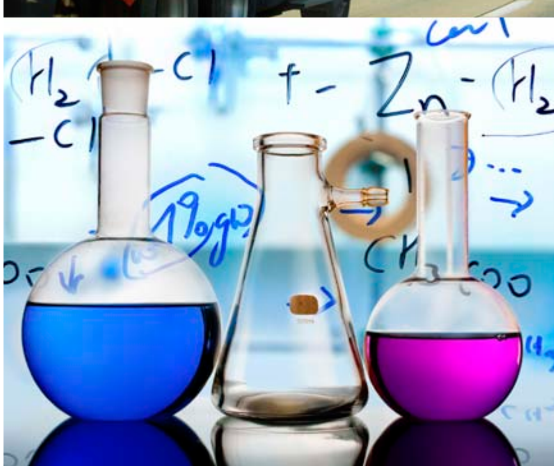
U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

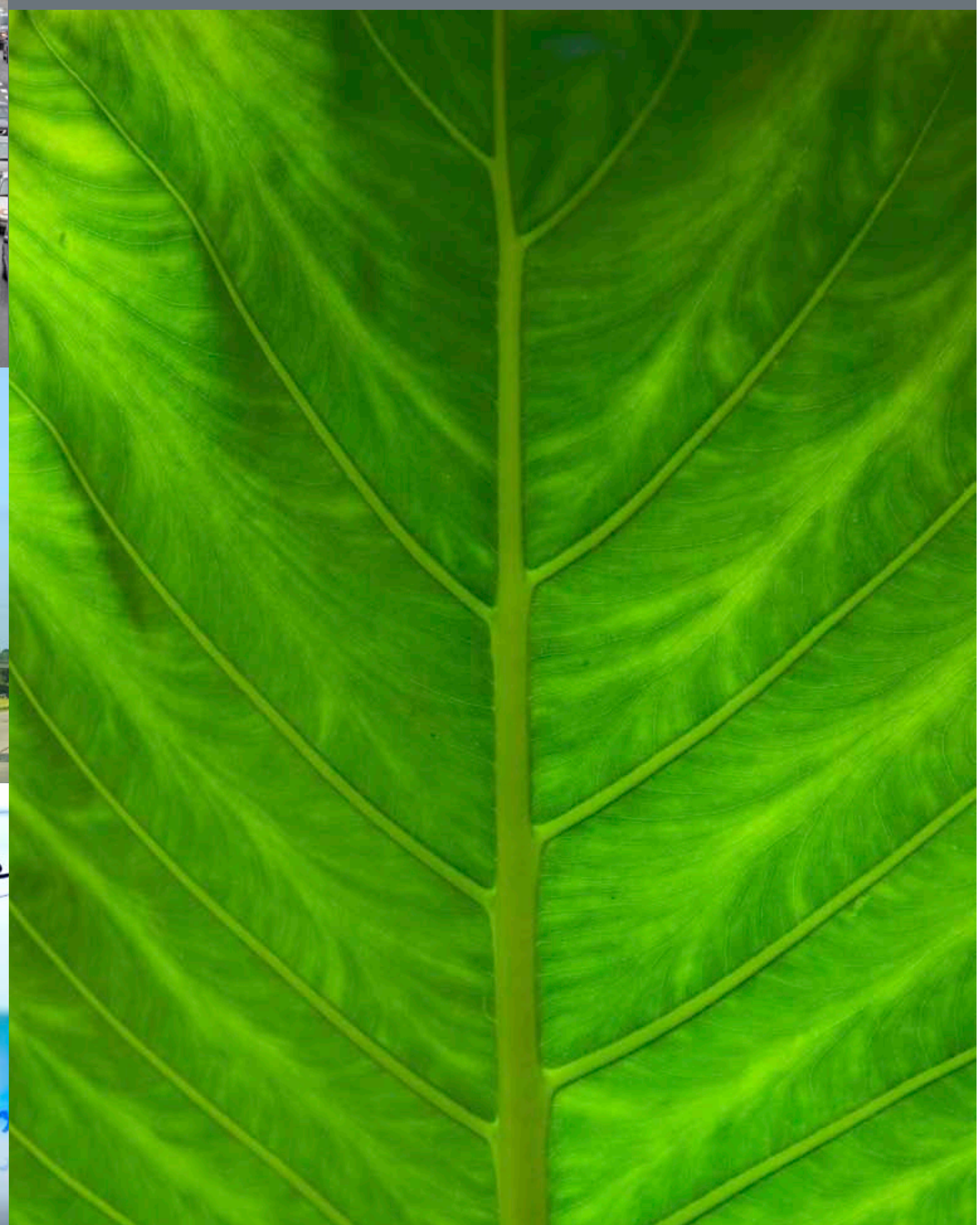
BIOENERGY TECHNOLOGIES OFFICE



Replacing the Whole Barrel

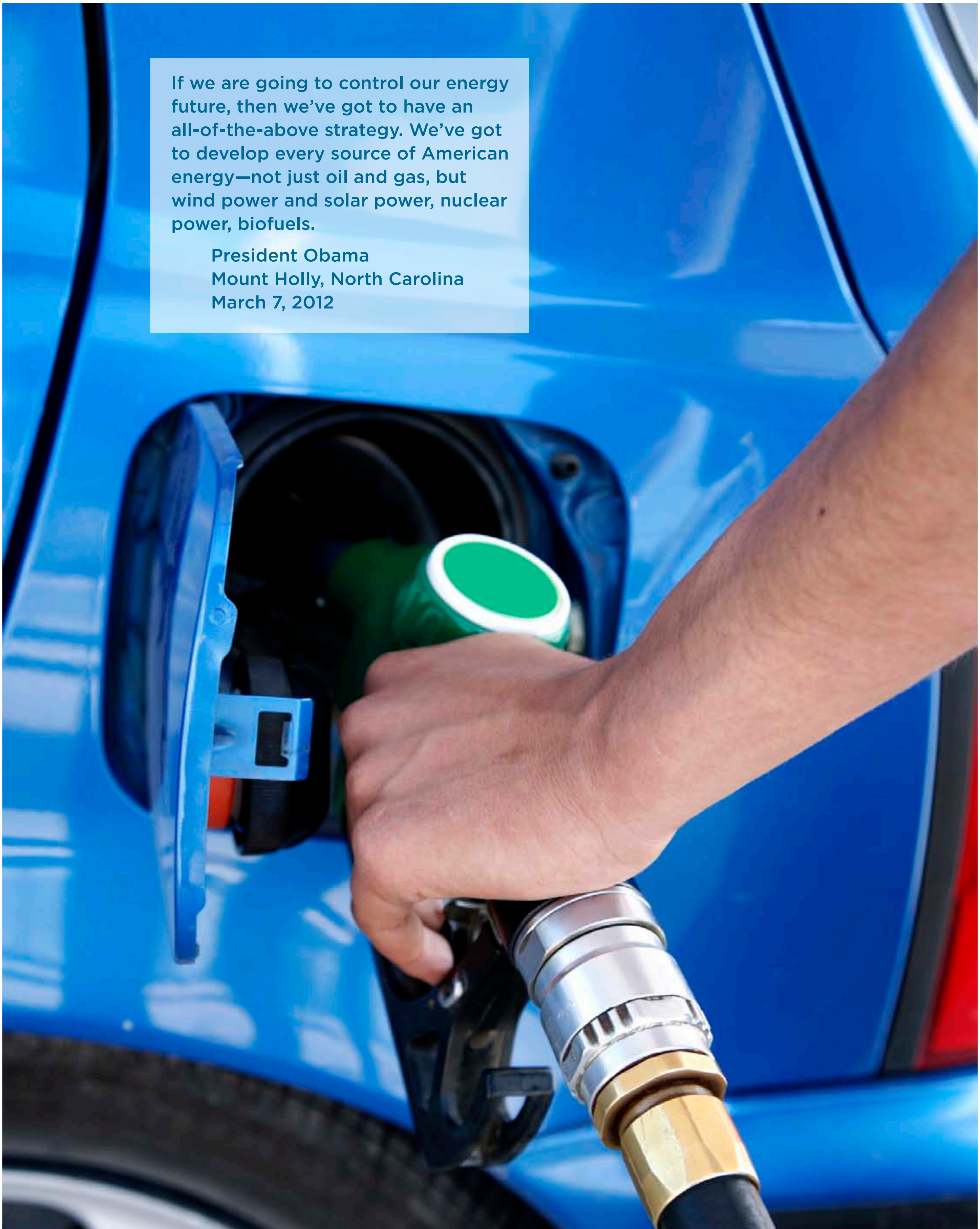
To Reduce U.S. Dependence on Oil

July 2013



If we are going to control our energy future, then we've got to have an all-of-the-above strategy. We've got to develop every source of American energy—not just oil and gas, but wind power and solar power, nuclear power, biofuels.

President Obama
Mount Holly, North Carolina
March 7, 2012

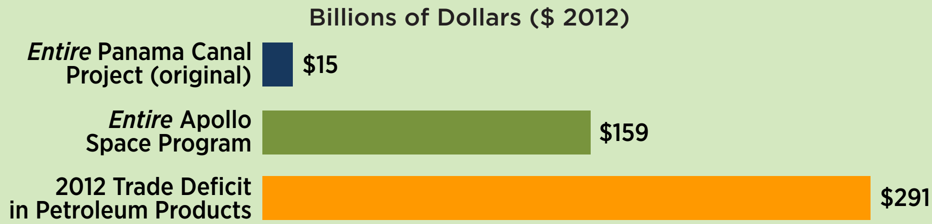


Biofuels are improving America's energy security and helping to lower prices at the pump. *Photo: iStock/ 3295439. Cover photos from iStock/ 13311982, 8047298, 6019274, 16059398, 6439341*

Photo: iStock/7315816

U.S. Trade Deficit Related to Petroleum Products

The U.S. trade deficit in petroleum-related products was about $291 billion in 2012 (refined products included).[a] The chart below puts that sum in perspective.[b]



[a] U.S. Census Bureau, *U.S. International Trade in Goods and Services*, Exhibit 9, 2013.

[b] Estimates from whatitcosts.com with dollar conversions from dollartimes.com.

