

**Examining Advancements in Biofuels Research:
Progress and New Directions for the Department of Energy
Bioenergy Research Centers**

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Chairman Biggs, Chairman Weber, Ranking Member Bonamici, Ranking Member Veasey, and Members of the Committees: Thank you for the opportunity to appear before you today. My name is Paul Gilna, and I am the Director of the BioEnergy Science Center (BESC) at the U.S. Department of Energy's Oak Ridge National Laboratory (ORNL) in Oak Ridge, Tennessee. It is an honor to provide this briefing today on the fundamental research in biofuels technology and the impact of federal research.

INTRODUCTION

ORNL is the Department of Energy's largest and most diverse science and energy laboratory. Our mission at ORNL is to deliver scientific discoveries and technological breakthroughs that will accelerate the research and development in solutions for clean energy and global security, thus creating economic opportunity for the nation. Our signature strengths in materials science and engineering, neutron science, nuclear science and engineering, and high-performance computing—the product of decades of investment by the nation—underpin an exceptionally broad set of core capabilities for delivering scientific leadership and discovery to address the Department's energy, environmental, and national security missions.

The Department of Energy (DOE) is the nation's only federal agency focused uniquely on energy-related research and development for clean energy innovation, nuclear security, and environmental stewardship of the nuclear weapons complex. DOE's history of providing the basic underpinnings for modern scientific breakthroughs has enabled important advances, from the advancement of nuclear energy for electricity, to the fracturing of shale for low-cost, reliable energy, to the sequencing of the human genome as a foundation for biotechnology.

DOE's Office of Science is the nation's largest funder of the physical sciences. Through its stewardship, science tools such as supercomputers and accelerators have become essential to explore materials and processes at the molecular level and to advance basic scientific understanding that can enable breakthrough technologies. The national laboratory system was

specifically designed for such research, and its capabilities are available to all who want to develop and scale basic science advances to the industrial level.

DOE's Office of Biological and Environmental Research

The Biological and Environmental Research (BER) programs within DOE's Office of Science support fundamental research to predict, manage, and control biological systems to support mission needs in bioenergy production, environmental remediation and stewardship, and understanding the environment. The operation of its unique scientific user facilities is critical to driving innovations in these areas for a secure energy future.

DOE has a long history of success in advancing biological and environmental research.

- The origins of this research trace back to the mission of DOE's predecessor agency, the Atomic Energy Commission.
- The advent of the Manhattan Project spurred scientists to understand the impacts of radiation fallout and byproducts of nuclear energy production on human health and the environment.
- Research originating from this mission has played a central role in advancing our understanding of the structure and function of DNA, and in 1986 prompted DOE to initiate the Human Genome Project which has become the foundation of genomic research including a host of practical applications in medical research, the biotechnology industry, and in the areas of agriculture and environmental protection.
- Acquired over decades, this historical knowledge and expertise is stewarded by the DOE Office of Biological and Environmental Research, and informs world-leading energy and earth systems research that it continues to support today.

THE U.S. ROLE IN LEADING BIOFUELS-RELEVANT FUNDAMENTAL RESEARCH

Bioenergy Research Centers

In 2007 during the Bush Administration, DOE-BER established three Bioenergy Research Centers (BRCs) to address the scientific challenges associated with achieving the cost-effective, sustainable, commercial production of fuels from cellulosic biomass—the fibrous woody and generally inedible portions of plant matter. A critical driver for the creation of these centers came from the findings of a DOE sponsored workshop that led to the report “Breaking the Biological Barriers to Cellulosic Ethanol.” The report summarized that “key to energizing a new biofuel industry based on conversion of cellulose... is to understand plant cell-wall chemical and physical structures—how they are synthesized and can be deconstructed. With this knowledge, innovative energy crops—plants specifically designed for industrial processing to biofuel—can be developed concurrently with new biology-based treatment and conversion methods.”

The BRCs were intended to leverage revolutionary breakthroughs in modern biological science, including those supported by the Genomic Science Program within BER. Each center sought to address a major, distinct bioenergy challenge:

- **BioEnergy Science Center** (BESC; Oak Ridge, Tennessee): to develop better understanding of how to modify plant cell wall components to facilitate deconstruction and conversion of biomass into biofuels by engineered highly-efficient microbes for advanced bioprocessing.
- **Great Lakes Bioenergy Research Center** (GLBRC; Madison, Wisconsin; Lansing, Michigan): to increase the energy density of grasses by understanding and manipulating the metabolic and genetic circuits that control the accumulation of easily digestible, energy-rich compounds in plant tissues.
- **Joint BioEnergy Institute** (JBEI; Emeryville, California): to apply synthetic biology to engineer microbes that convert sugars into advanced biofuels, and engineer plants that overproduce preferred polysaccharides.

The BRCs consisted of multidisciplinary teams involving many national lab, university, and industry partners. Together, these three centers represented the work of more than 1,000 scientists at partners located in 19 states.

PROGRESS FOR IMPROVED PRODUCTION OF CELLULOSIC BIOFUELS

The Bioenergy Research Centers have made significant progress in their goal to understand the fundamental science of cellulosic ethanol production as part of the three strategy areas. This same understanding has provided the foundation for the future development and production of advanced biofuels, and other, high-value, bio-based products.

