid Fuels

Pyrolysis and direct liquefaction are the two major types of thermochemical conversion processes that produce a liquid fuel from biomass. Pyrolysis processes typically require dry feedstock, high temperatures, and short residence times; they are frequently performed at reduced pressures (Pofer and Bauer 1977). Liquefaction processes typically utilize wet feedstocks, lower temperatures, longer residence times, and high pressures (Donovan, Molton, and Demmitt 1981). Both processes produce an oil with moderate heating value, relatively high oxygen content, and poor storage stability. The byproducts of pyrolysis include char in relatively high yield and a low Btu gas; for liquefaction, they include char in lower yield and an aqueous phase with some dissolved polar compounds.

Most process development work is being done on a laboratory scale. Approximate energy calculations have been made for a laboratory-scale batch-type process for sewage sludge liquefaction that was developed at PNL (Donovan et al. 1980). Under these conditions, 4.84×10^3 Btu is needed to convert 2.2 lb (1 kg) of sludge, dry basis, to products containing a total energy of 14.1×10^3 Btu. The only pilot plant for wood liquefaction does not yet have energy balances.^(a)

Pyrolysis processes of wood have been under sporadic development since the latter half of the 19th century (Molton and Demmitt 1977), but energy analyses could not be found for any pilot plant currently in operation. Liquefaction may turn out to conserve more energy than pyrolysis, since the feedstock does not require drying. Although liquefaction processes are at a less developed stage than fermentation and gasification processes, they do have the potential to be net energy producers. However, the high oxygen content of the product fuel oil limits its usefulness unless it is hydrotreated. Further information in thermochemical conversion is needed to develop energy analyses.

(a) Personal communication from D. C. Elliot, PNL.

3.1.2 Current Potential Energy Savings from Bio-derived Fuels

The following assumptions were made for this analysis: 1) harvested grain, agricultural residues, and urban wastes are used to produce ethanol; 2) agricultural residues, urban wastes and forest and mill wastes are gasified to medium-Btu gas or methanol; and 3) anaerobic bacteria convert manure and sewage to methane.

Energy balances described previously for appropriate production processes are used to calculate the current potential for fossil energy savings from bio-derived fuels. Several technologies are evaluated for ethanol production, but the process with the largest net energy gain is utilized as the basis for calculations.

The amount of thermal energy currently available in the United States from biomass is about 12.0 quads (see Table 3.8). However, only about .29 quads, or 1% of liquid fuel and 2.84 quads (or 16%) of gaseous fuel used in this country in 1982 could be replaced by biomass-derived fuels (see Table 3.9). These

TABLE 3.8. Available Biomass Sources and Energy Values, 1980

Source	Energy Value (in Quad) ^(a)	Quantity, billion short ton/year
Harvested grain	.8 ^(b)	.06
Agricultural residue (collectible)	6.4	.4
Forest and mill wastes (collectible)	1.6	.1
Urban wastes	1.4	.2
Manure and sewage	<u>1.8</u>	<u>.25</u>
	12.0	1.01

(a) Figures for harvested grain come from Pimentel et al. 1981; all others from Sarbolouki and Moacanin 1980, and Sheppard and Young 1983.

(b) Total crops equal 3.70×10^8 short tons (Pimentel et al. 1981). 56 lb/bushel was assumed (David et al. 1978), and 350,000 Btu/bushel (David et al. 1978, Chambers et al. 1979). Of the 4.6 quad of total grain produced, only one sixth, or .77 quads are surplus and available for fuel (Chambers et al. 1979).

TABLE 3.9. Amount of Fuel that Could be Produced from Biomass

Fuel Type	Source	Net Fuel Produced, Quads
Ethanol	Hydrolysis of surplus grain available	.24
Methanol	Gasification and conversion of 50% of all agricultural, wood, and urban wastes available	.05

1. There are 3.70×10^8 short tons of grain produced, of which 6.16×10^7 short tons are surplus. Since 1 bushel of grain gives 2.6 gal ethanol and 16.8 lbs DDG (David et al. 1978), and assuming 56 lb/bu (David et al. 1978), 84,000 Btu/gal ethanol (Chambers, et al. 1979), and 7740 Btu/lb DDG (David et al. 1978, Chambers, et al. 1979), then 6.16×10^7 short tons of grain yields 5.72×10^9 gal ethanol and 3.69×10^{10} lbs DDG, with a combined energy content of 7.7×10^{14} Btu. From this figure the collection energy of 47,000 Btu/gal ethanol (Table 3.4), which is 2.57×10^{14} Btu for 5.72×10^9 gal ethanol, was subtracted. The processing energy of 45,000 Btu/gal ethanol (Table 3.4), which is 2.57×10^{14} Btu for 5.72×10^9 gal ethanol, was also subtracted. The net energy is therefore $(7.7 \times 10^{14}) - (2.69 \times 10^{14} + 2.56 \times 10^{14}) = 2.4 \times 10^{14}$ Btu.

2. The amount of methanol that can be obtained from half of the available agricultural, urban, and forest waste available is calculated as follows. The yield of methanol for the mixture is assumed to be the same as for wood residues. The quantity of 50% of these wastes available is estimated to be 3.5×10^8 short tons/yr (Sarbolouki and Moacanin 1980; Sheppard and Young 1983). The yield of methanol is .50 lb per pound of dry biomass, and the methanol has an energy content of 9.82×10^3 Btu per pound of methanol (Mudge, et al. 1981). The methanol energy which can be obtained therefore is about 3.43×10^{15} Btu. The energy required for processing, collecting, chipping, and transporting the biomass is 9.63×10^3 Btu per pound of methanol produced; this includes the credit for using byproducts as a fuel. This energy requirement is subtracted from the product methanol energy. The net energy which can be

TABLE 3.9. (contd)

Fuel Type	Source	Net Fuel Produced, Quads	
Methanol (contd)			obtained from conversion of 50% of dry agricultural, forest, and urban wastes to methanol is therefore $.05 \times 10^{15}$ Btu.
Gas	Gasification of 50% of all agricultural, wood and urban wastes available	2.6	3. The amount of gas that can be obtained from the other half of the available agricultural, urban, and forest wastes is calculated as follows. Dry weight of these wastes is 3.5×10^8 tons/yr. Yields of gas and char from the mixture are assumed equal to yields from wood. The yield of gas is 16.0 scf/lb dry wood, and the gas has a heating value of 361 Btu/scf (Mudge, et al. 1983). The yield of char is 10% of the dry wood weight, and has a heating value of 1.3×10^4 Btu/lb. The energy which can be obtained therefore is 5×10^{15} Btu. The energy required for processing, transporting, collecting, and chipping the biomass is 3.40×10^3 Btu/lb dry wood; this energy requirement must be subtracted from the product gas energy. The net energy that can be obtained from gasification of 50% of dry agricultural, forest, and urban wastes, therefore, is 2.6×10^{15} Btu.
Gas	Anaerobic digestion of sewage and manure	.24	4. Sewage and manure can be converted to methane by anaerobic digestion (see Section 5.3 on pollution control). The total energy shown in Table 3.8, 1.8 quad/yr, represents a total weight of 2.5×10^8 dry tons/yr. Since one ton of dry sewage and manure can produce about 3.12×10^6 Btu of methane, the energy value of the methane would total about .78 quad/yr. Collection energy is required for manure, although not for urban sewage, and is estimated to be similar to agricultural residue collection at 1.9×10^5 Btu/ton. Processing energy would be about 2.0×10^6

TABLE 3.9. (contd)

<u>Fuel Type</u>	<u>Source</u>	<u>Net Fuel Produced, Quads</u>
Gas (contd)		
Total liquid fuel replacement		.29
Total gas fuel replacement		<u>2.84</u>
Grand Total		3.13

Btu/ton (EPA 1979). The net energy that would be available from anaerobic digestion of sewage and manure would be about .24 quads/yr.

numbers are much smaller than those shown in Table 3.8 because production, collection, and processing energy have been subtracted.

The calculations for determining the fuels available from biomass are described in Steps 1 through 4 in Table 3.9.

3.1.3 Research Needs for Fuels Production

There is a large discrepancy between the amount of thermal energy originally available in the biomass and the amount of energy available after conversion to liquid or gaseous fuels. Although some processes are net energy producers, the net energy gain is only about half of the fuel value of the products even in the best cases. This illustrates the need for research to increase the process energy efficiency of biomass conversion processes.

Several energy savings developments could reduce process energy requirements. These include advanced separations technologies to concentrate and purify products in liquid streams and more selective gasifier catalysts.

3.2 BIOMASS AS A CHEMICAL FEEDSTOCK

Figure 3.1 illustrates the structure of the bulk chemicals industry. The chemicals industry currently produces several thousand products and is comprised of several distinct categories: resources, feedstocks, primary chemicals, intermediate chemicals, and end use or specialty products. A resource is defined as a raw material as it enters the economy. After suitable treatment by physical or chemical means, the resource becomes feedstock. A primary chemical is the first homogenous material derived from a feedstock. An intermediate chemical is synthesized from a primary chemical, and can be the source of an end product or another intermediate chemical. In many cases, a substance can be both an intermediate and an end product. For example, ethylene glycol is used as antifreeze (end product) and is also a precursor to polyester manufacture (intermediate) (Lipinsky 1978).

Currently the entire U.S. chemical industry consumes about 4% of petroleum, 10% of natural gas, 21% of natural gas liquids, 6% of coal and 8% of electricity. In 1982, total energy use was about 5.6 quads. If a 33%

FIGURE 3.1. Structure of Organic Chemicals Industry

efficiency is assumed for electricity, the total energy consumed is actually ^{8.9}~~6.7~~ quads. Approximately 2.5 quads of energy can be attributed to feedstock consumption and the remainder is utilized during processing (~~U.S. DOE~~ ^{OTA} 1983).

