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Biomass Research and Development Board

Leading the Federal Interagency Biomass Research and Development Initiative

National Biofuels Action Plan

October 2008

BR&Di
BIOMASS RESEARCH & DEVELOPMENT INITIATIVE

This document was developed through the efforts of the Biomass Research and Development Board

For additional information about the Biomass Research and Development Board, please contact the Departments which Co-Chair the Board: U.S. Department of Agriculture (USDA) and U.S. Department of Energy (DOE).

Office of the Assistant Secretary Energy Efficiency and Renewable Energy (EERE), DOE at (202) 586-9220. The DOE EERE website is located at http://eere.energy.gov/

Office of the Under Secretary for Rural Development, USDA at (202) 720-4581. The USDA Rural Development website is located at http://www.rurdev.usda.gov/

The Biomass Research and Development Initiative (BRDi) website provides information about the Board, the Technical Advisory Committee (TAC), and the Initiative. The BRDi website is located at http://www.brdisolutions.com

The interagency Biomass Research and Development Board was created by the Biomass Research and Development Act of 2000 and is comprised of numerous Federal Departments and agencies.

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Current National Fuel Challenges

America has one-third of the world's automobiles (230 million) and uses twenty-five percent of the world's oil. The American economy depends on liquid transportation fuels, principally derived from petroleum, to power our cars, buses, trucks, locomotives, barges and airplanes. Use of these fuels has given rise to energy security concerns, contributions to climate change and other environmental challenges. In the absence of alternatives to petroleum products, the Energy Information Administration projects that reliance on foreign producers for oil will increase 30% through 2030, and our transport sector's greenhouse gas emissions will grow by nearly 40% (see AEO 2007 tables 11 and 18). Action is needed now to ensure that viable petroleum alternatives are developed in conjunction with efficiency improvements to address these growing concerns.

Administration Action

Biofuels is one of the Administration's near-term strategies to address energy security and climate change. In his 2006 State of the Union Address, President Bush declared that America "is addicted to oil" and rolled out the Advanced Energy Initiative (AEI), which included increased research funding for cutting edge biofuel production processes. In early 2007 President Bush announced the "Twenty-in-Ten" initiative, a plan to reduce gasoline consumption by 20% in 10 years. A major element of the plan was a request that Congress mandate an increase in domestic renewable and alternative fuels production to 35 billion gallons per year (BGY) by 2017.

Congress responded in December 2007 by passing a Renewable Fuel Standard (RFS) as part of the Energy

Figure 1: *U.S. petroleum production capacity and demand*

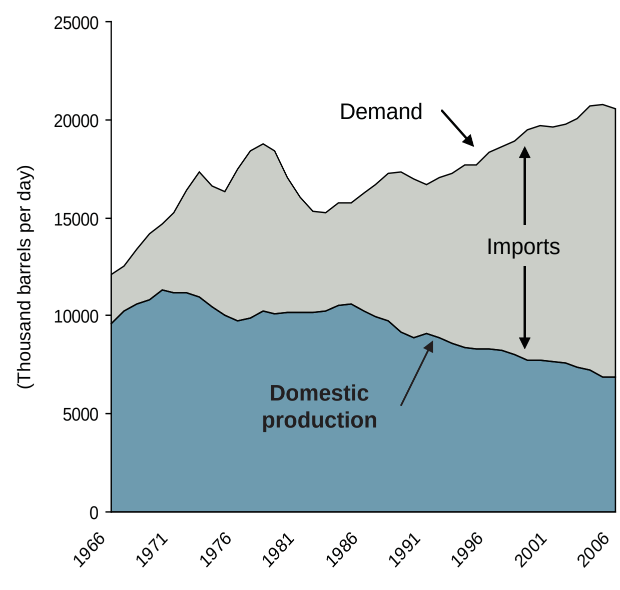
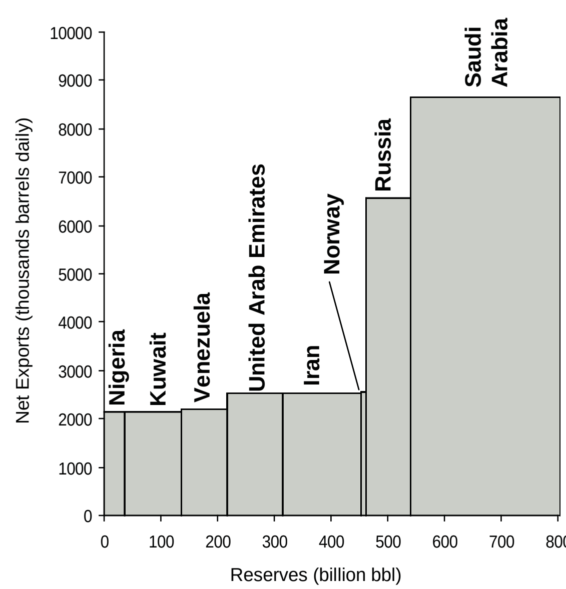


Figure 2: *Top eight world-wide countries for petroleum reserves and net exports*



Source: EIA Top World Oil Producers & Consumers. Available at http://www.eia.doe.gov/emeu/cabs/topworldtables1_2.htm; BP Statistical Review of World Energy, 2007

Independence and Security Act (EISA) of 2007 that the President signed into law. The RFS requires 36 BGY of biofuels by 2022, and includes specific provisions for advanced biofuels, such as cellulosic ethanol and biomass based diesel contributions that pave the way for advanced technologies.

Also in 2007, the Bush Administration proposed a Farm Bill that included $1.6 billion in new renewable energy and energy efficiency-related spending at the U.S. Department of Agriculture (USDA), including $210 million to support loan guarantees for cellulosic ethanol projects. In May 2008, Congress passed the 2008 Farm Bill, titled the Food, Conservation, and Energy Act of 2008, with just over $1 billion in mandatory funding for such energy activities.

Meanwhile, Federal agencies have taken major steps since 2006 to implement the AEI. The Department of Energy (DOE) has announced plans to invest nearly $1 billion in partnership with the private sector and academia to research, develop, and deploy advanced biofuel technologies by 2012. This includes up to $272 million for commercial-scale biorefineries, up to $240 million for demonstration scale biorefineries working on novel refining processes, and more than $400 million for bioenergy centers.

Biomass R&D Board

To help industry achieve the aggressive national goals, Federal agencies will need to continue to enhance their collaboration. The Biomass Research and Development (R&D) Board was created by Congress in the Biomass Research and Development Act of 2000, as amended, "to coordinate programs within and among departments and agencies of the Federal Government for the purpose of promoting the use of bio-based fuels and bio-based products by (1) maximizing the benefits deriving from Federal grants and assistance; and (2) bringing coherence to Federal strategic planning." The Board is co-chaired by senior officials from the Departments of Energy and Agriculture and currently consists of senior decision-makers from the DOE, USDA, Treasury, Transportation (DOT), Interior, Commerce, Defense (DoD), Environmental Protection Agency (EPA), National Science Foundation (NSF), Office of the Federal Environmental Executive, and the President's Office of Science and Technology Policy.

Figure 3: *The biofuels supply chain*

The Board's Action Plan

This Action Plan outlines areas where interagency cooperation will help to evolve bio-based fuel production technologies from promising ideas to competitive solutions. In developing the plan, the Board used a five part supply-chain framework (see Figure 3) to identify Board action areas:

- **Feedstock Production** comprises the cultivation of biomass resources such as corn, crop residues, and woody residues used as raw material inputs for biofuels production and is discussed in Action Area 2: Feedstock Production.
- **Feedstock Logistics** consists of harvesting or collecting feedstock from the area of production, processing it for use in biorefineries, storing it between harvests, and delivering it to the plant gate. The Board addresses these issues in Action Area 3: Feedstock Logistics.
- **Conversion** is the transformation of the processed feedstock to liquid fuels. Currently, cellulosic ethanol and other technologies essential to achieving the EISA production targets are too costly to compete effectively in the marketplace. Because the pace of technological breakthroughs required to lower costs is inherently uncertain, the availability of advanced technologies to contribute to the EISA goal on an economically and ecologically sustainable basis cannot be assumed. The Board addresses these R&D issues in Action Area 4: Conversion Science and Technology.
- **Distribution** is the transfer of the fuel from the biorefinery to the point of retail sale. A network of trucks, trains, barges, blending and storage terminals, and, possibly, pipelines, must be able to handle significant volumes safely and economically. The Board's approach to meeting these challenges is outlined in Action Area 5: Distribution Infrastructure.
- **End Use** is the purchase of biofuels by the consumer for use in either traditional vehicles at low level blends or vehicles that are specially modified to accommodate higher biofuels blends. Action Area 6: Blending describes the need for increasing blending from E10 to meet EISA, articulates the challenges to doing so, and describes activities the Board has undertaken in this area including the Board's statement on intermediate blends.

In addition, the Board has identified two crosscutting action areas:

- Supporting the **sustainability** of biofuels production and use, such that the social, economic, and environmental requirements of Americans can be met now and into the future. Action Area 1: Sustainability explores this theme;
- Ensuring the **environment, health, and safety** of the public and those working at all stages of the supply chain as new fuels and processes come into use. These topics are explored in Action Area 7: Environment, Health, and Safety.

In the final section, Moving Forward, the Plan draws these individual actions into a cohesive vision for allowing industry to deploy advanced technologies in the market and achieve significant production scale in the next 15 years.

Board Action Area 1: Sustainability

As President Bush recently noted in a major address to the renewable energy community, the production volumes specified by EISA are not just goals; they are mandatory requirements. He further added that these volumes are needed for the "sake of economic security, national security, and for the sake of being good stewards of the environment." The Federal government is playing a vital role in achieving all of these objectives by mobilizing teams of the best and brightest scientists from all agencies.

A key goal of the National Biofuels Action Plan is to maximize the environmental and economic benefits of biofuels use by advancing sustainable practices and improvements in efficiency throughout the biofuels supply chain from feedstock production to final use. The Board aims to provide the interagency leadership to steer biofuels development on a sustainable path through the compilation and evaluation of biofuels sustainability criteria, benchmarks and indicators. The Board activities will promote close coordination among federal and state agencies and industry to identify best agricultural and land use practices and the most efficient production, conversion, transportation and storage systems that assure economic growth and viability of the biofuel system while protecting ecosystem and human health.

Historical Context

"Sustainable" as defined by Executive Order 13423 means to "create and maintain conditions under which human and nature can exist in productive harmony, that permits fulfilling the social, economic, and other requirements of present and future generations of Americans." The EISA amendments to the RFS program promote sustainability by (1) directing that significant reductions in greenhouse gasses be achieved for different feedstocks; (2) requiring that biofuels production not adversely impact the environment or natural resources; (3) focusing on the development of cellulosic and other feedstocks which will promote the sustainable production of biofuels; (4) stipulating that every 3 years EPA assess and report to Congress on environmental impacts of biofuel systems.

Biomass R&D Board Actions

As demonstrated by EISA and domestic environmental, agricultural, and conservation policies, the U.S. is an international leader in promoting sustainable biofuels production. The Board will continue its focus on active issues by receiving briefings on key aspects of United States policy including EPA methodologies for greenhouse gas lifecycle analysis conducted under its RFS requirements and the State Department's involvement in the Global Bioenergy Partnership. To further advance its leadership, the Board is:

- Defining, by November 2008, a set of science-based national criteria and identifying science-based indicators to assess sustainable production of biofuels across the biofuels supply chains. These criteria and indicators will be coordinated with ongoing international activities, and will be used to evaluate the environmental, economic, or social performance of biofuels production and use.
- Establishing a Sustainability Interagency Working Group led by DOE, USDA, and EPA, with participation from other agencies, to facilitate strategic planning and coordinate Federal activities; interface with industry and environmental groups; coordinate EISA studies across different agencies; and define and evaluate sustainability criteria, benchmarks and indicators.
- Planning a series of workshops with internal and external stakeholders. Internal workshops will inventory key research efforts in the area of sustainability; identify relevant models, and identify strengths and weaknesses of existing models and gaps. External workshops will involve discussions of analytical and modeling efforts to address pressing issues/challenges, and also inform R&D priorities through dialogues between decision-makers and scientists.

Board Action Area 2: Feedstock Production

The rapid growth of the biofuels industry has been driven by private sector innovation. To sustain that growth it is essential for the Federal government to work in partnership with the private sector to achieve improvements across feedstocks likely to be in use over the near- and longer-terms:

- **First generation** feedstocks include corn for ethanol and soybeans for biodiesel. These feedstocks are currently in use and their yields have been increasing.
- **Second generation** feedstocks consist of the residues or "left-overs" from crop and forest harvests. They show much promise for near-term adoption with the development of cellulosic conversion technologies.
- **Third generation** feedstocks are crops which require further R&D to commercialize, such as perennial grasses, fast growing trees, and algae. They are designed exclusively for fuels production and are commonly referred to as "energy crops". They represent a key long-term component to a sustainable biofuels industry.

Federal agencies are conducting R&D into high-yield biomass systems and dedicated energy crops that do not disrupt current production paradigms and sustain and enhance the critical natural resource assets required for their production (e.g., water, air, and soil). They are also developing dedicated bioenergy crops through traditional breeding and advanced biotechnology.

