Biofuels

PROGRAM PLAN
FY 1992 - FY 1996

Contents

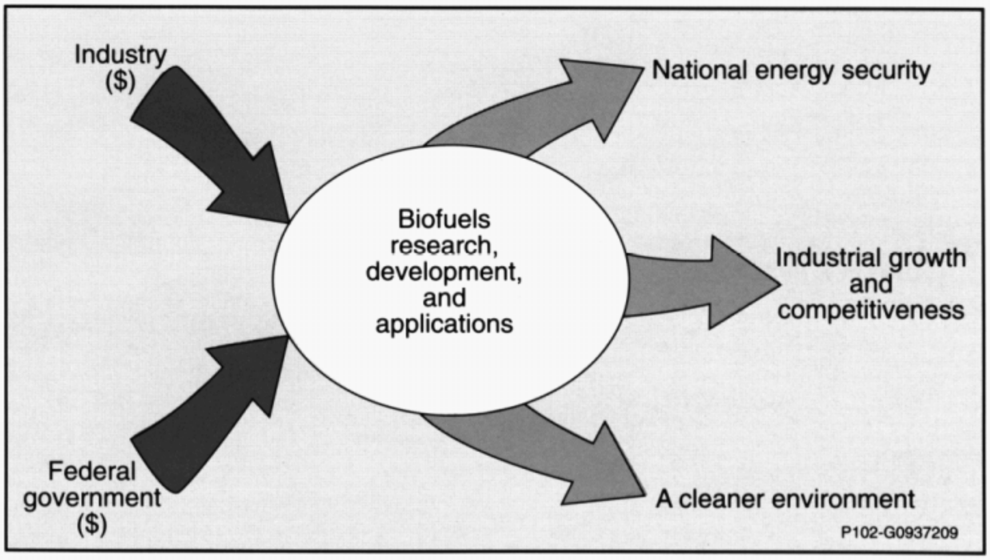
Executive Summary 1
Background 1
The Biofuels Vision 5
Legislative Impetus 6
Societal and Economic Benefits 7
Major Objectives and Strategies 7
The Technical Plan 9
Energy Crop R&D 11
Interface Activities and Systems Integration 17
Biofuels Conversion R&D 19
Meeting the Challenge 33
Transferring the Technology 33
Organizing the Program 34
Managing the Program 36
Biofuels and the Environment 38
Appendices 40

Printed in the United States of America
Available from:
National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Road
Springfield, VA 22161

Price: Microfiche A01
Printed Copy A03

Codes are used for pricing all publications. The code is determined by the number of pages in the publication. Information pertaining to the pricing codes can be found in the current issue of the following publications which are generally available in most libraries: *Energy Research Abstracts (ERA)*; *Government Reports Announcements and Index (GRA and I)*; *Scientific and Technical Abstract Reports (STAR)*; and publication NTIS-PR-360 available from NTIS at the above address.

Executive Summary



The return on DOE's investment can be measured in terms of security, economics, and the environment.

This five-year program plan describes the goals and philosophy of the U.S. Department of Energy's (DOE) Biofuels Systems Division (BSD) program and the BSD's major research and development (R&D) activities for fiscal years (FY) 1992 through 1996. The plan represents a consensus among government and university researchers, fuel and automotive manufacturers, and current and potential users of alternative fuels and fuel additives produced from biomass. It defines the activities that are necessary to produce versatile, domestic, economical, renewable liquid fuels from biomass feedstocks.

The BSD program focuses on the production of alternative liquid fuels for transportation—fuels such as ethanol, methanol, biodiesel, and fuel additives for reformulated gasoline. These fuels can be produced from many plant materials and from a significant portion of the wastes generated by municipalities and industry. Together these raw materials and wastes, or feedstocks, are called biomass.

The success of the BSD program will help achieve many of our national priorities including the goals set forth in the *National Energy Strategy*, the Alternative Motor Fuels Act (AMFA) of 1988, and the Clean Air Act Amendments (CAAA) of 1990.

Background

Wood is the original biomass fuel and was the world's primary source of energy for much of recorded history. Wood remained dominant in the United States until late in the 1800s, when coal became the chief source of energy. Oil and natural gas then preempted coal and further hastened the decline of wood use. Another form of biomass, municipal solid waste (MSW), was used to provide electricity in New York City at the beginning of the 20th century. But by 1960, the well-developed infrastructure for the delivery of oil products and natural gas had reduced the use of biomass energy to near nothing.

By 1990, the United States was consuming a total of 8.86 x 10^{19} joules (84 quads: one quad equals 10^{15} Btu) of energy annually. In that year, biofuels contributed approximately 2.95 petajoules (2.8 quads) to the national energy mix, or about 3.3% of all energy consumed in the United States. A major portion of the biofuels contribution was consumed by the paper and wood products industry in cogeneration systems using wood wastes to fuel their industrial processes. A significant contribution was also made by the growing corn-to-ethanol industry, predominantly centered in the U.S. Midwest where

The BSD program focuses on the production of alternative liquid fuels for transportation—ethanol, methanol, biodiesel, and reformulated gasoline.

CRADAs

The execution of the *National Energy Strategy* depends partially on technology transfer programs at DOE and its national laboratories. The National Competitiveness Technology Transfer Act, passed in 1989, enabled DOE to create cooperative research and development agreements (CRADAs). CRADAs allow committed industry partners to team up with the national laboratories; together they research and develop new energy technologies to the point of commercialization. In some instances, universities, industry consortia, and other laboratories may also be involved. The addition of university cooperation helps to give a fresh angle to the research and also provides opportunities to train personnel in innovative energy technologies.

More than 100 potential CRADA partners have applied to DOE programs since November 1990. The applicants include large, diversified, well-capitalized U.S. firms and small businesses that have the resources to successfully take new renewable energy technologies to market.

CRADAs represent the single most productive tool for government-industry collaboration aimed at commercialization. Participants may acquire exclusive licensing rights to any inventions (intellectual property) developed during the performance of CRADA work. Data generated under the agreement may be protected from public disclosure for up to five years. DOE gives priority to the approval of all CRADAs, recognizing industry's need for timely reviews and approvals.

Each task area has well-defined objectives, consistent with technical needs and Congressional budget directives.

In addition to meeting the program's technical and cost goals, we intend to aggressively support the development of the industrial base needed for alternative fuels such as ethanol and methanol to penetrate the various transportation markets. This is an evolutionary process, beginning with our concentrated R&D efforts and complemented by the formation of industry/government partnerships.

Both government and industry will play essential roles in bringing biofuels technologies to the marketplace. The BSD program, while pursuing essential research, continues to keep industry apprised of progress through technical meetings, conferences, and the publication of research advances. Recently, the program established several cooperative research and development agreements (CRADAs) with industry to utilize BSD program technology in the production of ethanol and methanol from biomass.

Renewable biofuels have a prominent role to play in this nation's energy future. Renewable energy reduces the demands placed on our other finite natural resources. It enhances our energy security and, clearly, it protects the environment. Cost-effective renewable energy technologies can contribute to a strong and growing economy. We must continue focused, industry-driven R&D in concert with the environmental community to realize the full potential of these technologies.

The Biofuels Vision

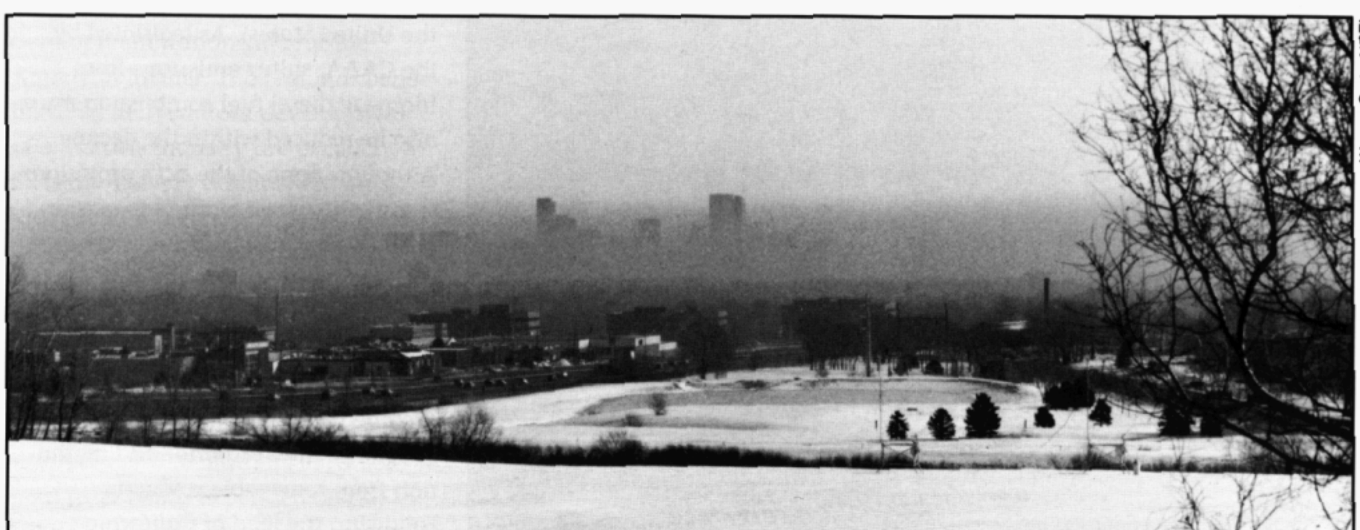
Since the last program plan was published in 1988, U.S. demand for alternative transportation fuels and fuel oxygenates has grown steadily and is expected to skyrocket in the next two decades. Several factors including energy security, economic prosperity, and environmental concerns, are responsible for this increased demand. As a nation, we are striving to break away from our reliance on imported oil and the economic imbalance and environmental damage that dependence has engendered.

Domestic transportation fuels are almost exclusively (>97%) derived from petroleum and account for about 64% of total U.S. petroleum consumption. In 1990, more than 40% of the petroleum used domestically was imported. Because the United States has only 5% of the world's petroleum reserves and the countries of the Middle East have about 75%, U.S. imports are likely to continue to increase. With our heavy reliance on oil and without suitable substitutes for petroleum-based transportation fuels, the United States is extremely vulnerable, both strategically and economically, to fuel supply disruptions.

A strong DOE role, in partnership with industry and agriculture, will be crucial in reducing our dependence on oil and bringing biofuels into increasingly widespread acceptance and use by 2000 and beyond. Working closely with the private sector, the DOE BSD program is aggressively pursuing research in both biofuels feedstock production and conversion in the next five years. Our goal is to develop technologies that are competitive with fossil fuels, in both cost and environmental performance, by the end of the decade.

The BSD program is working to develop technologies that will reduce our dependence on foreign oil, bolster our domestic and international economic competitiveness, and address national and global environmental concerns.

Our goal is to develop technologies that are competitive with fossil fuels, in both cost and environmental performance, by the end of the decade.



Conventional transportation fuels have had significant adverse impacts on our air, land, and water resources. Air pollution, visible in this city skyline, oil spills, and toxic-waste generation all result from our production and use of petroleum-based transportation fuels.

Legislative Impetus

It is with the nation's strategic, economic, and environmental well-being in mind that DOE has renewed and strengthened its commitment to alternative fuels technology. Two newly enacted pieces of legislation are a major impetus behind this commitment—AMFA (passed in 1988) and the CAAA of 1990. In addition, the recently revised *National Energy Strategy* offers official affirmation of the federal thrust to develop a strong technology base for the emerging U.S. alternative fuels industry.

AMFA promotes the use of alternative fuels and alternative-fueled vehicles (AFVs) in government fleets as a first step toward large-scale commercialization of these technologies. In 1990, DOE initiated programs that respond to AMFA.

Federally funded fleet operators in several cities across the United States are currently gathering data on the operation and maintenance of light-duty vehicles, commercial trucks, and urban buses running on alternative fuels. The data gathered from the federal demonstration fleets will help researchers and industry decision makers to determine what combinations of vehicle designs and fuels are the most cost-effective, energy efficient, and environmentally sound. The federal government plans to become a leader in the acquisition and use of AFVs such that an alternative fuel infrastructure will develop, alternative fuel availability will increase, and more AFVs will be produced.

Possibly the most influential and far-reaching legislation of this decade, the CAAA will be a driving force behind increased production and use of alternative fuels, especially alternative fuels that can be used as a basis for oxygenates (such as ethanol and methanol) in reformulated gasoline (RFG). Under this act, oxygenates are required for blending into gasoline used in urban centers that exceed the allowable levels for carbon monoxide and ozone (there are currently 39 such areas in the United States). As legislated by the CAAA, sulfur emissions from highway diesel fuel combustion must also be reduced within the decade. Although none of the act's provisions specify the use of biofuels to accomplish these goals, as biofuels become cost-competitive, they can and likely will be used to meet the standards.

In addition, the federal government and several state governments provide incentives for the production of alcohol fuels (ethanol and methanol) from renewable resources. Following the lead of California's aggressive clean air policies, legislation is pending in many states that

Warren Gretz, NREL

Increased use of biofuels can spawn an increase in the growth of industries across the United States—industries such as this ethanol plant in Indiana...

will necessitate the use of alternative fuels and AFVs.