The U.S. trade deficit in petroleum products is finally shrinking. Policies that foster better fuel economy, increased oil production, and expanded use of renewable fuels have helped reduce our reliance on imported fuels from 60% in 2005 to 40% in 2012—and the trend continues. By keeping more of the roughly $430 billion spent on foreign oil in 2012 here at home, we can stimulate the economy and create more American jobs.

For the Bioenergy Technologies Office (BETO), this year marks an important milestone. After more than a decade of research, development, and demonstration (RD&D) involving our national laboratories and industrial partners, we have validated at pilot scale our modeled cost target for making ethanol from cellulosic biomass (organic material not used for food or feed). This success is the culmination of protracted, collaborative research to sustainably expand biomass production, streamline logistics, improve conversion technologies, and integrate processing systems. The result is a strong signal to U.S. companies that, as the industry matures, they can expect to make and sell cellulosic ethanol at a competitive cost.

This accomplishment has allowed for a greater emphasis on RD&D to produce bio-based hydrocarbon fuels and bioproducts that can displace *all* of the products made from a barrel of oil. Since only about 40% of a barrel of crude is used to make petroleum gasoline, we need technologies that will help us convert biomass into affordable diesel, jet fuel, heavy distillates, and other chemicals and products. These bio-based hydrocarbon fuels are nearly identical to the petroleum-based fuels they are designed to replace—so they're compatible with today's engines, pumps, and other infrastructure.

I'm pleased to report that our staff, researchers, and partners are diligently working to solve the technology challenges associated with developing this next generation of advanced biofuels and products. I invite you to learn more about our new goals for developing sustainable jet fuel, renewable gasoline, and other bio-based products that will keep our energy dollars within our borders.

Respectfully,

Director, Bioenergy Technologies Office (Acting)
Office of Energy Efficiency and Renewable Energy

CONTENTS

All of us in the Bioenergy Technologies Office (BETO) are proud of our role in diversifying America's clean energy portfolio—helping to build a secure and sustainable energy future while strengthening the U.S. economy.

Why Biomass?

Building a national biofuels industry generates construction jobs, refinery jobs, and economic opportunities in rural communities throughout the country. In addition, every gallon of biofuel consumed near where it is produced cuts transportation costs and improves energy security.
Photo: iStock/19819967

Converting domestic biomass into affordable fuels, products, and power supports our national strategy to diversify energy resources and reduce dependence on imported oil. Indeed, biomass is the only renewable energy source that can offer a substitute for petroleum-based, liquid transportation fuels for the near term.[1]

Developing domestic biomass as a clean, sustainable energy resource for transportation fuels offers a range of significant benefits.

Stimulate the economy: The dollars that America spends on biofuels will recirculate in our own economy—instead of enriching foreign interests or adding to the trade deficit. Employment in the U.S. biofuels industry has grown an average of 8.9% annually since 2004[2] and represented 87,000 direct jobs in 2011.[3] The industry's continued growth will generate new job opportunities across the country—particularly in rural areas.

Improve our trade balance: Petroleum-related products accounted for about 40% of the roughly $540 billion total U.S. trade deficit in 2012.[4] U.S. biofuels improve this balance in two ways. First, they directly reduce imports; ethanol is estimated to have displaced about $47.2 billion worth of imported crude in 2012 (based on an acquisition cost of $101.53 per barrel).[3] In addition, every job in the biofuels sector generates a significantly greater value of exports than the average U.S. job.[5]

Mitigate climate impacts: Biofuels typically offer a net life-cycle reduction in greenhouse gas (GHG) emissions relative to petroleum-based fuels. The GHG impact of a particular biofuel depends on the energy used to grow and harvest the feedstock as well as the energy used to produce the fuel (e.g., coal, natural gas, biomass). If processing uses clean, renewable energy, emerging technologies for advanced biofuels could reduce GHGs by 70% to more than 100%, relative to conventional gasoline.[6]

Increase energy security: Domestic biofuels diversify our energy portfolio and decrease our dependence on foreign sources of energy. Biorefineries may potentially serve as regionally self-sufficient energy facilities, independent of national transportation and power networks. These attributes provide each region and the nation with greater energy security and resilience, enabling the continuation of critical regional operations in the event of a natural disaster or national emergency.

[1] Many biofuels are compatible with the nation's existing vehicle fleet, whereas electric vehicle technology is likely to require replacement of that fleet—typically a 15- to 20-year process (according to the EPA).

[2] M. Muro, J. Rothwell, and D. Saha, *Sizing the Clean Economy: A National and Regional Green Jobs Assessment*, 2011, based on *Brookings-Battelle Clean Economy Database*; Brookings analysis of United States International Trade Commission, Bureau of Economic Analysis, and Moody's Economy.com data.

[3] J. M. Urbanchuk, *Contribution of the Ethanol Industry to the Economy of the United States*, Renewable Fuels, Association, 31 Jan. 2013.

[4] International Trade Administration, U.S. Dept. of Commerce, *U.S. Export Fact Sheet*, Feb. 2013. www.trade.gov/press/press-releases/2013/export-factsheet-february2013-020813.pdf

[5] M. Muro et al, *Sizing the Clean Economy*, Metropolitan Policy Program at Brookings, 2011.

[6] Paul Bryan, "The Future of Biomass-Based Energy," presented at the Agricultural Outlook Forum, February 25, 2011.

High-yield energy crops like switchgrass hold great potential as biofuel feedstocks. *Photo: Idaho National Laboratory (INL)*

Draw on abundant resources: The United States is capable of growing enough biomass to displace more than 30% of U.S. petroleum consumption.[8] This estimate includes the use of agricultural residue, forest resources, perennial grasses, woody energy crops, algae, and municipal solid waste.

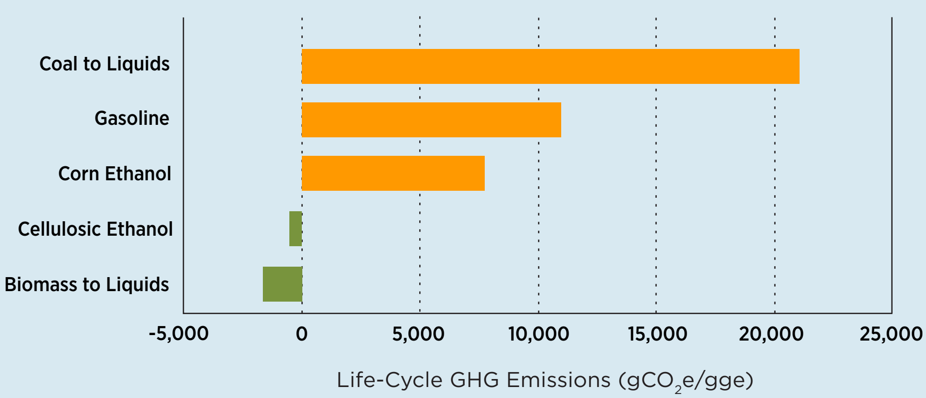
Benefit diverse regions: Biomass for the production of biofuels can be found or grown throughout the country. Dedicated bioenergy crops are being developed for local climate, soil, and agronomic or forestry management practices. Continued development of this range of crops can increase the productivity of local land resources and support local energy needs.

Boost U.S. technology leadership: Breakthroughs in bioconversion technologies and successes in scaling up technologies for commercial operations promote U.S. leadership in global clean energy technology. Advances can provide benefits in such related areas as agricultural production and food processing. Investments in bioprocessing will also help to reduce production costs, improve process and product reliability, and increase profitability. U.S. leadership in this growing sector will improve competitiveness in global markets.

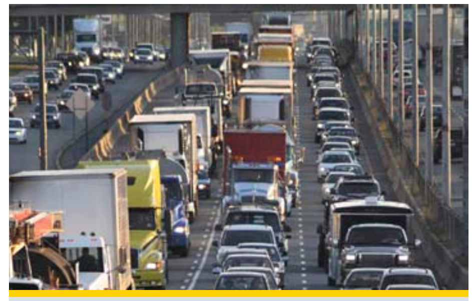
Enhance sustainability: Unlike petroleum products, biofuels can be developed in a manner that meets requirements for environmental and socio-economic sustainability. Work is ongoing to fully understand and address the direct and secondary impacts of biomass and biofuels production. Standards are being developed to ensure that biomass production avoids adverse impacts on food supply and prices and that biofuels offer an alternative to the chronic concerns and environmental risks associated with oil extraction and transport.

[8] U.S. Department of Energy, 2011. *U.S. Billion-Ton Update: Biomass Supply for a Bioenergy and Bioproducts Industry*, R.D. Perlack and B.J. Stokes (leads), ORNL/TM-2011/224. Oak Ridge National Laboratory, Oak Ridge, TN. 227p.

Advanced biofuels offer significant life-cycle reductions in greenhouse gas emissions compared to other liquid fuel alternatives



Source: U.S. Energy Department, *Quadrennial Technology Review*, September 2011



Fuel Use and Emissions

- The transportation sector accounts for two-thirds of U.S. oil use and contributes one-third of the Nation's greenhouse gas (GHG) emissions.
- Cars and light-duty vehicles use the most energy and emit the most GHGs in the transportation sector.[a] In 20 years, the global vehicle fleet is expected to grow by 60%.[b]
- Medium- or heavy-duty vehicles use large amounts of fuel because of their low fuel economy and intensive use in fleets.
- Biofuels can be used in most vehicles that are on the roads today, unlike some other renewable alternatives that would require replacement of our current vehicle fleet.
- Aircraft already contribute 9% of U.S. transportation sector emissions, and aviation fuel usage is expected to increase.[a]

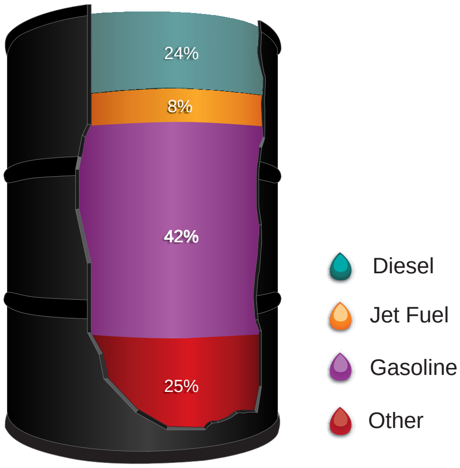
[a] U.S. Energy Information Administration (EIA), *Annual Energy Outlook 2013*, Table A7, Washington, DC: US EIA. www.eia.gov/forecasts/aeo/

[b] BP, *BP Energy Outlook 2030*, London, Jan. 2012.