Major energy consuming product groups for the chemicals industry are shown in Table 3.10. Production of industrial organic chemicals and nitrogenous fertilizers from biomass-derived feedstocks (instead of fossil feedstocks) was evaluated in this study. Currently production of these materials consumes approximately 50% of the fuels and electricity purchased by these groups.

The following categories of chemicals were not included in this study: industrial inorganic chemicals, plastics and synthetics, drugs, soaps, cleaners and toilet goods, "others," and paints and allied products. Industrial inorganics do not use hydrocarbon feedstocks, so they could not be replaced by biomass derivatives. Plastics and synthetics can be displaced indirectly by cellulosic products, but they are excluded because 1) impacts will be diverse, 2) facilities already exist for the synthetic counterparts and 3) product

TABLE 3.10. Energy Consumption Pattern for the Chemicals Industry

<u>Category</u>	<u>% of Purchased Energy Consumed, 1981</u>
Industrial Organics	40
Plastics and Synthetics	16
Drugs	3
Soaps, Cleaners, Toilet Goods	2
Paints and Allied Products	1
Industrial Inorganics	21
Nitrogenous Fertilizers	10
Other	<u>7(a)</u>
Total	100

(a) Includes all fertilizers except nitrogenous fertilizers.

Source: (U.S. DOC 1982a)

acceptance will hinder development. Although biotechnology is already causing massive changes in the drug industry, it was not included because energy consumption is minimal. Paints and allied products and the "others" category were also excluded because of low energy consumption and limited bioprocess applicability.

3.2.1 Structure of Biomass-Based Chemicals Industry

Industrial organic chemicals and nitrogenous fertilizers are the products with substantial domestic energy consumption that would primarily be affected by direct substitutions of biological derivatives. Hydrocarbon sources such as petroleum and natural gas are currently the primary feedstock for organic chemicals and nitrogenous fertilizers, but biomass feedstocks could replace all the fossil feedstocks used by the chemicals industry (O'Brien 1982). As a result, existing primary chemicals would be directly replaced by fermentation chemicals, phenol, or benzene. Current technologies could then be used for downstream processing of intermediates and end products (see Figure 3.2).

Direct imitation of petrochemicals by a biomass-based industry was analyzed in this study because it has the advantage of instant product acceptance and many existing opportunities for transformation to end-products. However, materials comparable to petrochemical derivatives can be found in nature. Indirect substitution of these materials would eliminate the process energy requirements for synthesis of polymers and complex intermediates from simple hydrocarbons. The analysis of the indirect substitution scenario would be much more complex and was therefore beyond the scope of this report. The recommendations from this analysis should still be applicable to both direct and indirect substitution scenarios because the production of both types of materials is similar.

In a biomass-based industry, direct substitution for primary chemicals could be accomplished by the methods shown in Figure 3.3. Cellulose and hemicellulose would be hydrolyzed to sugars that are converted to ethanol, isopropanol, and ~~1,3-butanediol~~ ^{n-butanol}. These alcohols would then be dehydrated and deoxygenated to ethylene, propylene, and butadiene and directly substituted for

FIGURE 3.2. Biomass-Based Organic Chemicals Industry

FIGURE 3.3. Synthesis Routes to Major Chemical Intermediates

the fossil fuel derivatives. The residual lignin would be treated by hydrogenolysis and hydrodealkylation to yield phenol, benzene, and other mono-phenolic compounds, which could potentially be alkylated to toluene and xylene, although the technology is not yet available. Synthesis gas, ammonia, and methanol would be produced by steam gasification of biomass.

3.2.2 Comparison of Energy Consumption for Chemicals

In this analysis, all energy is converted to its primary fuel equivalent. The production of electricity is assumed to have a 33% efficiency (Gaines and Shen 1980), while steam production is estimated to have a 71% efficiency (Brown 1979). Feedstock energy is defined as the heat of combustion of the feed plus any additional processing energy before the feed enters the process sequence. If fuel byproducts are recovered, the heats of combustion are subtracted from the feedstock energy, so that the net feedstock energy is used for calculations.

The primary energy consumed by the conventional manufacture of primary chemicals in 1983 is shown in Table 3.11 for chemicals that would be replaced by biomass derivations. Approximately 2.1 quads of feedstock energy and

TABLE 3.11. Energy Consumption^(a) of Primary Chemicals in Conventional Scenario, 1983

Chemical	Production Level (Billions of lb)	Unit Feedstock (Btu/lb)	Unit Fuel (Btu/lb)	Total Feedstock (10 ¹² Btu)	Total Fuel (10 ¹² Btu)	Total Energy (10 ¹² Btu)
Acetone	1.87	(b)	6,463	(b)	12.09	12.09
Ammonia	27.37	11,435	6,455	312.98	176.67	489.65
Benzene ^(h)	9.48	18,947	6,363	179.62	60.32	239.94
Butadiene ^(f)	2.31	26,266	7,859	60.67	18.15	78.82
Ethanol	1.10	(c)	8,032	(c)	8.83	8.83
Ethylene	28.59	27,768	7,800	793.89	223.00	1,016.89
Isopropanol	1.21	(b)	4,555	(b)	5.51	5.51
Methane	6.35 ^(d)	23,861	0	151.52	0	151.52
Propylene	13.98	27,717	6,784	387.48	94.84	482.32
Xylene ^(g)	5.57	23,686	5,293	131.93	29.48	161.41
Toluene ^(g)	3.76 ^(e)	18,379	5,293	69.11	19.90	89.01
Total				2087.20	648.79	2,736.00

(a) Primary fuels are assumed to be converted to electricity at 33% efficiency and to steam at 71% efficiency.

(b) Feedstock included in propylene and benzene.

(c) Feedstock included in ethylene.

(d) Amount required for methanol, acetylene, and small use hydrogen manufacture.

(e) Does not include amount used to make benzene.

(f) Weighted average of energy requirements for butadiene produced as 1) a byproduct of ethylene manufacture and 2) as the desired product from dehydrogenation of butane or butene.

(g) Extracted from petroleum reformat.

(h) Weighted average of energy requirement of benzene produced by extraction from petroleum reformat and by toluene disproportionation.

0.5 quads of process fuel are consumed. Feedstock values in Table 4.11 include some process energy so they may be larger than the values reported in other references. Energy balances from published sources (Gaines 1980; Brown 1979) were used, and production data were derived from C&E's Top 50 List (Chemical and Engineering News, June 11, 1984).

Energy balances derived by Donaldson and Culberson (1983) were utilized to calculate the process energy consumption of biomass-based chemicals shown in Table 3.12. Production levels reflect the amount of biomass-based chemicals required to produce downstream chemicals in quantities equivalent to that of the fossil-based scenario in 1983.

The process energy required for the production of major primary chemicals from biomass is estimated to be approximately 1.67 quads. Since the wood is assumed to be a residue, agricultural energy to grow the wood is not included. If the fossil energy to collect and transport the wood (293 Btu/lb of wood) is included, the calculated process energy requirements for the biomass-based chemicals industry must be increased from 1.67 to 1.80 quads.

Approximately 439 billion lb, or 0.22 billion tons, of wood would be required to produce the chemical feedstocks. If the feedstock energy of 0.22 billion tons of dry wood at 8000 Btu/lb is included, total feedstock energy consumed by the biomass-based scenario is 3.51 quads.

3.2.3 Research Needs for Biomass as a Feedstock for Chemicals

All the 2.1 quads of feedstock energy required for the synthesis of organic chemicals and nitrogenous fertilizers could be met using currently available supplies of wood and wood residues, neglecting additional process fuel requirements. Crop residues could also be used, but they were not analyzed in this study. The saving is still desirable despite the fact that burning the equivalent quantity of wood feedstock directly could provide 3.51 quads of energy; however, chemical production is more desirable because the dollar value of a feedstock as a chemical is about three times its value as a fuel (Palsson et al. 1981). In addition, the use of biomass frees the chemical industry of its reliance on fossil sources of feedstock and has many ecological benefits, such as the formation of less caustic effluents.

TABLE 3.12. Energy Consumption^(a) for Biologically-Based Chemicals

Chemical	Production Level (billions of lb)	Unit Feedstock (per lb product)	Unit Fuel (Btu/lb)	Total Feedstock (10 ⁹ lb)	Total Fuel (10 ¹² Btu)
Acetone	1.87 ^(b)				
Ammonia	27.37	1.73 lb wood	7,462	47.35 wood	204.23
Benzene	9.48 ^(c)				
1,3-Butanediol	4.81 ^(m)	11.39 lb wood	37,611	54.79 wood	180.91
n-BUTANOL Ethanol	47.62 ^(d)	4.37 lb wood	15,327	208.10 wood	729.87
Ethanol	.71 ^(b)				
Ethylene	27.92 ^(e)		4,000 ^(k)		111.68
Isopropanol	17.84 ^(f)	5.71 lb wood	15,327 ^(k)	101.87 wood	273.43
Synthesis Gas	17.03 ^(g)	1.59 lb wood	1,390	27.08 wood	23.67
Phenol	13.58 ^(h)	4.95 lb lignin	4,452	67.22 lignin	60.46
Propylene	11.85 ⁽ⁱ⁾		4,000 ^(k)		47.40
Toluene	3.76 ^(j)		4,000 ^(k)		15.04
Xylene	5.57 ^(j)		4,000 ^(k)		22.28
				439.19 wood	1,669.0
				67.22 lignin	

(a) Primary fuels are assumed to be converted to electricity at 33% efficiency and steam at 71% efficiency.

(b) Produced as byproduct in ~~n-butanol~~ production.

(c) Produced as byproduct in phenol production.

(d) Includes amount necessary to satisfy ethylene feedstock requirement.

(e) By dehydration of ethanol, 0.67 billion lb of ethylene feedstock not needed to make ethanol.

(f) Includes amount necessary to satisfy propylene feedstock requirement.

(g) Includes amount required in conventional scenario plus additional amount for alkylation of phenol to toluene and xylene.

(h) Amount required to manufacture toluene and xylene at 80% yield.