Societal and Economic Benefits

The development of biofuels as an energy source offers a number of benefits to the nation. Biofuels can provide a large, renewable source of liquid and gaseous fuels and can serve as a feedstock for electricity production. With the success of innovative technologies currently under development in the BSD program and in other government programs, fuels and electricity derived from biomass could ultimately contribute up to 1.8 x 10^{19} joules (17 quads) to the U.S. energy mix, according to national laboratory studies. Biofuels represent the only existing renewable technologies capable of producing liquid transportation fuels and fuel additives that can displace conventional fossil fuels.

The growth of a biofuels industry could prove beneficial to the U.S. economy. Biofuels are the only renewable resource that can provide desperately needed local jobs and economic development nationwide for the American farmer. The regional benefits to be derived from development of a biofuels industry are excellent—80 cents of every dollar spent on biofuels in a given region would stay in that region, while 80 cents of every dollar spent on petroleum leave the region. At a price of $3/cubic meter ($20/barrel) of oil equivalent, the biofuels alternative would keep approximately $11 billion/year of U.S. monies (1990 dollars) from being expended on oil imports—a strong benefit to our national trade deficit.

Within the next 10 to 40 years, millions of acres of cropland in the United States could support the growth of energy crops for biofuels production. Soil-enhancing short-rotation woody crops may grow vigorously alongside corn, sorghum, and conventional crops on flat cropland. Lush fields of perennial grasses may stabilize the soil on gently sloping hillsides. Barren deserts may become oases for growing oil-rich aquatic energy crops. And the overcrowded landfills of the early 1990s could become the energy-rich "oil fields" of the next century.

Major Objectives and Strategies

The *National Energy Strategy* establishes the basis for a secure and sustainable energy future. The objective of the *National Energy Strategy* is to achieve balance among our increasing need for energy at reasonable prices, our commitment to a safer, healthier environment, our determination to maintain an economy second to none, and our goal to reduce our dependence and that of our friends and allies on potentially unreliable energy suppliers.

The BSD's objectives and strategies are consistent with the foundation laid by the *National Energy Strategy*. The BSD is striving to stimulate the development, acceptance, and use of cost-competitive alternative fuels such as ethanol, methanol, biodiesel, and reformulated gasoline additives produced from renewable biomass feedstocks. To accomplish the entry of these alternative fuels into the marketplace and promote their use, BSD has formulated a strategy consisting of the following:

Warren Gretz, NREL

...and this one in Illinois.

Table 1. Biofuels Systems Division Program Goals

Technology	Goals
Ethanol	Fully demonstrated, environmentally suitable technology for production of ethanol from biomass wastes and residues at \$0.18/liter (\$0.67/gallon; gate cost in 1990 dollars) by 2000. Cost presumes biomass cost of \$0.04/dry kilogram (\$34/dry ton) and a plant capacity of 1.74 million dry kilograms (1920 dry tons) of biomass per day.
Methanol	Fully demonstrated, environmentally suitable technology for production of methanol from biomass wastes and residues at \$0.14/liter (\$0.54/gallon; gate cost in 1990 dollars) by 2000; cost presumes biomass cost of \$0.04/dry kilogram (\$34/dry ton) and a plant capacity of 1.81 million dry kilograms (2000 dry tons)/day.
Reformulated Gasoline Components	Fully demonstrated, environmentally suitable technology for production of mixed ethers from refuse-derived fuel (RDF) at \$0.25/liter (\$0.95/gallon; gate cost in 1990 dollars) by 2000; cost presumes RDF cost of \$0.03/dry kilogram (\$25/dry ton) and a plant capacity of 900,000 dry kilograms (1000 dry tons)/day.
Biodiesel from Aquatic Species	Fully demonstrated, environmentally suitable technology for production of lipid-rich microalgae and conversion of lipids to biodiesel fuel at a total cost of \$0.26/liter (\$1/gallon; gate cost in 1990 dollars) by 2000 (cost to be competitive with conventional diesel fuel by 2010); cost presumes a CO_2 cost of \$0.13/liter (\$0.48/gallon), and a plant size of ≈ 1000 hectares (3.9 square miles).
Energy Crops	Fully demonstrated, environmentally suitable technology for production of dedicated energy crops on average cropland in the North Central and South/Southeastern regions with average yields of 18 dry kilograms/square meter (8 dry tons/acre); input costs (exclusive of land costs) at \$0.66/dry kilogram (\$6/dry ton in 1990 dollars) and cutting/field handling costs at \$0.02/dry kilogram (\$16/dry ton in 1990 dollars) by 2010. It is assumed that total feedstock costs will range from \$0.04-\$0.06/dry kilogram (\$34-\$55/dry ton).

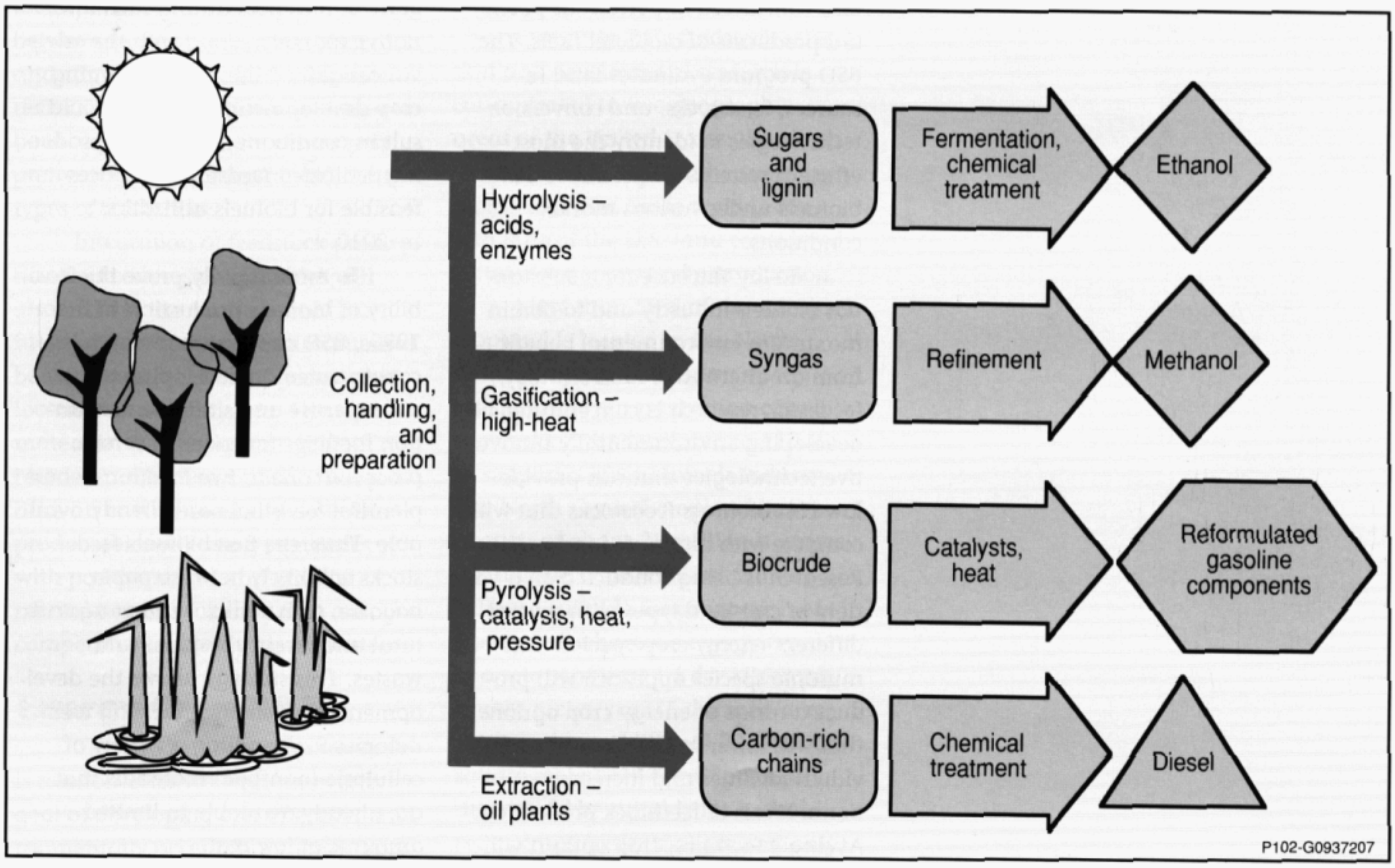
- Provide the technology base for the private sector to increase sustainable supplies of biomass feedstocks suitable for economic conversion processes
- Provide the technology base for the thermochemical and biochemical conversion of biomass feedstocks to liquid fuels
- Provide early transfer of technology to private industry by verifying technical feasibility and environmental benefits of integrated feedstock production and conversion technologies through cost-shared projects.

Since the inception of the program, the government and the private sector have worked together to develop an extensive biofuels knowledge base. This research has helped to identify the technical barriers to cost-competitiveness and to determine priorities among the viable research options.

The Technical Plan

The BSD research program focuses on the production (growth) of dedicated biofuels feedstocks and their conversion into liquid transportation fuels, including ethanol, methanol, ethers for RFG, and biodiesel. Production of dedicated biofuels feedstocks (woody and herbaceous energy crops) must be made environmentally advantageous and cost-competitive with the production of other agricultural products in order to provide a substantial and dependable supply for a biofuels industry. The alcohol fuels, ethers, and biodiesel produced from these feedstocks must also exhibit environmental advantages and be economically competitive with conventional transportation fuels and fuel additives if they are to enter the marketplace without subsidies. These facts drive our R&D. Biofuels feedstock research must reduce costs by optimizing yields and increasing the efficiency of getting feedstocks from production fields to conversion hoppers while simultaneously developing environmentally sound growing, harvesting, and delivery techniques. Conversion research must reduce costs by improving yields, decreasing conversion times, and increasing process efficiencies while developing environmentally sound industrial systems. The development of systems

The BSD research program focuses on the production (growth) of dedicated biofuels feedstocks and their conversion into liquid transportation fuels.



BSD researchers are investigating several conversion processes that can be used to make liquid fuels from biomass.

Warren Gretz, NREL

Short-rotation systems, such as this commercial plot in Washington state, are already entering the pulp paper market.

that are cost-competitive without either agricultural or fuel subsidies is a primary goal.

Because there are several conversion processes that can be used to make liquid fuels from biomass, it seems prudent to proceed with multiple lines of conversion research until it becomes clear that one or more of the process options offer significant benefits. These processes utilize various types of biofuels feedstocks, which include short-rotation woody crops and herbaceous energy crops, MSW, and forestry and agricultural residues, with thermochemical or biochemical conversion processes to produce ethanol, methanol, and reformulated gasoline components. Aquatic and oil-seed energy crops are also considered important as potential producers of biodiesel fuels. The BSD program evaluates land resources, feedstocks, and conversion technologies to identify the most efficient systems for production of biofuels under various market conditions.

To lay the base for a substantial biofuels industry and to obtain maximum environmental benefit from an alternative fuels strategy, feedstock research is concentrated on developing environmentally innovative technologies that can provide low-cost biomass feedstocks that will compete with alternate land uses. Research is being conducted on a variety of cropland types with several different energy crop species. This multiple species approach will produce a range of energy crop options that will lower feedstock costs at individual facilities and increase national levels of feedstock production. At single facilities, crop options will be available for the range of land economically available within a confined radius. Crops will also be available for large-scale production across several regions. Analyses of land resources, economic conditions, cost-supply relationships, and environmental limitations are being conducted to identify the locations around the country that offer the best opportunities for siting the first generation of biofuels industries. Short-rotation production systems for wood are already becoming commercial in pulp markets that can afford to pay relatively high prices for the feedstock. High-yielding herbaceous species identified in energy crop screening trials are also being examined as forage crops. The environmental and economic information gained from penetrating such alternative markets, along with the advances gained through continuing crop development research, should result in conditions suitable for producing dedicated feedstocks at prices feasible for biofuels utilization by 2010.

To more rapidly prove the feasibility of biofuels production in the 1990s, BSD conversion research is concentrated on developing technical expertise and siting demonstration facilities for each conversion process at one or two locations where plentiful feedstocks are already available. Thus, the first biofuels feedstocks will likely be wastepaper, bagasse, corn stalks, or other agricultural and forestry residues and wastes. This strategy allows the development of efficient conversion technologies for handling a variety of cellulosic (nonfood) materials that are already available in limited amounts at low cost.

Energy crops, however, are expected to be the key to expanding the biofuels industry. Consequently, work has already begun on evaluating dedicated energy crops and conversion processes as optimized systems. One effort involves examining the effect of different cellulosic feedstock types and storage options on conversion efficiency and on total system costs. Data are being collected on differences between feedstocks and on differences within feedstocks as a function of storage time, handling procedures, and geographic location. Such data will contribute to overall systems analysis efforts directed at optimizing feedstock types, handling procedures, conversion processes, and overall facility size. As the relationships between feedstock characteristics and conversion efficiencies become better understood, efforts are likely to be initiated to fine tune conversion pretreatment processes for different types of feedstocks.