Photo: iStock/47298

Strategic Approach

Uses of a Barrel of Crude Oil (by percentage)



Source: Energy Information Administration; data for 2011; image by BCS, Inc.

Replace the Whole Barrel

- Cellulosic ethanol can displace only the 42% of a barrel of crude oil that is used to produce light-duty gasoline.
- Research, development, and demonstration (RD&D) activities are needed on a range of technologies to displace the other 58% of the barrel.
- At least 7% of each barrel is used to make products other than fuels, such as glues, cleaners, solvents, and plastics.
- Hydrocarbon biofuels are "drop-in" fuels that can act as true petroleum substitutes to replace diesel, jet fuel, heavy distillates, and a range of other chemicals and products.
- These advanced biofuels can be sustainably produced from cellulosic and algal feedstocks.
- Their compatibility with the existing infrastructure suggests smooth process integration and the potential to leverage available capacity in traditional refineries.

Biofuels: Part of Our National Strategy

Rapid growth in global energy demand and uncertainties surrounding traditional oil supplies are raising concerns about U.S. energy security. Recognizing that no single energy source can reliably meet all of America's growing energy needs, the nation has adopted a comprehensive energy strategy that calls for responsible oil and gas development, increased vehicle fuel economy, and investment in renewable domestic energy sources. This "all-of-the-above" strategy specifically supports development of solar, wind, geothermal, and biomass energy.

Delivering Unique Value

Biomass is unique among renewable energy sources in that it can be easily stored until needed and provides a liquid fuel alternative for use in today's vehicles. Biofuels are the only near-term renewable energy option that can address our transportation sector's heavy dependence on imported oil without replacing our vehicle fleet.

To effectively reduce crude oil imports, domestic producers must be able to convert biomass into the full range of fuels and products currently derived from crude oil (see chart at left). Cost-effective technologies are needed to sustainably produce biofuels that are suitable for "drop-in" use in today's cars, trucks, and jets. These biomass conversion technologies will produce intermediate products that can be substituted for high-value chemicals to diversify and bolster the biorefining value chain.

This approach provides a domestic resource for the U.S. petroleum industry and takes advantage of the extensive existing infrastructure (oil refineries, pipelines, and distribution networks). Development of the U.S. bioindustry can be carried out in a manner that simultaneously protects land, food, and water resources; strengthens America's energy security; maintains a strong economy; and creates local jobs.

The Energy Department's all-out, all-of-the-above energy strategy lowers costs for consumers, better protects our wildlife and environment, and reduces reliance on imported oil. *Photo: iStock/7247383*

Role of the Bioenergy Technologies Office

The U.S. Department of Energy (DOE) is working to remove barriers to the production of clean, domestic biofuels that can help displace all fractions of a barrel of crude oil. The Department's Bioenergy Technologies Office has advanced the technology for producing ethanol from non-food (cellulosic) resources and is now researching technologies for converting cellulosic and algal biomass into advanced hydrocarbon fuels and bioproducts. BETO is validating critical cost targets through research, development, and demonstration (RD&D) and facilitating construction of the first commercial-scale biorefineries.

A Clear Federal Role

The production of advanced biofuels relies on novel and emerging technologies that face a difficult transition from research into commercialization. Private industry is particularly risk averse in today's tight credit market, and investors are wary of the innovative, high-risk technologies required to bring advanced biofuels to market. By sharing RD&D costs, the federal government reduces risk to future investors and helps to lead development along sustainable pathways aligned with national goals.

To deliver the broad benefits of advanced biofuels, BETO works to understand all critical linkages along the supply chain, explores new approaches, and helps guide technology development along the most promising pathways to a robust and sustainable domestic bioindustry. The Office is one of the lead federal agencies conducting RD&D on biofuels.

Feedstock Supply & Logistics – BETO explores technologies to transform cellulosic and algal biomass into high-quality, stable, uniform, transportable feedstocks. It then assesses the impacts of these technologies on storage, transport, and feedstock performance.

Conversion Processes – Cost-shared projects improve processing and reduce costs by finding innovative ways to deconstruct biomass into sugars or bio-oil and subsequently upgrade them into fuels or products. The Energy Department provides cost-shared funds for the construction and start-up of integrated biorefineries that explore cost-effective pathways for the integrated production of biofuels and bioproducts.

KDF

U.S. DEPARTMENT OF ENERGY

The Bioenergy Technologies Office engaged national laboratory and university partners to develop this online, geospatial analysis tool for policymakers, researchers, and industry. The KDF is based on a geographic information system (GIS) that can generate tailored maps of complex geospatial data. The GIS and supporting tools enable users to easily visualize, analyze, and share scenarios for current and projected biomass production, conversion, distribution, and demand.

The Bioenergy Technologies Office

Mission

Develop and transform our renewable biomass resources into commercially viable, high-performance biofuels, bioproducts, and biopower through targeted research, development, demonstration, and deployment.

Strategic Goal

Develop commercially viable biomass technologies to enable sustainable, nationwide production of advanced biofuels that are compatible with today's transportation infrastructure and can reduce U.S. dependence on imported oil.

Cost Targets

2017:

Achieve a modeled pump price of $3.00 per gallon (2007 dollars) for renewable gasoline, diesel, and jet fuel

2022:

Model pathways to sustainably produce more than 1 billion gallons per year of cost-competitive algal biofuels

Photo: National Renewable Energy Laboratory (NREL)/16322

Next Generation: Advanced Hydrocarbon Fuels

Cellulosic Ethanol Paves the Way for the Next Generation of Biofuels

Over the past decade, the Bioenergy Technologies Office focused its RD&D on cellulosic ethanol, investing in technology advances throughout the supply chain. These activities successfully validated critical technologies for cellulosic ethanol production.

Knowledge gained through research on cellulosic ethanol directly helps accelerate technology advances for hydrocarbon fuels. The earlier research on cellulosic feedstock supply, pretreatment, and logistics has helped improve feedstocks for other advanced biofuels.

Similarly, technologies to break down biomass into bio-oils for further processing apply equally to the processing of advanced biofuels. The subsequent processing of intermediates and byproducts into useful bioproducts and chemicals also improves the value stream for advanced biorefineries.

In short, the Office's past work on cellulosic ethanol provides a valuable springboard for advances in the hydrocarbon biofuels that make up the current RD&D portfolio.

While the Office met its technical and cost goals for cellulosic ethanol in 2012 (see next page), it continues to support demonstrations of commercial-scale biorefineries producing this renewable fuel. These demonstration projects are expected to continue through 2014 to validate integrated systems of novel technologies, reducing technical and financial risks for future investors.

The Bioenergy Technologies Office focuses its current RD&D on high-risk biomass conversion pathways to produce advanced hydrocarbon fuels, such as renewable gasoline, diesel, and jet fuel.

Compatible with Existing Infrastructure

Hydrocarbon biofuels, also known as "drop-in" fuels, can serve as petroleum substitutes in existing refineries, tanks, pipelines, pumps, vehicles, and smaller engines—though their compatibility must still be confirmed. These fuels deliver more energy per gallon than ethanol. Conversion processes can also yield a range of co-products that can substitute for specialty petrochemicals, helping to replace the whole barrel of oil and enhancing the economic and environmental sustainability of biorefineries.

Expanding End-Use Markets

Infrastructure compatibility greatly expands the appeal of biofuels across markets. Biobased hydrocarbon fuels can help overcome concerns over fuel security and sustainability in all transportation sectors, including heavy road transport and aviation.

Advanced Hydrocarbon Fuels

Renewable Gasoline: Biogasoline is identical to its existing petroleum-derived counterpart—except that it is derived from domestic biomass and produces substantially fewer GHG emissions over its life cycle. *Photo: iStock/5417609*

Diesel: Sustainable diesel fuel alternatives are in demand by commercial shipping fleets, rail operators, manufacturers of heavy equipment, metropolitan transportation agencies, and the military. *Photos: iStock/13244613, 5037271, 1943391*

Jet Fuel: Bio-based jet fuels are identical to their petroleum-based counterparts yet help the aviation industry reduce its carbon footprint and insulate it from the price swings in traditional jet fuel. The Air Force plans to use biofuels for 50% of its domestic aviation needs by 2016. *Photo: iStock/17461860*

Next-Generation Biofuels

Current RD&D activities pursue the efficient, affordable, and sustainable conversion of domestic biomass feedstocks into the full range of fuels and products currently produced from a barrel of crude oil.

After a decade or more of research, BETO successfully demonstrated multiple systems for producing cellulosic ethanol at a competitive cost.

TODAY

FUTURE

Corn ethanol has not been the focus of any DOE research.

Corn ethanol is produced by a mature technology based on fermentation.

Cellulosic Ethanol

Benefits

- Energy security
- Abundant feedstocks
- Economic growth
- GHG reduction

2012 Goals Met

☑ Produced cellulosic ethanol at a modeled cost of less than $3.21 per gge.

- Conducted R&D to reduce the modeled conversion cost to $1.33 per gallon of ethanol.
- Reduced delivered cost for biomass to $0.49 per gallon of ethanol (about $35 per dry ton).

"Drop-In" Hydrocarbon Biofuels

Benefits

In addition to delivering or multiplying the benefits of cellulosic ethanol, hydrocarbon biofuels will be fully compatible with existing infrastructure and equipment, including diesel and jet engines.

2017 Goals

☐ Achieve modeled cost of $3 per gallon of gasoline equivalent (gge) for "drop-in" renewable gasoline, diesel, and jet fuel via pyrolysis pathway.

☐ Develop additional pathways to enable use of a variety of biomass types and conversion technologies in meeting the $3 per gge cost goal.