(i) By dehydration of isopropanol, .91 billion lb propylene not needed to make isopropanol, 1.22 billion lb not needed to make cumene.

(j) Via alkylation of phenol or benzene.

(k) Estimate based on published partial data and/or data from similar processes.

(l) 3.36 billion lb Toluene got need to make benzene.

(m) Amount to make 2.31×10^9 lb butadiene.

Currently, the process fuel requirements of a biomass-based chemical industry are estimated to exceed conventional process energy requirements by 1.02 quads. If collection and transportation energy for wood is included, the estimated additional energy consumption increases to 1.15 quads.

Improvements to bioprocess technologies are necessary to change the energy efficiency and allow economic entry into the chemicals manufacturing industry. Separation costs are high for fermentation processes because of the

dilute nature of the products. Bioreaction systems that yield higher concentrations could be developed. Separations costs could also be reduced by the development of less energy-intensive technologies such as membranes.

Energy for gasification reactions to produce SNG, ammonia, and methanol could be reduced by improved gasifier designs and also by the development of biocatalysts resistant to high temperatures and pressures. Biocatalysts (described further in Section 4.0) could also reduce energy requirements for fossil-based processes.

Although not analyzed in this report, a large potential for energy-savings exists from the development of biomass-derived substitutes for petroleum-based plastics, fibers, rubbers, and resins. Large complex molecules provided by nature could theoretically be converted directly to intermediates and final products with minimal processing.

4.0 APPLICATIONS FROM GENETIC ENGINEERING

The development and improvement of genetically-engineered materials should provide industry with revolutionary new techniques for the production of goods and services. The large-scale implementation of these techniques would result in substantial energy savings over conventional scenarios.

The developments in genetic engineering that will affect major industries are discussed in the following section. Energy-saving applications are evaluated for fuels production, chemicals production, mining, pollution control, agriculture and food processing. First, the current consumption of primary energy is discussed for each industry. Second, specific applications of genetically-engineered materials are identified. Then, the potential energy savings resulting from the large-scale implementation of genetically-engineered materials is determined. Finally, recommended areas for research are identified.

4.1 FUELS PRODUCTION

Bio-derived fuels do not have a large-scale potential to substitute for fossil fuels, given the current process efficiencies and yields of biomass. The potential for genetic engineering to improve the feasibility of large-scale fuels production from biomass is discussed in the following section. Technologies for the production of bio-derived fuels are discussed in Section 3.0.

4.1.1 Current Limitations to Large-Scale Fuels Substitution

Based on PNL calculations (see Appendix B), the 26.9 quads of liquid fossil fuels consumed in 1982 could be replaced by the manufacture of 45 quads of methanol or 55 quads of ethanol. The excess bio-derived fuel must be produced to provide fuel for cultivation, fertilization, harvest, transportation, and processing of the biomass feedstock. Calculations indicate that growth of the required quantities of biomass for methanol production would require 1.82 billion acres of forestland, or for ethanol, 2.85 billion acres of cropland. This is 253% more forestland or 792% more cropland than is currently available in the United States.

If current yields of biomass feedstocks could be improved through genetic engineering, the land requirements for growth would be reduced. According to Edward S. Lipinsky and Dr. William Sheppard at Battelle Columbus Laboratories (BCL), genetic engineering could realistically be expected to improve current yields of plants by a factor of three. Table 4.1 illustrates the percentages of currently available U.S. land that would be required for biomass feedstock production at current yields and three times the current yields. This analysis is based on the assumption that other energy inputs per unit of biomass output do not increase.

TABLE 4.1. Land Requirements for Biomass Production to Meet the 1982 Fuel Demand

Fuel	Production Required for 1982 Fuel Demand, Quads	Biomass Feedstock Required (tons) ^(a)	% of 50 State Area for Growth ^(b)		% of Currently Available U.S. Land	
			Current Yields ^(c)	Improved Yield ^(d)	Current Yield	Improved Yield
Ethanol	26.9	7.1×10^9	124	41	792	264
Methanol	26.9	9.1×10^9	78	26	253	84
SNG	17.9	3.87×10^9 ^(e)	34	11	108	36

- (a) Methanol and SNG are derived from wood biomass. Ethanol is derived from corn.
 (b) 50 state area is 2.3×10^9 acres, of which 16% is cropland and 31% is forestland (Meyers 1983).
 (c) Current yield for corn is assumed to be 2.5 tons/acre of grain (Burwell 1980) and for wood it is assumed to be 5 tons/acre of biomass (Meyers 1983).
 (d) Estimated for genetically improved yield is 3 times current yield.
 (e) Corn is grown on cropland, wood is grown on forestland.
 (f) Approximately 11% is for a methanol product to provide liquid fuels for growth and collection and 89% is for conversion to SNG.

4.1.2 Potential Impact of Genetic Engineering

To put this analysis in perspective, results are shown graphically in Figures 4.1, 4.2, and 4.3. Comparison of land requirements in the figures at current yields and three times the current yields illustrate that genetic engineering should improve the feasibility of large-scale fuel production from

FIGURE 4.1. Potential Availability of Biomass to Provide Liquid Fuel from Methanol

FIGURE 4.2. Potential Availability of Biomass to Provide Liquid Fuel from Ethanol

FIGURE 4.3. Potential Availability of Biomass to Provide Gaseous Fuel from SNG

biomass feedstocks. It is unlikely, however, that the total fuel demand can be supplied using biomass feedstocks, although the potential for partial replacement is significant.

It is assumed in this analysis that yields of biomass feedstocks can be improved without significant increases in other energy inputs. Increasing yields will require a balanced program of genetic research to increase photosynthetic efficiency, biologically fixate nitrogen, and improve the water retention of soil. The development of any other traits that ensure consistent biomass yields despite the year-to-year variability of natural growing conditions would also increase the feasibility of large-scale biomass production.

Genetic engineering to improve the process efficiency of biomass conversion technologies would also reduce the land requirements for large-scale fuels production. Twice as much ethanol must be produced, for example, than the amount required to substitute for the fossil fuel demand. Process energy requirements could be reduced if the products streams could have higher concentrations of ethanol. Another way to reduce process energy is to improve the ability of the biomass feedstock to dry naturally in short periods of time. This has already been accomplished for several varieties of corn.

Energy for both gasification and fermentation of biomass could be reduced by the development of biocatalysts, which are discussed further in Section 4.2. Development of enzymes that are stable at high temperatures and pressures could increase conversion efficiencies and reduce energy inputs, especially for the gasification process. Continued work on bioreactor designs that incorporate immobilized microbes and enzymes is also necessary.

4.2 CHEMICALS PRODUCTION

Current energy consumption for biomass-based chemicals production, discussed in Section 3.0, is prohibitive. The use of genetically-engineered materials could significantly reduce the energy consumed by the U.S. chemicals industry by promoting the feasibility of biomass feedstock and reducing process energy requirements. Several advantages of biosynthetic processes are described in the following paragraphs. Limitations to large-scale implementation of these technologies are also discussed.

4.2.1 Advantages of Bioprocessing

In bioprocessing, microorganisms or the enzymes produced by microorganisms (biocatalysts) are used to convert raw materials to products. Biocatalysts are genetically-engineered materials that have particular energy-savings potential. Biocatalysts are enzymes or protein structures that expedite the conversion of a raw material to a product. These enzymes are usually produced by microorganisms and then purified. In many cases, the microorganisms can be added directly to the raw materials, where the cells produce the enzymes as a result of their genetic mechanisms.

Microorganisms and biocatalysts show great promise for both fossil-based and biomass-based industrial applications. Some biocatalysts can accelerate reactions up to 14 orders of magnitude, which is 4 to 6 orders of magnitude beyond the effect of most chemical catalysts. They are very specific in the products they synthesize, which inherently offers control over the products formed and decreases undesirable side products. As a result, separation and purification requirements are reduced, and this in turn reduces the need for disposal and management of pollutants.

Microorganisms and biocatalysts can carry out several steps of a synthetic process in one vessel, which eliminates the need for capital equipment for separation and purification of currently manufactured intermediates (Dunnill 1980). Therefore, most of the process energy used for the production of chemical intermediates could theoretically be saved.

Whole cell or enzyme systems can be developed for existing processes or they can be engineered for novel synthesis routes. Revolutionary developments from genetic engineering, such as microbial processes that convert low-value materials such as biomass, coal, or even toxic wastes directly into end products, are theoretically possible. These processes would eliminate the need for energy to depolymerize large complex molecules available from nature into the small chemical building blocks that must be repolymerized into chemical intermediates or end products.

4.2.2 Limitations to Implementation of Bioprocesses

Utilization of biocatalysts for industrial reactions will not be realized without developments in genetic engineering and bioreactor design. Catalyst systems that immobilize whole cells or enzymes must be designed to withstand the harsh conditions of typical chemical synthesis environments. This must be accomplished without affecting the stability or the catalytic properties necessary for economic commercial application of bioprocesses in the chemicals industry.

Enzymes and support systems that are stable under high temperatures, high pressures, and acidic or caustic conditions are an important research challenge for processes that favor these equilibrium states. In addition, many important enzymes, such as hydrogenase, nitrogenase, or formate dehydrogenase cannot be exposed to air without loss of activity. Genetic engineering to develop enzyme counterparts that are stable in the presence of oxygen is a potential solution, along with the design of bioreactors that minimize the exposure of the enzyme to oxygen.

Scale-up problems related to large-scale bioreactor design must also be solved. Competitive chemical processes require high volumetric productivity to minimize capital investment. In traditional fermentation, processes minimize volumetric productivity because they are usually batch-fed. This allows high product concentrations to accumulate by letting the volumetric flow rate approach zero. However the use of highly active immobilized enzymes should make it possible for reactors to run continuously with high formation rates.