Integration of feedstock production and conversion activities will also include the evaluation of biofuels product cost and environmental benefits as a function of geographic location and facility size. The ultimate goal is to design integrated biofuels production systems that produce an environmentally desirable product (biofuel) using feedstocks with positive social and environmental benefits for costs that are competitive in worldwide markets.

Energy Crop R&D

The BSD's energy crop research is mission-oriented with an overall goal of developing cost-effective, environmentally acceptable energy crops and cropping systems suitable for a variety of locations in the United States. The crops must be able to compete with alternate land uses in providing revenue to landowners at prices that allow cost-competitive production of biofuels. Achieving the program's feedstock goals is closely linked to finding suitable and available land; thus, BSD's energy crops research includes analyses of land resources, cost/supply relationships, environmental limitations, and evaluation of economic and policy conditions affecting land resources. The program's energy crop research is primarily managed and conducted through the Oak Ridge National Laboratory (ORNL) in Oak Ridge, TN.

Priority Regions for Feedstock Production

Currently, BSD feedstock selection and development research is concentrated in two geographic areas of the United States: the North Central and South/Southeastern regions. Together, these regions contain 80% of the U.S. land considered suitable for energy crop production.

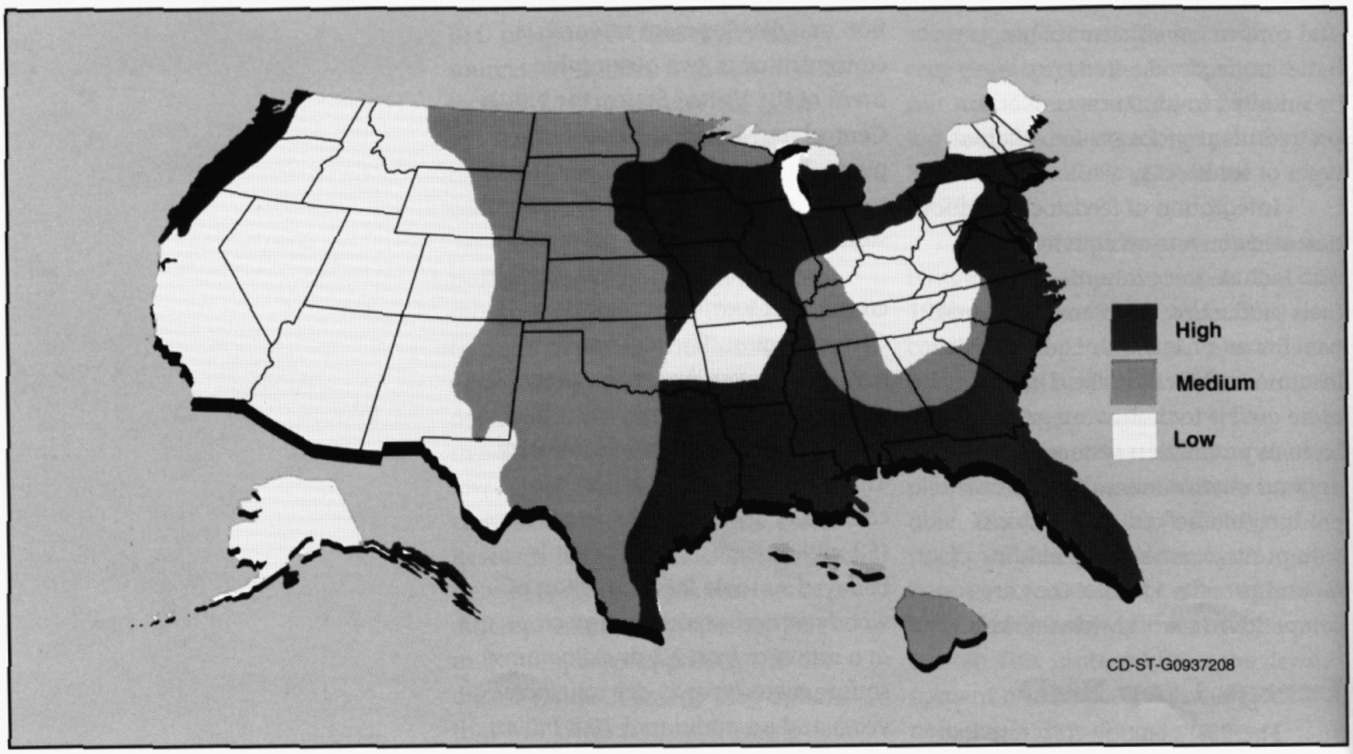
More than 50% of the suitable cropland is located in the North Central region. The region's deep soils and proven production capabilities make it the territory most likely to support a large biofuels industry. The North Central cropland base consists of about 21 million hectares (52 million acres) of land that is believed suitable for production of woody or herbaceous energy crops at a rate of at least 1.1 dry kilograms/square meter/year (5 dry tons/acre/year) and an additional 70.8 billion square meters (17.5 million acres) that would be suitable for herbaceous crops (perennial grasses) only. Altogether, about 33% of all land in

John Mattila

BSD-funded researchers at Iowa State University are studying energy crops such as the hybrid poplars and tropical corn shown in this test plot.

the region is suitable for energy crop production, but potential economic availability of land is uncertain. Average land rental rates in the region vary from $114-$247/hectare ($46-$100/acre) by state. Within individual states in the region, the ranges are much wider.

About 30% of the land suitable for growing energy crops is located in the South/Southeastern region of the United States. The region's long growing season and warm weather are conducive to plant growth, but poor soils, summer drought, and weed competition can reduce production in many areas. The BSD's woody and herbaceous crop screening projects have shown that a number of energy crop choices will be needed to maximize land utilization in the South/Southeastern region; however, perennial herbaceous grasses may perform well on a wide variety of sites. The South/Southeastern region has about 12 million hectares (29 million acres) of land believed to be suitable for producing woody crops or herbaceous crops at a rate of at least 12.5 metric tons/hectare/year (5 dry tons/acre/year) and an additional 7.3 million hectares (18 million acres) that may be suitable only for perennial herbaceous crops. About 21% of the region appears suitable but economic availability is uncertain here as well. Average land rental rates are relatively low, varying from $44-$111/hectare ($18-$45/acre), reflecting the relatively low returns from conventional crops.



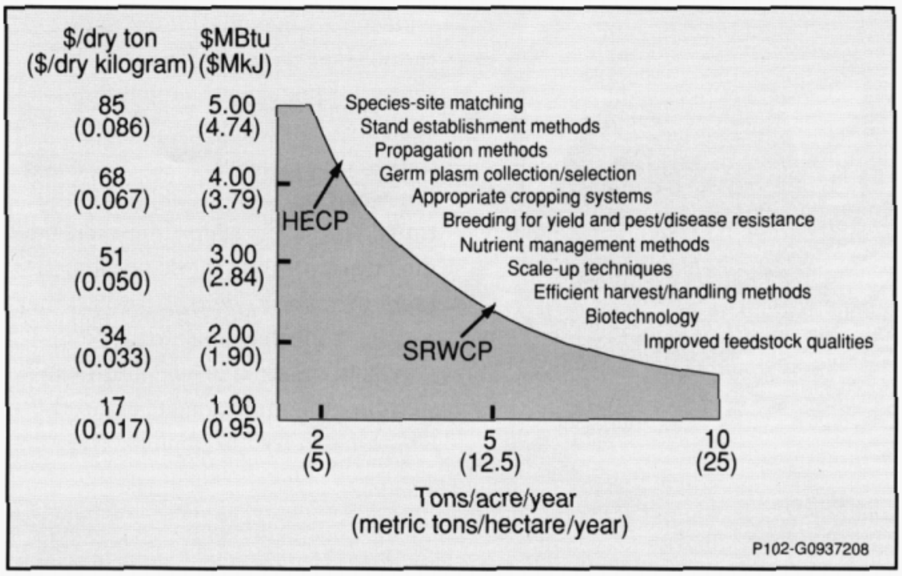
The long-term potential for U.S. energy crop production is diverse and widespread across the country.

Development of Model Species as Energy Crops

The BSD is pursuing crop development of a very limited number of "model" species. Almost every plant known to man produces biomass that can be converted to liquid fuels. The selected model species show a high potential for cost-effective production of biomass feedstocks on common types of cropland. Focusing on a few species allows investigation of the physiology and genetic traits associated with yield improvement and stress resistance. Site limitations and disease risks can be addressed using cutting-edge biotechnology approaches. This innovative research is producing improved crops for near-term commercial use, but more importantly the research is serving as a model for the development of energy crop species for additional sites and regions.

Model wood energy species, selected by the BSD in 1986 after eight years of screening, include poplars (cottonwoods and their hybrids), silver maple, black locust, sycamore, and sweetgum. Of these, the cottonwoods and their hybrids have received the most attention from both the BSD and industry because of the early identification of poplars' extraordinarily superior growth potential.

The BSD-supported research on hybrid poplars (genus *Populus*) in the Pacific Northwest has been a particularly successful model for energy crop development. There, researchers have developed new poplar clones that are now growing on thousands of commercially owned acres. Outstanding increases in yield have been produced through hybridization and clonal selection coupled



These requirements must be met for successful energy crop development.

Table 2. Key Research Strategies: Energy Crops

- Identify and characterize, through Geographic Information System evaluations and resource analysis, sub-regions and locations within the North Central and South/Southeastern United States that offer the greatest opportunity for environmentally beneficial, cost-effective energy crop production.
- Concentrate crop development and cropping systems research on one woody species (poplars) and one herbaceous species (switchgrass) while continuing to screen other species and systems for their adaptability to varied site, climatic, and pest situations.
- Continue hybrid poplar crop development through breeding, selection, and biotechnology to identify clonal resistance to septoria canker and leaf rust, serious diseases known to cause significant yield reductions in the North Central and Pacific Northwest regions, and resistance to drought stress conditions to ensure long-term crop sustainability.
- Improve switchgrass yield potential by concentrating on the near-term goal of selecting the best available varieties for the South/Southeast and the long-term goal of breeding improved varieties for a broad range of sites and conditions.
- Develop environmentally beneficial and cost-effective methods of feedstock production by incorporating superior clones and varieties into field trials and testing methods of establishment, nutrient and pest management, and harvest.
- Develop and use national, regional, and farm-scale models to define the economics necessary for obtaining landowner interest in energy crop production and for describing the environmental effects likely to occur as a result of changing land-use patterns.
- Coordinate environmental evaluation with industries, environmental groups, and a variety of local, state, and federal agencies to obtain consensus on critical issues, experimental procedures, and analytical approaches. Collect preliminary data on the effects of energy crops on plant diversity, wildlife habitat, water quality, nutrient utilization, and erosion.

with innovative physiology and crop management studies. Industry currently supports complementary research to develop a genetic mapping of the *Populus* genome and to associate molecular markers with specific traits. This basic information will be directly applicable to the development of *Populus* energy crops in other regions. Industry is also heavily involved in research aimed at understanding the mechanisms of disease resistance in hybrid poplars. The *Populus* success model—resulting from carefully coordinated, interdisciplinary research among several institutions and organizations—will be applied to the development of other energy crops.

Short-rotation woody crops research in the North Central and South/Southeastern regions is focusing on additional species and issues. Careful screening for high-yielding disease-resistant hybrids currently characterizes the major effort on hybrid poplars in the North Central region, where early commercial ventures failed largely because of disease problems. Improved seed sources of cottonwoods, sycamore, and sweetgum are being developed by the pulp and paper industries in the South, although progress has been slow. New cooperative work between the BSD and industry, now in the planning stages, is expected to speed up crop development of wood energy species for the South. Silver maple and black locust, although in the very early stages of energy crop development, have been used to demonstrate the feasibility of establishing plantations with tissue-cultured plantlets and evaluating gene transfer methods.

Researchers conducting herbaceous screening trials in the North Central region and the South have identified switchgrass (*Panicum virgatum*) as a model species suitable for development as an energy crop. It is a native prairie species with high potential for utilization on a wide variety of sites. DOE, the U.S. Department of Agriculture (USDA), and several universities in the North Central region are cooperating in studies to evaluate new switchgrass germ plasm collected from remnant prairie sites, and to compare these

Iowa State University

A researcher at Iowa State University harvests a stand of four-year-old hybrid poplar, one of the most promising energy crops in the North Central United States.

newly collected switchgrasses with genetically improved varieties developed for animal forage. In the South, new cooperative switchgrass studies have been initiated at five universities. Switchgrass variety trials and agronomic studies will identify the best currently available varieties and most productive crop management practices for the South. A breeding program is developing improved varieties for the future, while switchgrass tissue culture and physiology projects will lay the foundation for future use of biotechnology to improve energy crop yields, composition, stand longevity, and pest resistance.

Economics, Environment, and Policy

The most significant challenge in commercializing energy crop production for a biofuels industry is that success will depend on the individual decisions of thousands of landowners who together comprise the agricultural industry in this country. Each producer must be convinced that a profit can be made from growing energy crops for a biofuels industry. Profit during the early stages of industry development will be marginal. Economic analyses indicate that success or failure will be closely linked to agricultural crop programs and policy decisions. Analyses also indicate that valuing environmental and socioeconomic externalities could be important in the economic viability of energy crops. A major effort of the BSD feedstock development program is to identify the locations and conditions where energy crop production can provide environmental advantages and profits. This entails evaluating and understanding the linkages between economics,

Here, tissue-cultured switchgrass plantlets are being studied at the University of Tennessee. Switchgrass has been assessed to have high potential as an energy crop for the southern United States.