Feedstock Supply & Logistics

Toward Commodity Feedstocks

The Process Demonstration Unit at Idaho National Laboratory allows large-scale testing of new feedstock preconversion technologies. The goal is to sustainably provide biomass at a commodity scale within national cost targets. *Photo: INL*

The Bioenergy Technologies Office works with the U.S. Department of Agriculture (USDA), industry, universities, and other partners to expand and improve the supply of biomass as potential feedstocks for biofuels across the country. These efforts focus on the development of a range of sustainable feedstocks, including terrestrial and aquatic biomass, such as agricultural and forest residue, dedicated energy crops, municipal solid waste, and algae. The objective is to identify biomass varieties that require minimal water, fertilizer, land use, or other inputs. At the same time, feedstocks must provide high energy content, be easy to grow and harvest in large quantities, and be compatible with conversion processes. In addition, the Office conducts RD&D on the technologies and logistics needed to supply high-quality, stable, and infrastructure-compatible feedstocks from diverse biomass resources to biorefineries. This effort includes development of technologies for cost-effective harvest and collection, preprocessing, storage, and transport.

Terrestrial Feedstock Supply

DOE recently updated an analysis of the nation's biomass production potential. The 2011 *U.S. Billion-Ton Update:Biomass Supply for a Bioenergy and Bioproducts Industry*

Sustainable Feedstocks

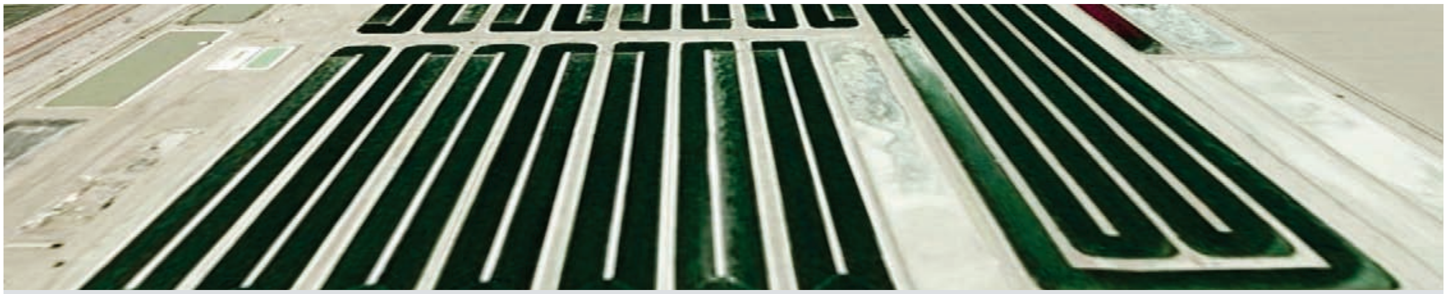
Agricultural Residues: Plant parts left in the field after harvest are commonly called agricultural residues. This plant matter and secondary residues like manure and food processing wastes can be useful feedstocks. *Photo: iStock/6710081*

Forest Residues: Leftover wood or plant material from logging operations, forest management, and land-clearing are available feedstock resources. Secondary residues like mill wastes supplement this category. *Photo: NREL/04190*

Energy Crops: Fast-growing trees and perennial grasses are specifically grown for energy uses. Trees and perennial grasses can often be grown on land that is less suitable for conventional crops and can stabilize the soil. These crops have high biomass production potential. *Photo: iStock/4373820*

Algae: Many macroalgae, microalgae, and cyanobacteria carry out photosynthesis to drive rapid biomass growth. Algae biomass can contain high levels of oil, making it a promising feedstock for biofuels, including renewable gasoline, diesel, and jet fuel. *Photo: NREL/01726, 19549*

Municipal Solid Waste: MSW has potential as a gasifier feedstock. Its near-term availability and pre-existing collection and transport infrastructure make it a particularly attractive resource. *Photo: iStock/14910937*



Algae are often grown in outdoor raceway ponds to ensure adequate exposure to sunlight. Research suggests biofuels from microalgae alone could displace 17% of today's transportation fuel imports. *Photo: Pacific Northwest National Laboratory (PNNL)*

found that with continued developments in biorefinery capacity and technology, the nation could potentially grow enough terrestrial biomass to produce about 85 billion gallons of biofuels—enough to replace approximately 30% of the nation's current petroleum consumption.

The Bioenergy Technologies Office has been working in partnership with the national land grant universities through the Sun Grant Initiative since 2008. The partnership has developed a national research structure that has established 110 research plots in 39 states to determine biomass yields as a function of site, climatic, and management factors across the United States.

The Office's national laboratory partners are also analyzing various feedstock species and optimizing plant systems to improve their tolerance to drought and poor soils. The objective is to make use of marginal or non-arable lands for feedstock production—improving sustainability.

This laboratory study has developed projections for the feedstock types and quantities that will become available at a range of costs through 2030. These projections are performed at the county level and support the emerging industry by delineating the timeline and potential costs for the development of feedstock resources.

Algal Feedstocks

Bio-oils, such as those obtained from algae, are promising feedstocks for advanced biofuels. Certain strains of aquatic microalgae make extremely efficient use of light and nutrients and are among the fastest-growing photosynthetic organisms. Moreover, more than half of the algae plant mass consists of the lipids or triacylglycerides that yield bio-oils.

Adding to the appeal, some strains of microalgae grow robustly in diverse environmental conditions, including brackish water, wastewater, and other lower-quality water resources. This capability has introduced the opportunity to couple the use of microalgae for biofuels production with environmental bioremediation. Microalgae naturally remove and recycle nutrients (e.g., nitrogen and phosphorous) from water and wastewater and can be used to sequester carbon dioxide from the flue gases emitted from fossil fuel-fired power plants. To guide RD&D on algal biofuels, the Office facilitated development of the *National Algal Biofuels Technology Roadmap* released in June 2010.

Algal Biofuels Consortia

The Bioenergy Technologies Office significantly expanded the scope of its technology RD&D for algae-based biofuels by creating the Algal Biofuels Consortia. This initiative created four public/private partnerships among universities, national laboratories, and industry to explore key facets of the algal biofuels supply chain. These partnerships were led by the Donald Danforth Plant Science Center, Arizona State University, the University of California at San Diego, and Cellana, LLC from September 2010 through August 2012. To build on their research, BETO awarded four new projects in 2012 (see inset).

Advancements in Sustainable Algae Production

In August 2012, BETO selected three projects to advance nutrient and water recycling in algal production and a fourth to develop regional algal technology testbeds.

- **California Polytechnic State University** to develop and demonstrate recycling of 75% or more of the water and nutrients used in algal biofuels production while maintaining the algae's stability and productivity. Part of this work will take place at a water treatment plant.
- **University of Toledo** to evaluate growing algae using the nutrients in dairy, municipal, and other wastewater and to test novel technologies for returning nitrogen and phosphorus for reuse in algae cultivation.
- **Sandia National Laboratories** to develop a novel, cost-effective process to liberate phosphorus and nitrogen from residual algal biomass, recycling them back to algae growth systems.
- **Arizona State University** to establish a sustainable network of regional testbeds, increasing access to high-quality cultivation facilities, downstream process equipment, and analytical and technical expertise. Long-term cultivation trials will enable comparison of promising strains and algal culture systems and processes across diverse conditions.

A pull-type forage harvester, tip wagons, and trucks stand ready for harvest at the edge of a switchgrass field. The harvester (scalable for commercial use) creates the bulk format, and the tip wagons and trucks collect the loose bulk format for transport to nearby storage. Bulk compaction increases the density of low-moisture switchgrass for transport over longer distances. *Photo: Al Womac*

Prepping the Feedstock

The Bioenergy Technologies Office is collaborating with industry to develop next-generation feedstocks that are optimized for conversion. Preparing these feedstocks entails three key processes:

Preconversion

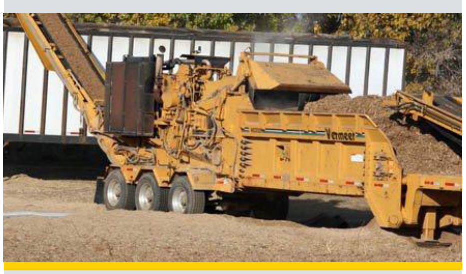
Mechanical treatments reduce feedstock size, providing fractionation and separation of the feedstock. Thermal and chemical processes manage moisture content, remove contaminants, and effect structural changes to improve digestibility and stability to reduce fouling or slagging in process equipment (such as gasifiers and boilers).

Formulation

Treated or untreated biomass is typically blended or mixed in specific proportions, often with biological or chemical additives to improve conversion efficiency.

Densification

Temperature and pressure are used to form and fix the chemical and mechanical bonds needed to produce a high-quality, high-density, stable feedstock for efficient handling, storage, and transport.



New technologies are reducing the cost of preparing biomass for conversion. *Photo: INL*

Logistics

The Bioenergy Technologies Office aims to successfully integrate the necessary steps and technologies to format and deliver diverse terrestrial feedstocks for efficient conversion. To assist producers, the Office has sponsored the redesign of crop harvesting machinery to collect agricultural residues while preventing erosion and preserving soil quality. Once the biomass has been harvested, new thermal and chemical treatments are applied to manage moisture content; remove contaminants; and improve feedstock quality, processing, and stability. These treatments also produce molecular and structural changes that enhance biomass performance during conversion processes.

To integrate the overall preparation (production, harvest, storage, transport, and pretreatment) of an advanced, uniform-format, feedstock supply, the Office is pursuing development of a system that links local biomass preprocessing depots to a network of supply terminals and, ultimately, biorefineries (see below). The goal is to successfully integrate time-sensitive feedstock collection, storage, and delivery operations into efficient, year-round supply systems that deliver consistently high-quality biomass.