The development of bioreactor systems has been difficult to achieve because of engineering limitations and physical constraints. In an immobilized biocatalytic system, substances must diffuse from the bulk solution to the catalytic sites. As volumetric productivity increases, so do the diffusional requirements of the bioreaction system. Nutrients (in the case of whole cells) and substrates must be transferred to the catalytic site, while products and excess heat must be diffused back into the bulk solution. Without effective heat and mass transfer within an immobilized catalyst system, high enzymatic reaction rates cannot be achieved.

To minimize diffusional limitations, continuous bioprocesses can currently be characterized by high volumetric flow rates and low product concentrations. Bioprocessing research to maximize the concentration of the products leaving the reactor is necessary to reduce energy consumption for isolation and purification. Genetic engineering to reduce nutrient requirements and increase conversion efficiencies of biocatalytic reactions are potential solutions to these problems. Development of biocatalysts that are phobic toward the material produced would also increase diffusion rates.

4.3 METALS MINING AND RECOVERY

Metal mining consumes about 7% of the energy used by the minerals industries. If we include the efficiency of electrical generation, energy used by metal mining (major group SIC 10) was about 0.25 quads in 1977. Preliminary reports indicate that energy use was less in 1982 than in 1977, but exact data are not yet available (Bureau of the Census 1984).

Major energy-consuming metal mining and recovery techniques that could use microbial methods include the leaching of copper, lead, zinc, uranium, gold and silver deposits. Recovery of these ores consumes about 45% of the energy used by industries in category SIC 10. In 1980, the amount of energy used to recover these ores, based on data in Tables 4.2 and 4.3, is estimated to have been about 0.17 quads. This includes the smelting and refining of copper, lead, and zinc and the refining of gold and silver, which are not included in industry category SIC 10.

4.3.1 Bacterially-Assisted Recovery Methods

Two microbial interactions with metals that are of potential industrial importance are 1) microbial leaching of metals from ores and, 2) bioaccumulation of metals from dilute mixtures. The first method could be implemented on a large scale for the recovery of copper, uranium, lead, and zinc from vast quantities of low-grade solid materials. Bioaccumulation would be of primary importance for recovering higher value metals such as gold and silver from dilute waste streams. The potential production rates for the metals recovered

TABLE 4.2. Process Energy Required per Ton Product (10^6 Btu)

	<u>Mining</u>	<u>Crushing/Grinding</u>	<u>Concentrating</u>	<u>Smelting</u>	<u>Refining</u>	<u>Total</u>
Copper	20.1 ^(a)	29.4 ^(a)	12.6 ^(a)	29.5 ^(b)	10.1 ^(b)	101.7
Lead ^(b)	4.31	3.33	1.20	12.9	5.1	26.8
Zinc ^(b)	5.57	4.06	1.68	--	54.18	65.5 ^(c)
Gold	73,544 ^(d)	16,397 ^(e)	28,422 ^(e)	--	5,389 ^(e)	123,752
Silver ^(e)	1,586		477.5	--	510.9	2574.4
Uranium ^(f) Oxide	532	117.5	448.4	--	1097.9	2195.8

(a) University of Utah (1980).

(b) BCL (1975).

(c) Weighted average of production methods.

(d) Derived by author from energy and production data in 1980 Minerals Yearbook (U.S. Bureau of Mines 1981) and 1977 Census of Minerals Industries (Bureau of the Census 1981).

(e) Derived from data in BCL (1976).

(f) Average of values in BCL (1975)

TABLE 4.3. Energy Consumption in Metal Production (10^{12} Btu), 1980

	Production (st) ^(a)	Mining	Grinding	Concentrating	Smelting	Refining	Total
Copper	1,054,000 ^(b)	21.2	31.0	13.3	31.1	10.6	107.2
Lead	604,432 ^(c)	2.6	2.0	0.7	7.8	3.1	16.2
Zinc	368,384 ^(c)	2.1	1.5	0.6	(g)	20.0	24.2
Gold	21.8 ^(d)	1.6	0.4	0.6	(h)	0.1	2.7
Silver	234.7 ^(e)	0.4	(g)	0.1	(h)	0.1	0.6
Uranium Oxide	16,388 ^(f)	8.7	1.9	7.3	(h)	(h)	17.9
		36.6	36.8	22.6	38.9	33.9	168.8

(a) In short tons. Source: U. S. Bureau of Mines (1980).

(b) This value represents 82% of production recovered by conventional techniques. Surface mines yield about 80% of conventionally recovered copper while underground mines yield 20% according to Minerals Yearbook 1980 (U.S. Bureau of Mines 1981).

(c) Domestic ores are predominantly sulfide ores from underground mines according to BCL (1975).

(d) This value represents 67% of gold from precious metal ores Minerals Yearbook 1980. Approximately half of production is from underground mines and half from surface mines according to BCL (1976).

(e) This value represents the 22% of domestic production from silver ores. Most silver is from underground mines according to BCL (1976).

(f) This value represents the 46% of domestic production from underground mines, and the 29% of domestic production from surface mines according to Statistical Data on Uranium Industry (DOE 1981). Production estimated from Statistical Abstract of the United States National Data Book, Guide to Sources (Bureau of the Census 1982).

(g) Included in other activities.

(h) Not applicable.

by microbial leaching are much greater than the production rates for precious metals. Microbial leaching therefore has the most significant energy-savings potential.

Both microbial and non-microbial heap leaching techniques begin by taking ore out of the ground and milling the rocks to reduce particle size. Instead of expensive beneficiation techniques, ore is transported to dump sites where aerators spray acidified water over the top surface. Since the organisms are ubiquitous, they proliferate with the introduction of the water. The metal-laden solution accumulates in reservoirs at the foot of the piles. The metal is removed via solvent extraction and precipitation or other techniques.

A similar procedure is also used for in-situ leaching of uranium. Instead of mining, crushing, and grinding the ore, wells are drilled into mineralized zones and a solution containing oxidants is injected. Recovery wells pump the solution to the surface where the metal is removed from the leachate.

4.3.2 Energy Savings from Biotechnology

Based on methods currently used for copper production, the energy required for bacterially-assisted heap leach methods exceeds the energy required for conventional processing. The following energy comparison dictates this conclusion: the heap leaching of copper requires at least 107.1×10^6 Btu/ton of copper.^(a) The energy required for conventional processing is 101.7×10^6 Btu/ton of copper. A BCL (1976) study concluded that little can be done to change the current dump leaching process to save energy.

The in-situ leaching of copper from a deep-seated deposit appears to be the least energy-consuming biological recovery process. Approximately 80×10^6 Btu/ton copper is required even at 50% recovery. About 56×10^6 Btu/ton of

(a) Approximately 41×10^6 Btu/ton of copper is due to pumping of waste solution to the top of the dump. The other 46×10^6 Btu/ton of copper is the energy represented by the steel scrap consumed while precipitating copper from the leach liquor (BCL 1975). An additional 35×10^6 Btu/ton of copper is used in the subsequent refining process (University of Utah 1980). In addition, energy for mining is accounted for at 20.1×10^6 Btu/ton of copper. Since the low-grade ore is a byproduct of surface mining, the energy for mining is not usually included.

copper is used in drilling, fracturing, and leaching. The remaining 24×10^6 Btu/lb is used for electrowinning. Currently, energy requirements for in-situ leaching are about 20% lower than for conventional methods. If higher recoveries could be achieved, in-situ extraction would be even more attractive (University of Utah 1980).

Detailed energy consumption data for the heap and in-situ leaching of the other metals studied were not available; however, the conclusions drawn from copper recovery probably indicate an energy-savings potential of bacterial leaching of other metals. Therefore, it is assumed that all ores currently recovered by underground methods could be recovered by in-situ leaching methods using acid-producing or bioaccumulating bacteria. Using the data shown in Table 4.3, it is estimated about 0.11 quads are required to recover the copper, uranium, lead, and zinc metals by underground methods. Approximately 20%, or 0.014 quads could be saved if bacterially-assisted in-situ methods were used.

4.3.3 Research Needs for Metals Mining and Recovery

In the future, deep deposit underground mining is expected to become more important as surface deposits are depleted. However, the geology or mineralogy of the underground deposits may not be suitable for in-situ leaching. In fact, studies have shown that considerable R&D would be necessary to bacterially leach the uranium ores of the Rocky Mountains and south Texas because of their low pyrite concentrations (Brierley 1979). Thus, genetic engineering is necessary to increase effectiveness of bacterially-assisted in-situ leach methods.

The impact of bioaccumulation on the energy required for gold and silver mining is uncertain. Bioaccumulation techniques for recovery of gold and silver from dilute solutions could potentially increase the amount of gold and silver recovered in the United States. Since these solutions are waste streams, the energy currently required for mining, crushing, and grinding of gold and silver ores would not be necessary. Because of the high value of precious metals, however, the economics of recovery is not of as much concern as product quality and security. An optimistic evaluation is that the 0.002 quads currently required for mining, crushing, and grinding would be saved because gold and silver demand could be met more economically using bioaccumulation techniques.

A very practical emphasis of bacterially-assisted leaching may be the mining of strategic minerals that are contained in ores that are of too low a grade to mine conventionally. The lower cost and specificity of biological recovery methods could decrease our reliance on foreign sources for these materials. Strategic minerals were not analyzed in this study because their recovery does not currently consume much energy.

4.4 POLLUTION CONTROL

An analysis by Serth and Hockett (1978) estimated that the U.S. consumed 1.7 quads of energy in 1977 for control of all pollutants. Their study estimated that in the future 2.5-3% of total domestic energy demand will be required for control of pollution. Using a 3% estimate, in 1982 about 2.2 quads of energy were consumed and by the year 2000 an estimated 3.0 quads will be needed to control pollution.

There has been increased emphasis on environmental concerns, particularly in the areas of water quality, acid rain, and hazardous materials in the environment. It is expected that there will be changes to federal environmental regulations which will result in stricter standards for each of these areas. If stricter standards are enforced, the energy consumed by pollution control could exceed the 2.5-3% range estimated by Serth and Hockett.