Warren Gretz, NREL

Packets of feedstock samples, developed with the assistance of NREL and ORNL, are being shipped as part of an international effort to standardize biomass and lignin analysis.

environment, policies, and markets. Technology transfer efforts and integrated biofuels systems scaleups can then proceed with the greatest hope of success in those locations.

The BSD's approach to environmental analysis is to work with industries engaged in biomass production; environmental groups that have or intend to take public positions on biomass-related issues; and local, state, and federal agencies with similar interests. Economic and environmental studies are closely linked because both will affect the acceptance and commercialization of energy crops. Analysis is being performed at several scales to ensure that all linkages affecting the commercialization of biomass-based fuel cycles are considered in program research and planning.

Farm-scale economic models, tailored to several different regions of the country, are providing an understanding of the effect of integrated farm management requirements and agricultural policies on land-use changes that might occur at the individual landowner level. A national scale model is being refined to project possible cost-supply relationships between energy crop production and land use changes at a larger scale. Components of both the farm-scale and national models will track changes in soil erosion, chemical use, and fuel use as functions of predicted land use changes.

Regional resource assessments are being conducted to evaluate potential energy crop supplies in subregions of the Midwest and South. These studies will identify cost-supply relationships as a function of land rental values, yields, and policy changes. They will also characterize the possible environmental effects of energy crop deployment by tracking shifts in erosion, fertilizer use, pesticide use, and biodiversity changes associated with energy crop production.

These data are being collected from existing experimental and commercial plantings on how energy crop production may affect the environmental balance of a region—diversity of plant species, wildlife habitat, water quality, and erosion effects. The data will be used to design improved energy crop management methods and to develop guidelines for production that will ensure that potential benefits to biodiversity, sustainability, and water quality are realized. BSD researchers are working with industry and environmental groups to develop key principles for environmentally acceptable biofuels feedstock production.

Data on environmental and economic factors will be critical for focusing crop development research on those regions and species likely to provide the greatest returns on the research investment. The data will also be valuable for policy makers at the federal and state levels who can have a major effect on determining the economic viability of energy crop production.

Interface Activities and Systems Integration

Projected demand for biofuels feedstocks will surpass the 2.1-3.2 x 10^{18} joules (2-3 quads) that may be available from wastes and residues within the next 15 to 20 years. Interfacing of production and conversion technologies by simultaneously addressing production, conversion, operational, and sustainability issues will promote the dynamic development of the biofuels industry. The key challenge will be to work within the very complex overlap of the energy, agricultural, and environmental sectors involved with biomass production and biofuels conversion.

In order to attract industry interest in biofuels technologies, we must be able to assure a continuous supply of high-quality, low-cost feedstocks. Production of energy crops is only one part of the supply scenario because many of the crops can only be harvested during limited intervals of the year. Determining how, where, and for what length of time crops can be stored without serious degradation in quality or energy content is a significant question that affects supply logistics and the final cost of the feedstocks. Data are being

Table 3. Key Research Strategies: Interface and Integration R&D

- Determine how the chemical composition of feedstocks correlates to the conversion efficiency of producing ethanol, methanol, biodiesel, and reformulated gasoline additives using biochemical, pyrolysis, and gasification technologies.
- Determine the effects of species, variety, storage method, and geographic location on feedstock composition and dry matter loss during long-term storage.
- Evaluate the trade-offs between improving feedstock quality to meet conversion system requirements and modifying conversion parameters to adjust to feedstock characteristics by developing assessment models.
- Develop models to evaluate the effect of scale on total system cost-effectiveness of individual facilities.
- Develop an assessment framework for integrating environmental, sociopolitical and economic considerations into decision-making processes in designing and locating biofuels conversion facilities.
- Develop a better understanding of how to optimize integrated systems by initiating cost-shared projects with industry to build energy facilities supplied with dedicated energy crop feedstocks.

The effects of long-term storage on compositional stability of feedstocks and the production of liquid fuels are currently being studied by researchers at ORNL and NREL. Here, switchgrass is field-dried and stored in circular bales, with and without netting and rock pads.

collected on the effects of different storage conditions on quality and content of several types of dedicated feedstocks and agricultural residues. Differences among species, within varieties of the same species, and in geographic location are all being investigated. These studies should produce recommendations on preferred storage and handling methods to sustain efficient and cost-effective year-round supplies.

Investigations into the effects of feedstock variation on conversion efficiencies are being coupled with feedstock storage studies. The chemical composition of feedstocks is being thoroughly evaluated and correlated with the efficiencies of several conversion processes. The information from such studies will be useful to crop breeders who may be able to genetically select for characteristics that will enhance conversion system operations.

The linkage among land resources, crop yields, and conversion facility locations is also being evaluated. Although it may be demonstrated, based on conversion efficiency studies, that one specific crop provides the best conversion characteristics, the land area around a specific facility may more cost-effectively produce other crops. Models and experience will be used to fully evaluate the trade-offs between feedstock quality and cost and to determine if specific feedstocks are optimally linked to specific conversion technologies. These results will show to what extent conversion technologies need to be modified for handling feedstocks of varying qualities.

The effect of scale on total system cost is a very important component of systems integration. Scale not only affects the cost of the conversion process but also will have a very large impact on the average price that can be cost effectively paid to obtain feedstocks. Although conversion costs will decrease with increasing facility size, feedstock costs will increase. Models will be developed to determine the optimum size that minimizes total system costs.

As better data on the economic and environmental aspects of dedicated feedstock production are combined with storage and conversion efficiency data, the BSD will come closer to designing integrated biofuels systems based on dedicated feedstocks. One approach is to cost-share the development of small-scale liquid fuel conversion systems supplied with dedicated feedstocks to obtain systems information. The environmental, economic, and procurement concerns will be similar for either ethanol or methanol.

Optimizing these systems to produce fuels competitive in world markets is the ultimate goal of both feedstock and conversion research.

Biofuels Conversion R&D

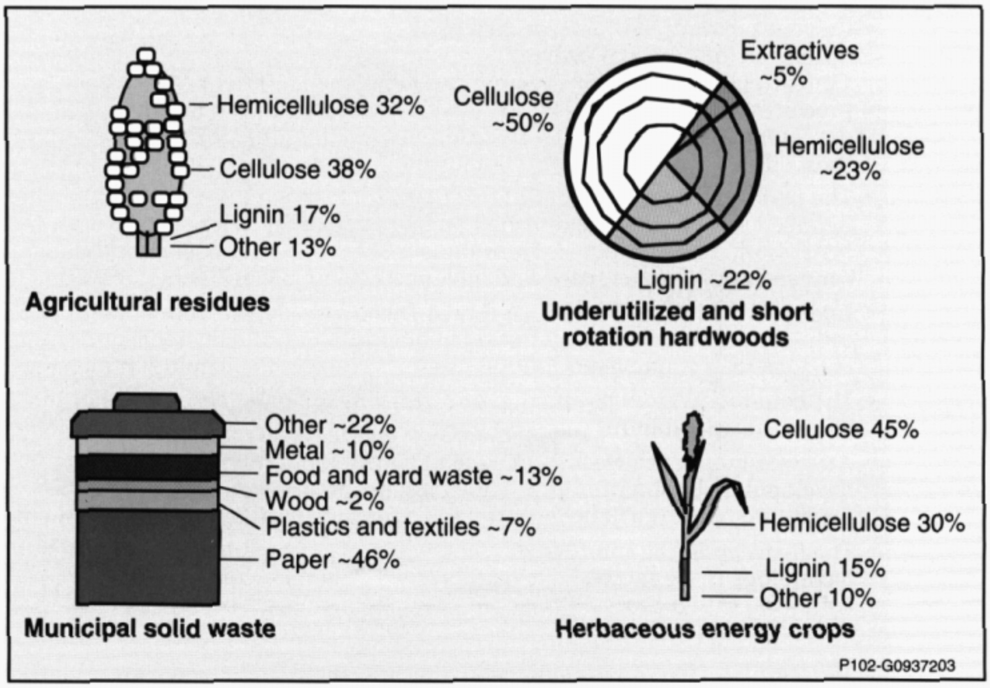
Alcohol fuels (ethanol and methanol) can be produced from biomass through either biochemical or thermochemical processes. Current research focuses on the biochemical conversion of biomass to ethanol and the thermochemical conversion of biomass to methanol. In addition to cost-effective ethanol and methanol production processes, BSD-sponsored researchers are working on converting biomass resources to ethers and alcohols that can be used as oxygenating additives in reformulated gasoline mixtures, and on increasing oil (lipid) yields from aquatic species for conversion to diesel fuel.

Ethanol

Approximately 4 billion liters (1 billion gallons) of fuel ethanol are produced annually in the United States today—mostly from corn. Ethanol from corn sells for \$0.29-\$0.41/liter (\$1.10 to \$1.55 per gallon) and is commercially competitive because of tax credits and substantial profits from coproducts (animal feed and food additives). At current levels, U.S. production of ethanol from corn poses no threat to the food crop market. However, should fuel ethanol production rise to 15-19 billion liters (4-5 billion gallons) annually, it could cause unacceptable increases in grain prices and a glut in the coproduct market.

A promising alternative to ethanol from high-carbohydrate corn

Approximately 4 billion liters (1 billion gallons) of fuel ethanol are produced annually in the United States today—mostly from corn.



The cellulose and hemicellulose components of biomass feedstocks (including the paper and yard waste portions of MSW) can be broken down and fermented into ethanol.

feedstocks is ethanol made from lignocellulosic biomass such as that produced by energy crops and found in a significant portion of MSW. Lignocellulosic fibers make up the structural parts of plants, much as the bones and muscles do in animals. These fibers are composed of three major components: cellulose, hemicellulose, and lignin. Cellulose and hemicellulose are chains of sugar molecules that can be broken down (hydrolyzed) and fermented to produce ethanol. The lignin component of biomass is a highly ordered complex of phenolic molecules that can be converted to high-value chemicals. In the near term, the most cost-effective use for lignin will be as a fuel to power the biomass-to-ethanol process.

Cellulose and hemicellulose are the ethanol-producing components of biomass, and each has special characteristics that must be addressed in the conversion process. Cellulose has a rigid crystalline structure, making it difficult to hydrolyze to sugar. The sugars in cellulose (mostly of the six-carbon glucose variety), once hydrolyzed, are easily fermented to an ethanol solution with common industrial yeasts. Hemicellulose, on the other hand, is a randomly structured molecular chain composed of mostly five-carbon sugars such as xylose. Unlike cellulose, hemicellulose is easily hydrolyzed, but the resulting five-carbon sugars cannot be fermented with common commercial yeasts without further treatment.

The first step in the conversion of cellulose to ethanol is to pretreat the feedstock. Pretreatment separates the three major components and opens up the physical structure of the cellulose component to allow greater penetration of sugar-forming catalysts during hydrolysis.

Research and analysis have shown pretreatment of chipped or shredded biomass with dilute sulfuric acid to be the most cost-effective method. The pretreatment process dissolves the hemicellulose to xylose, which is removed from the mixture, leaving behind the cellulose and lignin.

BSD researchers have studied several techniques for hydrolyzing the cellulose portion of biomass feedstocks. Nearly all of the techniques use either acids or enzymes to break down the cellulose to glucose. Enzymatic hydrolysis appears to have the greatest potential to produce cost-effective ethanol in the

Table 4. Key Research Strategies: Ethanol

- Current pretreatment process design and dilute acid technology will be optimized, and improvements in the acid process will be proposed. Concurrent with this effort, preliminary analyses of other pretreatment processes will be undertaken, and recommendations about further development will be made. Any technologies that appear more promising than dilute acid will be evaluated further.
- The performance of continuous recombinant *E. coli* xylose conversion from hemicellulose must be established; in addition, other xylose conversion systems must be evaluated. From these assessments, a model for xylose conversion will be proposed and advanced xylose conversion established.
- Establishment of the reproducibility of *Trichoderma reesei*, development of a cellulase production model, testing of alternative configurations, and the production of improved cellulases are the strategies for cellulase production.
- The beta-glucosidase production of *T. reesei* must be increased. In addition, improved recombinant cellulase must be analyzed.
- An assessment of the technical feasibility and economic viability of the development of potential coproducts will be undertaken. The most promising options will be recommended for further study and development.
- The first step in the commercial application of biomass-to-ethanol technology is the successful integration of the bench-scale process. Following this, a process development unit (PDU) must be developed and operated efficiently.
- The commercial feasibility of the technology when applied to energy crops must also be demonstrated to be economically viable.
- Near-term opportunities for the technology in the area of low-value feedstocks must be demonstrated.