Advanced Uniform-Format Feedstock Supply System

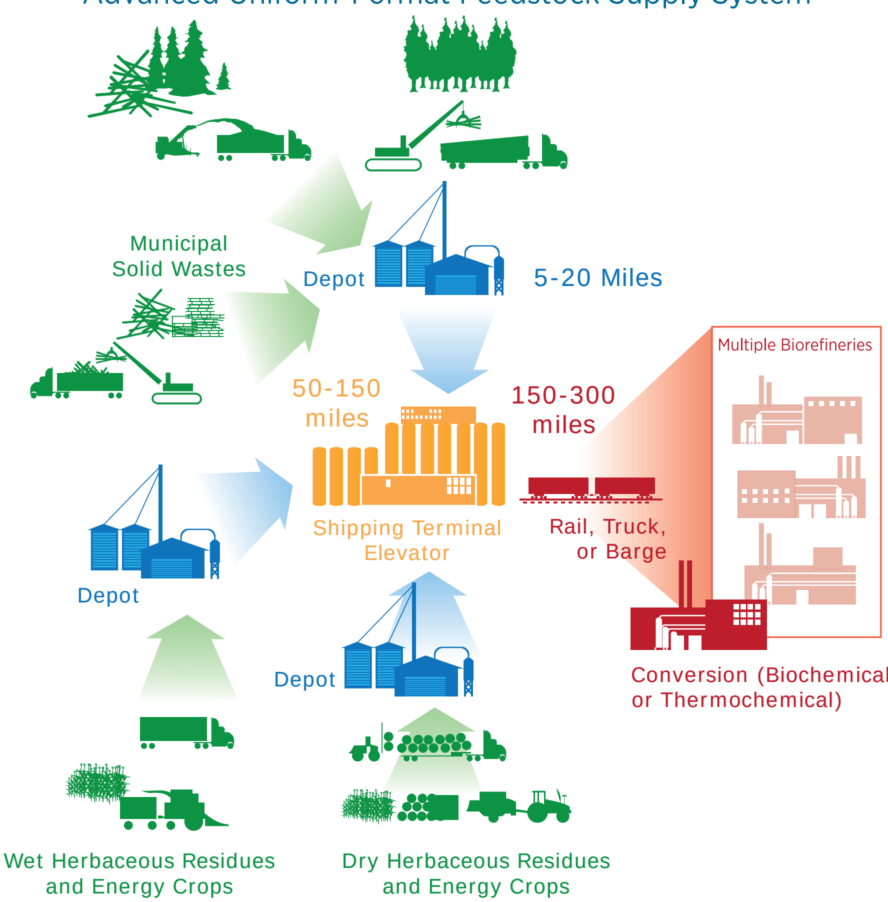
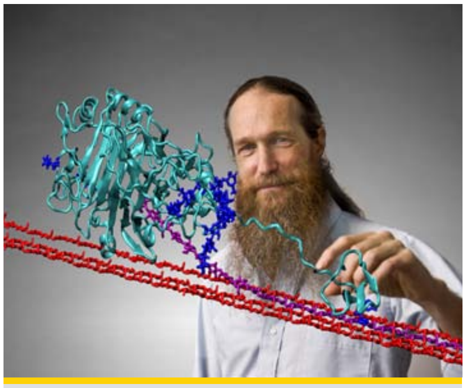


Illustration from BCS Inc.

After passing through the forage harvester, low-moisture switchgrass becomes a free-flowing bulk material that can be easily deposited in the receiving pit. Properly timed use of the forage harvester yields better particle size distribution and bulk flow than tub grinding of baled switchgrass. *Photo: Al Womac*

Conversion



The search for enzymes that efficiently break down the cell walls of plants (called cellulases) has led researchers to analyze the saliva of termites and leaf cutter ants, the intestines of large herbivores, and thousands of other candidate proteins. *Photo: NREL/15957*

Substantial development work is required to economically produce biofuels that are compatible with our existing vehicles and infrastructure. Federal investment can significantly accelerate progress in bringing these hydrocarbon biofuels to market.

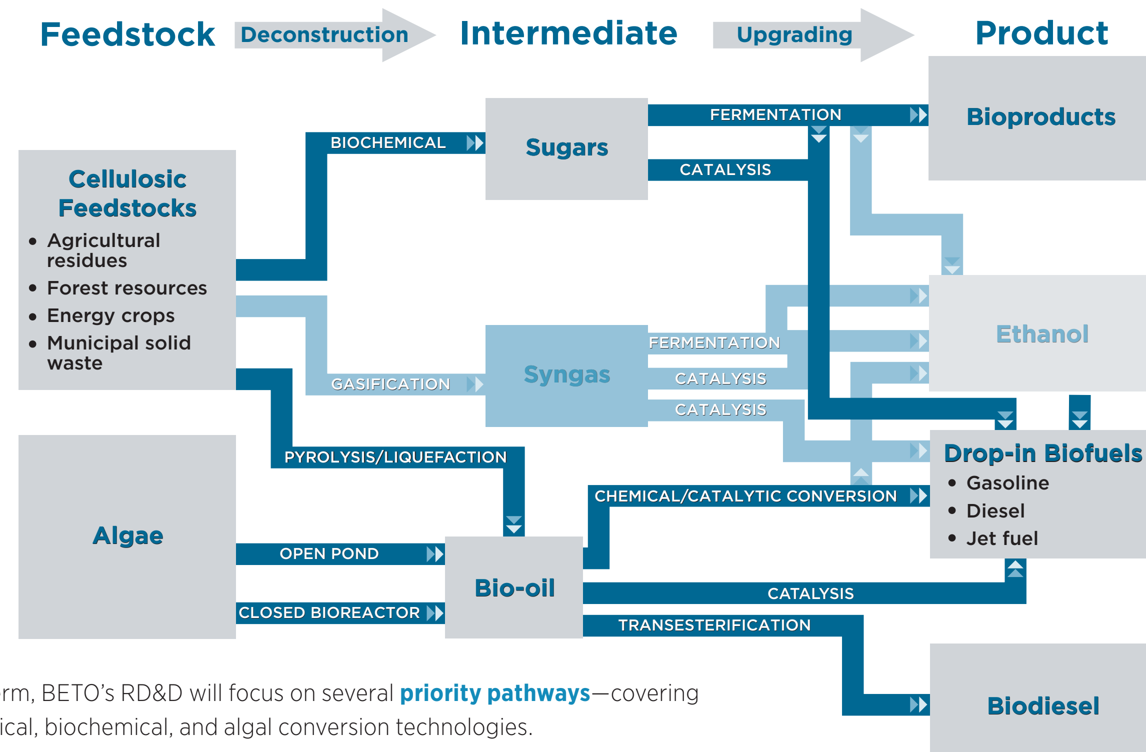
The Bioenergy Technologies Office's partnerships and projects emphasize high-risk efforts to increase the efficiency and lower the costs of key pathways for efficiently converting biomass into hydrocarbon fuels. As shown in the diagram below, the Office's conversion efforts focus primarily on pathways to deconstruct biomass into intermediates and subsequently upgrade them into biofuels and bioproducts. High-priority areas for further research include the following:

Feedstock pre-processing: High-quality lignocellulosic material must consistently meet the narrow specifications of target conversion processes.

Catalysis and biocatalysis efficiency: The enzymes and microorganisms that enable conversion of intermediates must be optimized for use with process streams derived from a wide variety of biomass feedstocks.

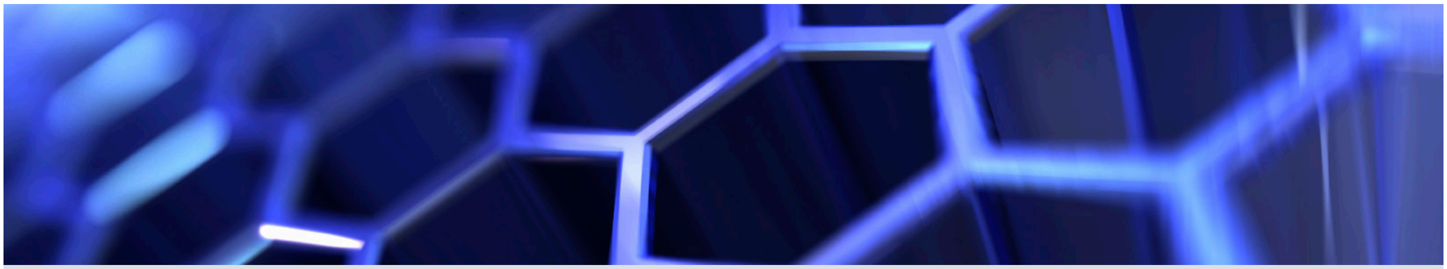
Separation science: Costs must be lowered for the multiple steps required to isolate desired products in complex mixtures.

Techno-economic analysis: Robust models are needed to integrate process design and cost analysis of current technologies.



In the near term, BETO's RD&D will focus on several **priority pathways**—covering thermochemical, biochemical, and algal conversion technologies.

The Bioenergy Technologies Office is concentrating high-value, high-risk RD&D on the key conversion pathways for deconstructing biomass into sugars and bio-oils and then upgrading those intermediates into advanced hydrocarbon fuels. *Chart by Energetics Incorporated*



New metabolic pathways will enable energy-efficient, biochemical conversion of woody (lignocellulosic) biomass into biofuels that are compatible with today's vehicles and infrastructure. *Photo: iStock/784883*

Sugars or Carbohydrate Derivatives

Deconstruction

Barriers to converting lignocellulosic biomass into sugars vary with the properties of the particular feedstock and the conversion approach used (bio-based/enzymes or chemical/catalytic processes).

Pretreatment and enzymatic saccharification: Pretreatment breaks down the cell walls, making lignocellulosic biomass accessible for the catalytic enzymes, microorganisms, and other catalysts to process it into sugars. Traditional pretreatment approaches alone result in predominately larger carbohydrates (or oligosaccharides) and solid residues. Subsequently or concurrently, these streams can be exposed to enzymatic or microbial processes that transform them into simple sugars (monosaccharides) ideal for downstream processing (e.g., fermentation or catalytic upgrading).

Non-enzymatic routes to carbohydrates: Non-enzymatic routes for producing sugar from lignocellulose typically require a mechanical system to deconstruct or fractionate a biomass slurry (in the presence of acid, base, or other reagents) under varying temperatures and pressures. Non-enzymatic methods offer the potential to rapidly hydrolyze biomass-based sugars yet impose the need to economically recycle reagents and develop a closed-loop system. Research focuses on the clean separation of organic and water layers, improved bulk solids separations, membranes and other materials that tolerate acid inhibitors, and mechanical separation systems.

Upgrading

Barriers to converting lignocellulosic intermediates into products vary with the properties of the streams resulting from the selected deconstruction process.