Industry generates the major portion of this country's environmental pollution and also consumes the most energy for its control. Power generation and handling of municipal refuse are two other areas that consume appreciable amounts of energy for pollution control. Table 4.4 presents energy requirements for pollution control in these categories by pollutant type.

Natural biological systems have been available for many years to handle solid and liquid wastes, but as new biotechnological developments occur, it is possible that existing biological systems will be improved and that totally new pollution control methods will be created. The following sections discuss conventional methods for pollution control, potential energy impacts of biotechnology in this area, and future biological developments.

TABLE 4.4. Pollution Control Energy by Consumer and by Pollutant Type

Source	Quadrillion Btu	
	1977 ^(a)	1982 ^(b)
<u>Industry^(c)</u>		
Water	0.35	.43
Air:	0.65	.82
SO _x	0.38	.48
Particulates	0.17	.22
Other	0.10	.12
<u>Power Generation</u>		
Air:	0.19	.24
SO _x	0.18	.24
Particulates	0.01	
Thermal ^(d)	0.15	.19
<u>Municipal</u>		
Water	0.27	.35
Solid waste	0.10	.13
Total	1.71	2.16

(a) (Hockett 1978)

(b) Estimate based on 3% of total domestic energy demand of 72 quads.

(c) Industrial users as follows: Primary Metals (36%); Chemicals (15%); Paper (9%); Petroleum (8%); Fabricated Metals (3%); Stone, Clay, Glass (5%); Food (7%); and all others (18%); 1977.

(d) Thermal includes cooling water treatment.

4.4.1 Possibilities for Biotechnological Pollution Control

There are three types of pollutants that are of concern: those in the atmosphere, those in aqueous environments, and solid materials. This section discusses biological techniques for reducing a major atmospheric pollutant--SO_x from coal. Next, biological methods for treating industrial organic wastes, both aqueous and solid, are evaluated. Then the effects of large-scale usage of anaerobic digestion treatment for municipal waste water are estimated.

Finally, calculations are provided for total energy savings if biological pollution control methods could be implemented.

4.4.1.1 Control of SO_x from Coal

Most energy losses due to air pollution control are involved with SO_x emissions. Since coal is the primary source of the SO_x emissions, coal cleanup, including flue gas desulfurization, sulfur recovery, physical and chemical coal cleaning, coal gasification, and forced draft cooling towers, can be regarded as major air pollution control methods. Since industrial and power plant use of coal is expected to increase, control of SO_x may become the largest single energy consumer in the future. If biotechnology is to make a significant impact on pollution control energy, methods for cleanup of coal must be developed.

Many different groups have studied the microbial removal of inorganic sulfur from coals (Brierley 1982; Andrews and Maczuga 1982; Beier 1982; Hoffman et al. 1981; Torma and Murr 1980; Detz and Barvinchak 1979). Inorganic sulfur can be removed microbially with about 90% efficiency, giving sulfuric acid as a byproduct (Brierley 1982). The process is very time-consuming, requiring usually one to two weeks for complete removal (Andrews and Maczuga 1982; Hoffman et al. 1981; Torma and Murr 1980). For best removal, the coal must be finely ground and the pH controlled at a highly acidic level. Additional heat is not needed.

A typical high sulfur coal might contain about 2% inorganic sulfur and 2% organic sulfur (Seward, Hollis, and Opalanko 1978), with the exact quantities varying depending on the coal source. Organic sulfur is not removed under the conditions described in the preceding paragraph. When technologies are developed for removal of organic sulfur, the additional energy consumption is estimated to be fairly small; coal is already ground prior to burning, and little additional heat would be required.^(a) Organic sulfur can currently be removed with about 20% efficiency if different bacteria are used and if the temperature

(a) Conversation with Dr. Minoo Dastoor, Jet Propulsion Laboratory.

is maintained at 70°C.^(a) These studies have been at a bench scale only; there have been no large-scale determinations of economic feasibility or of energy consumption.^(a,b)

4.4.1.2 Control of Organic Aqueous and Solids Industrial Waste

Aqueous organic wastes are typically concentrated and then either buried or incinerated, depending on the degree of hazard (Zaborsky 1983). Some waste streams can be treated with activated sludge (Siegrist 1981), which will degrade some organic compounds to acceptable discharge levels. Other types of microbial degradation are not widely used.

Microbes that will degrade specific chemical pollutants with high efficiency are being identified or genetically engineered (Siegrist 1981; Zaborsky 1983). There are organisms that can degrade long-lasting toxins, such as 2,4,5,-T (an herbicide) and dioxins (toxic byproducts of herbicides), as well as a host of other highly persistent phenolic compounds. Currently, many technical and economic considerations limit practical use of these microbes for control of specific pollutants (Zaborsky 1983).

In addition, innovative biodegradation techniques have been developed and tested for organic wastes from chemical plants and other sources (De Renzo 1980). These techniques use some variety of aerobic microbial degradation that reduces biological oxygen demand (BOD) by about 90%, chemical oxygen demand (COD) by about 80%, and total dissolved solids by about 20% to 50%. These techniques include series lagoons for combining anaerobic with aerobic treatment, pure oxygen aeration for increased oxygen transfer and higher activated sludge concentrations, high-volume activated sludge treatment combined with fluidized bed combustion, and deep-shaft aeration to increase oxygen transfer with pressure. Energy calculations show that deep-shaft aeration would require the least energy per lb of BOD removed (Table 4.5).

(a) Conversation with Dr. Minoo Dastoor, Jet Propulsion Laboratory.
(b) Conversation with Dr. R. Attia, BCL.

TABLE 4.5. Energy Requirements for Four Biodegradation Techniques

<u>Technique</u>	<u>Energy Required, Btu/lb BOD Removed</u>
Series lagoon	4.0×10^3
Washburn tunnel (high-volume activated sludge)	1.7×10^3 (a)
UNOX (pure oxygen aeration)	1.4×10^3 (b)
Deep-shaft aeration	1.1×10^3 (c)

(a) Aeration power only, does not include pumping or raking energy.

(b) Mixing and O_2 generation power requirements only.

(c) Based on total power consumed.

4.4.1.3 Treatment of Municipal Waste Water

Anaerobic digestion is currently a net energy producer used extensively for treatment of sewage sludge. It generates a 50% to 60% methane gas (Kemmer 1979; EPA 1979) that can be burned to fuel other plant operations. Other types of waste have limited possibilities for treatment by anaerobic digestion, because fairly concentrated wastes are required, and because any sulfates are converted to sulfides, causing possible odor problems. Energy flows are well established for digestion of sewage sludge (see Table 4.6). Energy input is primarily for heating the sludge, and approximately 4800 thousand Btu/ton of dry solids is generated, as surplus gas.

Anaerobic digestion is a proven technology, which could be more widely used for treatment of primary municipal waste water. One source estimated that if all municipal waste water were anaerobically digested, all of the electrical energy requirements for primary treatment plants could be supplied (Serth and Hockett 1978).

4.4.2 Energy Savings Impact of Available Biotechnology

Three potential methods were identified in the previous section for biotechnological pollution control: 1) removal of sulfur from coal to reduce SO_x emissions into the atmosphere; 2) treatment of industrial organic wastes using

TABLE 4.6. Energy Balance for Anaerobic Digestion of Sewage Sludge

<u>Item</u>	<u>Energy, 10³ Btu/Ton Dry Solids</u>
Raw sludge heating	1300
Secondary sludge heating	500
Mixing	<u>200</u>
Total energy in	2000
Gas produced	<u>4800</u>
Total energy out	2800

Source: EPA 1979.

deep-shaft aeration; and 3) anaerobic digestion used more extensively to treat municipal waste water in addition to sewage sludge.

The energy used for SO_x removal necessitated by the burning of coal was estimated to be about .72 quads in 1982. If all coal were microbially cleaned prior to use, about 45% of all the sulfur could be removed and energy required for SO_x removal would be reduced. Assuming that microbial pretreatment would require about 20% of the energy for postcombustion cleanup, about .25 quads of energy could be saved (see Table 4.7). It should be emphasized that this energy savings estimate is hypothetical, since microbial desulfurization of coal is neither being done nor developed on a commercial scale.

TABLE 4.7. Potential Energy Savings for Microbial Desulfurization

<u>Item</u>	<u>Energy, Quad</u>
Energy for microbial treatment of coal, estimated	.07
Energy for cleanup of nondegradable sulfur	<u>.40</u>
Total energy required if biotechnology used	.47
Total energy currently used	.72
Possible energy savings	.25

As mentioned previously, anaerobic digestion could be more widely used for treatment of primary municipal waste water. Based on the Serth and Hockett (1978) estimate that if all municipal waste water were anaerobically digested, all of the electrical energy requirements for primary treatment plants could be supplied; this would mean that about .26 quads per year of the .35 quads consumed for treatment of municipal waste water in 1982 (see Table 4.4) could be saved. This assumes that about .09 quads of power from sources other than electricity were also required.

If deep-shaft aeration were used to treat all industrial organic waste, about 0.20 quads of energy could be saved per year (see Table 4.8). Since deep-shaft aeration will not affect inorganic chemical concentrations, these were omitted from the energy savings estimate. The amount of energy that could be saved for the three combined pollution control methods discussed totals .71 quads, or 33% of the energy now estimated to be used for pollution control.

4.4.3 Future Developments in Pollution Control

In order to handle future environmental problems, research must be directed toward the development of economic, energy-efficient pollution control operations. Environmental groups, such as the Clean Air Coalition, are calling for reduced emissions of pollutants and stricter environmental regulations (Barton 1984). If stricter regulations are enacted, pollution control efforts should require larger energy inputs and become more costly. The Department of Defense predicts it will spend over one billion dollars in 1984 for cleaning up defense waste (Daley 1984), and pulp and paper companies are planning to spend more than 240 million dollars this year for environmental projects (Brusslan 1984).