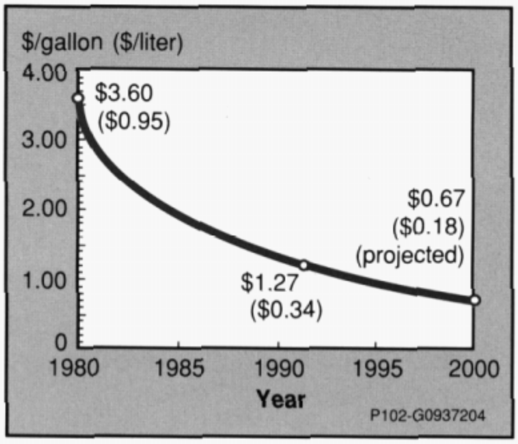
long run. This option uses cellulase enzymes to degrade the cellulose. Cellulase enzymes are produced by fungi that grow on a portion of the biomass feedstock. They are naturally occurring catalysts that operate like the stomach enzymes in animals, breaking down food into useful nutrients. After the cellulose has been converted to glucose sugar by the cellulase enzymes, it can be easily fermented to ethanol by commercial yeasts.

Fermentation of the xylose sugars has been the most challenging step in the biomass-to-ethanol process. The most promising technique devised thus far uses genetically engineered *E. coli* to ferment the xylose. This improved process has yielded 0.38 liter of ethanol/kilogram (91.4 gallons of ethanol/ton) of feedstock in the laboratory, for a product cost of $0.34/liter ($1.27/gallon).

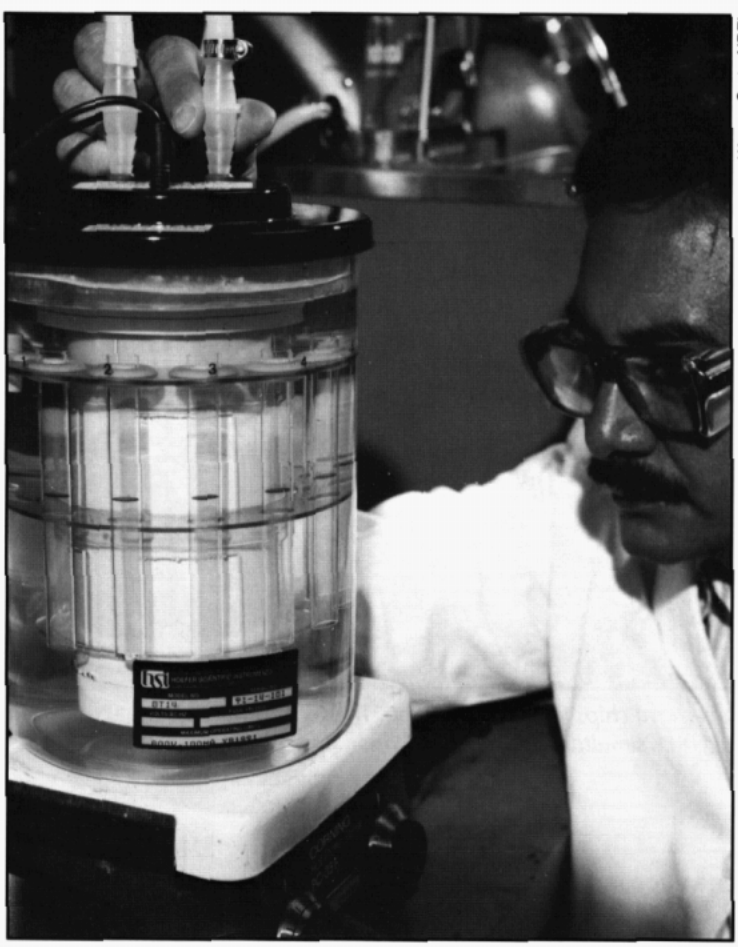
The overall goal of DOE's ethanol research program is to reduce the cost of producing fuel-grade ethanol to $0.18/liter ($0.67/gallon), making it competitive with current gasoline prices.

The BSD ethanol program is dedicated to excellence, innovation, and leadership through partnerships with the private sector. This past year, the program established two CRADAs with industry to develop and utilize program technology for the production of ethanol from biomass. One agreement is with New Energy Company of Indiana, and the second is with Amoco. The Amoco CRADA marks the first involvement by a major fuel supplier with NREL's pioneering work in the enzymatic conversion of ethanol from biomass.

The National Renewable Energy Laboratory (NREL) in Golden, CO, is



The overall goal of the ethanol research program is to reduce the cost of producing fuel-grade ethanol to $0.18/liter ($0.67/gallon), making it competitive with the cost of gasoline.



An NREL scientist uses polyacrylamide gel electrophoresis to identify and characterize cellulases that possess desirable properties for converting cellulosic biomass to ethanol.

Warren Gretz, NREL

An NREL researcher prepares wood chips for fuel conversion. These chips will be ground up, pretreated, and used in the NREL simultaneous saccharification and fermentation (SSF) process.

investigating biological systems that use enzymes and microorganisms to convert cellulose and hemicellulose to ethanol. The major areas of research are (1) characterization of different feedstocks in terms of their feasibility for ethanol production; (2) conversion of cellulose to glucose; and (3) conversion of hemicellulose to ethanol via xylose production, with emphasis on the fermentation of xylose to ethanol.

Feedstock Characterization

BSD feedstock characterization efforts at NREL have included improvement of analytical procedures for feedstock characterization, and planning of storage stability studies for various feedstocks. To establish standard methods and materials for the analysis of biomass feedstocks, NREL researchers organized and coordinated efforts among laboratories located in several countries. Through this effort, a wide range of analytical procedures for a series of "standard" biomass materials was developed. NREL scientists have completed initial plans for storage stability studies for a variety of biomass feedstocks. These stability studies are under way in the priority regions of the United States for four herbaceous crops, two agricultural residues, and four short-rotation woody crops.

Cellulose Conversion

In 1991, NREL researchers continued to look at the simultaneous saccharification and fermentation (SSF) process, which combines enzyme-catalyzed breakdown of cellulose to glucose with fermentation of glucose to ethanol. To enhance understanding of this process, a mathematical model was developed. This model will enable researchers to predict optimum conditions for maximum enzyme productivity and high yields of ethanol. Experimental work is now under way to validate the model and to estimate key unknown physical parameters of the process, which are required to fully utilize the model.

Improved Cellulase Enzymes

Research progress in the development of new cellulases, the enzymes that degrade cellulose to glucose, led to the filing of a key patent, recently approved by the U.S. Patent Office, on several new, temperature-resistant enzymes isolated from novel bacterial strains. Another patent was filed on a new method of immobilizing β-D-glucosidase (a key enzyme in the cellulase family). The method makes use of the enzyme more practical and economical in industrial biofuels conversion systems.

New Energy Company of Indiana

New Energy Company of Indiana, Inc. (NEC) is the first company to be awarded a CRADA with NREL. NEC is the second largest American manufacturer of ethanol, producing about 265 million liters (70 million gallons) of ethanol per year from the dry milling of corn at its plant in South Bend, IN.

Warren Gretz, NREL

NEC is participating with NREL in the construction and operation of a $1 million pilot plant for the conversion of corn fiber into ethanol. The cellulosic fiber comprises about 10% of the corn kernel and if converted to ethanol, would increase the amount of ethanol from current yields of 19.1 liter/cubic meter (2.55 gallons) per bushel to 2.47 liter/cubic meter (3.30 gallons) per bushel.

Currently, NEC's focus is on the conversion of corn fiber to ethanol using the NREL-developed simultaneous saccharification and fermentation (SSF) process. However, should the SSF process prove economically attractive, ethanol could be made from a wide variety of cellulose feedstocks, including corn stalks, wheat straw, sawdust, tree trimmings, and grass clippings.

Significant progress has been made on the NEC CRADA including engineering analysis and bench-scale experimentation to demonstrate the feasibility of process options and the reproducibility of results. Start-up and testing of the corn fiber to ethanol pilot plant is scheduled for mid-1993.

Amoco Oil Company

The CRADA with Amoco marks the first involvement by a major fuel supplier with NREL's pioneering work in converting cellulose to ethanol. Cellulose is the primary constituent of trees and grasses, even yard and paper waste. The NREL ethanol production method offers the potential of using these abundant, domestic, renewable feedstocks to produce alternative transportation fuels.

Amoco will work with NREL to assess the economic and engineering feasibility of converting selected feedstocks. A pilot-scale facility will be constructed at NREL in 1994 to demonstrate the process. The process uses enzymes to break down cellulose into sugars that can be converted to ethanol. After a more definitive process design, the partners intend to advance to a commercial-scale demonstration facility, which will be provided by Amoco.

Amoco Oil Company

Hemicellulose Conversion

Because conversion of hemicellulose to xylose is a relatively straightforward process, emphasis continues to be placed on the biological conversion of xylose to ethanol. In the past, efforts focused on a two-stage process, requiring enzymatic conversion of xylose to xylulose, followed by fermentation of xylulose to ethanol. This approach was used because few organisms were known to directly ferment xylose. However, recent work has identified naturally occurring yeasts and recombinant (genetically engineered) bacteria that can directly ferment xylose to ethanol. The greatest success has been achieved with a recently developed recombinant strain of *E. coli* bacterium.

Process Scaleup

The procurement effort for engineering services to design and install a biomass-to-ethanol pilot facility to be located at NREL is under way. Design of the new facility began in mid-1992. The facility will demonstrate ethanol conversion technology at a one ton of biomass per day scale (minimum) and will represent the first of several phased scale-up and demonstration efforts for biomass to ethanol. A larger scale process development unit has been designed that will replicate equipment used in a commercial facility.

Methanol

Most methanol is currently produced from natural gas by steam reforming the methane component of natural gas with a catalyst to form carbon monoxide and hydrogen. Another catalyst is then introduced to adjust the carbon monoxide to hydrogen ratio to form methanol.

Methanol can also be produced from biomass using thermochemical conversion processes. Thermal processes convert the biomass directly to a synthesis gas (syngas) composed of carbon monoxide and hydrogen. Following cleaning, the syngas from biomass can be used in commercial units to produce methanol.

Thermochemical Conversion

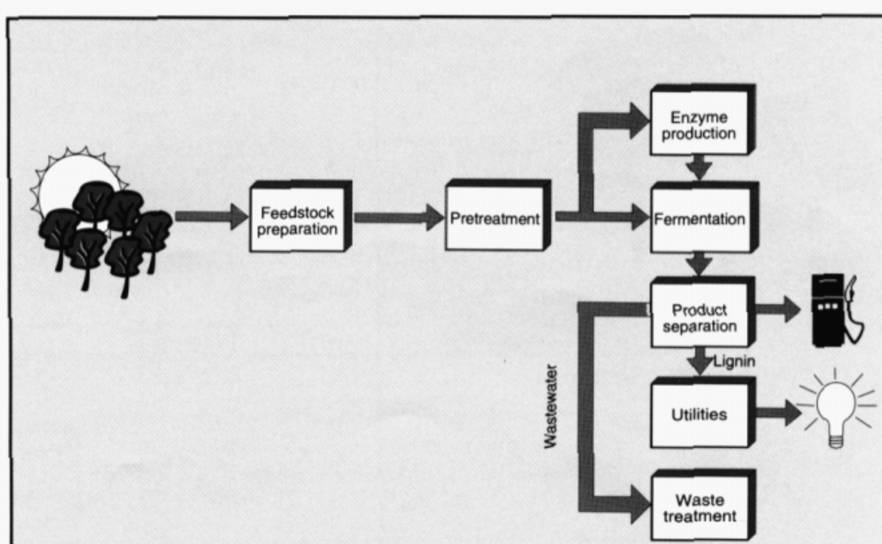
The production of methanol from biomass requires an integrated process consisting of feedstock pretreatment, conversion to syngas, conditioning of the syngas, and conversion of the syngas to methanol.

Biomass gasification systems are designed to maximize carbon monoxide and hydrogen (the major components of syngas), while minimizing unwanted products including methane and other light hydrocarbons. Gasification takes place rapidly (0.5 to 20 seconds) in an atmosphere of steam and/or oxygen at moderate temperatures 700° to 980°C (1300° to 1800°F). Gasifiers are operated at pressures ranging from atmospheric to about 2.76 million Pa (400 psi). The gasification process may include both endothermic pyrolysis (a process that uses heat and biomass and steam to produce carbon monoxide and hydrogen) and exothermic partial oxidation (a process that uses biomass and oxygen to produce carbon monoxide and hydrogen).

The most important single determinant of the viability of the overall methanol production process is the gasification technology selected for generating syngas. The gasifier should produce the highest yield of syngas per unit of biomass feedstock


Warren Gretz, NREL

The SSF method of ethanol production (the SSF process vessel is shown here) increases yields, decreases process time, and lowers production costs because the saccharification and fermentation steps take place simultaneously.



The new NREL biomass-to-ethanol pilot facility will be based on this PDU design.