Microbial conversion of carbohydrates to biofuels: Many microorganisms naturally produce fatty acids and other energy-rich molecules directly from sugars and other carbohydrates. Such microbes can be engineered to efficiently express structurally tailored fatty acids, alcohols, esters, and other biofuel precursors. These precursors can then be extracted from the organism or its environment and upgraded to produce hydrocarbon biofuels. Barriers include efficient carbon utilization during bioconversion, lack of cost-efficient hydrocarbon product separation systems, inadequate understanding of biological conversion inhibitors, and ultimate acceptance of these fuel molecules.

Catalytic processes for converting carbohydrates to biofuels: Chemical conversion represents a relatively new route to hydrocarbon fuels—one that uses a wide range of sugars and sugar-derived intermediates. The formulation of these catalysts must consider the highly aqueous environment, which differs from that of classic thermochemical catalysts. Barriers are related to the feedstocks, catalysts, carbohydrate processing, and fuel production. This area could also include catalytic upgrading of alcohols (such as ethanol) to hydrocarbon fuels.

Sugar Upgrading:

Amyris is developing a pilot-scale production process for microbial fermentation and the subsequent chemical finishing of farnesene (a hydrocarbon intermediate) into renewable diesel fuel and chemicals. Amyris' bio-based diesel meets ASTM D975 standards and is registered with EPA as a 35% blend. This technology is on the pilot-ready track of the National Advanced Biofuels Consortium.
Photo: Amyris

Wood Waste to Gasoline:

Haldor Topsoe, Inc. is demonstrating an economical new thermochemical process for converting woody biomass and wood waste into gasoline. All feedstock wood comes from milling processes at UPM-Kymmene, a pulp and paper company. The pilot project is being conducted at the Gas Technology Institute's Gasification Testing Complex in Des Plaines, Illinois.
Photo: Haldor Topsoe, Inc.

Multidisciplinary teams are exploring novel routes to increase the quality and yield of bio-oils from diverse sources. *Photo: NREL/18070*

Sounding Out Biofuels:

Los Alamos National Laboratory received the RD&D 100 Award in 2010 for its **Ultrasonic Algal Biofuel Harvester**, a device that uses extremely high-frequency sound waves to efficiently extract oils and proteins from algae—separating out and recycling the water, all in one integrated system.

Photo: Los Alamos National Laboratory (LANL)

Bio-Oil Upgrading:

W.R. Grace & Company of Maryland is working with Pacific Northwest National Laboratory to develop a specialized catalytic reactor for upgrading bio-oils into gasoline, diesel, and jet fuel. The three-phase, fluidized reactor is designed to overcome reactor corrosion and poor catalyst life—two key barriers to successful bio-oil upgrading.

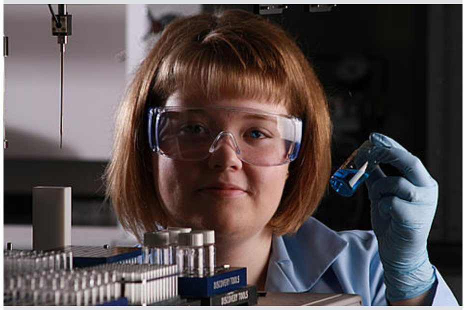


Photo: PNNL

Bio-Oils

Deconstruction

Bio-oils can be produced from various biomass feedstocks via pyrolysis or liquefaction processes. Some of these bio-oils can have high oxygen, organic acid, and moisture content. While high oxygen content and other destabilizing components can render bio-oils unsuitable for direct use as liquid fuels, these bio-oils can be stabilized and further upgraded to produce liquid hydrocarbon fuels and bioproducts. To enable further processing, the destabilizing components must be removed using chemical/catalytic conversion or separation techniques.

Engineering systems to produce bio-oils with desirable qualities will require a better understanding of pyrolysis (e.g., how lignin, hemicellulose, and cellulose in biomass thermally break down into simple monomers, how the inorganic content varies by biomass material, and how these factors impact bio-oil production and upgrading).

Bio-oils derived from algae are also of interest to the Bioenergy Technologies Office. Lipids from algae are similar to bio-oils from more conventional plant sources, so they do not require cleaning and stabilizing. The primary challenges in using algae as a feedstock are to increase the cost efficiency of its production, harvesting, and extraction.

Upgrading

Bio-oils may be converted to biofuels through hydrotreating, hydroprocessing, or hydrocracking (a form of hydrotreating that breaks molecules into smaller fragments). These processes can be performed in traditional refineries to leverage their economies of scale and the existing infrastructure, though this would likely require some modifications to either the bio-oil products or the refinery processes. Significant challenges in bio-oil upgrading include the following:

High-temperature solid-vapor separation: Researchers need a better understanding of high-temperature, solid-vapor separation, particularly as it applies to the scale-up of bio-oil technologies.

Hydrogen cost and supply: Catalytic hydrogenation (hydrotreating) is the leading candidate process for oil upgrading. Hydrogen is already used in refineries for this purpose, but the cost and logistics of hydrogen supply pose a challenge for distributed biomass-based systems. Promising options include improved processes for producing hydrogen from biomass and aqueous fractions of bio-oil.

Catalytic processing limitations: Inexpensive and robust processing systems will require heterogeneous catalysts that are resistant to fouling and offer a long service life. Studies of fouling and deactivation fundamentals are underway, as are catalyst discovery and process modifications to extend catalyst life.

Oxygen removal without hydrogen addition: Oxygen may be removed from bio-oil as water or carbon dioxide (CO_2). Unfortunately removing it as water requires hydrogen, and removing it as CO_2 lowers yield.

Fundamental studies related to upgrading: Information on catalyst performance and failure modes is not publicly available. Better understanding of these mechanisms will advance the technology.

To reduce the risks of new technology deployment, the Department works with industry to build and validate biorefineries, such as the one recently constructed by INEOS at Vero Beach. *Photo: INEOS*

Integrated Biorefineries

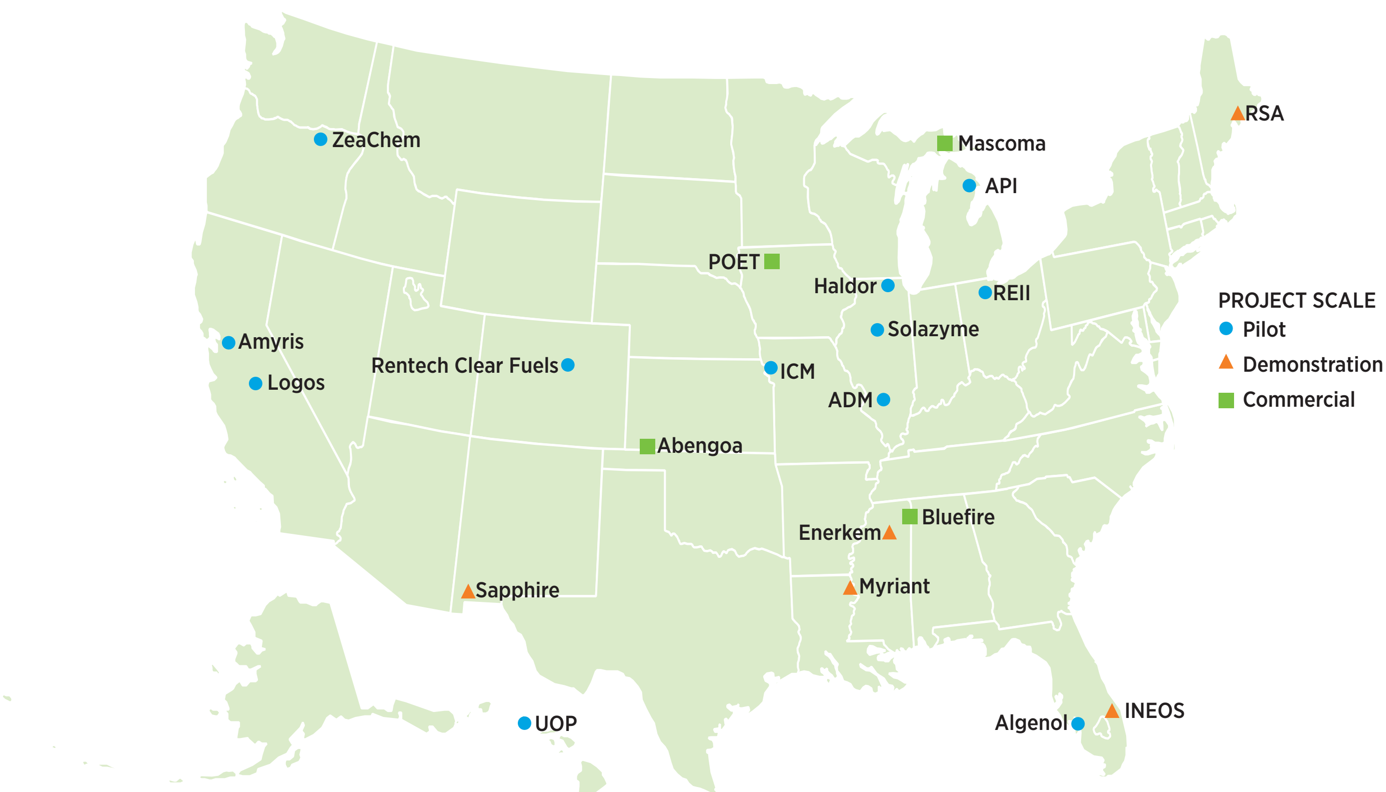
The Bioenergy Technologies Office works in partnership with industry to develop, build, operate, and validate integrated biorefineries at progressive scales (pilot, demonstration, and commercial). These biorefinery public-private partnerships are located around the country and use a range of non-food feedstocks and conversion technologies. Federal support for first-of-a-kind, integrated biorefineries can validate the costs and significantly reduce the technical and financial risks associated with new technology, thus accelerating growth in the U.S. bioindustry.

These biorefinery projects also offer a unique opportunity to leverage additional assets to resolve underlying technical challenges. The key product of these partnerships is operational data, which the Office uses to validate the cost and performance of the relevant technology. The partnerships must report on technical progress, including process flow diagrams, mass and energy balances, and process performance parameters by unit operation. They also provide financial data, including capital and operating costs, as well as sustainability metrics associated with the facility or system.