Developments in the biotechnology area suggest that the biological behavior of microorganisms can be genetically manipulated to enhance characteristics that would aid pollution control efforts. Two emerging areas are enzyme degradation systems to handle hazardous organic chemicals, and systems utilizing metallothioneins to extract heavy metals from waste waters.

Enzymes are biochemicals, usually produced by microorganisms, which can be concentrated and purified. Once a microorganism is identified as having an

TABLE 4.8. Series of Calculations to Determine Potential Energy Savings for Deep-Shaft Aeration of Organic Wastes

Step	Item Being Calculated	Value of Item Being Calculated
1	Total energy requirement for deep-shaft aeration (De Renzo 1980)	1.1×10^3 Btu/lb BOD removed
2	Conversion of Step 1 value to energy/lb dry waste	
	a. BOD removed/day (De Renzo 1980)	1.9×10^3 lb BOD/day
	b. Energy required per day to remove all BOD	1.3×10^3 Btu/day
	c. Total dissolved solids per day (De Renzo 1980) (a)	2.8×10^2 lb solids/day
	d. Energy required per lb to aerate solids (b)	9.5×10^2 Btu/lb solids
3	Total dry organic waste produced (De Renzo 1980) in 1982	6.0×10^6 ton/yr
4	Total amount of energy to aerate all organic wastes (Step 2d units converted and multiplied by Step 3)	1.1×10^{13} Btu/yr
5	Amount of energy used in 1982 for organic waste (d)	2.1×10^{14} Btu/yr
6	Amount of energy savings with deep-shaft aeration (Step 5 minus Step 4)	2.0×10^{14} Btu/yr

(a) Assumes that total dissolved solids = total chemical waste in the water.

(b) Estimated assumed equal to value report by De Renzo 1980.

(c) Since about 60% of the total chemical waste is organic, we assumed that about half of the pollution control energy would be used to process organic wastes.

(d) Assumes that total energy need for BOD removal = total energy for dissolved solids treatment.

enzyme that can hydrolyze an organic pollutant, the enzyme structural genes could be transferred to a host organism capable of producing large volumes of the enzyme in industrial units. Using genetic engineering, researchers believe enzymes will become commercially available to provide an alternative to the currently available chemical, biological, or physical pollution control methods (Rogers 1984).

Metallothioneins are proteins, mainly found in higher organisms, which have a high affinity for various heavy metals (OTA 1984). It appears these proteins could be produced in large amounts by bacteria and immobilized on a solid support system. This system would then be used to extract the contaminant as the waste water passed over the immobilized protein. This process could be developed to decontaminate aqueous waste streams, particularly those from industry.

Genetic engineering advances and improved bioreactors systems may result in pollution control methods that are superior to many of the methods currently in use. However, there are many biological and technological difficulties to overcome before new microbial systems can affect this area in a manner that will reduce energy consumption and be cost-effective.

4.5 FOOD INDUSTRY

The food industry consists of establishments primarily concerned with the manufacture and processing of food for human and animal consumption. Energy consumed by the food industry in 1982 has been estimated at 1.27 quads (U.S. DOE 1983). Of this, 0.66 quads of fossil fuel are used, of which natural gas is the major fuel and 0.5 quads of electricity. This industry is clearly fossil fuel-intensive, with natural gas as the major fuel form. Most of the fossil fuels purchased are used for process heat, with a small percentage used for space heating, refrigeration, and onsite electric power generation (Vitullio 1979).

According to the 1980 Annual Survey of Manufacturers (U.S. DOC 1982a), grain milling and sugar production were the top two energy users of purchased fuels and electricity in this industry. Table 4.9 presents the top five categories and the estimated energy consumed in 1980.

TABLE 4.9. Top Five Food Industry Energy-Consuming Groups in 1980

<u>Industry Group</u>	<u>Electric Energy (million kWh)</u>	<u>Fuels (trillion Btu)</u>	<u>Total (a) (trillion Btu)</u>
1. Grain mill	7118.6	131.2	154.6
2. Sugar	2229.1	123.0	130.3
3. Preserved fruits and vegetables	5992.4	106.1	124.8
4. Fats and oils	3789.9	101.8	115.2
5. Meat	7112.4	89.5	112.8

(a) 10,400 Btu/kWh

General energy-consuming activities that utilize heat include the following steps (Opila 1978):

1. dehydration by drying
2. concentration by evaporation
3. dewatering through centrifugation or filtration
4. thermal treatment by pasteurization or sterilization
5. hot water cleaning.

Washing and cooking represent the most intensive thermal-energy processes; refrigeration, although only a small energy user, is the most significant mechanical process (Palmer 1980).

4.5.1 Potential Biotechnological Developments

The application of biotechnology has potential for energy savings in the areas of food processing, cleaning/sanitation, and waste management.

Food Processing

Protein engineering will play an important role in the development of innovative, energy-efficient food processing methods. One such method uses enzymes to liquefy fruits and vegetables. Enzymatic processing methods have the potential to reduce energy requirements during production of juices, nectars, pulps, baby food, and possibly wines (Rohm 1983).

Cleaning/Sanitation

The development of low-temperature enzyme-based cleaning systems may play an important part in reducing the energy required for cleaning (Barror and Swientek 1981). The proposed cleaning systems combine enzyme activity (to break down protein-based soiling compounds) with surfactants that penetrate and suspend the soiling materials (Dellweg 1983).

Waste Management

Food processing generates large quantities of organic wastes that have an important biomass energy potential. As much as 25% of raw fruit input may end up as waste material in the juice processing industry (Davis and Kranzler 1981). In the dairy industry, 5 to 10 pounds of fluid dairy wastes (whey) are obtained for every pound of cheese produced (Goldstein 1981).

4.5.2 Potential Energy Savings from Biotechnology

Biological organisms and their enzymes have been used commercially for many years in the production of bread, cheese, beer, wine, and other products. New developments in enzyme technology and genetic engineering have resulted in another biotechnological application--energy savings.

Two food processing industries that have a potential for energy savings through biotechnology are fruit and vegetable processing and meat packing. In 1980, approximately 5 billion pounds of juice was consumed in the United States (U.S. DDC 1982b). It has been estimated that juice pulping requires 7.3 Btu/lb juice and heat treatment requires 83.3 Btu/lb juice (Brown and Hamel 1979). Up to 50% energy saving has been projected for these operations if enzyme liquefaction methods are used,^(a) or an energy saving of 0.23 trillion Btu. Besides juice production, other areas that could derive energy savings from enzyme-liquification techniques are processing fruits and vegetables into pulps, nectars, and baby foods.

Fifteen percent of the fuel input to boilers in the meat packing industry is needed for hot water cleanup (Vitullio 1979). In 1980, 9-10 trillion Btu were used during hot water cleanup. Using enzyme-based cleaners, which require lower water temperatures, water temperatures could be reduced by 20° to 30°F, resulting in up to 0.38 trillion Btu of energy savings. Refrigeration energy requirements would be also reduced, since refrigerated rooms would not be heated as much during cleanup.

Cleaning and sanitation developments in the food industry could also save energy. Petrochemicals are a traditional feedstock for surfactants used in many food industry cleaning solutions. Replacing these with microbial biosurfactants would reduce the industry's petrochemical consumption. Energy savings estimates were not calculated, however.

Significant contributions to process heat requirements might be made by the waste generated by the food industry. Due to the seasonal nature of many

(a) Telecommunication from Rohm Tech, New York, January 20, 1984.

of the food industries and the variety of residues, the energy savings potential of food wastes would have to be assessed at the plant level. Candidate energy recovery technologies that may be affected by biotechnological developments for food processing wastes include anaerobic digestion and fermentation.

4.5.3 Research Needs for Foods Production

The ability of biotechnology to support the energy conservation goals of the food industry will depend upon the direction of future research. This research should support those biological areas that have been identified as having potential energy-saving application in this industry. Particular attention should be paid to the development of enzymatic applications.

4.6 AGRICULTURE

Modern farming relies heavily on machinery, agri-chemicals, and conditioning methods to cultivate the soil, produce crops, and raise livestock. In 1974 about 2.2 quads of energy were used by farmers, mainly in the form of gasoline, diesel fuel, and natural gas (Table 4.10). The 1990 farm energy demand is projected to be 2.4 quads. This 9% increase in energy demand is expected to result in a 20% increase in farm production for food and fiber, and in enough additional grain to produce 10 billion gallons of ethanol (Gavett 1980).

TABLE 4.10. Energy Use in Farm Production 1974-1990
(trillion Btu)^(a) (Gavett 1980)

<u>Item</u>	<u>1974</u>	<u>1980^(b)</u>	<u>1990^(c)</u>
Fossil Fuels	1188.2	1108.1	1143.9
Electricity ^(d)	332.8	289.3	349.3
Fertilizers	621.2	649.2	822.9
Pesticides	<u>95.3</u>	<u>101.8</u>	<u>123.2</u>
Total	2237.5	2148.4	2439.3

(a) Livestock (13%); crops (87%)

(b) Estimated

(c) Projection

(d) Conversion to Btu: 1,000 kWh = 10.400×10^3 Btu

Ten billion gallons of ethanol has a liquid fuel value of about 800 trillion Btu. Diesel fuel is expected to be the dominant on-farm fuel, and natural gas is expected to contribute almost half the Btu in the form of fertilizers, pesticides, irrigation pumping, and crop drying (Gavett 1980).

4.6.1 Energy Use for Conventional Methods

Energy use in the food and fiber system is characterized by diversity and varying intensity depending on the region, crop, or process involved. Energy required to produce major feed grains is about 2,000 Btu/lb, compared with cotton, which requires 24,000 Btu/lb (USDA 1980). Consumption can also vary with the region. In North Dakota corn production requires about 1,700 Btu/lb and in New Mexico it requires 8,400 Btu/lb (USDA 1980). Overall, it is estimated that crop production accounts for about 89% of the energy used by the agricultural sector (Eakin 1981).