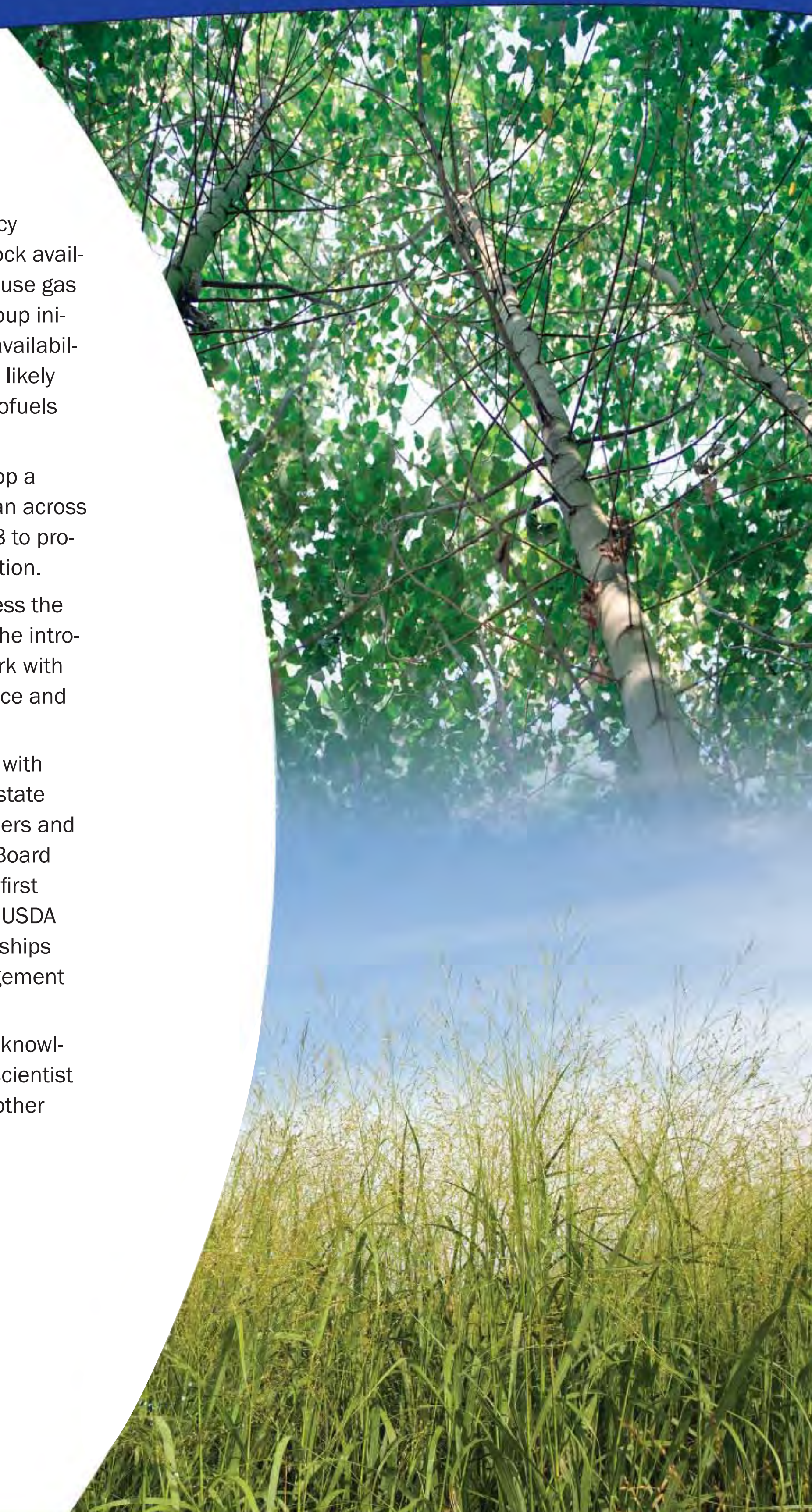
Next Steps

Interagency studies suggest that the U.S. has enough indigenous biomass available to meet the EISA targets. However, key activities need to take place in order to do so:

- Environmental implications and balance between food, feed, and fiber, need to be considered as use of first generation feedstocks (e.g., oilseeds and grain) increases. Environmental implications, such as the effect of feedstock production on soil, water and air quality, and market implications of increased production of feedstocks used for biofuels, for food, feed, and fiber, need to be considered as use of first generation feedstocks (e.g., oilseeds and grain) increases.
- Utilization of second generation feedstocks should sustain and enhance water and air quality and other ecosystem services. The availability and cost of these feedstocks need to be inventoried to qualify plant siting opportunities.
- Third generation feedstocks should be developed to increase drought and stress tolerance; increase fertilizer and water use efficiencies; and provide for efficient conversion.
- Improvements in the yields of all feedstocks will be necessary to support future targets.

Biomass R&D Board Actions

- The Board has commissioned an interagency feedstock working group to address feedstock availability and cost, sustainability, and greenhouse gas emissions from feedstock activities. The group initially delivered, in June 2008, a feedstock availability and cost study to provide perspective on likely feedstock costs associated with meeting biofuels production targets.
- Another feedstock working group will develop a long-term integrated feedstock research plan across the Federal government by December 2008 to promote enhanced coordination and collaboration.
- The Board will use this information to address the impact of current regulatory processes on the introduction of modified energy crops and to work with farmers and foresters to increase acceptance and introduction of new crops and trees.
- The Board also seeks greater collaboration with private sector researchers, academia, and state governments, as well as international partners and agencies not currently represented on the Board to ensure leveraging of existing funds. As a first step, Federal agencies including EPA, DOE, USDA and NSF will inventory their current partnerships in these areas in order to develop an engagement plan by November 2008.
- The Board will further promote interagency knowledge sharing by expanding the USDA-DOE scientist exchange program to include the NSF and other agencies in the near future.



Board Action Area 3: Feedstock Logistics

The vast expansion in biofuels production and use mandated by EISA will require the development of new methods and equipment to collect, store, and pre-process biomass in a manner acceptable to biorefineries. These activities, which constitute as much as 20% of the current cost of finished cellulosic ethanol, are comprised of four main elements:

- **Harvesters & collectors** that remove feedstocks from cropland and out of forests.
- **Storage facilities** that support a steady supply of biomass to the biorefinery, in a manner that prevents material spoilage.
- **Preprocessing/grinding equipment** that transform feedstocks to the proper moisture content, bulk density, viscosity, and quality.
- **Transportation of feedstocks** from the field to the biorefinery (as noted in Board Action Area 5: Infrastructure).

Federal agencies are actively collaborating with universities and industry to address this critical segment of the biofuels supply chain. Despite the important role of logistics and the relative immaturity of the needed equipment, to date this area of the supply chain has received limited Federal attention. Increased attention and R&D effort will be required for this supply chain element to achieve targets for delivered biomass.

Next Steps

Highly effective process management must be integrated with specialized equipment to ensure feedstocks maintain quality, consistency, and reliability of supply over time, while maintaining a reasonable delivered cost. However, natural irregularities of the agricultural system, including year-to-year variations in production, crop rotations, and maintenance of soil nutrients over the long term make cost-cutting measures a challenge. The hurdles that must be overcome fall into two main categories:

- **Logistics enterprise design & management:** The design of feedstock collection, storage and preprocessing systems will vary based on feedstock type, regional geography, and system ownership structures. The challenge is to reduce labor and fuel costs which constitute virtually all the expenses in this supply chain element.
- **Technology development:** New technologies are required to support efficient, economic, and sustainable biomass collection and handling. These include creative approaches to moving feedstocks from field to plant, such as sending slurry through dedicated pipelines, single pass harvesters for agricultural residue collection during commodity crop harvest and in-forest grinders to enable forest residue densification at time of collection. Equipment is being developed and tested by industry and academia to facilitate the collection of these new biomass resources.

Biomass R&D Board Actions

- The Board will facilitate collaboration to develop and deploy logistics systems that can supply cellulosic feedstocks to demonstration facilities currently planned for construction. An active interface with private sector partners will be critical to the success of this research. A working group consisting of the USDA, DOE, and other agencies will lead a planning process to develop milestones culminating in the implementation of logistics systems demonstrations in partnership with industry.
- The Board will ensure that consideration of feedstock logistics issues is integrated into the work of both the Feedstock Production working group (Board Action Area 2) and the Board's Transportation Infrastructure activities (Board Action Area 5).

Board Action Area 4: Conversion Science and Technology

Although R&D on cellulosic ethanol has made progress in reducing estimated conversion costs (see Figure 4), production costs remain too high for biomass-based fuels to compete in the marketplace. Transformational breakthroughs in basic and applied science will be necessary to make plant fiber-based biofuels economically viable. For example, one key barrier is the natural “recalcitrance” or resistance of plant fiber to break down into sugar intermediates. The scientific and technological challenges here are formidable. Significant work is needed to better understand plant cell walls, where the plant fiber or lignocellulose is embedded, to enable cost-effective breakdown and deconstruction of plant material. The biotechnology revolution -- with its powerful new tools of genomics and systems biology -- holds promise for developing the biological knowledge at the system, cellular, and molecular level that could enable us to re-engineer plants, enzymes, and microbes to overcome recalcitrance.

Another key barrier is to understand how plant material breaks down thermally. In addition, there is potential for new progress in chemical and thermochemical conversion processes through improved catalysis. In short, significant transformational basic research and applied R&D will be necessary to meet the challenge of developing cost-effective, commercially viable conversion technologies that will be needed to support a major move to cellulosic biofuels.

To date, researchers have focused predominantly on cellulosic ethanol, and ethanol is likely to be the first cellulosic biofuel to become commercially available. But the potential also exists to produce other fuels including higher alcohols, “green” gasoline and diesel, and aviation fuels produced via enzymatic and microbial and/or chemical catalytic processing of biomass. Significant issues of feasibility, cost, and scalability remain. Yet such advanced biofuels would have numerous advantages, for example, having energy content comparable to current petroleum based fuels, and easier integration into the existing fuel infrastructure.

Next Steps

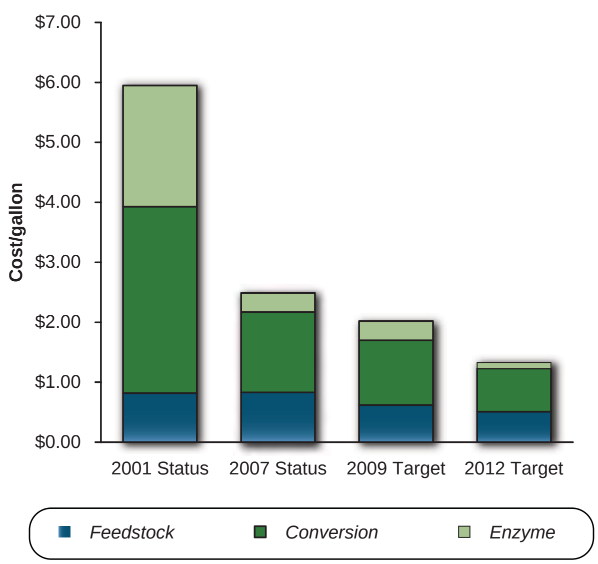
- Developing the knowledge of plants, microbes, and enzymes at the system, cellular, and molecular levels so as to enable re-engineering of these biological systems to substantially reduce conversion costs and increase product yields.
- Developing technologies to enable co-production of marketable fuels and value-added co-products that can improve overall production economics.
- Discovering and developing better technologies for the production of hydrocarbon fuels from lignocellulosic biomass, utilizing microbial, thermochemical, or catalytic processes.
- Addressing fundamental issues of catalysis in the gas and liquid phases, including characterization and durability.
- Addressing the feedstock-conversion interface with the ultimate goal of robust utilization of regionally diverse, multiple, variable, and potentially complex feedstocks.
- Optimizing processes to make technologies economically viable on a small scale.
- Identifying processes and innovations achieved in related industries, such as petroleum refining that can be leveraged to improve the performance of biofuel conversion pathways.

Biomass R&D Board Actions

The Board has established an interagency working group to guide the exploration of concepts capable of leading to cost-effective and commercially viable processes for converting cellulosic and other forms of biomass to biofuels, including: ethanol; higher alcohols; and green gasoline, diesel, and aviation fuels. The interagency working group is comprised of NSF, DOE, USDA, EPA, DOD, and other agencies. Immediate actions are as follows:

- The Biomass Conversion Interagency Working Group (BCIWG) developed and implemented mechanisms to improve interagency coordination, promote interagency knowledge sharing, and track on-going biomass conversion Research, Development, and Deployment (RD&D) across the Federal sector in May 2008.
- The BCIWG will also develop a comprehensive, integrated 10-year federal RD&D biomass conversion plan that includes agency roles, goals and key milestones and identifies gaps by December 2008.

Figure 4: *2012 cost competitive target and status (biochemical)*



Source: DOE EERE Office of the Biomass Program, Multi-year Program Plan, Appendix C.

Board Action Area 5: Distribution Infrastructure

The national fuel transportation and storage infrastructure must accommodate the current and future growth of domestic biofuels production and transportation. Future production goals envision wider use of a variety of fuels, the production of which is currently centered in the Midwest and other rural areas. However, fuel demand is currently concentrated in large population centers on the east and west coasts. As a result, expanded biofuels production may require transportation of fuels and feedstocks over significant distances.

These current geographical dislocations between supply and demand may necessitate increasing the capacity of existing modes of biofuel transport (rail, truck, barge) and possibly adding new ones. Pipelines, which are considered the least expensive means of safely transporting bulk fuel shipments, may prove to be an economical biofuels transportation solution – provided various technical issues such as stress corrosion cracking can be overcome. Also, infrastructure location and configuration may not be optimal for interconnection of feedstocks, biorefineries, and consumer markets.

Other infrastructure upgrades will also be required, including expanded blending terminal storage capacity, retail infrastructure such as underground storage tanks, as well as seal and gasket materials capable of handling higher biofuels blends. One of the most significant hurdles to retail expansion is the current lack of an Underwriters' Laboratory certification for pumps dispensing blends of E15 or higher. Absent this certification, large operators of fuel pumps ranging from the Postal Service to large retailers will be reluctant to sell E85 or any other approved intermediate blend.