Clean, Renewable Diesel

ThermoChem Recovery International has tested and validated a thermal gasification and gas-to-liquids process for converting forest residue into diesel fuel and paraffin waxes, opening the door for full-scale commercialization. *Photo: NREL/00081*

Integrated Biorefinery Projects at Progressive Scales



Biorefineries can provide intermediate products to U.S. petroleum refineries as an alternative domestic resource. *Photo: iStock/784409*

Chemicals from Biomass

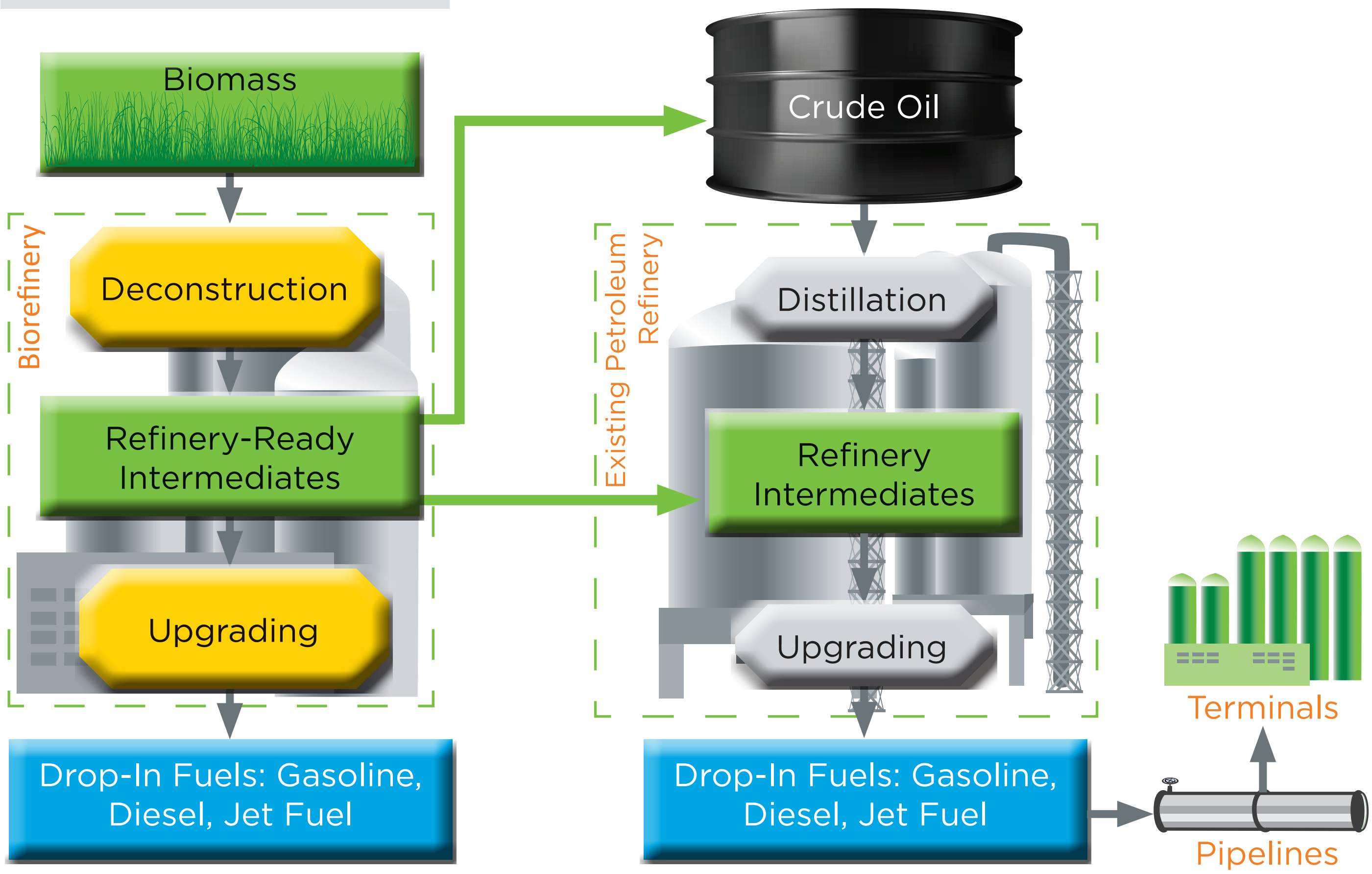
With support from the Energy Department, **Myriant Technologies, Inc.** is building a biorefinery in Louisiana to demonstrate technologies for the conversion of sorghum into succinic acid, an industrial chemical building block. *Photo: Myriant*

Integration with Traditional Petroleum Refineries

Successfully integrating biomass product streams for processing in traditional petroleum refineries would provide refineries with a secure, domestic feedstock source. Researchers are investigating the compatibility criteria for crude bio-oils, biofuel intermediates, and finished hydrocarbon biofuels at various insertion points. The goal is to produce biomass-based feeds that are identical (at the molecular level) to products now found in the traditional petroleum refining product chain.

For successful integration, the biomass feed streams will need to be low in oxygen, blend well with petroleum, and be free of contaminants that could poison the refinery catalysts or degrade the product. Bio-based insertion streams under study include:

- A bio-crude that can be co-processed with conventional crude oil
- Refinery-ready intermediates that are compatible with specific refinery streams for further processing at the refinery
- A near-finished fuel or blendstock that will be minimally processed at the refinery.



Biomass feed streams show potential as secure, domestic resources for integration into traditional petroleum refineries.

Sustainability

The emerging U.S. bioenergy industry must look beyond economic viability and market growth to address concerns about biological diversity, climate change, food security, and workforce. The Office works with its partners in industry, the national laboratories, and academia to enhance the benefits of bioenergy while mitigating concerns.

While there is broad agreement on the importance of sustainability, there is little consensus on the criteria for measuring it (definitions, approaches, system boundaries, and time horizons). BETO and its partners are developing the data to establish baselines, metrics, and targets. The Office conducts applied research and analysis to better understand and address sustainability issues in the following areas.

Environmental

Climate: Analyzing and reducing greenhouse gas (GHG) emissions associated with the production of biofuels

Air quality: Maintaining or improving air quality

Soil health and agronomics: Maintaining or improving soil quality and land productivity

Water quality and quantity: Increasing water use efficiency and maintaining or improving water quality

Biological diversity: Conserving plant and wildlife diversity

Land use: Minimizing adverse land-use changes

Economic

Efficiency and productivity: Ensuring efficient use and recovery of nonrenewable resources; maximizing conversion efficiency and productivity

Profitability: Improving cost competitiveness and net returns for all stakeholders along the supply chain

Workforce training and job creation: Assessing emerging opportunities and training requirements

Social

Energy diversification and security: Reducing dependence on foreign oil and increasing energy supply diversity

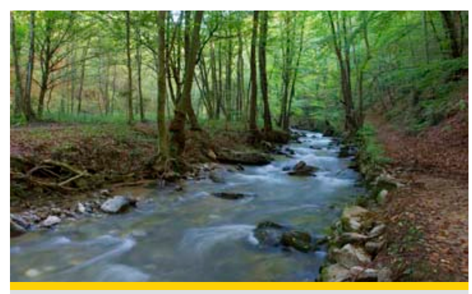
Energy access: Increasing access to affordable energy

Net energy balance: Demonstrating positive net energy balance relative to fossil fuels

Rural development and workforce training: Ensuring a trained workforce and promoting rural livelihoods

Food security: Reducing impacts on food access and prices.

The Bioenergy Technologies Office is committed to developing sustainable sources of renewable energy that displace fossil fuels, enhance energy security, promote environmental benefits, and create economic opportunities.
Photo: iStock/10392219



Sustainability Research

Sustainability indicators: To reflect major environmental effects of biofuels production, researchers at Oak Ridge National Laboratory have identified 19 measurable indicators for soil quality, greenhouse gases, biodiversity, air quality, water quality and quantity, and productivity.

National microalgae biofuel production potential: Based on a high-resolution assessment of microalgae production, researchers at Pacific Northwest National Laboratory found that, even with minimized water usage, biofuels from microalgae can displace 17% of today's transportation fuel imports.
Photo: iStock/4364622

Program Partnerships

Enzyme Combination Proves Powerful

NREL researchers have found that enzymes use two distinct mechanisms to break down biomass. Analysis suggests that the two systems may work together to deconstruct cell walls. Combining both types could dramatically improve catalysis efficiency–leading to less-expensive biofuels. *Photo: NREL/06047*

Pond Crash Forensics

By analyzing the susceptibility of open ponds to contamination and infection, researchers at Sandia National Laboratories have developed several technologies to help the algae industry guard against and recover from rapid losses in algae productivity (known as pond crashes). Sandia is making use of the testbed facility at Arizona State University to collect data and apply its technologies. *Photo: Steffan Schulz, Sandia National Laboratories*

Intra-Agency Partnerships

National Laboratories Working In Biomass

The U.S. Department of Energy's (DOE's) National Laboratories perform cutting-edge RD&D activities with diverse partners. This work includes many projects funded by the Bioenergy Technologies Office.

Argonne National Laboratory: Reaction engineering and separations, life cycle analysis

Idaho National Laboratory: Feedstock logistics technology

National Renewable Energy Laboratory: Biorefinery RD&D

Oak Ridge National Laboratory: Feedstock development and resource assessment

Pacific Northwest National Laboratory: Syngas, catalysis, and bioproducts

Sandia National Laboratories: Cellulosic and algal biofuels

The DOE Office of Science

The Office of Science conducts basic science research on biomass and biofuels to increase fundamental knowledge and expand the suite of tools available to the research community.

Advanced Biofuels Process Demonstration Unit (ABPDU)

The Department of Energy created this state-of-the art facility at Lawrence Berkeley National Laboratory to expedite the commercialization of advanced, next-generation biofuels by providing industry-scale testbeds. The facility includes bioreactors for the production of microbial or fungal enzymes, capabilities for fermentation or further conversion of sugars into advanced biofuels, and the capacity to purify these fuels. The Department's Bioenergy Research Centers are major users of the ABPDU.