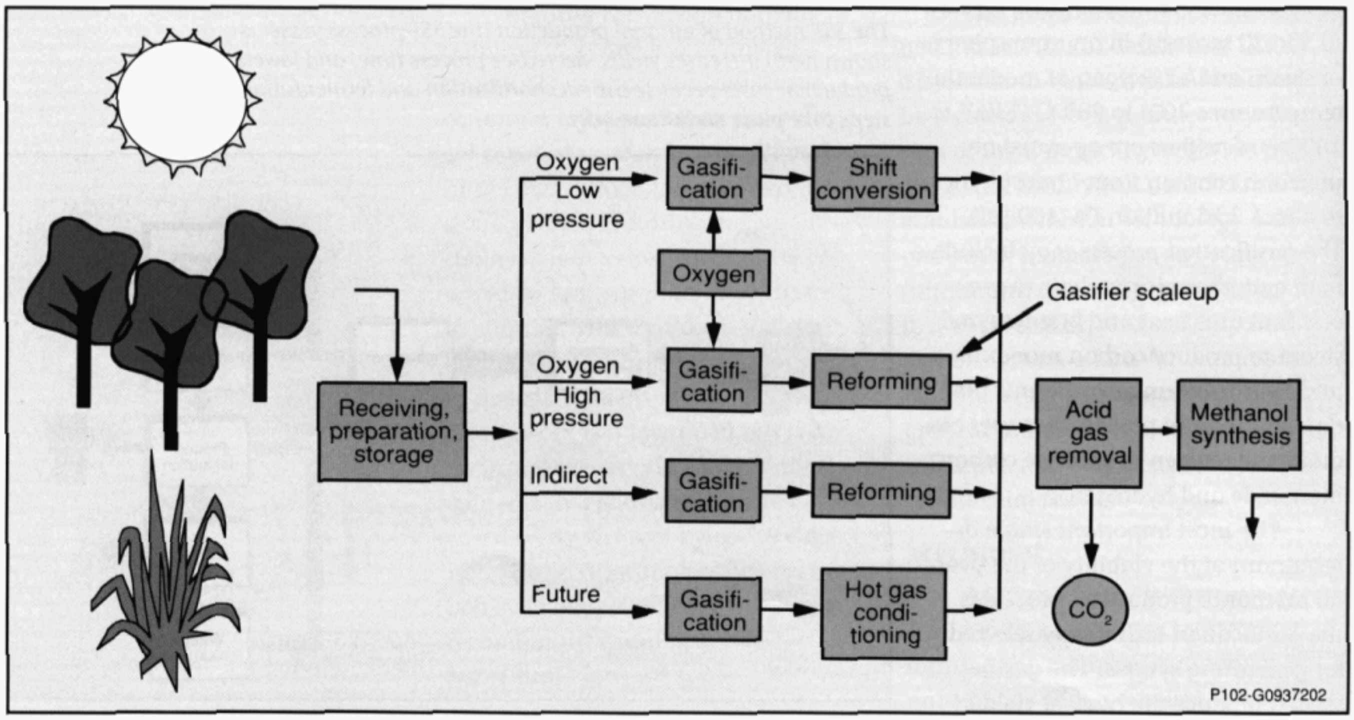
in a manner consistent with the requirements of methanol synthesis. There are two design philosophies on how to achieve this: the first is to design and operate the gasifier to produce an acceptably clean syngas at the gasifier exit; the other is to conduct a two-stage process that uses gasification and reformer/shift steps to achieve higher yields of syngas.

Improvements in the gasification process center on optimum conditions of temperature, pressure, steam, and oxygen rates for maximum yield, gas composition, and thermal efficiency. Improvements are also possible in the various gas processing steps: raw gas conditioning, compression, shift reaction, acid gas removal, and methanol synthesis.

Feedstock availability, suitability for thermal processing, and cost are important aspects of the integrated biomass-to-methanol process. Advances in each of these areas are anticipated during the duration of this five-year research program. Biomass yields should increase, suitability for gasification should improve as feedstocks are characterized and examined for thermal processing, and biomass costs should diminish. All these factors will improve the technical and economic feasibility of the biomass-to-methanol process.

Several technical advantages exist for biomass facilities over plants using other methanol feedstocks as the result of the following characteristics inherent to biomass:

- Low gasification temperatures
- Short reaction times
- Reduction or elimination of oxygen demand
- Reduction of ash disposal
- Minimization of sulfur removal problem
- Elimination of slagging.

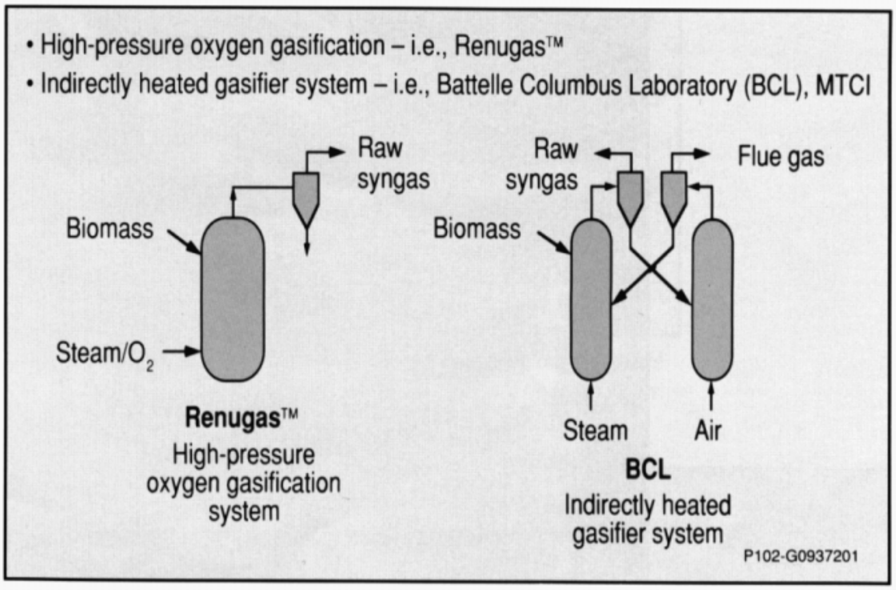


BSD researchers are pursuing several routes for producing methanol from biomass.

Recent BSD studies show that methanol production economics can potentially be improved if hot gas conditioning is successfully developed. In the past three years, new tar-cracking and steam-reforming catalysts have been identified in the laboratory that can potentially improve gas conditioning for methanol production. These concepts must be tested at a reasonable scale to maximize the chances for successful development.

The BSD program of work has a major technoeconomic analysis component that is used to integrate and guide the research, development, and demonstration program. NREL began compiling existing technoeconomic analyses on thermochemical fuels in FY 1989. In FY 1990-91, the effort was expanded to include detailed process analysis using a commercial process simulator. This analysis resulted in methanol production models consistent with those developed for ethanol. The models can be readily changed and are continually updated as new information becomes available.

Current biomass-to-methanol technology can produce methanol at a cost of about $0.22/liter ($0.84/gallon—1990 dollars). This cost is significantly reduced from the $0.30/liter ($1.13/gallon) projected in the early 1980s. BSD researchers have an economic goal of producing methanol for $0.14/liter ($0.54/gallon—1990 dollars). For comparison, the cost to produce methanol from natural gas is about $0.10/liter ($0.40/gallon). At $0.12 liter ($0.46/gallon), methanol is equivalent on a contained energy basis to $0.22/liter ($0.85/gallon) of gasoline produced



BSD researchers are pursuing two major gasification technology avenues. Both need novel reforming catalysts.

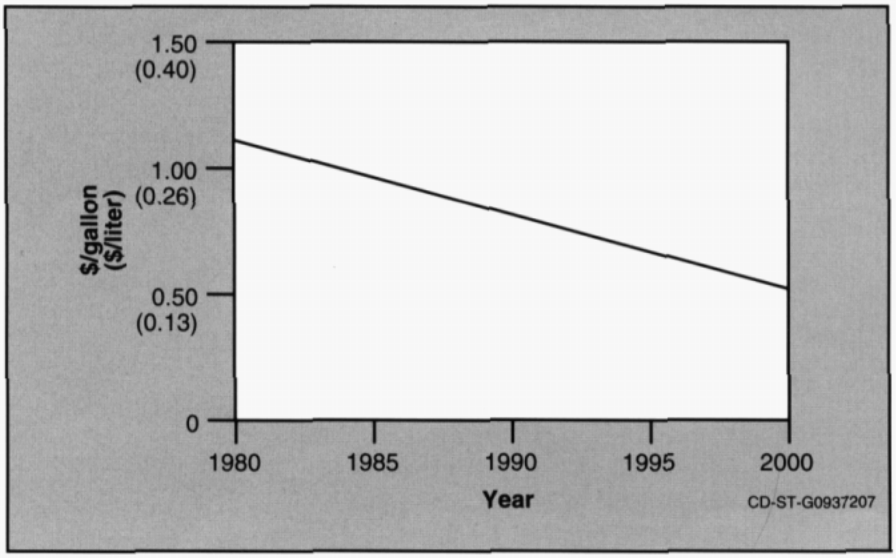
Table 5. Key Research Strategies: Methanol

- An engineering evaluation of gasifier auxiliaries such as pressurized feeding and instrumentation, raw gas cleanup, syngas modification, and methanol synthesis will be undertaken. Promising strategies will be identified and further analysis performed.
- The potential of innovative catalytic methanol synthesis systems will be evaluated for technical feasibility, economic viability, and potential positive effects on other unit operations, such as gasification and gas cleanup, will be evaluated.
- A 45,000-180,000 kilograms/day (50-200 tons/day) experimental test bed facility will be constructed and operated. It is likely that the methanol synthesis loop will be attached to the output of the DOE/Pacific International Center for High Technology Research gasifier scaleup in its third phase of operation.
- After component reliability is established in the test bed facility, commercial cosponsors will be incorporated into the development of catalysts as the facility moves toward production scaleup.
- Ongoing research in hot gas conditioning will be performed at the laboratory scale for catalysis and also at the BCL gasifier.

from crude oil at $4/cubic meter ($25/barrel).

Battelle

The Battelle high-throughput biomass gasification process is one of the most promising methanol production technologies being investigated by the BSD program.



BSD researchers have an economic goal of producing methanol for $0.14/liter ($0.54/gallon) (1990 dollars) by the turn of the century.

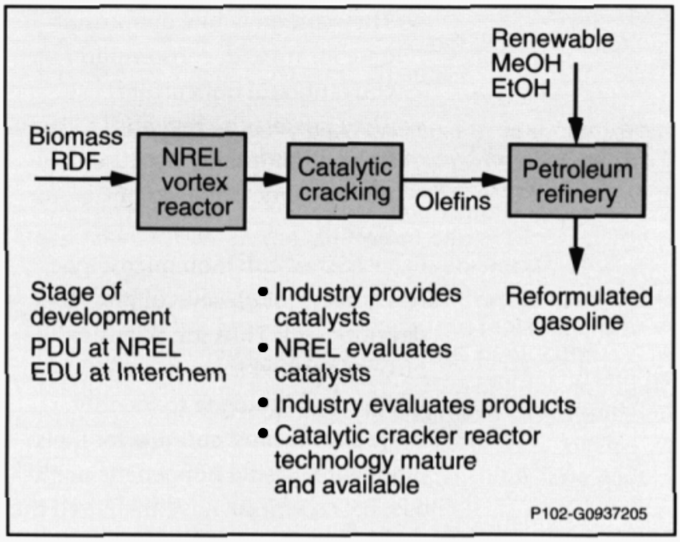
Reformulated Gasoline Components

Biomass may also be converted to olefins using a new technology developed by NREL that is based on fast pyrolysis catalytic cracking. The biomass-derived olefins may then be used to produce RFG components such as methyl tertiary butyl either (MTBE) or ethyl tertiary butyl ether (ETBE). Although biomass such as wood and herbaceous energy crops can be used in the process, the RDF fraction of MSW is currently being investigated. RDF contains about 6-8 wt % of nonrecyclable plastics as well as significant amounts of biomass (40%-60%), both of which are good olefin feedstocks in the NREL process.

There are three major components in the technology for producing RFG from biomass: the fast pyrolysis unit (vortex reactor), the catalytic cracking unit, and the ether production unit. Fast pyrolysis of the biomass requires very rapid heating of the feedstock to temperatures where oxygenated crude oil vapors are formed instead of char, water, or gases. NREL's current scale of fast pyrolysis is a nominal 23 kilograms/hour (50 pounds/hour) PDU and an engineering development unit (EDU) at 1.400 kilograms/hour (1.5 tons/hour) scale under construction in cooperation with industry.

The catalytic cracking unit uses much commercially available technology; however, the key to the technology lies in the specificity of the catalyst system in producing the preferred olefin stream. Proof of concept has already been demonstrated using a standard cracking catalyst in a fixed-bed reactor. Superior catalysts that will produce the olefin stream preferentially and will have long lives during cyclical catalyst regeneration procedures are required. These catalysts are under development jointly with the University of Utah and are being screened at NREL. This is a critical area of development because the olefin yield is key to the cost-effectiveness of the process.

Preliminary economic analysis of the advanced catalytic process suggests that production of the mixed RFG components from biomass would cost $0.18/liter ($0.67/gallon) compared with today's estimated cost of $0.25/liter ($0.96/gallon). Although initial development of this technology will likely be based on utilization of RDF, eventually renewable biomass will be used.



NREL is working with Interchem Co. to develop and demonstrate the biomass (in this case, RDF) to ethers process. The ethers can be used to produce RFG.