DOT is leading the design of frameworks in which the development of safe, adequate, and cost-effective biofuels transport infrastructure can occur. One of its chief initiatives is a Joint Industry Project whose objective is to determine the effects of ethanol blends on pipelines and storage tanks. DOT also has efforts underway to assess the infrastructure capacity requirements necessary to accommodate additional biofuels transport. DOT and USDA are collaborating to determine the impact of biomass transportation costs on feedstock economics.

Next Steps

The future biofuels infrastructure must address each of the following areas:

- **Capital:** Appropriate regulations and policies need to be put into place to attract adequate capital for needed infrastructure growth.
- **Corrosion:** The physical properties of ethanol, biodiesel, and other biofuels may require modifications to existing infrastructure as well as new, specially-designed systems to ensure safe transport.
- **Capacity:** Existing infrastructure will need to be optimized to handle increased liquid fuels throughput. Over the longer term, dedicated infrastructure may be necessary to safely and efficiently transport additional volumes of biofuels. Since the biofuels industry is in its infancy, little is known as to where and in what magnitudes the commodities will flow. This creates challenges to assure that sufficient transport and storage capacity will be available to enable them to do so.

Biomass R&D Board Actions

The Board will establish an interagency working group led by DOT to study and make recommendations to the Board by December 2008 on the following issues:

- Feasibility of pipeline use for biofuels transport, including facilitation of the necessary interagency collaboration on standards development.
- Liquid fuel flows over infrastructure, including pipelines, rail, barge and truck transportation to identify short and long-term infrastructure bottlenecks that will inhibit biofuels development.
- Integration of Geographic Information System (GIS) based tools housed at agencies such as DOT, USDA, EPA, and DOE in order to begin to link transportation infrastructure, demand, feedstock location, as well as water and other resources.

Board Action Area 6: Blending

As ethanol production ramps up to meet renewable fuel levels required by the new RFS, we must ensure that retail markets can deliver large volumes of ethanol to U.S. consumers. The E10 market will be saturated in the next few years and the number of E85 fueling stations and flex-fuel vehicles (FFVs) will likely not grow fast enough to accommodate the higher volumes of ethanol. One potential option for increasing U.S. market opportunities is to raise the amount of ethanol allowed in gasoline to beyond 10 percent (see Figure 5). In order to allow E15, E20, or other intermediate blends* to be used in regular vehicles -- that is, non-FFVs -- we must first understand how these fuels could affect emissions, catalyst durability, driving performance, and materials compatibility, among other factors.

To that end, DOE, in partnership with the EPA, is undertaking an Intermediate Blends Test program to evaluate the potential impacts of intermediate blends on the existing vehicle fleet as well as on smaller engines such as those in lawn mowers, tractors, and other small off-road engines. This program will begin to provide the data needed for Federal fuel registration and approval for the use of intermediate blends of ethanol and gasoline in today's vehicles.

Further increasing the demand for blended ethanol can be expedited by resolving inconsistencies in state interpretations of American Society for Testing and Materials (ASTM) fuel standards when ethanol is blended with gasoline. It will also be important to ensure that the distribution infrastructure is in place to effectively deliver intermediate blends to consumers.

Next Steps

Necessary steps to increase the availability of blended ethanol:

- Air quality impacts of higher blends need to be quantified. While E10 helps reduce overall vehicle emissions of criteria pollutants, the impact of higher blends on emissions is not currently well understood. There is a need to understand how higher fuel blends may affect state and local air quality situations or attainment of National Ambient Air Quality Standards (NAAQS).
- Ethanol use and limitations on use may be a function of the fleet's ability to legally and technically absorb higher volumes of ethanol, and that is a function of both fuel and vehicle allowances and constraints.
- Materials used in current infrastructure (tanks, piping, dispensers, etc.) may not be compatible with higher blends.

Biomass R&D Board Actions

- The Board has approved a statement on ethanol blend policy (see Figure 6).
- As noted, the Board's member agencies are conducting an interagency testing program to evaluate the impact of intermediate blends on vehicle emissions and material compatibility to support potential fuel supplier waiver applications. Initial test results are targeted to be available in Fall 2008.
- The Board will work with state and local agencies to ensure full national penetration of E10 through resolving obstacles posed by state regulations and the private sector.

** E10, E15, E20 and E85 denote the percent of ethanol blended with gasoline (10%, 15%, etc.).*

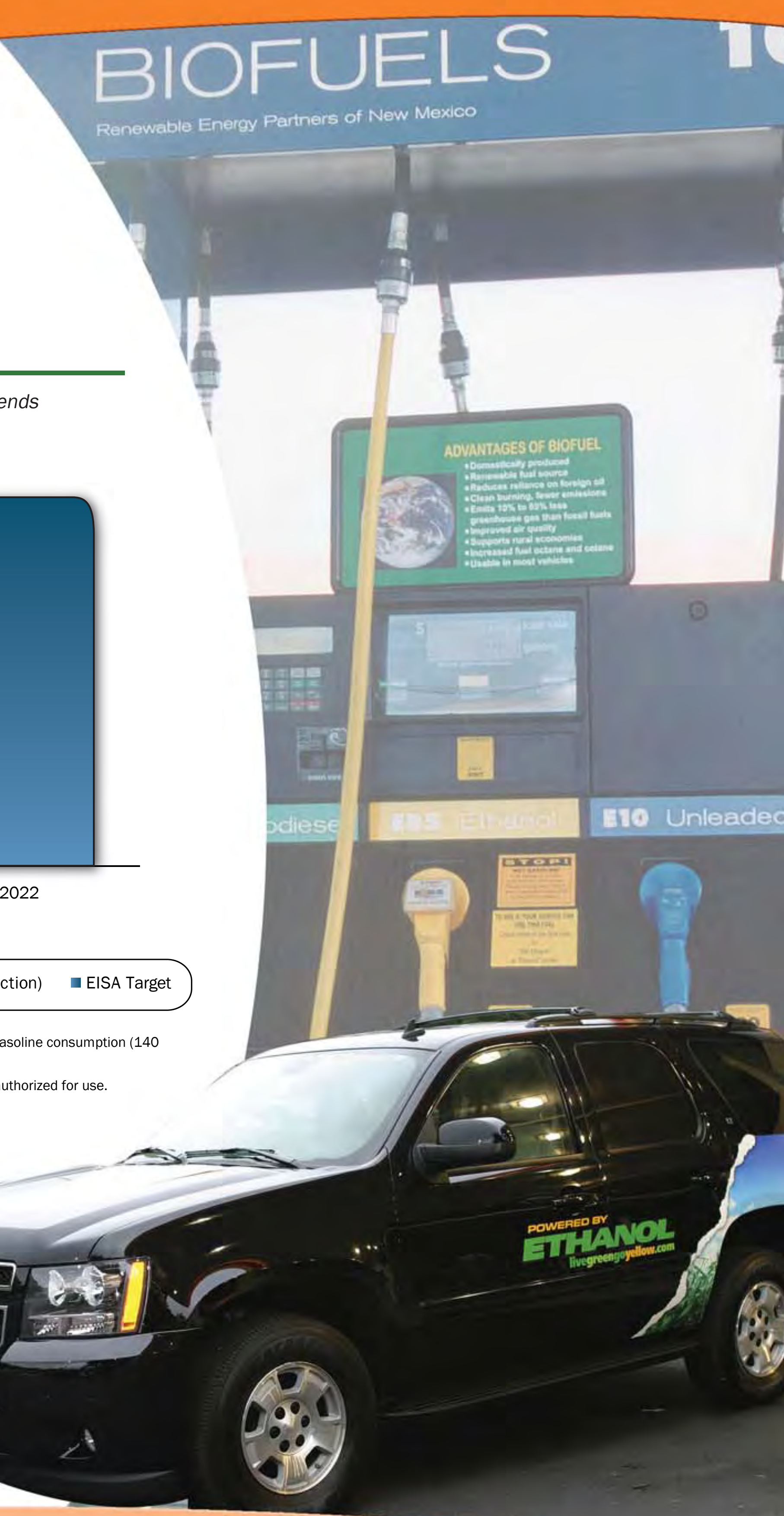
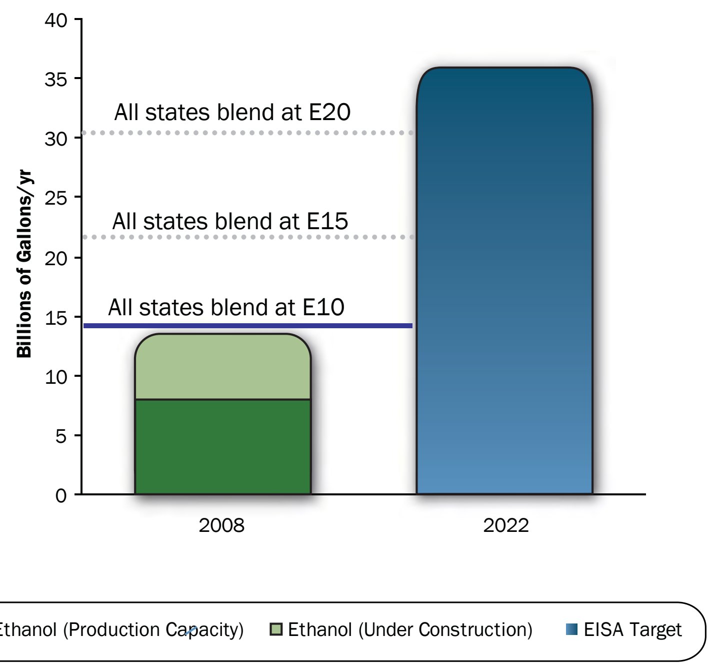


Figure 5: *Volumes of ethanol absorbed by several blends*



Source: Renewable Fuels Association for ethanol capacity; EIA AEO for gasoline consumption (140 billion gallons of motor gas/yr).

Note: E15 and E20 testing is underway; these blends are not currently authorized for use.

Figure 6: Board Ethanol Blends Policy Statement

Alleviating Oil Dependency and Greenhouse Gas Emissions on an Accelerated Basis Through Biofuels Deployment

The interagency Biomass Research and Development Board, on behalf of its respective agencies, is committed to the President's goal of reducing petroleum-based gasoline usage in the United States by 20 percent in the next 10 years ("the Twenty-in-Ten" initiative). Our national fuel infrastructure must accommodate the current and future growth of domestic biofuel production and delivery. As we develop the technology for the next generation of biofuels, it is essential that we enable both full utilization of increased biofuels production and nationwide retail access, while minimizing disruptions, cost and infrastructure challenges, and potential environmental, health and safety impacts. In addition to the present and projected growth of E10 and E85 sales, federal fuel registration and national market access for intermediate ethanol blends of gasoline (defined as blends between 10% and 85% ethanol, e.g., E12, E15, E20) that meet applicable statutory and regulatory requirements represent a critical pathway to meet the Twenty-in-Ten goal. The Board will continue to monitor and assess closely issues regarding the development, availability, and potential impacts of intermediate ethanol blends of gasoline.

Board Action Area 7: Environment, Health and Safety

Helping develop and maintain a world-class safety, public health, and environmental protection record is one of the Federal government's most important roles in supporting the industry's future growth. The Federal government has a number of comprehensive and proactive public health, safety, and environmental protection programs involving many agencies. As biofuels come into greater contact with our infrastructure as their use increases, and as innovation produces fuels that are not currently in wide use (such as green hydrocarbon fuels or biobutanol), these programs will need to understand and manage any associated risks. This will require maintaining and upgrading a wide range of expertise including biofuels, fire protection, human health exposure, environmental, occupational safety and health and transportation.

Next Steps

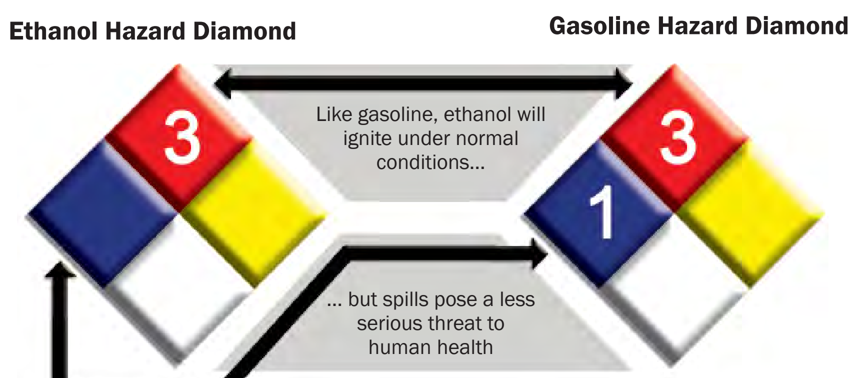
Biofuels have been safely produced, transported, and used in the U.S. for decades and have hazard characteristics similar to those of gasoline (see Figure 7). While many of the characteristics of various biofuels are already known and documented in material safety data sheets, the broader application of these fuels, as well as entry into service of advanced fuels not currently in use, will require attention to anticipate risks, control potential hazards, and prevent mishaps. This requires an approach to health and safety that comprehensively protects public health and worker safety, while doing so without excessively constraining businesses serving the biofuels supply chain.

Biomass R&D Board Actions

The Board will establish an interagency working group to benchmark agricultural and biofuels industry successes and practices.

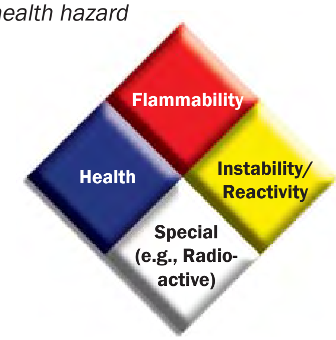
- The group will inventory the Federal government's activities and areas of jurisdiction with respect to public health, safety, and environmental protection.
- It will review and summarize potential public health, safety, and environmental issues related to the life-cycle of biofuels and identify research needs and potential mitigation options.
- This information will be used to conduct outreach to the public, industry, and other entities in the biofuels economy as well as to prioritize Federal government research in these areas.