Energy Frontier Research Center: Institute for Atom-Efficient Chemical Transformations (IACT)

The Office of Science established the IACT at Argonne National Laboratory to increase understanding of the chemistry involved in converting cellulose- and lignin-derived molecules to fuels and to identify the needed catalysts. In partnership with Northwestern University, Purdue University, and the University of Wisconsin-Madison, the work addresses key catalytic conversions that could improve the efficiency of fuel production and achieve the type of controlled and efficient chemical conversions found in nature. A major emphasis of IACT is to synthesize materials that offer new models for catalysis.

The Great Lakes Bioenergy Research Center uses genomic insights to develop bioenergy crops with improved cell-wall degradability, crop sustainability, and biomass and biofuel yields. *Photo: DOE Great Lakes Bioenergy Research Center*

The Office of Science created three Bioenergy Research Centers in 2007 to pursue the fundamental scientific breakthroughs needed to make cellulosic biofuels cost effective on a national scale. In 2013, following favorable evaluations by outside peer review teams, DOE renewed funding for these three centers so they might continue to move the science forward for another five years. In their first five years of operation, the three centers produced more than 1,000 peer-reviewed publications and more than 400 invention disclosures or patent applications.

Joint BioEnergy Research Center (JBEI)

Led by Lawrence Berkeley National Laboratory, JBEI researchers are engineering microbes and enzymes to process the complex sugars of lignocellulosic biomass into biofuels that can directly replace gasoline. Using synthetic biology, JBEI is developing new bioenergy crops to improve the fermentable content of biomass and transform lignin into a source of valuable new products.

BioEnergy Science Center (BESC)

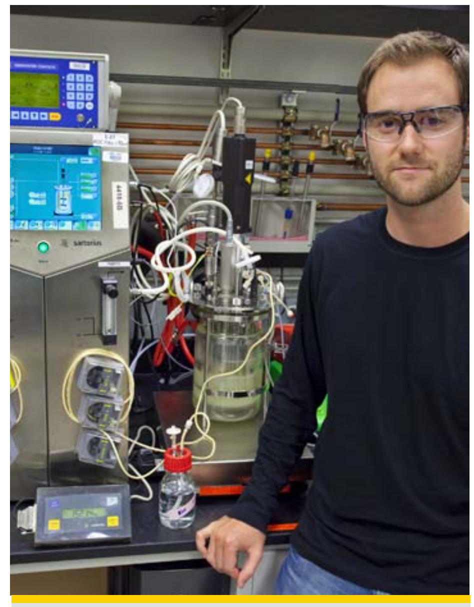
BESC, led by Oak Ridge National Laboratory, focuses on overcoming biomass recalcitrance—the resistance of cellulosic biomass to enzymatic breakdown into sugars. BESC approaches the problem by closely linking (1) plant research to make cell walls easier to deconstruct and (2) microbial research to develop biocatalysts tailor-made to produce biofuels from this modified plant material.

Great Lakes Bioenergy Research Center (GLBRC)

GLBRC is led by the University of Wisconsin–Madison in close partnership with Michigan State University. The GLBRC is exploring scientifically diverse approaches to converting sunlight and various plant feedstocks—agricultural residues, wood chips, and grasses—into biofuels. In addition to its broad range of research projects, the GLBRC is collaborating with agricultural researchers and producers to help develop the most economically viable and environmentally sustainable practices for bioenergy production.

Advanced Research Projects Agency-Energy (ARPA-E)

The Bioenergy Technologies Office regularly coordinates with ARPA-E, which shares information on its relevant projects. Of particular interest are projects in its Plants Engineered To Replace Oil (PETRO) Program, which seeks to optimize the biochemical processes of energy capture and conversion. ARPA-E conducts high-risk research to accelerate technology development from basic science to application.



Fuel Synthesis at JBEI

Researchers in JBEI's Fuels Synthesis Division are using the tools of synthetic biology to engineer new microbes that can quickly and efficiently ferment cellulosic sugars into transportation fuels and other valuable chemical products. *Photo: LBNL*

A growing number of vehicle fleets, including the Greater Peoria Mass Transit District, are switching to renewable biofuels. *Photo: NREL/02203*

DOE-USDA Competitive Grant Program

DOE and USDA jointly fund projects to improve the production of cellulosic energy crops for biofuels—by increasing their yield, quality, and ability to adapt to extreme environments. These awards continue a 2006 commitment to facilitate and accelerate the use of woody plant tissue for biofuels.
Photo: USDA

Vehicle Technologies Office

The Bioenergy Technologies Office partners with the Vehicle Technologies Office to support fuel characterization and combustion testing for novel biofuels and biofuel blends. Under this partnership, the Program also works with the Clean Cities Program on infrastructure expansion to facilitate biofuel deployment.

Fuel Cell Technologies Office

The Fuel Cell Technologies Office is exploring ways to produce hydrogen from a wide range of domestic resources, including sunshine and biomass. Significant research remains to develop this long-term technology.

Developing a sustainable U.S. biofuels industry requires coordination across organizations in government and the private sector.

Interagency Partnerships

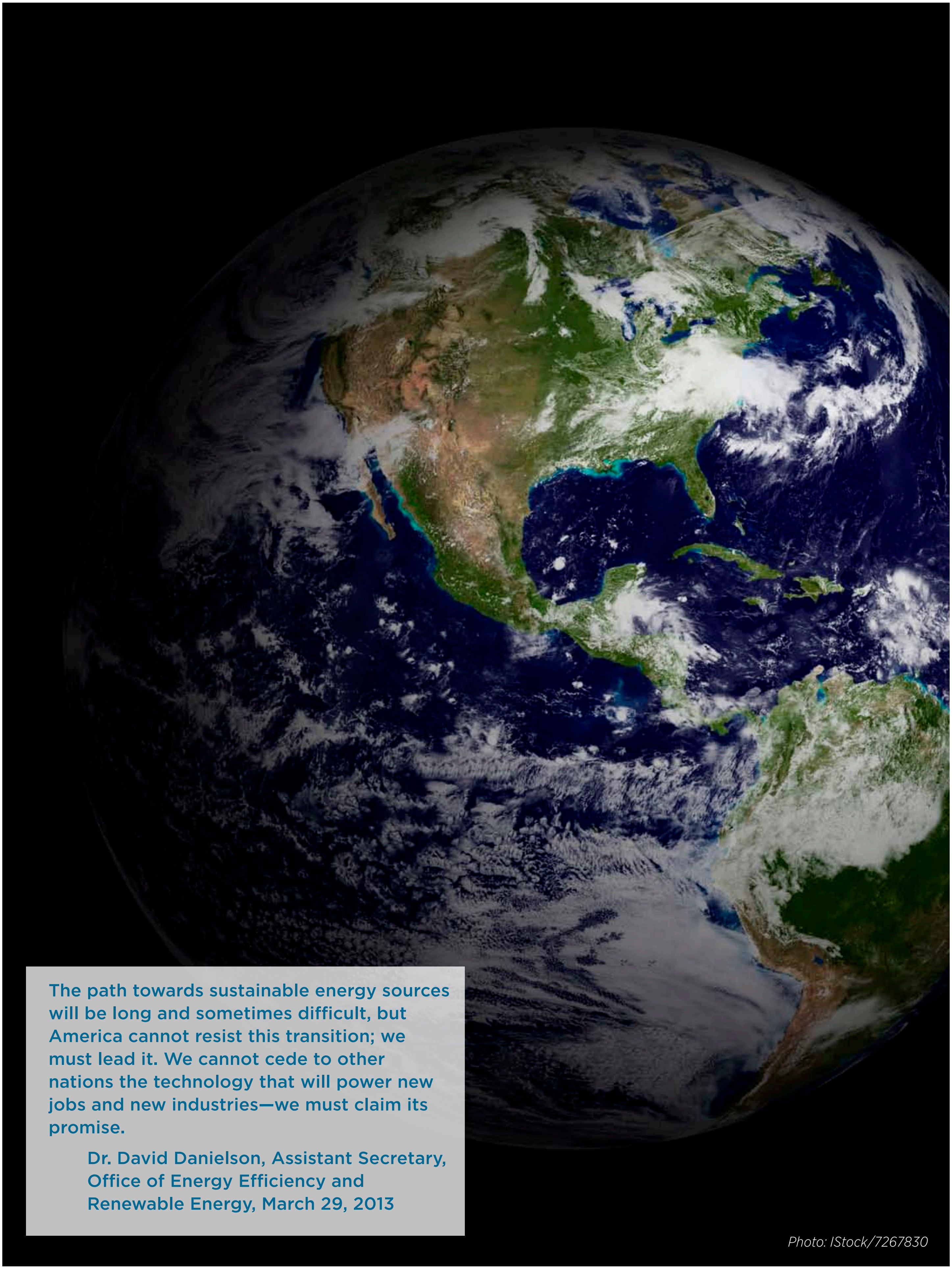
DOE works closely with USDA, the Environmental Protection Agency, the Department of Defense, the Department of Transportation's Federal Aviation Administration, and other departments and agencies to accelerate deployment and commercialization of biomass technologies.

Biomass Research & Development Board: DOE and USDA co-chair this council that coordinates federal RD&D programs to promote biofuels and bioproducts. It includes members from the Departments of Interior, Transportation, Defense, and the Environmental Protection Agency, the National Science Foundation, and the Office of Science and Technology Policy. In 2008, the Board released its National Biofuels Action Plan, outlining areas for interagency cooperation. The Board receives guidance from the Biomass RD&D Technical Advisory Committee, a group of 30 senior stakeholders from industry, academia, and state government.

USDA: DOE collaborates with USDA on the assessment and development of promising biomass feedstocks and the two entities annually issue a joint solicitation for RD&D projects.

EPA: BETO supports EPA activities as required to evaluate biofuel performance in various equipment or components of end-use markets.

U.S. Navy: BETO is working with USDA and the U.S. Navy in developing a public-private partnership to produce advanced drop-in aviation and marine biofuels to power military and commercial transportation.



The path towards sustainable energy sources will be long and sometimes difficult, but America cannot resist this transition; we must lead it. We cannot cede to other nations the technology that will power new jobs and new industries—we must claim its promise.

Dr. David Danielson, Assistant Secretary, Office of Energy Efficiency and Renewable Energy, March 29, 2013

Photo: IStock/7267830

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DOE/EE-0920 • July 2013

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