Manufactured agri-chemicals such as fertilizers (especially nitrogenous fertilizers) use large amounts of energy, with petrochemicals as the traditional feedstock. The use of these chemicals must be considered as an indirect energy input to agriculture.

Fertilizers, pesticides, and herbicides used to increase crop yields represent a large energy consumption and require an estimated 31% to 37% of the total energy input to crop production. Most of the energy used to manufacture these chemicals is due to the natural gas required to produce fertilizers. Once manufactured, the energy needed to distribute the fertilizers has been estimated at 60 trillion Btu/yr (Vansuch 1979).

A typical pesticide spray at 1.12 lb active ingredient per acre is produced at an energy cost of 250×10^6 Btu/lb active ingredient per acre (Vansuch 1979). An accepted value of the energy used to manufacture herbicides is about 44,000 Btu/lb active ingredient (USDA 1980). This figure does not include the petroleum base used as a carrier for many herbicides.

At the farm level, fossil fuels are the major direct energy source; however, electricity is a major input for irrigated crops and dairy operations. Irrigation requires about 13% of the energy used in production agriculture.

Tillage operations require 5.7 to 7.7 gallons of diesel fuel/acre tilled, or about 5% of the total industry energy consumption (USDA 1980).

Crop drying is an energy-intensive operation. To reduce moisture in corn by 10% from an acre yielding 125 bushels requires about 16 to 20 gallons of LP gas (USDA 1980). This energy consumption often exceeds the total needed for seed-bed preparation, planting, cultivation and harvesting (Vansuch 1979).

4.6.2 Energy Savings Potential of Biotechnology

Considerable energy savings could be realized in production agriculture if the genetic engineering of plants, bacteria, and algae continues to make progress. Energy-saving alternatives include genetic engineering to: 1) reduce the consumption of agri-chemicals and fuels, and 2) develop the growth of algal proteins for food.

The potential exists to use agricultural wastes for energy production through biomass conversion methods. Obstacles to developing agricultural wastes as a reliable source are encountered during collection, transportation, and storage of the material, and because of the seasonal nature of the industry. Biomass conversion technologies are discussed in the fuels and chemicals section.

Reducing Consumption of Agri-chemicals and Fuels

Conventional breeding programs may be combined with tissue-culture practices and recombinant DNA methods to allow screening for desired traits in single cells or plantlets in the laboratory. Progress is expected to be slow, however, because of the complex genetics of plants. For example, some plants (such as string beans) have ten times more DNA than human beings, and others have multiple pairs of chromosomes (Siwolop 1983). Some bacteria have a single gene that determines a specific trait, while plants often have many. Scientists believe that a plant's ability to fix nitrogen from the air is determined by a complex set of 17 genes (Siwolop 1983). The following is a list of biotechnological approaches that would reduce demand for agri-chemicals:

- Fertilizers

1. Breed plants that assimilate fertilizer more efficiently, since it is estimated worldwide that only 50% of the applied nitrogen is absorbed by the plants, and only 3% of the phosphate. A 10% increase in efficiency is thought to be possible (Oelhaf 1978).
2. Transfer nitrogen-fixing genes from the bacterium Rhizobium to nonleguminous crops, such as corn and wheat, that cannot fix nitrogen. One paper reports that genetic engineers feel this will be possible in ten years (Siwolop 1983).
3. Develop microbial fertilizers by utilizing the nitrogen-fixing functions of certain bacteria and blue-green algae (Frankin 1983).

- Pesticides

1. Create varieties of crops that are disease- and pest-resistant.
2. Develop the insecticidal properties of bacteria, viruses, and funguses so that crop insect problems could be handled by microbially-produced insecticides.

- Herbicides

Use increased photosynthetic rates and/or improved breeding methods to develop varieties with better leaf coverage and faster earlier growth so that the plant will be established before the weeds grow.

Reducing the amount of agri-chemicals needed by agriculture should also reduce the direct fuel consumption of farm machinery used during distribution of chemicals. Fuel consumed during tillage operations could be reduced by the development and use of microbial or algal soil conditioners. Irrigation demands would be reduced through plant breeding of drought-resistant crops. In the case of corn, progress has been made in developing varieties with lower moisture content, which should reduce energy demands for crop drying. For

orchard crops, development of frost prevention techniques using bacterial virus sprays could replace a portion of the energy used in conventional frost protection methods (Genetic Tech. News 1983).

Through the use of advanced plant genetic techniques, a 10% reduction in both direct and indirect crop energy consumption appears possible. This would mean an energy savings of 170 to 195 trillion Btu/yr. Before any real savings can be achieved, however, the problems inherent in plant genetics must be overcome and public approval must be obtained for the release of genetically-engineered organisms to the environment.

Alternative Food Source

The algae Spirulina can be grown in mass cultures in large outdoor tanks or reservoirs and has the potential for making large volume, low-cost food proteins. Growing algae as a protein source appears to be less energy-intensive than many conventional protein sources. Table 4.11 compares energy requirements for farming the algae Spirulina with other protein sources. In

TABLE 4.11. Analysis of Spirulina Algae and Other Protein Sources^(a)

Product	Percentage Protein	Energy Output, Energy Input ^(b)	Land Area for Year/Ton Product Acres/Ton
1. <u>Spirulina</u>	65.7	4.33	0.45
2. Soybeans	34.0	1.18	1.19
4. Catfish	17.6	0.10	3.95
5. Oats	14.5	3.15	1.17
6. Beef ^(c)	13.6	0.38	71.52
7. Eggs	11.5	0.14	1.43
8. Corn	9.0	3.02	0.44
9. Pork	8.0	0.17	2.71

(a) Adapted from Leesley (1980).

(b) In calculating energy inputs, solar energy input was not included, which allows vegetable sources to have ratios greater than one.

(c) Values averaged for range and feedlot beef.

the table a ratio of total energy input to total energy output is presented. For the animal protein sources the ratio is much less than one, which indicates that they are energy inefficient. The vegetable protein sources are much more efficient. On the basis of energy efficiency, Spirulina is 3.67 times more efficient than soybeans (Leesley 1980).

In order for any energy savings to be realized from alternative food sources such as algae there must be an appreciable change in consumer demand, which currently favors the energy-intensive animal protein sources.

5.0 SUMMARY OF ENERGY SAVINGS FROM BIOTECHNOLOGY

The use of biomass conversion technologies would result in a large savings of fossil feedstocks by the fuels and chemicals industry. In addition, the use of genetically engineered materials could also significantly reduce process fuel consumption for several industries.

5.1 BIOMASS CONVERSION TECHNOLOGIES

Biomass conversion deals with processes that produce renewable feedstocks and fuels from biomass to replace fossil-based materials. For biomass conversion, liquid or gaseous fuels production and utilization of biomass as a chemical feedstock were evaluated. The potential for energy savings is discussed below.

5.1.1 Fuels Production

The analysis performed in this study indicates that several newer ethanol processes show net energy gains, assuming the byproducts are burned as fuel for the process. Synthesis gas and methanol from wood gasification also show net energy gains. Although net energy gain is useful for evaluating which fuels consume more energy in the conversion process than the product contains, it does not focus on the true advantage of biomass conversion processes: they convert low-value biological materials into desirable fuels.

Using wastes residues, surplus crops, and the technology currently available, about .3 quads of liquid fuels and 2.8 quads of gaseous fuels could be replaced by biomass-derived fuels. This represents 1% of the current liquid fuel consumption and 16% of gaseous fuel consumption in the U.S. in 1983.

5.1.2 Chemicals Production

The development of a biomass-based chemical industry is practical based on biomass availability and a potential fossil feedstock savings of 2.1 quads. However, the process energy requirements could exceed conventional process fuel requirements by up to 1.15 quads due to problems such as diluted products. The development of energy-efficient bioprocess technologies is of critical importance to the technical and economic feasibility of a biomass-based chemical

industry. In fact, the production costs must be sufficiently low so that even with new investments in plant and capital equipment, a biomass-based chemicals industry would be competitive with the already established fossil-based industry.

5.2 GENETIC ENGINEERING

Genetic engineering facilitates the use of biologically-engineered enzymes and microorganisms to reduce process energy requirements. Applications evaluated for genetic engineering include fuels production, chemical feedstocks production, metals mining and recovery, pollution control, foods, and agriculture. The potential energy savings are discussed below.

5.2.1 Fuels Production

Based on PNL calculations, the 26.9 quads of liquid fuels consumed in 1982 could be replaced by 9.1 billion tons of wood for methanol production or 7.1 billion tons of corn for ethanol production. The 1982 demand for gaseous fuels could be supplied by 3.87 billion tons of wood for SNG production. At current yields, production of ethanol, methanol, and SNG in these quantities would require 792%, 253%, and 108% of the estimated land available in the U.S. for the appropriate biomass feedstock.

Utilization of genetic engineering could realistically improve biomass feedstock yields to three times current levels. This would increase the feasibility of large-scale production of fuels from biomass feedstocks. It is unlikely, however, that the total liquid and gaseous fuel demand could be replaced using biomass, although there is the potential for partial substitution.

5.2.2 Chemicals Production

Bioprocessing methods to produce chemicals from biomass using microorganisms or enzymes have several potential advantages over conventional methods, but they currently consume more energy. Developments in biocatalyst and bioreactor design could minimize process energy requirements for both the conventional and biomass-based chemicals industry. With biomass feedstocks and low-energy bioprocesses, most of the fossil energy consumed by the industry

could theoretically be saved, because the energy consumption of bio-derived chemicals would no longer be prohibitive. Genetic engineering will also save energy by stimulating the development of novel synthesis routes that directly convert low-value feedstocks such as biomass and coal into chemical end-products.

5.2.3 Metals Mining and Recovery

Approximately 20% or 0.014 quads (in 1980) of the energy used for metal mining could be saved if bacterially-assisted in-situ recovery methods were utilized. Bioaccumulation techniques for the recovery of gold and silver from waste streams could potentially save most of the 0.002 quads (in 1980) required for mining of precious metals. Because of the high value of precious metals, product quality and security are important factors in addition to the economics of recovery.