Figure 7: *Ethanol and gasoline hazard diamonds*



Source: National Fire Protection Association

Each corner of the diamond represents a health hazard



Each color is rated on a scale from 0 (no hazard; normal substance) to 4 (severe risk)

Moving Forward

Expanding biofuels usage to 36 BGY over 15 years on a sustainable basis will be a key component to America's movement toward clean, affordable, and secure energy solutions. Success will require a coordinated approach between the public and private sectors to advance biofuel technologies and create market conditions that will enable their use. A combination of policy and R&D (public and private investment) has already led to progress toward achieving the 2022 requirement. Current and near term production of corn-based ethanol and biodiesel are progressing to meet market demand. However, meeting the 2022 goal, as well as interim targets, will require development of advanced biofuel technologies and the construction of technologically innovative biorefineries utilizing these technologies. The scientific and technological challenges entailed in meeting these ambitious national goals are significant, and both transformational basic science research and applied research will be essential to break through the considerable technological barriers at present to producing cellulosic biofuels cost-effectively on a commercial scale. The federal government is devoting considerable resources to this research.

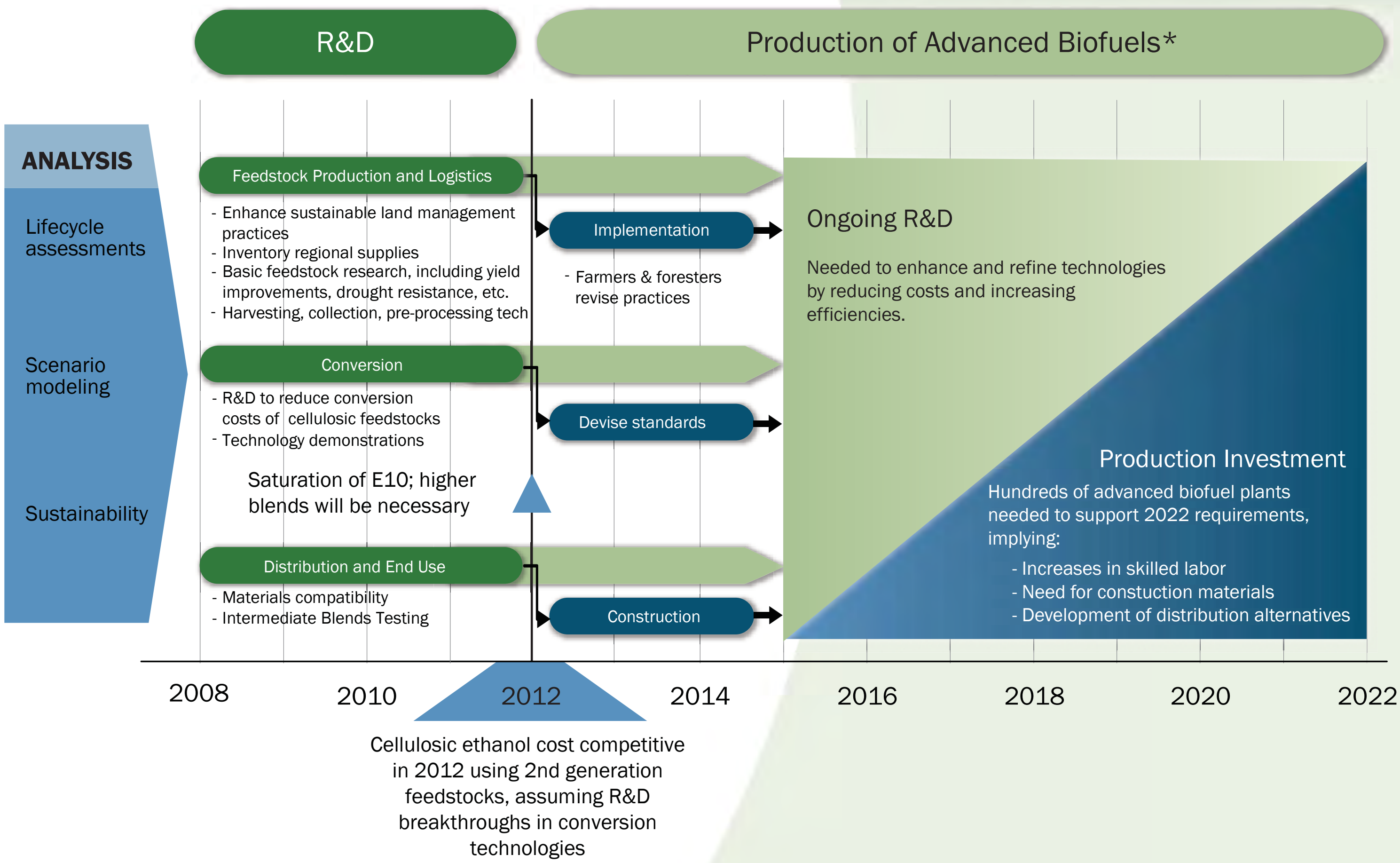
The path to achieving the 2022 goals requires a comprehensive review of all aspects of the biofuels supply chain to identify critical interdependent activities and their sequencing. A top-level perspective, as depicted in Figure 8, suggests the following as critical near term areas to enable advanced biofuels development and market penetration:

- **Feedstock Production and Logistics:** R&D advancements in crop production, the use of multiple feedstocks, and increased yields must be developed and implemented to meet biorefinery needs. Also, advancements are needed in harvesting, collection, storage, and pre-processing for multiple feedstocks.
- **Conversion:** Advanced conversion technologies must progress to attract commercial production investment by 2012. Current public/private demonstration plants are underway to prove the viability of multiple advanced technologies using multiple feedstocks. Major increases in commercial construction will need to start on or about 2012 to justify acquisition of capital assets and mobilization of the required resources including workforce.
- **Distribution and End Use:** The increased production capacity will require full saturation of the E10 blending market along with expansion into intermediate blends and further E85 consumption. In addition, R&D on corrosion and other issues related to environment, health and safety must be resolved to support industry growth. Finally, potential expansion of transport and distribution networks to move the fuel to demand centers across the U.S. must be evaluated to ensure needed upgrades can be initiated in the near term.

Progress against these tight timelines will require an adequate supply of skilled technicians, builders, and managers. Human capital development will be important to maintain the pace of biofuels production capacity growth. To meet this challenge, government agencies will need to work collaboratively with university and other partners to assess workforce development needs and respond with well-crafted technical training and advanced science education programs.

Moving forward, the Biomass R&D Board will continue to coordinate Federal agency involvement in biomass R&D, demonstration, and implementation activities to promote the advancement of the biofuels industry. The Board will also reach to the private sector to advance the commercialization of the new technologies to meet the 2022 production requirements.

Figure 8: *Top level advanced biofuels commercialization timeline*



** Advanced biofuels can include 2nd generation cellulosic ethanol, biobutanol, biodiesel, etc.*

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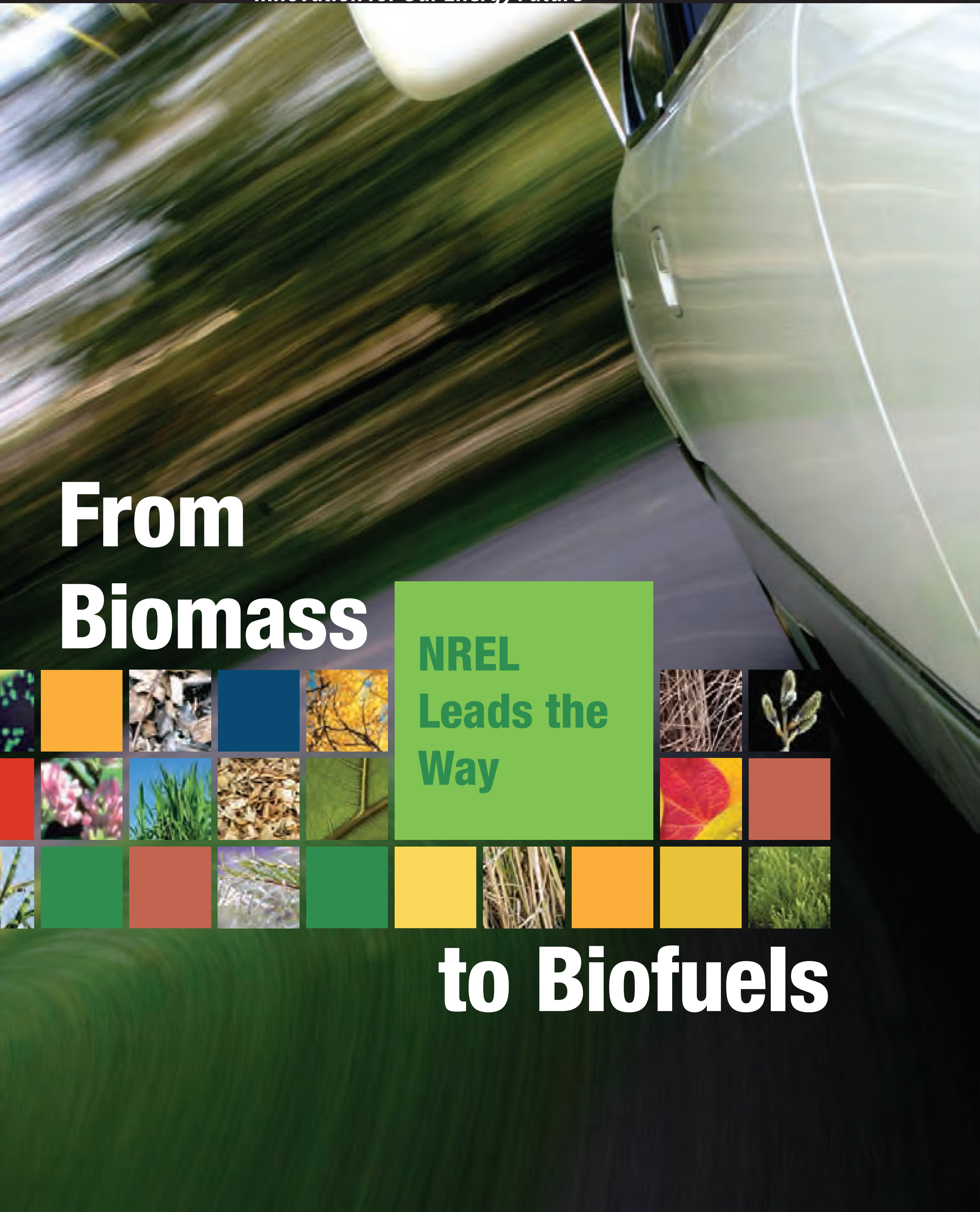
NREL National Renewable Energy Laboratory

Innovation for Our Energy Future



From Biomass to Biofuels

NREL Leads the Way

The Wide World of Biofuels

Fuel	Source	Benefits	Maturity
Grain/Sugar Ethanol	Corn, sorghum, and sugarcane	• Produces a high-octane fuel for gasoline blends • Made from a widely available renewable resource	Commercially proven fuel technology
Biodiesel	Vegetable oils, fats, and greases	• Reduces emissions • Increases diesel fuel lubricity	Commercially proven fuel technology
Green Diesel and Gasoline	Oils and fats, blended with crude oil	• Offer a superior feedstock for refineries • Are low-sulfur fuels	Commercial trials under way in Europe and Brazil for fuel
Cellulosic Ethanol	Grasses, wood chips, and agricultural residues	• Produces a high-octane fuel for gasoline blends • Is the only viable scenario to replace 30% of U.S. petroleum use	DOE program is focused on commercial demonstration by 2012
Butanol	Corn, sorghum, wheat, and sugarcane	• Offers a low-volatility, high energy-density, water-tolerant alternate fuel	BP and DuPont plan to introduce butanol fuel in 2007
Pyrolysis Liquids	Any lignocellulosic biomass	• Offer refinery feedstocks, fuel oils, and a future source of aromatics or phenols	Several commercial facilities produce energy and chemicals
Syngas Liquids	Various biomass as well as fossil fuel sources	• Can integrate biomass sources with fossil fuel sources • Produce high-quality diesel or gasoline	Demonstrated on a large scale with fossil feedstocks, commercial biomass projects under consideration
Diesel/Jet Fuel From Algae	Microalgae grown in aquaculture systems	• Offer a high yield per acre and an aquaculture source of biofuels • Could be employed for CO_2 capture and reuse	Demonstrated at pilot scale in 1990s
Hydrocarbons From Biomass	Biomass carbohydrates	• Could generate synthetic gasoline, diesel fuel, and other petroleum products	Laboratory-scale research in academic laboratories

Most Mature ↔ Least Mature

How Biofuels Are Produced

Biomass resources run the gamut from corn kernels to corn stalks, from soybean and canola oils to animal fats, from prairie grasses to hardwoods, and even include algae.

In the long run, we will need diverse technologies to make use of these different energy sources. Some technologies are already developed; others will be. Today, the most common technologies involve biochemical, chemical, and thermochemical conversion processes.

Ethanol, today's largest volume biofuel, is produced through a *biochemical conversion process.* In this process, yeasts ferment sugar from starch and sugar crops into ethanol. Most of today's ethanol is produced from cornstarch or sugarcane. But biochemical conversion techniques can also make use of more abundant "cellulosic" biomass sources such as grasses, trees, and agricultural residues.