Table 6. Key Research Strategies: Reformulated Gasoline Components
• Initial development of this technology will concentrate on RDF because of its low cost, its enhanced olefin production from plastics in RDF, and the immediacy of demand. In addition, the location of RDF in urban centers makes it possible to start the scale-up process with only a partial plant. In fact, if the fast pyrolysis and catalytic cracking trains were installed at a refinery site, the olefins produced could be processed into ethers using existing units.
• The total concept must be proved at the laboratory scale using RDF.
• The fast pyrolysis and catalytic cracking processes will be scaled up in an EDU capable of processing roughly 36,000-91,000 kilograms/day (40-100 tons/day) of RDF and will be located at a refinery; a stand-alone unit may be constructed later.
• A catalyst development program will be emphasized throughout the engineering development phase. Improving the selectivity to olefins and increasing catalyst life will be the major areas of effort.

Biodiesel Fuel from Microalgae

Microalgae are a form of aquatic plant that grows suspended in water or attached to surfaces in aquatic habitats. Microalgae are important biomass energy feedstocks because of their rapid growth and high lipid (oil) content. When harvested, microalgal lipids can be converted directly to high-energy liquid fuels such as diesel.

There are numerous advantages to utilizing microalgae for liquid fuels production, including:

- Growth rates are as much as five times those of most terrestrial plants.
- They can be cultured (grown) on arid lands.
- Pests and weeds are easily controlled.

- They can grow in water unsuitable for human consumption or conventional agricultural use.
- They possess the potential to benefit local air quality because they require large amounts of CO_2 for growth.

BSD research on microalgae has gone through several phases of development. Thus far, scientists have examined more than 3000 strains of microalgae to identify those strains most suitable for fuels production. Using nongenetic methods, BSD scientists have increased the lipid content of microalgal cells found in nature (5% to 20% lipids) to more than 60% in laboratory culture and more than 40% in outdoor culture. Using genetic manipulation, these percentages can be enhanced even further.

To date, genetic improvement research has focused on the purification and cloning of key lipid enzymes, a better understanding of the genetics and biochemistry of these enzymes, and the introduction of foreign genes into microalgae. Current research involves genetic transformation and stabilization and is aimed at controlling the timing and

Warren Gretz, NREL

These are some of the more than 3000 strains of microalgae that scientists have examined to identify those strains most suitable for fuels production.

magnitude of lipid accumulation. Increased lipid content, a major project goal, is essential to reducing fuel cost.

Outdoor culturing experiments have been conducted in 1000-square-meter (1/4-acre) ponds at Roswell, NM. These studies demonstrated CO_2-trapping efficiencies greater than 95% for the most productive periods (summer months) of the year. In smaller (3-square-meter) outdoor ponds, more than 15 strains of microalgae were evaluated for outdoor mass culture potential and significant lipid production.

Microalgae biofuels research is additionally important because of its potential impact on the environment. Biodiesel derived from microalgae is considerably cleaner burning than conventional diesel fuel from the standpoint of particulates and sulfur emissions. Further, because microalgae require large quantities of CO_2 as a nutrient, a biodiesel facility affords the potential to reduce this greenhouse gas when the microalgae growth facility is operated in tandem with a fossil fuel plant. Flue gases from the fossil fuel plant could serve as a CO_2 source for the microalgae.

The goal of this program is to produce diesel fuel at a competitive market price by 2010.

Table 7. Key Research Strategies: Biodiesel from Aquatic Species

- Microalgal strains have been collected from many areas in the United States; these strains have been screened to select species that are temperature- and salinity-tolerant, have high productivity, and are good lipid producers. A collection of organisms is being maintained to provide a gene pool for use in the laboratory and outdoor energy crop research and as a starting material for genetic engineering.
- Microalgae will be genetically transformed to develop organisms with growth and lipid production levels that reach the technical and cost goals necessary for competitive biodiesel fuel production.
- Methods for the economical extraction of lipids from microalgae and conversion of lipids to gasoline and diesel substitutes will be developed and evaluated.
- Close interface with other federal agencies will be undertaken to assess the environmental advantages of biodiesel.
- Systems to maintain optimal levels of nutrients, CO_2, salinity, and temperature will be developed and tested.
- Cost goals, economic sensitivities, resource assessments, and environmental impacts for the technology are continually updated. Potential constraints and data gaps will be identified and project guidance provided on an ongoing basis.

Table 8. Biofuels R&D Objectives

Fuels	Process Performance Parameters	Proof of Concept	Demonstration of Commercial Feasibility
Ethanol	• Cellulose-to-ethanol yield at 90% • Xylose-to-ethanol yield at 95% • Xylan-to-xylose yield at 90% • Cellulose conversion time at 3 days • Xylose fermentation time at 1 day • Ethanol concentration after fermentation at 6.6% • Ethanol recovery at 99.8% • Cellulase loading at 3 IU/g cellulose	• Successful operation of PDU for ethanol production from energy crops	• Successful operation of fully integrated and optimized demonstration plant for production of ethanol from energy crops with an on-stream time of 98% and no significant environmental impacts
Methanol	• Gasification efficiency >95% • Overall process efficiency 60%	• Successful operation of PDUs for methanol production from energy crops	• Successful operation of fully integrated and optimized demonstration plant for production of mixed ethers from RDF with an on-stream time of 98% and no significant environmental impacts
Reformulated Gasoline Components	• Process yield >0.02 liter/ kilogram (84 gallons/ton) RDF	• Successful operation of PDUs for mixed ethers from RDF.	• Successful operation of fully integrated and optimized demonstration plant for production of mixed ethers from RDF with an on-stream time of 98% and no significant environmental impacts
Biodiesel from Aquatic Species	• High microalgal productivity (high growth rates at 50 grams/square meter/day and microalgal lipid content at 60%) • High yields of diesel from algal lipid and high rates of lipid conversion to diesel	• Successful operation of integrated PDU for algal production and conversion of algal lipid to diesel	• Successful operation of fully integrated and optimized demonstration plant for production of lipid-rich algae and conversion of algal lipid to diesel fuel with an on-stream time of 98% and no significant environmental impacts
Energy Crops	• Establishment success of >90% • Annual losses caused by disease, pests, flooding, drought, or lodging held to <20% by selection for resistant varieties • Nitrogen emissions in ground-water meet Environmental Protection Agency drinking water standards • Standing yield of 1.8-2.2 dry kilograms/square meter/year (8-10 dry tons/acre/year)	• Provide a year-round supply of more than 9.1 million dry kilograms/year (10,000 dry tons/year) of energy crop feedstock to an energy facility	• Successfully supply entire feedstock requirements of a biofuels facility with no significant environmental impact with energy crop production systems that provide profit to surrounding landowners

Meeting the Challenge

Liquid biofuels technologies are mid- to long-term energy options that will achieve their greatest impact after the turn of the century. The BSD program strategy is to prove the feasibility of the technologies by sponsoring R&D that industry is unable to pursue alone. Although the burden of developing these technologies is expected to remain essentially with DOE for the near term, DOE is developing mechanisms to ease the transition to increased industry responsibility. In the midterm, DOE expects its role to decrease as industry takes additional responsibility for further development of maturing biofuels technologies. In the long term, the responsibility for demonstration and commercialization will rest with industry.

The involvement of the private sector in every aspect of the program helps to ensure that BSD program goals and priorities are relevant to the needs of industry and that the resulting technologies can be readily employed when market conditions allow. A central and critical feature of the BSD program strategy is to encourage government-industry cooperative efforts. Working with industry, the program will establish technologies that are expected to improve the energy economy. In the final stage, it is assumed that the responsibility for commercialization will rest with the private sector.

Warren Gretz, NREL

In the near future, government and industry cooperative research, development, and demonstration will make alternative-fueled vehicles such as these common on U.S. roads.

Transferring the Technology

Implementation of the BSD program is based on optimizing the interactions among the federal government, private industry, universities, and other interested research organizations. The program benefits from private sector innovation and experience in both the planning and conduct of this research. Industry and universities benefit from federal support to develop the technologies. To ensure success, the BSD program includes provisions for:

- Cost-shared research efforts that require commitments by both industry and government
- University research efforts to explore new research frontiers and train professional personnel
- Government/industry dialogue in outyear planning activities
- Prompt, accurate, and complete transfer of information gained from R&D conducted through national laboratories.

The BSD program is working with industry to identify critical technical barriers to improved efficiency, improved performance, and reduced

A central and critical feature of the BSD program strategy is to encourage government-industry cooperative efforts.

costs of biofuels. To remove these barriers and assure timely and effective transfer of technology, the program sponsors and encourages projects that are cost-shared with industry when technologies approach commercialization.

Organizing the Program

In 1990, DOE's Assistant Secretary for Conservation and Renewable Energy (CE) established five new offices to implement energy strategies established by DOE in response to the nation's energy needs. The BSD is now under the Office of Alternative Fuels, which is part of CE's Office of Transportation Technologies.

The Biofuels Systems Division

The director of CE's BSD provides the leadership needed to ensure that the National Biofuels Program conforms to national energy policy, priorities, and directives. The director also develops and implements program concepts and plans; provides guidance for priorities; conducts regular program reviews and evaluations; distributes resources; and responds to requests from DOE staff, other federal agencies, and Congress for information about the program and project activities. Division personnel with specific technical expertise manage the program's technical activities.

CORECT

Established by Congress in 1984, the Committee on Renewable Energy Commerce and Trade (CORECT) is a working group of 14 federal agencies (including DOE and the BSD) whose mission is to facilitate the cost-effective use of U.S. renewable energy products and services around the world. Many problems in developing countries are tied to energy; CORECT seeks to utilize sources indigenous to the country in order to alleviate its energy needs. In doing this, the problems of finance and educating and training users are addressed as well.

The U.S. Department of Commerce and the U.S. Export Council for Renewable Energy have teamed up under the umbrella of CORECT to recreate a marketing strategy modeled after previously successful work in the Caribbean. This strategy includes four primary goals:

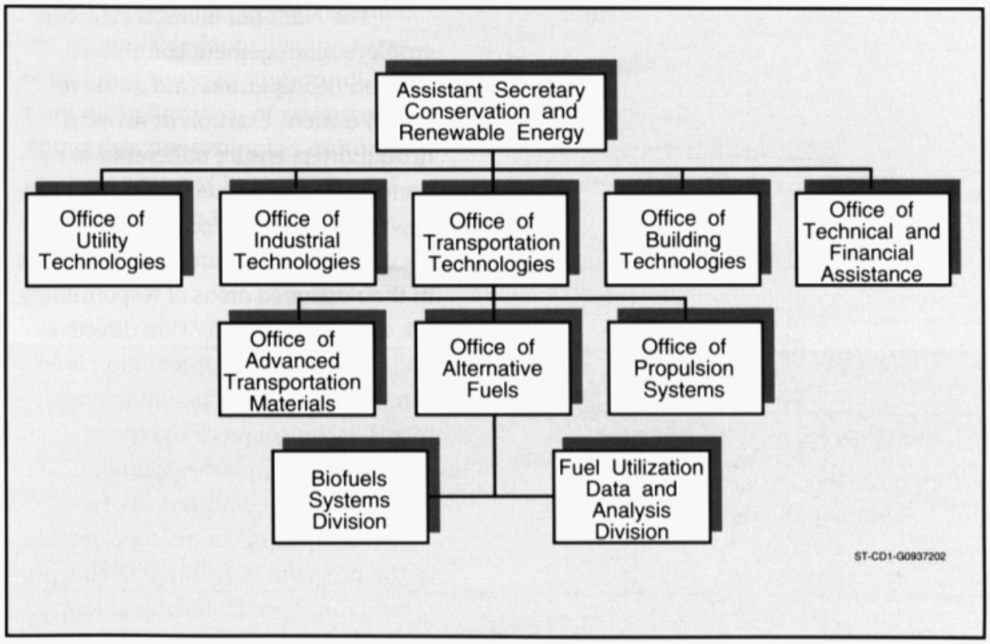
- To identify opportunities for renewable energy in end-use sectors
- To introduce the potential of renewable energy in these sectors
- To encourage increases in energy supplies
- To promote prospects for private power generation.

Because the United States does not use "tied aid" (as do Japan and several European countries), our competitive edge in these endeavors is somewhat inhibited. Tied aid is financial assistance that is offered by an outside government to developing countries for specific projects. The aid is tied by the requirement that the receiving country purchase goods and services for the project from companies in the assisting country. Instead of using tied aid to supplement costs for U.S. companies involved in projects in developing countries, Congress renewed the "war chest" funds. Some of the war chest funds are combined with the CORECT financing for energy projects in transportation and telecommunications in order to allow U.S. industry to compete based on technology rather than financing.

The Research Centers

Two research centers, NREL and ORNL, provide management and technical support to the National Biofuels Program. These research centers are responsible for the day-to-day management of biofuels research and development and for meeting the technical goals of the national program. They manage program activities, in-house research projects, and subcontracted work in areas assigned to them by the director of CE's BSD.

The research centers allocate a significant portion of their resources to projects that are performed by universities, private companies, and other research organizations. The remaining resources are allotted to activities performed at the research centers themselves.



The BSD is part of the DOE's Office of Conservation and Renewable Energy.