5.2.4 Pollution Control

Use of microorganisms for pollution control could save at least 0.71 quads or 33% of the total energy (see Table 5.1). The three technologies discussed include microbial desulfurization of coal, anaerobic digestion of sewage, and deep-shaft aeration of industrial organic waste. Only anaerobic digestion is currently used commercially.

TABLE 5.1. Total Energy Savings Estimate for
Biological Pollution Control, 1982

<u>Pollution Control Method</u>	<u>Energy Savings, Quads</u>
Microbial Desulfurization	0.25
Anaerobic Digestion	0.26
Deep-Shaft Aeration	<u>0.20</u>
Total	0.71

5.2.5 Foods

Existing biotechnological developments in the foods industry have a potential for energy savings in the areas of food processing, waste management, and cleaning/sanitation. Two food processing industries that have a potential for

energy savings through biotechnology are fruit processing and meat packing. Approximately 50% of the energy required during the fruit maceration process, or 0.23 trillion Btu, could be saved using enzymatic liquefaction methods. Use of enzyme-based cleaners by the meat packing industry would save 0.38 trillion Btu. Process heat requirements could be reduced by burning wastes, and the use of microbial surfactants could replace surfactants from petrochemicals.

5.2.6 Agriculture

Considerable energy savings could be realized in agriculture if genetic engineering of plant, bacteria, and algae continues to make progress. Reducing the consumption of agri-chemicals and fuels for growing and collecting crops would result from the development of disease- and pest-resistant plants. It is estimated that this development would save 0.17 to 0.20 quads per year. Low-cost algal food proteins could conserve much of the energy consumed by conventional protein production technologies; however, implementation is severely restricted by public acceptance.

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APPENDIX A

PROCESS DETAILS OF LIQUID AND
GASEOUS FUELS PRODUCTION

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PROCESS DETAILS OF LIQUID AND GASEOUS FUELS PRODUCTION

This appendix contains some process details for the technologies briefly mentioned in Section 4.0 on the production of liquid and gaseous fuels. This information may be of interest if more detail is needed about any of these technologies.

Technology	Purpose	Procedure
Conventional Grain Processing	To produce beverage-quality ethanol from grain	1) Grain is ground, heated with dilute aqueous acid. 2) Glucose from (1) fermented to ethanol. 3) Distillation to 50% ethanol, removal of solids. 4) Drying of solids to produce DDG. 5) Distillate from (3) concentrated to 95% ethanol. 6) Remaining water removed from alcohol with benzene distillation.
ACR Grain Processing	To produce a gasoline/ethanol blend	1) Saccharification and fermentation procedures similar to conventional. 2) All distillation steps are combined. 3) Gasoline used to remove alcohol as well as to dewater it, saving processing energy.
Katzen Grain Processing	To produce a fuel-grade alcohol from grain	1) Saccharification and fermentation procedures similar to conventional. 2) All distillation steps are combined. 3) Heat recycled to dry the DDG.
Chemapec Grain Processers	To produce a fuel-grade alcohol from grain	1) Separation of starch from grain residues before fermentation is begun. 2) Continuous vacuum evaporation of alcohol during fermentation. 3) Methane production from waste streams, fuel used for plant boilers.
Conventional Acid Hydrolysis of Agricultural Residue	To produce ethanol by acid hydrolysis of agricultural residues	1) Residue ground, digested with dilute acid to remove hemicellulose. 2) Strong acid digestion to dissolve cellulose. Lignin filtered out. 3) Methanol added to acid solution from (2) to precipitate

Technology	Purpose	Procedure
Conventional Acid (contd)		cellulose. 4) Cellulose from (3) acid-hydrolyzed to glucose. 5) Glucose fermented to ethanol. 6) Distillation and drying steps for ethanol similar to those in conventional grain processing.
Acid Hydrolysis of Wood	To produce ethanol from acid hydrolysis of wood	1) Very similar to procedure for acid hydrolysis of agricultural residues. More collection, transportation energy required.
Natick Process	Enzymatic hydrolysis of cellulosic wastes	1) Cellulosic material finely ground. 2) Cellulose degraded with enzyme derived from fungus <u>Trichoderma viride</u> to form glucose. 3) Glucose fermented to ethanol. 4) Ethanol stream concentrated, distilled, dried as before, but more energy required for the more dilute product streams.
Wilke Process	Enzymatic hydrolysis of cellulosic wastes	1) After grinding, cellulosic wastes partially hydrolyzed with dilute acid. 2) Cellulose degraded with protease peptone. 3) Glucose streams fermented to ethanol. 4) Process streams concentrated and distilled as in the Natick process.
Gulf Process	Enzymatic hydrolysis of cellulosic wastes	1) Cellulosic wastes finely ground. 2) Saccharification and fermentation steps are simultaneous, and on a continuous basis. 3) Enzyme production is continuous. Steps (2) and (3) reduce the volume of the product streams, and the ethanol distillation energy required.
Pacific Northwest Laboratory Wood Gasification	To produce low-to-medium Btu gas or methanol from wood	1) Collection and chipping of biomass. 2) Reaction of steam with wood or biomass chips in a fluidized bed gasifier at 750 C. 3) Catalyst selection determines final product composition. 4) Shift conversion to control desired hydrogen/carbon monoxide ratio. 5) Removal of acid gas and sulfur traces. 6) If methanol is produced, a final catalytic reaction between hydrogen and carbon monoxide.

Technology	Purpose	Procedure
Pyrolysis	To produce an oily liquid fuel from biomass	1) Collection, grinding, and drying of biomass. 2) Reaction of biomass at temperatures between 400-700 C, with inert atmosphere, reduced pressure, short residence time. 3) Separation of liquid products from char. 4) Further treating of liquid products to reduce oxygen content.
Liquefaction	To produce an oily liquid fuel from biomass	1) Collection and grinding of biomass. 2) Reaction of wet biomass at 300-350 C, 1500-2500 psi, sodium carbonate catalyst, retention times 15 min-1 hr. 3) Separation of liquid product from char. 4) Further treating of liquid products.

APPENDIX B

BIOMASS PRODUCTION REQUIREMENTS FOR LIQUID AND GASEOUS FUEL

APPENDIX B

BIOMASS PRODUCTION REQUIREMENTS FOR LIQUID AND GASEOUS FUEL

B.1 ETHANOL PRODUCTION REQUIREMENTS

1. The production of one quad of ethanol from corn by the Chemapec process requires about 1.29×10^8 tons of grain.
2. An additional 8.55×10^6 Btu/ton of corn feedstock would be required for manufacturing of fuel for growth, fertilization, collection, and processing. About 4.65×10^6 Btu/ton of the energy required for these activities could be met by burning the DDG by-product as fuel. Therefore, the actual energy required is 3.90×10^6 Btu/ton biomass, which is assumed to be liquid fuel to drive vehicles.
3. Based on a net value of 3.9×10^6 Btu/ton of biomass from Step 2, an additional 0.51 quads of ethanol must be manufactured to produce 1 quad of ethanol to replace liquid fossil fuels (Step 2 times Step 1).
4. The manufacture of an additional 0.51 quads of ethanol to produce 1 quad of ethanol to replace liquid fossil fuels will require 0.26 quads of ethanol, etc., etc.
5. The amount of ethanol that must actually be produced to obtain 1 quad of ethanol is approximated by the series

$$\sum_{n=0}^{\infty} 0.51^n = S_n$$

$$6. \sum_{n=0}^{\infty} 0.51^n \text{ quads} = 2.04 \text{ quads}$$

B.2 METHANOL PRODUCTION REQUIREMENTS

1. The production of one quad of methanol by gasification of wood requires about 2.03×10^8 tons of wood biomass (Mudge et al. 1980).
2. An additional $.59 \times 10^6$ Btu/ton of wood is required for manufacture of fuel to cultivate,^(a) fertilize, harvest, collect, and transport the short-rotation wood biomass feedstocks (Meyers 1983). This includes the energy cost of the ammonia fertilizer. Processing to methanol requires an additional 1.40×10^6 Btu/ton of wood.
3. Based on a value of 1.99×10^6 Btu/ton of wood from Step 2, an additional .40 quads of renewable fuel must be manufactured to replace 1 quad of non-renewable fuel (Step 2 times Step 1).
4. The production of .40 quads of methanol to manufacture 1 quad of methanol would require .16 quads of methanol etc. etc.
5. The amount of methanol that must actually be produced to supply all the energy requirements of 1 quad of fossil fuel substitute is approximated by the series

$$\sum_{n=0}^{\infty} .40^n = S_n$$

6. $\sum_{n=0}^{\infty} .40^n = 1.67$

B.3 SNG PRODUCTION REQUIREMENTS

1. Based on a feasibility study that investigates steam gasification of biomass, the production of 1 quad of methane requires 1.92×10^8 tons of wood biomass feedstock (Mudge 1983).
2. An additional $.86 \times 10^6$ Btu/ton of wood is required for manufacture of fuel to cultivate, fertilize, harvest, collect, transport, and process the short-rotation wood biomass (Meyers 1983, Mudge 1983).

(a) Assumes .07 Btu energy inputs required/Btu of wood output.

We assume $.47 \times 10^6$ Btu/ton of wood can be obtained from the byproduct char. Therefore $.39 \times 10^6$ Btu/ton of wood must be obtained from a liquid fuel such as methanol.

3. To produce $.39 \times 10^6$ Btu/ton of wood or .07 quads of methanol actually requires the production of .12 quads of methanol (Section B.2, step 6 times .07 quads).
4. The production of .12 quads of methanol requires the growth of $.24 \times 10^8$ tons of wood biomass (see Section B.2, step 1).
5. The total amount of wood biomass that must be grown to provide 1 quad of SNG is 2.16×10^8 tons (step 1 plus step 4).

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