NREL's researchers develop processes that use heat, pressure, chemicals, and enzymes to unlock the sugars in cellulosic biomass. The sugars are then fermented to ethanol, typically by using genetically engineered micro-organisms. Because cellulosic ethanol is the leading candidate for replacing a large portion of U.S. petroleum use, it is the focus of DOE's Biomass Program.

A much simpler *chemical process* is used to produce biodiesel. Today's biodiesel facilities start with vegetable oils, seed oils, or animal fats and react them with methanol or ethanol in the presence of a catalyst. In addition, NREL's genetic engineering work has produced algae with a high lipid content that can be used as another source of biodiesel.

Algae are a form of biomass which could substantially increase our nation's ability to produce domestic biofuels. Algae and plants can serve as a natural source of oil, which conventional petroleum refineries can convert into jet fuel or diesel fuel—a product known as "green diesel."

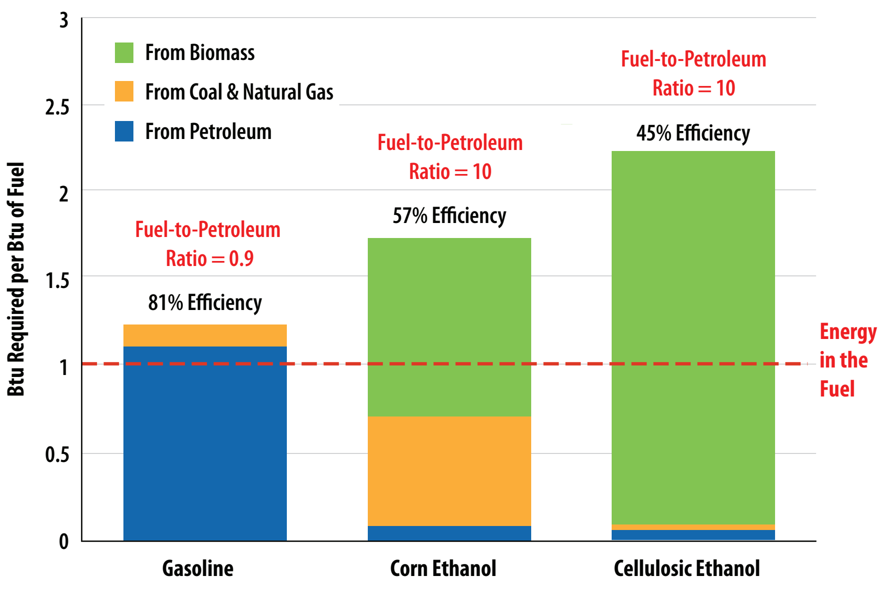
NREL researchers also explore and develop *thermochemical processes* for converting biomass to liquid fuels. One such process is pyrolysis, which decomposes biomass by heating it in the absence of air. This produces an oil-like liquid that can be burned like fuel oil or refined into chemicals and fuels, such as "green gasoline." Thermochemical processes can also be used to pretreat biomass for conversion to biofuels.

Another thermochemical process employed at NREL is gasification. In this process, heat and a limited amount of oxygen are used to convert biomass into a hot synthesis gas. This "syngas" can be combusted and used to produce electricity in a gas turbine or converted to hydrocarbons, alcohols, ethers, or chemical products. In this process, biomass gasifiers can work side by side with fossil fuel gasifiers for greater flexibility and lower net greenhouse gas emissions.

In the future, biomass-derived components such as carbohydrates, lignins, and triglycerides might also be converted to hydrocarbon fuels. Such fuels can be used in heavy-duty vehicles, jet engines, and other applications that need fuels with higher energy densities than those of ethanol or biodiesel.

Energy Required to Produce Fuels

Total Btu Spent for 1 Btu Available at Fuel Pump



Based on "Well to Wheels Analysis of Advanced Fuel/Vehicle Systems" by Wang et al. (2005)




The U.S. Potential for Biofuels

The United States now consumes about 7 billion barrels of oil each year, and we produce more than 100 million barrels of ethanol each year from corn grain. But corn is only a small fraction of the biomass resource available. If we draw on a variety of biomass resources, biofuels can meet a significant portion of our need for liquid transportation fuels.

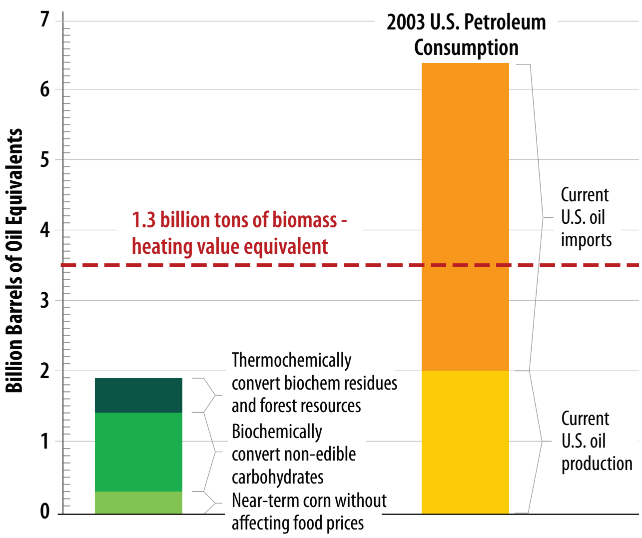
DOE and the U.S. Department of Agriculture recently demonstrated how 1.3 billion tons of biomass could be produced exclusively for energy production in the United States each year with only modest changes in terrestrial crop practices. With today's best available conversion technology, this quantity of biomass can replace about 30% of the petroleum our nation currently consumes. As conversion processes improve and we draw on a wider range of biomass resources, including aquatic forms of biomass, we should find that the potential for biofuels is even greater.

Some people believe that more fossil energy is required to produce ethanol than it provides as fuel. But in fact, a recent study by DOE's Argonne National Laboratory and General Motors Corp. concluded that today's corn growers and ethanol plants consume only about 7 British thermal units (Btu) of fossil-fuel energy for every 10 Btu of fuel they produce. In other words, it takes less energy to produce ethanol than is supplied by ethanol fuel, so the fuel provides a net energy benefit.

The benefits are even greater in terms of replacing petroleum. Because most of the fossil-fuel energy is supplied by coal and natural gas, only about 1 Btu of petroleum is consumed for every 10 Btu of ethanol fuel produced. That means that every gallon of ethanol fuel produced significantly reduces our use of petroleum.

The energy balance is even better for the production of cellulosic ethanol. Because the process residues will be used to produce heat and power for the conversion facility, biomass will provide 95% of the energy needed to make the fuel, with the remaining energy coming from petroleum. Because the process is only about 45% efficient, the net result is the same as that for corn ethanol: 1 Btu of petroleum is burned for every 10 Btu of ethanol fuel produced. However, the process uses

The 1.3-Billion-Ton Biomass Scenario



less fossil fuel overall and thus produces fewer greenhouse gas emissions. Gains in processing efficiencies and economies of scale should boost the petroleum replacement and greenhouse gas benefits of cellulosic ethanol significantly.

NREL's Approach to Efficient, Affordable Biofuels

The long-term vision for biofuels at DOE involves integrating a number of conversion technologies into a biomass-based refinery, or "biorefinery." Biorefineries could draw on a variety of biomass feedstocks and employ several conversion technologies to produce fuels, chemicals, and other products. NREL's approach is to help industry incorporate these technologies into today's agricultural, forestry, aquaculture, and petroleum industries to help the nation reap the many benefits of tomorrow's biorefineries.

NREL's research focuses on cellulosic ethanol, but we also work to increase the efficiency and reduce the cost of a wide range of biofuels. By working with industry on applied R&D, we aim to increase the yield of today's processes, such as corn ethanol production. By leading the R&D of new biofuels technologies, we are advancing not only cellulosic ethanol but also pyrolysis and gasification. And by exploring revolutionary biofuels concepts, we are opening the door for future fuels, such as the production of hydrocarbons from carbohydrates or algae.

Fueling The Future

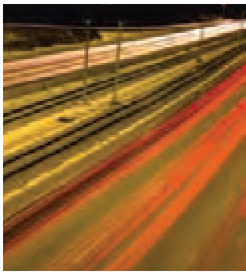
We rely on transportation fuels to keep the engines humming in our cars and trucks and trains and planes. And that reliance is expected to grow. Energy experts predict a 25% increase in U.S. petroleum consumption and a 35% increase in worldwide petroleum demand by 2025.

Where will all that fuel come from? We know from experience that all kinds of unexpected events—from hurricanes in the Gulf Coast to turmoil in the Middle East—can disrupt oil supplies and ramp up the prices of crude oil and commercial fuels. As a result, there is a pressing need for alternative, domestic sources of fuel.

Biofuels are ready to meet that need. Biofuels are one way to ensure adequate fuel supplies at a time when yields from existing oil fields are declining and new fields are not yet up and running. Biofuels can do much to help fill the gap between limited fuel supplies and increasing worldwide demand—a gap that is almost sure to widen in the coming years.

Can we produce enough biofuels to fill the gap? At the National Renewable Energy Laboratory (NREL), we think the answer is "yes." NREL, a U.S. Department of Energy (DOE) research facility, is the leading federal laboratory for biofuels research and development. Our expertise extends to a range of biofuels derived from a variety of agricultural, forest, and other feedstocks. Our researchers have achieved breakthroughs in the development and demonstration of biofuel processes, and they continue to lead the R&D community in the development of clean, inexpensive fuels from a virtually inexhaustible source of energy.

Biofuels are sure to be an exciting part of our energy future. Through our partnerships with industry, NREL is helping lead the way. You can be an important part of that future by joining with NREL today to enhance and develop tomorrow's biofuels.



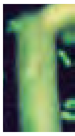
Partnering With NREL

There is no better time to get involved in biofuels research. Collaborations of experts from national laboratories, research organizations, and industry are key to moving biofuels production technologies into the marketplace.

NREL is ready to help you achieve your business goals. You can take advantage of NREL's biomass research capabilities and expertise in any of these ways:

- Your technical team can work collaboratively with NREL through a Cooperative Research and Development Agreement (CRADA). This is the most widely used means of industrial collaboration.
- You can stipulate specific research tasks at NREL through a Technology Partnership Agreement or Sponsored Research agreement. These are effective ways to take advantage of NREL's expertise and unique research facilities, such as our one-ton-per-day production capability.
- You can request simpler tasks through technical or analytical service agreements.

In addition, all of NREL's patented biomass technologies are available for licensing, and NREL's world-class biomass user facilities are available to industry, university, and government researchers. NREL may provide trained staff to conduct or direct the work, or activities can be performed by staff from the participating organization.



Contacts

For more information about working with NREL, please contact:

John Ashworth, Technical Lead for Partnerships and Contracts, (303) 384-6858

Please see the following Web sites:

NREL's R&D "Working With Us" Web page: http://www.nrel.gov/biomass/workingwithus.html
NREL's Biomass Research Web site: http://www.nrel.gov/biomass/
DOE Biomass Program Web site: http://www.eere.energy.gov/biomass/

The National Bioenergy Center is headquartered at NREL:

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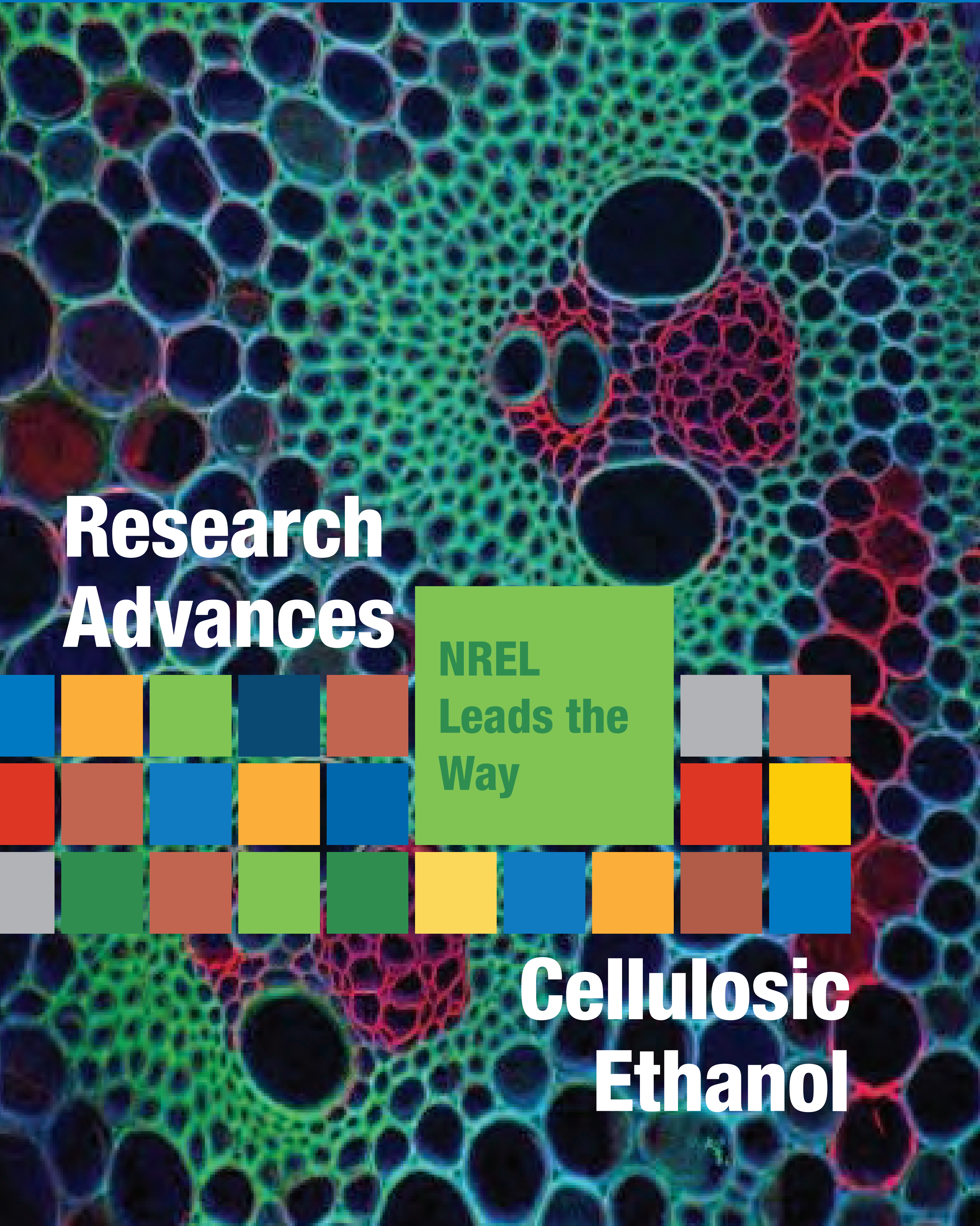
National Renewable Energy Laboratory