Oak Ridge National Laboratory

ORNL—the largest of DOE's multiprogram, nonweapons laboratories—focuses its resources on energy and other R&D challenges important to DOE and the nation. ORNL's programs are divided between applied energy technologies and more basic sciences. The 4600-member staff, along with more than 2300 guest researchers each year, conducts major programs in energy conservation technologies; renewable energy sources; materials development; magnetic fusion energy; environmental and life sciences; robotics and computing; and basic chemistry, mathematics, and physics.

ORNL's Environmental Sciences Division (ESD) has managed DOE's biofuels feedstock development research since 1978. ESD has more than 200 full-time staff members as well as a large number of guest researchers. The division emphasizes research on environmental analyses and modeling approaches, pollution effects and waste management, renewable resources, and global environmental studies. The goal of the ESD's Biofuels Feedstock Development Program (BFDP) is to develop cost-effective, environmentally acceptable crops and cropping systems for energy feedstocks. BFDP research and analysis are performed at ORNL and at cooperating institutions across the country. In 1992, the BFDP supported research at 14 universities and 5 USDA research facilities. Major tasks included development of model wood energy species, selection and development of model herbaceous energy species, environmental research and analysis, and economic analysis and integration.

The BFDP is also involved in interface and integration activities. Researchers conduct economic and environmental analyses that include resource analysis, site-specific cost and supply studies, national-scale economic modeling of the agricultural sector, and the development and synthesis of information on environmental effects. Evaluation of the effect of scale of individual facilities on energy crop cost and supply relationships and on landscape changes is an important BFDP effort. ORNL has involved a significant number of institutions and agencies in these cooperative efforts.

Managing the Program

The National Biofuels Program employs management controls at division headquarters and at the research centers. Controls at division headquarters ensure adherence to national policy and foster the overall success of the program; controls at the research centers ensure that operations in their assigned areas of responsibility are consistent with division directives and technical goals. Integration is accomplished through planning documents, technical progress reports, periodic program reviews, and frequent personal communications.

The general technical direction of the program is outlined in this program plan. Specific technical emphases and modifications are determined each year, when CE's BSD director approves planned research activities and project milestones based on technical progress and available resources. Each research center submits quarterly reports on resource expenditures, technical activities, and progress in each task area. Brief monthly and weekly highlights supplement the quarterly reports.

Program reviews are conducted periodically to inform program participants and the public of recent activities and developments. Each research center also conducts reviews of specific sub-programs to provide technical audiences with detailed information on work in progress.

The federal government plays a leading role in the R&D on biofuels for the transportation sector. The government allocates most of its program budget to biomass production and conversion research for improving yields and conversion efficiencies, with the ultimate objective to produce cost-competitive transportation fuels for the marketplace.

National Renewable Energy Laboratory

NREL was established by Congress in 1973 as the nation's primary center for renewable energy R&D. NREL develops renewable energy technologies to heat and cool buildings; run industries; light homes and offices; grow and cook food; power cars and trucks; produce plastics, clothing, drugs, and chemicals; clean our water; destroy toxic wastes; and absorb CO_2 from the atmosphere.

More than 650 staff members are engaged in renewable energy R&D and supporting activities at NREL's facilities in Golden, CO. The expertise of NREL's technical staff is augmented by approximately 30 visiting scientists from around the world; 45 postdoctoral researchers, graduate students, and undergraduate students; and scores of scientists and engineers from universities and industries that conduct cooperative or subcontracted research.

NREL's Alternative Fuels Division (AFD) supports DOE's BSD. The AFD is developing technologies for converting renewable resources such as biomass, municipal and industrial wastes, and simple substrates such as water, nitrogen, and carbon dioxide to fuels, commodity chemicals, and materials. The fully equipped, modern NREL Field Test Laboratory Building houses studies in aerobic and anaerobic microbiology, enzymology, fermentation, biochemistry, molecular biology, and analytical support. A high-level biological containment laboratory and several lower level containment laboratories are used for genetic engineering work with all microorganisms except human and animal pathogens. A separate Biotechnology Research Facility houses bioengineering research and pilot-scale development work. AFD activities range from bench-scale research to process- and engineering-scale experimentation and demonstration.

AFD staff members direct and manage contracted research performed at universities, other research centers, small businesses, and large industries. These activities include cost-shared, multiyear, government-industry partnerships and technology initiatives.

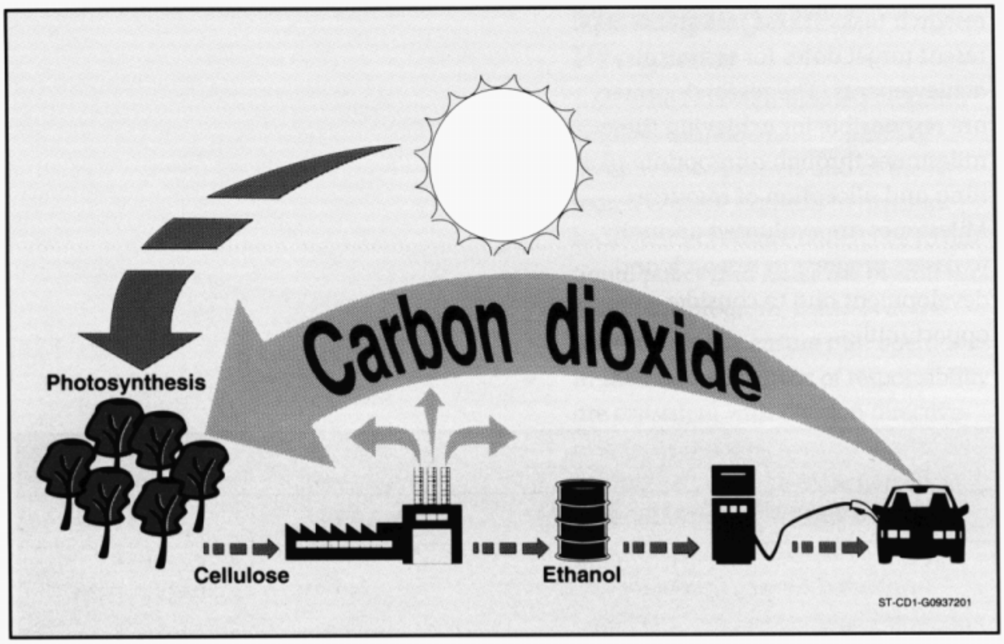
The National Biofuels Program awards a significant portion of its annual funds to industry, universities, and other research organizations. These awards are made chiefly through competitive procurements for R&D support.

Technical milestones and program assessment points are established to guide program managers in evaluating the progress and direction of research tasks. These milestones represent target dates for technical achievements. The research centers are responsible for achieving these milestones through appropriate planning and allocation of resources. Milestones are evaluated annually to assess progress in research and development and to consider new opportunities.

Table 9. BSD Program Plan

Program	FY 1992	FY 1993	FY 1994	FY 1995	FY 1996
Ethanol		• Complete integrated system • Construct PDU	• Debug and operate PDU		• Construct improved PDU
Methanol			• Reach full operation of indirect PDU gasifier • Award contract for construction of 91,000 kilograms/day (100 tons/day) EDU		• Construct 91,000 kilograms/day (100 tons/day) EDU
Reformulated Gasoline Components				• Initiate design/construction of EDU	
Biodiesel from Aquatic Species			• Stabilize gene expression		• Clone T-lipid genes • Design/construct small-scale facility
Energy Crops	• Initiate switchgrass development work in the South • Complete development and base-case studies for national-scale agricultural sector model	• Initiate industry cost-shared breeding work for hardwood yield improvement in the South • Identify black locust clones with best yield potential for Piedmont sites	• Report final results of herbaceous crop screening in Corn Belt and Northern Plains • Develop tissue culture techniques for propagation and genetic modification of switchgrass	• Identify mechanisms of resistance to leaf rust disease affecting hybrid poplar clones • Develop regional yield-potential map for switchgrass production in south central United States	• Report 10-year yield and cost data for hybrid poplar plantations in north central United States • Assess persistence of apparent septoria resistance in hybrid poplar somaclone

Biofuels and the Environment



Carbon dioxide released during the conversion and use of biofuels is absorbed during regrowth of the biomass feedstock.

From production to end use, biomass energy systems have the potential for solving environmental problems.

Biofuels have several environmental benefits when compared to the fossil fuels they will displace. From production to end use, biomass energy systems have the potential for solving environmental problems. They can turn municipal, agricultural, and forestry wastes into energy resources, relieving pressure on landfills. Perennial energy crops can provide year-round ground cover, keeping sites that are prone to erosion under conventional cropping systems productive and profitable. Combustion of biofuels can reduce vehicle-related air pollution in urban areas. And biofuels release little new CO_2 to the atmosphere because biofuels feedstocks recycle atmospheric carbon during growth.

Because of new federal clean-air legislation, it is important to emphasize the role that biofuels can play in achieving a cleaner environment. Use of biofuels, such as methanol, ethanol, and other oxygenated biomass derivatives, can have a beneficial impact on air quality, particularly in the transportation sector.

There is little doubt that the growth of biomass feedstocks is the only way to remove CO_2 from the air and ameliorate global warming. Biofuels are the only energy technologies that can both remove atmospheric CO_2 and reduce the amount of fossil fuels burned. In addition, displacement of fossil fuels by biofuels can eliminate or reduce atmospheric sulfur dioxide, nitrogen oxides, ozone, and unburned hydrocarbon fuels, all of which contribute heavily to poor air quality. Poor air quality in turn leads to poor public health and a deteriorating environment.

This is not to say that we should not be vigilant in the development and use of biofuels technologies, however. Like all energy systems, those that use biomass can also pose environmental questions. Biomass-based fuel cycles will require land and equipment for feedstock production, storage, and transportation. Commercial-scale biofuels markets will result in biomass production and conversion facilities, fuel transport, and fuel combustion. Questions can arise at each stage. As biofuels near commercialization, DOE's programs are addressing all relevant environmental issues.

Increased use of biofuels and other forms of renewable energy can help ensure a healthy productive planet for future generations.

Air quality and health, the sustainability of all agricultural and forestry systems, biodiversity, soil erosion, and water pollution are all significant concerns. Part of the BSD mission is to ensure that these concerns are addressed and to maintain the environmental integrity of program R&D.

The BSD program provides the leadership and direction needed to identify, develop, improve, and utilize our national biomass resources. Through its integrated approach to biomass and waste technology R&D, the program can help provide the nation with a large, renewable source of liquid fuels—fuels that contribute to environmental stability, and help to ensure economic prosperity and national security.

Appendix A. For More Information

Program Management

U.S. Department of Energy
Richard F. Moorer, Director
Biofuels Systems Division - CE-331
Office of Alternative Fuels
Office of Transportation Technologies
1000 Independence Avenue, S.W.
Washington, DC 20585
(202) 586-5350

National Renewable Energy Laboratory
Norman Hinman, Program Manager
Biofuels Program
Alternative Fuels Division
1617 Cole Boulevard
Golden, CO 80401-3393
(303) 231-1281

Oak Ridge National Laboratory
Janet Cushman, Program Manager
Biofuels Feedstocks Development Program
P.O. Box 2008, Mail Stop 6352
Oak Ridge, TN 37831-6352
(615) 574-7818

Technical Reports and Information

On-line data base of technical reports:

Office of Scientific and Technical Information (OSTI)
U.S. Department of Energy
P.O. Box 62
Oak Ridge, TN 37831
(615) 576-1303

Paper or microfiche copies of technical reports:

National Technical Information Services (NTIS)
U.S. Department of Commerce
5285 Port Royal Road
Springfield, VA 22161
(703) 487-4929

Information on technical and scientific documentation:

Biofuels Information Center, NREL
(303) 231-1947

On-line data base of statistical, graphic, and textual information:

The Alternative Fuels Data Center
National Renewable Energy Laboratory
1617 Cole Boulevard
Golden, CO 80401-3393
(303) 231-7006

Appendix B.
Key Publications

Five Year Research Plan 1988-1992
Biofuels and Municipal Waste
Technology Program
U.S. Department of Energy
July 1988
Available from NTIS:
Order No. DOE/CH10093-25

Biofuels Program Summary
Volume I: Overview
Fiscal Year 1989
U.S. Department of Energy
January 1990
Available from NTIS:
Order No. DOE/CH10093-68

Biofuels Program Summary
Volume II: Research Summaries
Fiscal Year 1989
U.S. Department of Energy
January 1990
Available from NTIS:
Order No. DOE/CH10093-69

Programs in Renewable Energy
Fiscal Year 1990
U.S. Department of Energy
January 1990
Available from NTIS:
Order No. DOE/CH10093-74

The Potential of Renewable Energy:
An Interlaboratory White Paper
U.S. Department of Energy
March 1990
Available from NTIS:
Order No. SERI/TP-260-3674

Conservation and Renewable Energy
Technologies for Transportation
U.S. Department of Energy
November 1990
Available from NTIS:
Order No. DOE/CH10093-84

Produced by the
National Renewable Energy Laboratory

A Division of Midwest Research Institute
1617 Cole Boulevard
Golden, CO 80401-3393

Operated for the
U.S. Department of Energy

DOE/CH10093-186
DE93000036
January 1993