Innovation for Our Energy Future



Research Advances

NREL Leads the Way

Cellulosic Ethanol

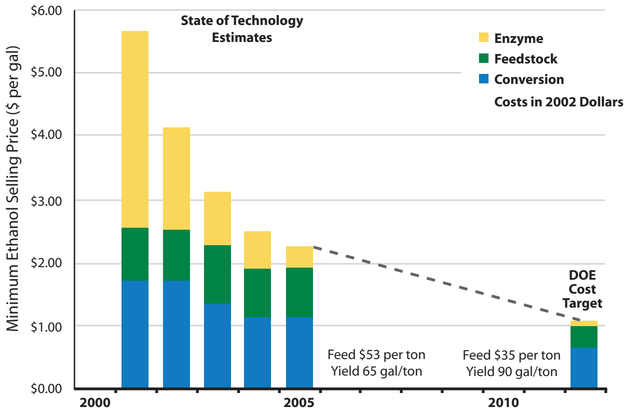
Fueling the Future

On the road to energy security

One of our greatest challenges is to reduce our nation's dependence on imported petroleum. To accomplish this, we need a variety of alternative fuels, including ethanol produced from cellulosic materials like grasses and wood chips. Fortunately, the United States has abundant agricultural and forest resources that can be converted into biofuels. Recent studies by the U.S. Department of Energy (DOE) suggest these resources can be used to produce enough ethanol – 60 billion gallons/year – to displace about 30% of our current gasoline consumption by 2030.

How do we get there? Currently, there are no commercial cellulosic ethanol refineries. The ethanol we use is derived primarily from corn kernels, a form of starchy biomass. When manufacturers produce ethanol from corn, they use enzymes to convert starches to simple sugars and yeasts to ferment the sugars into ethanol. Cellulosic biomass contains sugars as well, but they are much harder to release than those in starchy biomass. To complicate matters, the process of releasing the sugars produces by-products that inhibit fermentation, and some of the sugars from cellulosic biomass are difficult to ferment.

All this makes cellulosic ethanol production complicated—and expensive. To displace petroleum, cellulosic ethanol must be cost competitive. DOE has determined that competitiveness can be achieved at an ethanol production cost of $1.07/gallon (in 2002 dollars)

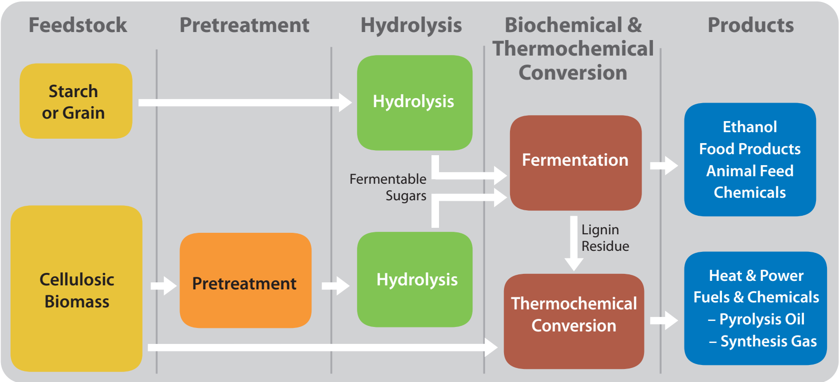


NREL has led progress toward DOE's cost target of $1.07/gallon for biochemically produced ethanol. Similar progress is being made for thermochemically produced ethanol.

and aims to achieve this goal by 2012. To do this, the technology used to produce cellulosic ethanol must be improved. That's where the National Renewable Energy Laboratory (NREL) comes in.

NREL leads DOE's National Bioenergy Center and is on the cutting edge of cellulosic ethanol technology. NREL's research addresses each step of the processes that produce cellulosic ethanol and valuable co-products. NREL's research covers the full spectrum from fundamental science and discovery to demonstration in fully integrated pilot plants.

This brochure highlights some of NREL's recent advances in cellulosic ethanol production. Research at NREL addresses both biochemical (chemicals, enzymes, and fermentative microorganisms) and thermochemical (heat and chemical) processes. For the biochemical processes, NREL investigates pretreatment, hydrolysis, and fermentation steps as well as process integration and biomass analysis. For the thermochemical processes, NREL researches catalyst development, process development, and process analysis.



Schematic of a hypothetical integrated ethanol biorefinery.

Cover image: Confocal laser microscope image of rind tissue in corn stover, showing the detailed structure of two vascular bundles.

Pretreatment

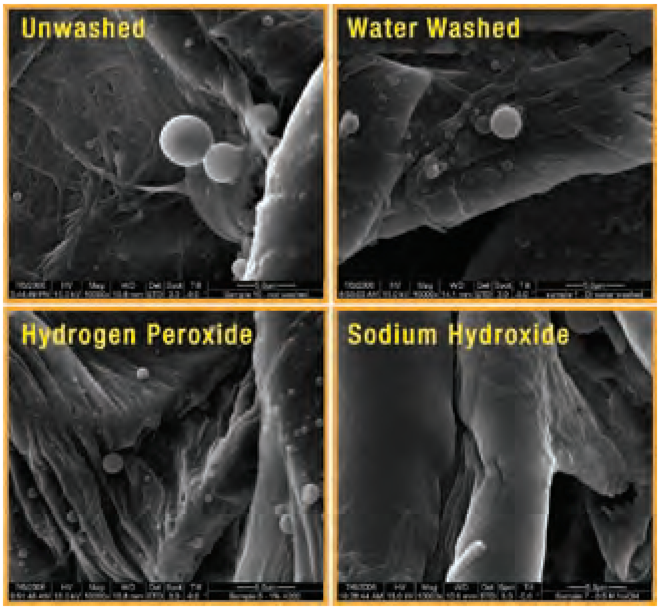
Improving the critical first step toward cost-competitive ethanol

To break down cellulose—the primary source of sugar in fibrous biomass—you have to first get past hemicellulose and lignin, which surround the cellulose in a protective sheath. This is the job of pretreatment. NREL typically uses a moderately high-temperature, high-pressure dilute acid pretreatment process to break down (hydrolyze) hemicellulose and disrupt or dissolve lignin. Hydrolyzing the hemicellulose also creates another important source of soluble sugars for later fermentation to ethanol.

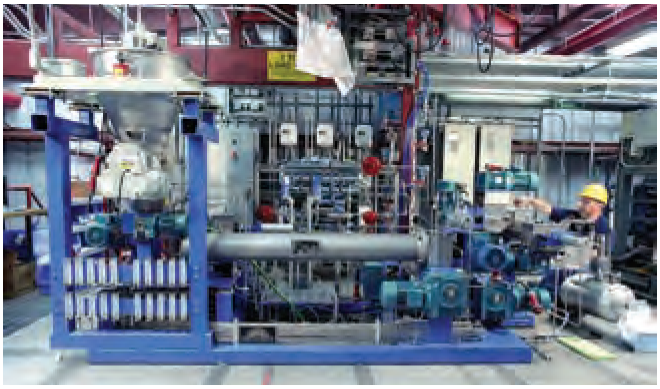
NREL is investigating potentially cheaper, but still effective, pretreatment methods. In one recent advance, NREL researchers applied their knowledge of biomass structural changes to pretreatment process development. Lignin dissolved under certain pretreatment conditions can apparently redeposit onto cellulose, creating a barrier to effective cellulose hydrolysis and reducing sugar yield. NREL is using its state-of-the-art imaging and analytical tools to understand lignin redeposition and design pretreatment processes that minimize its detrimental effects.

In another recent advance, NREL employed enzymes to enable milder pretreatment. Although dilute acid pretreatment can break down hemicellulose very effectively, the severe conditions require expensive processing equipment and tend to degrade the sugars. Using a milder pretreatment process could cut process costs dramatically and eliminate sugar degradation losses. The challenge is to maintain a high level of effectiveness with the milder process, which is accomplished by using enzymes to further break down the hemicellulose after pretreatment. NREL has shown that proper mixtures of enzymes can enhance hemicellulose hydrolysis. In an experiment on pretreated corn stover, adding a hemicellulase enzyme to break down the hemicellulose increased the yield of xylose (a sugar resulting from hemicellulose hydrolysis) by 12% across a range of pretreatment conditions. Breaking down the hemicellulose also enhanced cellulose hydrolysis, resulting in a 6% higher glucose yield.

To get a broader look at pretreatment options, NREL participates in the Biomass Refining Consortium for Applied Fundamentals and Innovation (CAFI). Each CAFI participant is evaluating a different pretreatment approach using standardized experimental design and data reporting protocols. The CAFI projects allow participants to compare pretreatment and downstream process performance across a range of lignocellulosic feedstocks. NREL is using this knowledge to help identify the best pretreatment approaches for near- and long-term biorefining platforms. (For more information on CAFI, see "Coordinated Development of Leading Biomass Pretreatment Technologies," *Bioresource Technology*, December 2005.)

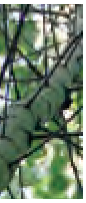


NREL used scanning electron microscopy to reveal what are thought to be lignin droplets remaining on pretreated filter paper after washing with various solvents. (T. Vinzant, NREL)



Warren Gretz, NREL PIX 11551

This pretreatment reactor hydrolyzes hemicellulose and solubilizes some lignin. The pressurized hot wash process separates these materials before they can reprecipitate. This system uses dilute sulfuric acid at increased temperature and pressure, but pressurized hot wash may work well with any pretreatment system.





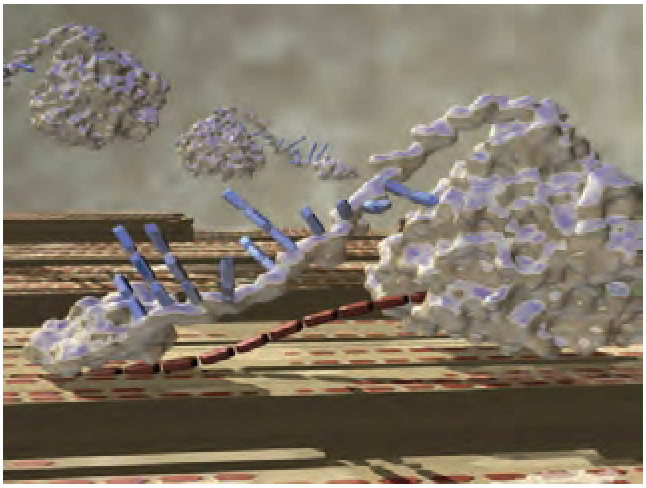
Enzymatic Hydrolysis

Unlocking the full potential of cellulosic biomass

Plants have evolved over several hundred million years to be recalcitrant—resistant to attacks from the likes of bacteria, fungi, insects, and extreme weather. Breaking down plants is no easy task. For cellulosic ethanol production, the primary challenge is breaking down (hydrolyzing) cellulose into its component sugars.

NREL is exploring the causes of biomass recalcitrance and ways to overcome it using cellulases (enzymes that break down cellulose). The goals are to maximize the conversion of cellulose to sugar, accelerate the rate of conversion, and use fewer, cheaper enzymes. NREL's recent advances include employing state-of-the-art capabilities to characterize plant structure and developing superior enzymatic hydrolysis processes.

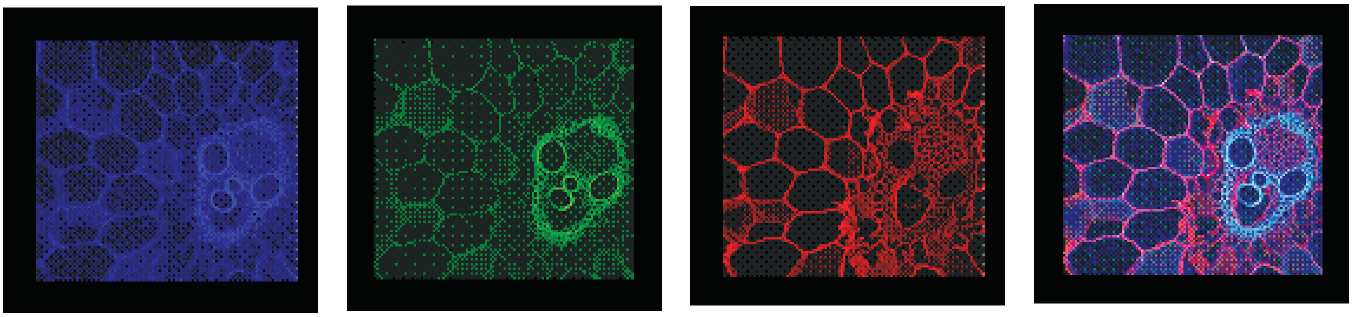
To make contact with cellulose, the enzymes must get past a complex maze of plant structures. NREL is mapping this labyrinth as a first step toward overcoming it. A unique array of microscopy tools and techniques in NREL's new Biomass Surface Characterization Laboratory enables researchers to image plant structures down to the molecular level. To probe even further—visualizing structures and processes at scales that cannot (yet) be observed—NREL and its partners are building a sophisticated molecular dynamics model of the cellulose-cellulase system. When complete, it will be the largest biological computer model ever developed.



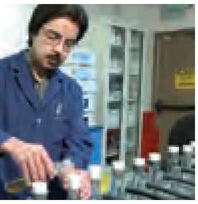
Advanced computer modeling capabilities help NREL understand and improve enzymatic hydrolysis processes. This illustration of the CBH I enzyme is based on models developed by NREL.

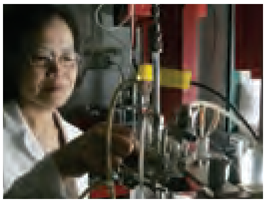
Once cellulases make contact with cellulose, the real work begins. Cellulases act very slowly. That's why dead trees take years to decompose in the forest. To accelerate cellulose conversion, it is critical to start with the best enzymes nature has to offer. The most active known cellulases are in the cellobiohydrolase I (CBH I) family, derived from fungi. But not all CBH I enzymes are equal. NREL recently confirmed the existence of CBH I enzymes that are twice as active as those from industrial sources.

NREL and its partners Genencor International and Novozymes have developed a "cocktail" of cellulases to improve hydrolysis. In combination with NREL's process development improvements, this advance has reduced enzyme cost twentyfold. This work received an R&D 100 Award in 2004.



These ultra-sharp laser microscope images were created with the Biomass Surface Characterization Laboratory's scanning confocal microscope, which can be used to build 3-D representations of plant structures. (S.Porter, NREL)





Fermentation

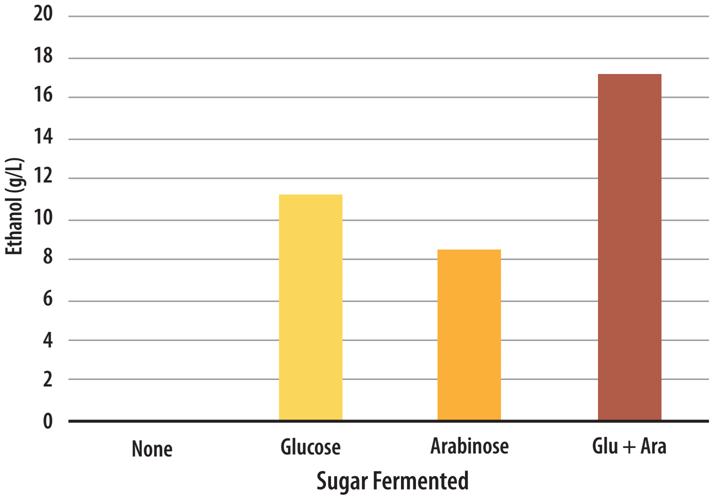
Creating "super-bugs" for superior ethanol yield

During fermentation, microorganisms (primarily fungi and bacteria) convert the sugars in biomass to ethanol. Under ideal conditions, these "bugs" will work contentedly, consuming sugars and producing ethanol and other products. But conditions in a cellulosic ethanol biorefinery are anything but ideal.

The hot soup—called a hydrolyzate—generated after pretreatment and hydrolysis contains not only fermentable sugars, but also compounds (such as acetic acid) that are toxic to the bugs. Other things that are toxic in the fermentation process and the hydrolyzate are a high-solids concentration and a rising ethanol concentration. Because microorganisms found in nature do not function well in this hostile environment, NREL is creating "super-bugs" that thrive in it.

Yeasts are currently the fermentation organisms of choice for the corn ethanol industry. They are reasonably tolerant of ethanol, acid, and moderately high temperatures. However, existing yeast strains cannot withstand highly toxic hydrolyzates or ferment 5-carbon sugars and minor 6-carbon sugars efficiently. NREL, along with the National Corn Growers Association (NCGA) and Corn Refiners Association (CRA), developed yeast capable of fermenting a particular 5-carbon sugar, arabinose, which constitutes up to 20% of the fermentable sugars in corn fiber. Three genes from a bacterium were inserted into the yeast Saccharomyces cerevisiae. This work resulted in the first ever demonstration, in 2000, of arabinose fermentation by yeast. Next, NREL plans to test the strain under real biorefining conditions—in the hydrolyzate.

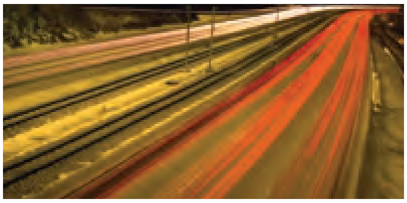
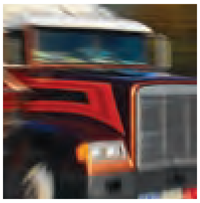
NREL also pioneered the use of a yeast alternative, the bacterium Zymomonas mobilis (Zymo). Zymo gives a high ethanol yield and tolerates high ethanol concentrations. Using genetic and metabolic engineering, NREL developed acetic acid-tolerant Zymo strains that can ferment arabinose and the most important 5-carbon sugar, xylose. This strain resulted in several patents and an R&D 100 Award. NREL also pioneered a technique to make the Zymo strain stable (the bacteria's offspring have the same genes as the parents) by inserting key genes into the genome. NREL's Zymo work has included successful collaborations with the NCGA and CRA, the chemical company Arkenol (now BlueFire Ethanol), and DuPont.



The yeast strain developed by NREL, NCGA, and CRA is the world's first yeast to ferment arabinose. These results show an ethanol yield of 83% from arabinose in a defined medium (not a hydrolyzate). From left to right, initial sugar concentrations were 0 g/L, 20 g/L glucose, 20 g/L arabinose, and 20 g/L glucose + 20 g/L arabinose. Expected ethanol from 20 g/L of sugar is 10.2 g/L at 100% yield. (A. Singh, NREL, patent pending)

Warren Gretz, NREL PIX 00945

Fermentation processes are tested in NREL's biochemical process development unit (PDU). This 9,000-L fermenter is large enough to produce sufficient lignin for processing in the downstream thermochemical PDU.

Process Integration

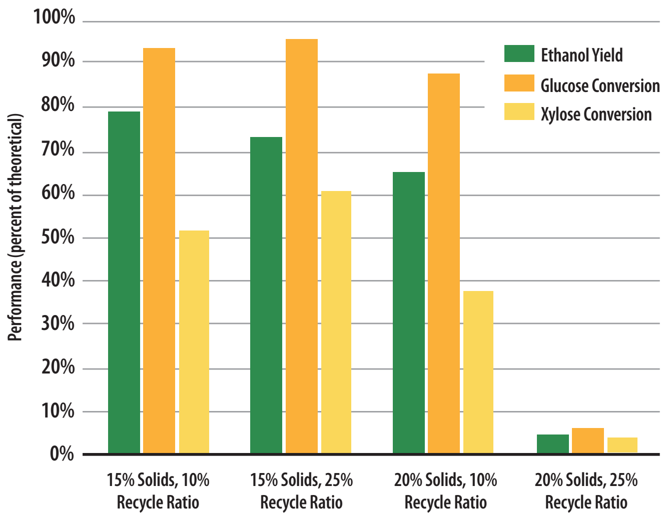
Tying together the integrated biorefinery

To produce low-cost ethanol, biorefineries will need to link the refining steps into an integrated process. However, optimizing conditions in one step of the process can influence performance in other steps. The challenge is to find the right combination of trade-offs that optimize the integrated process. Studying integrated biorefinery operations requires an advanced process development unit and state-of-the-art chemical analysis capabilities. NREL's research on high-solids operation is a good example.

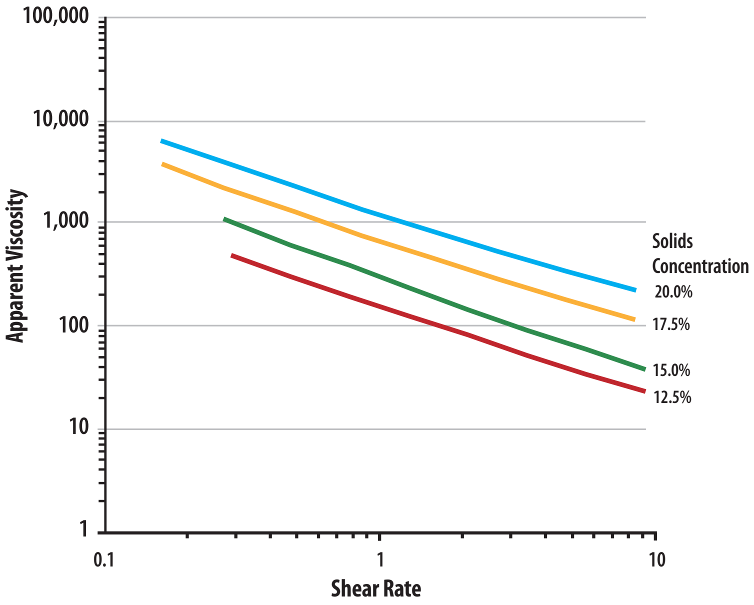
NREL has shown that high-solids operation—using a high ratio of biomass to water in the biorefining process—is one key to cutting ethanol costs. The less water introduced in the pretreatment step, the higher the potential sugar concentration and the less equipment and energy the process requires. The result is lower-cost ethanol. In a perfect world that would be enough, but high solids concentrations can create problems elsewhere in the process.

In a first-of-its-kind study, NREL demonstrated that a moderately high solids concentration combined with recycled process water severely inhibits fermentation and, consequently, lowers ethanol yield. This is important because commercial biorefineries will need to recycle water, taking it from the back end of the refining process and combining it with fresh water at the front end of the process. NREL's study identified the ability to achieve high solids concentration and high levels of process water recycle as an issue that must be considered in both pretreatment and fermentative microorganism development.

Managing the properties of high-solids mixtures is another process integration challenge. Like adding flour to water in a recipe, adding biomass to water makes the mixture thicker and more viscous. This has important implications for the efficient flow and conversion of biomass through the integrated process. NREL is developing unique capabilities in biomass rheology—the science of the deformation and flow of materials—to determine the best ways to manage high-solids biomass mixtures. This research is critical to providing process engineers with rheological information needed to design a commercial biorefinery.



Pioneering NREL research shows ethanol yield dropping dramatically at moderately high solids concentration and high recycle ratio (the ratio of recycled water to fresh water). (D. Schell, NREL)



NREL is quantifying the rheological properties of various biomass materials. These results show how the viscosity (resistance to flow) of pretreated corn stover increases with higher solids concentration and decreases with faster shear rate (speed of mixing). (J. McMillan, NREL)

Thermochemical Conversion

Honing a powerful path to economic ethanol

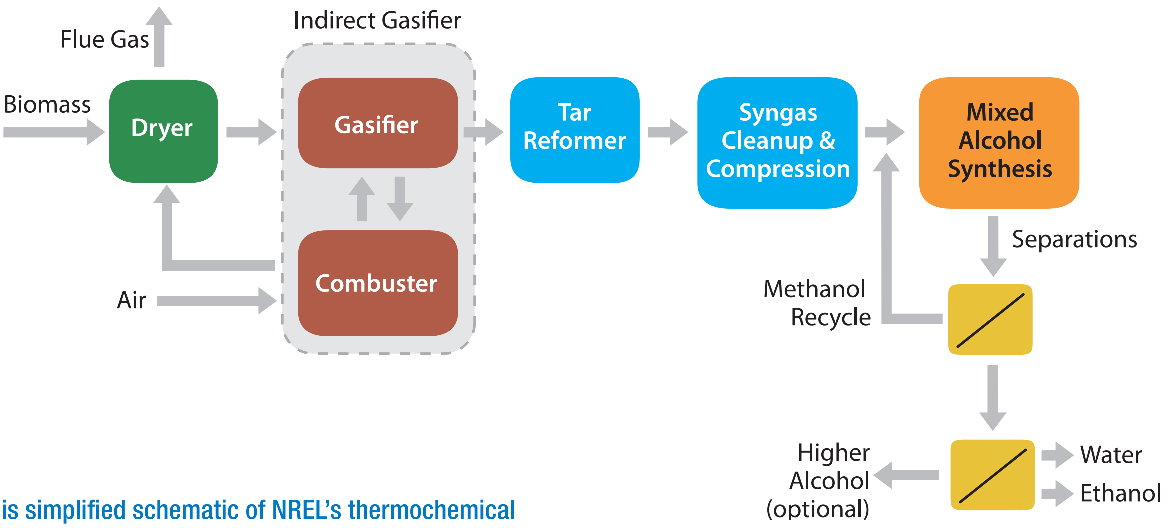
The advances described up to this point relate to biochemical conversion of carbohydrates to ethanol. However, ethanol can also be produced thermochemically from any form of biomass. In this approach, heat and chemicals are used to break biomass into syngas (CO and H2) and reassemble it into products such as ethanol. This method is particularly important because up to one third of cellulosic biomass—the lignin-rich parts—cannot be easily converted biochemically.

Forest products and mill residues typically have high lignin contents, making them unattractive feedstocks for biochemical conversion yet suitable for thermochemical conversion. In an integrated biorefinery, lignin-rich residues from the biochemical process could also be converted thermochemically.

A thermochemical biomass conversion process is complex, and uses components, configurations, and operating conditions that are more typical of petroleum refining. And, just like researchers in the petroleum industry, NREL uses a combination of experimental research together with process economic models to explore a large number of possible process configurations. A much simplified schematic of NREL's preferred configuration is shown below. This configuration employs an indirect gasifier, tar reforming, and a mixed alcohol synthesis step designed to maximize ethanol yield.

In thermochemical conversion, biomass is converted into syngas, and syngas is converted into an ethanol-rich mixture. However, syngas created from biomass is not "clean"—it contains contaminants such as tar and sulfur that interfere with the conversion of the syngas into products. These contaminants must be removed. NREL has developed tar-reforming catalysts and catalytic reforming processes that have demonstrated high levels of tar conversion—converting up to 97% of the tar into more syngas. This not only cleans the syngas, it also creates more of it, improving process economics and ultimately cutting the cost of the resulting ethanol. NREL has also made progress regenerating the tar-reforming catalyst after it has been partially deactivated by sulfur poisoning.

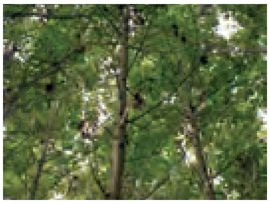
NREL is evaluating many different process options and their associated costs to help identify key barriers to low-cost ethanol production. For example, process models indicate that reducing tars and hydrocarbons from syngas can decrease the production cost of ethanol by 33%. NREL models also highlight the need for extensive heat integration and quantify performance targets needed to achieve DOE's ethanol cost goals thermochemically.



This simplified schematic of NREL's thermochemical conversion model shows the many steps that can be manipulated to optimize efficiency and cost.







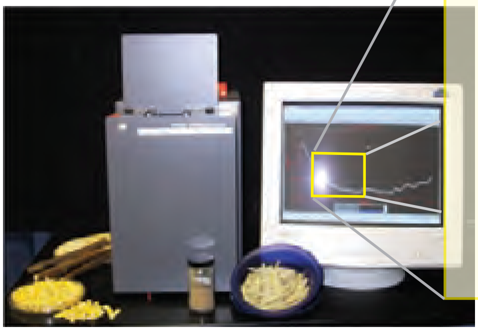
Biomass Analysis

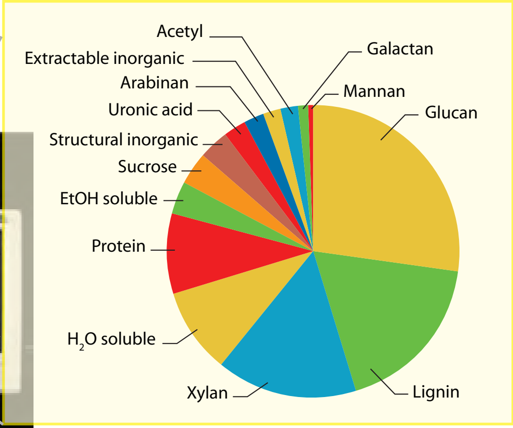
Enabling total control of ethanol production

You can't control what you can't measure. Biorefinery operators will need to know the precise composition of the biomass going through their processes so they can tightly control the cost and quality of the products coming out. The faster and more reliable the measurements are, the better and cheaper the final products will be.

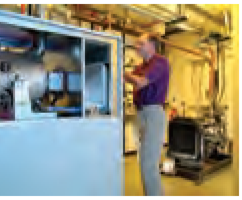
NREL's capabilities are constantly evolving to meet industry's need for accurate and rapid biomass analysis. Researchers recently developed a way to rapidly analyze biomass composition using near-infrared (NIR) spectroscopy. In this technique, light reflected off a biomass sample is analyzed to determine the sample's composition. Compared with traditional wet chemistry analysis, this is a huge leap forward. Analyzing a sample with this new approach takes minutes instead of weeks and costs tens of dollars instead of thousands of dollars—without sacrificing precision or accuracy. The rugged NIR instruments can even be adapted to a working biorefinery to measure, for example, the chemical composition of corn stover as it enters and exits pretreatment.

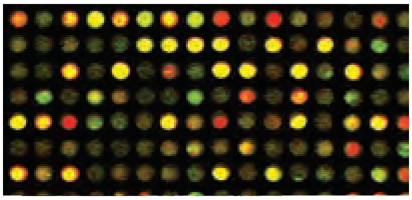
What if you could measure an adult plant's composition while it is still a sprout? You could grow plants that yielded the most ethanol, maximize cellulose content, and minimize lignin. Or what if, by knowing how genes affect plant composition, you could create the ideal ethanol feedstock? NREL's analytical capabilities are making these scenarios a reality. Using techniques such as molecular beam mass spectrometry and nuclear magnetic resonance spectroscopy, NREL is measuring cell wall chemistry more quickly and accurately than anyone else in the world. These measurements are used to predict adult plant composition. In 2006, NREL analyzed the cell wall chemistry of more than 10,000 samples for industry and university partners. These thermoanalytical capabilities can help accelerate crop breeding and genetic engineering.





NREL's NIR spectroscopy technique rapidly analyzes biomass composition and can be adapted to on-line use.





Contacts

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Please see the following Web sites for more information on biomass and related research at NREL:

NREL's R&D "Working With Us" Web page: www.nrel.gov/biomass/workingwithus.html

NREL's Biomass Research Web site: www.nrel.gov/biomass/

NREL's Chemical & Biosciences Center Web site: www.nrel.gov/basic_sciences/

DOE Biomass Program Web site: www.eere.energy.gov/biomass/

The National Bioenergy Center is headquartered at NREL:

National Renewable Energy Laboratory
1617 Cole Blvd.
Golden, CO 80401
303.275.3000 • www.nrel.gov
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NREL/BR-510-40742

March 2007

Biofuels from Switchgrass: Greener Energy Pastures

The grass stretched as far as the eye could see, and hundreds more miles beyond that. An ocean of grass—deep enough to swallow a horse and rider—swaying and singing in the steady wind of the Great Plains. ❧ The American prairie—tens of millions of acres—once looked like this. But that was centuries ago, before the coming of the white man, the railroad, and the steel plow. Today, corn and beans hold sway, and the remnants of America's tallgrass prairie are confined mostly to parks and preserves. ❧ Now, though, in research plots and laboratories in the Plains states and even in the Deep South the seeds of change are germinating. The tall, native grasses of the prairie, so vital to our land's ecological past, may prove equally vital to its economic future. Such grasses once fed millions of bison. Soon, grown as energy crops, they may help fuel millions of cars and trucks, spin power turbines, and supply chemicals to American industries.

The U.S. Department of Energy (DOE) believes that biofuels—made from crops of native grasses, such as fast-growing *switchgrass*—could reduce the nation's dependence on foreign oil, curb emissions of the "greenhouse gas" carbon dioxide, and strengthen America's farm economy. The Bioenergy Feedstock Development Program (BFDP) at DOE's Oak Ridge National Laboratory (ORNL), has assembled a team of scientists ranging from economists and energy analysts to plant physiologists and geneticists to lay the groundwork for this new source of renewable energy. Included are researchers at universities, other national laboratories, and agricultural research stations around the nation. Their goal, according to ORNL physiologist Sandy McLaughlin, who leads the switchgrass research effort, is nothing short of building the foundation for a biofuels industry that will make and market ethanol and other biofuels from switchgrass and at prices competitive with fossil fuels such as gasoline and diesel.

Not the grass in your backyard

First, a distinction: switchgrass and your suburban lawn grasses—bluegrass and zoysia grass—are about as similar as a shopping-mall ficus and an old-growth redwood. Switchgrass is big and it's tough—after a good growing season, it can stand 10 feet high, with stems as thick and strong as hardwood pencils.

But what makes switchgrass bad for barefoot lawns makes it ideal for energy crops: It grows fast, capturing lots of solar energy and turning it into lots of chemical energy—cellulose—that can be liquified, gasified, or burned directly. It also reaches deep into the soil for water, and uses the water it finds very efficiently. And because it spent millions of years evolving to thrive in climates and growing conditions spanning much of the nation, switchgrass is remarkably adaptable.

Test plots of switchgrass at Auburn University have produced up to 15 tons per acre in a single year, with eight-year average annual yields at 10 tons per acre. Expected yields in field-scale production are in the range of 5-9 tons per acre, enough to eventually produce 500-900 gallons of ethanol per acre per year.

Now, to make switchgrass even more promising, researchers across the country are working to boost switchgrass hardiness and yields, adapt varieties to a wide range of growing conditions, and reduce the need for nitrogen and other chemical fertilizers. By "fingerprinting" the DNA and physiological characteristics of numerous varieties, the researchers are steadily identifying and breeding varieties of switchgrass that show great promise for the future.

Yield of dreams

In the hard, shallow soil of southern Alabama, Dave Bransby is turning cotton fields into swatches of grassland. Some Alabama farmers joke that there's no soil in Alabama to farm—two centuries of King Cotton and steady erosion haven't left much behind. Yet Bransby, a forage scientist at Auburn University, has found a crop that thrives there: Among the 19 research sites in the Eastern and Central United States raising switchgrass for the BFDP studies, Bransby's site holds the one-year record at 15 tons per acre. Those are dry tons weighed after all the moisture's been baked out. Convert that into ethanol, an alcohol that can fuel vehicles, and it equals about 1,500 gallons per acre. Bransby's 6-year average, 11.5 tons a year, translates into about 11,500 gallons of ethanol per acre. An added bonus is the electricity that can be produced from the leftover portions of the crop that won't convert to ethanol.

Many farmers already grow switchgrass, either as forage for livestock or as a ground cover, to control erosion. Cultivating switchgrass as an energy crop instead would require only minor changes in how it's managed and when it's harvested. Switchgrass can be cut and baled with conventional mowers and balers. And it's a hardy, adaptable perennial, so once it's established in a field, it can be harvested as a cash crop, either annually or semiannually, for 10 years or more before replanting is needed. And because it has multiple uses—as an ethanol feedstock, as forage, as ground cover—a farmer who plants switchgrass can be confident knowing that a switchgrass crop will be put to good use.

Farmers working in production mode might not match Bransby's carefully tended research plots, but if the future brings rises in oil prices—or if environmental taxes are eventually imposed on fossil fuels—energy from switchgrass could prove economically competitive with petroleum and coal, making biomass crops attractive to American farmers. And with recent advances in the technology of gasification, switchgrass could yield a variety of useful fuels—synthetic gasoline and diesel fuel, methanol, methane gas, even hydrogen—as well as chemical by-products useful for making fertilizers, solvents, and plastics.

Strong environmental roots

Annual cultivation of many agricultural crops depletes the soil's organic matter, steadily reducing fertility. But switchgrass adds organic matter—the plants extend nearly as far below ground as above. And with its network of stems and roots, switchgrass holds onto soil even in winter to prevent erosion.

Besides helping slow runoff and anchor soil, switchgrass can also filter runoff from fields planted with traditional row crops. *Buffer strips* of switchgrass, planted along streambanks and around wetlands, could remove soil particles, pesticides, and fertilizer residues from surface water before it reaches groundwater or streams—and could also provide energy.

And because switchgrass removes carbon dioxide *(CO_2)* from the air as it grows, it has the potential to slow the buildup of this greenhouse gas in Earth's atmosphere. Unlike fossil fuels, which simply release more and more of the CO_2 that's been in geologic storage for millions of years, energy crops of switchgrass "recycle" CO_2 over and over again, with each year's cycle of growth and use.

Many farmers are already experienced at raising switchgrass for forage or to protect soil from erosion. Besides showing great promise for energy production, switchgrass also restores vital organic nutrients to farmed-out soils.

Switchgrass can be cut and baled with standard farming equipment.

Switchgrass offers excellent habitat for a wide variety of birds and small mammals.

The road ahead

One reason BFDP researchers are confident that switchgrass can become an important feedstock for ethanol production is the groundwork that's already been laid by corn growers. U.S. ethanol production from corn currently totals nearly 2 billion gallons a year. Some of this ethanol is blended with gasoline to make gasohol; some is further refined to make gasoline octane boosters; and some is burned, either in pure ("neat") form or mixed with a small percentage of gasoline, in fleets of research and demonstration vehicles.

Looking down the road, McLaughlin believes switchgrass offers important advantages as an energy crop. "Producing ethanol from corn requires almost as much energy to produce as it yields," he explains, "while ethanol from switchgrass can produce about five times more energy than you put in. When you factor in the energy required to make tractors, transport farm equipment, plant and harvest, and so on, the net energy output of switchgrass is about 20 times better than corn's." Switchgrass also does a far better job of protecting soil, virtually eliminating erosion. And it removes considerably more CO_2 from the air, packing it away in soils and roots.

Back to the future

At the turn of the last century, America's transportation system was fueled by biomass: 30 million horses and mules, give or take a few million, pulled buggies, hauled wagons, dragged plows. According to Ken Vogel, a U.S. Department of Agriculture forage geneticist helping develop and test switchgrass for the BFDP, replacing animal power with machine power freed up 80 million acres of U.S. land—land that had been used to grow grass and other feed for these millions of animals. Now, at the dawn of the next century, the wheel could begin to turn full circle. On millions of acres of farm land not needed for food crops, fast-growing energy crops of switchgrass—harvested and converted efficiently to clean-burning, affordable ethanol, methanol, or diesel—could once again supply vast amounts of horsepower.

In short, biomass could bring back a 21st-century version of the prairie. And along with the prairie, it could bring a new crop to America's farms, a boost to U.S. energy independence, and brighter prospects for a clean, sustainable future. According to BFDP and its research partners across the country, that's a future worth cultivating.

Produced for DOE's Office of Transportation Technologies and the Office of Utility Technologies within the Office of Energy Efficiency and Renewable Energy.

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http://www.esd.ornl.gov/bfdp/
on the Internet.**

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