1. *Develop next-generation bioenergy crops by unraveling the biology of plant development*
In pursuit of better biomass crops, the BRCs have examined plant cell wall structure and biosynthesis at the molecular level to better understand recalcitrance, or the natural resistance of plants to being broken down for fermentation. It is a key economic barrier, adding cost and decreasing energy yield. Scientists have used genetic engineering to select favorable variants that result in lower recalcitrance and improved biomass characteristics.
2. *Discover and design enzymes and microbes with novel biomass-degrading capabilities*
The BRCs have developed the most promising microbes, enzymes, and solvents for breaking down biomass into usable compounds such as sugars and conversion, leveraging their expertise in genetics, biochemistry, and other disciplines to select the best traits from other organisms and engineer them into commercially robust organisms. These microbes, enzymes, and solvents seek to lower the use of costly pretreatments and chemicals used in current biorefining.

3. *Develop transformational microbe-mediated strategies for advanced biofuels production*
BRC researchers have developed a combination of methods and microbes to best produce biofuels. Advances have been made in engineering microbes to more efficiently convert plant biomass into biofuels. These breakthroughs result in a less costly process for converting plants into useful products.

The **BioEnergy Science Center (BESC)** led by ORNL, has made crucial progress toward understanding, manipulating, and managing plant cell wall recalcitrance and conversion. Notably, the BESC team has proven that multiple genes control plant cell wall recalcitrance and furthermore, that manipulation of these genes has the potential to yield perennial bioenergy feedstocks with enhanced deconstruction properties—that is, that the sugars entrapped in the cell wall structures can be released more efficiently. Further, BESC has successfully demonstrated the ability to combine the processes of cellulose digestion and fermentation of released sugars into biofuel in a single microbial organism. These discoveries represent significant progress toward the goal of developing improved feedstocks and microbial deconstruction methodologies for advanced biofuel production.

At BESC, to improve bioenergy feedstocks, ORNL and its partners have built upon the work done to sequence the genome of *Populus*—a fast-growing perennial tree recognized for its potential in biofuels production—and have conducted the largest-ever study of natural diversity in these poplar trees. These achievements allow scientists to better find and select desirable traits like drought tolerance and lower resistance to processing. This work has led to the licensing of a number of genes that will be used by industry in the development of more easily digestible animal feed and biofuel feedstocks.

The **Great Lakes Bioenergy Research Center (GLBRC)** led by the University of Wisconsin and Michigan State University, has established a fundamental understanding of nitrogen and carbon cycling in the field, which is essential for creating sustainable biofuel landscapes. In the lab, GLBRC has pursued economic sustainability via biological and chemical routes to low-cost sugars. More recently, researchers have developed unique pretreatment methods that release lignin for potential conversion to fuel precursors and value-added co-products. Producing fuels and chemicals from both the sugar and lignin components of plant biomass offers added value and increases the profitability of cellulosic biofuels.

As an example, to improve biomass conversion, GLBRC scientists modified the lignin biosynthetic pathway to enable design of plant cell walls that are easier and cheaper to convert into fuels and chemicals. In addition, they have shown how marginal lands can provide significant cellulosic biomass, along with substantial environmental benefits, allowing fertile lands to be reserved for food production.

The **Joint BioEnergy Institute (JBEI)** led by Lawrence Berkeley National Laboratory, has used the latest tools in molecular biology and chemical engineering, including computational and robotic technologies, to transform biomass sugars into energy-rich fuels. JBEI has successfully altered biomass composition in model plants and crops, reducing inhibitors that impact downstream processing and making lignin more readily converted into useful chemicals. JBEI research has shown that new solvents, such as ionic liquids, permit near-complete dissolution of plant biomass, thereby facilitating its enzymatic conversion to sugars. JBEI's pioneering work in synthetic biology has enabled microbes to produce a variety of molecules from these sugars that can serve as jet, diesel, and gasoline blendstocks.

JBEI scientists, for example, to improve biosynthesis of new fuels, have worked on three biosynthetic pathways to produce drop-in fuel chemicals. Fatty acid biosynthetic pathways have been engineered to produce long hydrocarbon chains that can be utilized as diesel and jet fuels as well as surfactants and lubricants. The team has also engineered new biosynthetic pathways into microbes to digest pretreated biomass and to use the liberated sugars to produce a jet fuel precursor chemical.

In all, the three BRCs have produced 607 invention disclosures, 378 patent applications, 191 licenses or options, and 92 patents over the past decade, as well as 2,630 peer-reviewed publications. Thus, the centers have openly transferred their knowledge and data to the scientific community, and through their intellectual property activities have transferred substantial insight and expertise that is being translated into applications by the commercial biofuels industry.

MOVING TOWARD BIOPRODUCTS FROM BIOMASS: THE NEXT GENERATION OF BIOENERGY RESEARCH CENTERS

DOE-BER has recently announced the establishment of four new centers in order to build upon the underlying knowledge provided by the BRCs and to lay the scientific groundwork for a new robust bio-based economy. They will be focused on a new generation of sustainable bioproducts from non-food biomass—chemicals that can be made from plants that would otherwise come from petroleum refining. In addition, the centers will pursue the development of cost-effective specialty biofuels, i.e. advanced biofuels beyond ethanol that can serve as replacements to conventional petroleum and that can utilize the existing infrastructure.

The multi-institutional centers include research partners stretching across 25 states: Alabama, California, Colorado, Florida, Georgia, Idaho, Illinois, Iowa, Louisiana, Massachusetts, Michigan, Mississippi, Nebraska, New Hampshire, New Jersey, New Mexico, New York, Oklahoma, Pennsylvania, South Carolina, Tennessee, Texas, Washington, West Virginia, and Wisconsin.

Center for Bioenergy Innovation (CBI), led by ORNL

The vision for CBI is to accelerate domestication of bioenergy-relevant plants and microbes to enable high-impact, value-added co-product development at multiple points in the bioenergy supply chain. Conceived to foster a legacy of fundamental scientific understanding, enabling capabilities, and transformative innovations, CBI has identified research targets to overcome key barriers for a robust bioeconomy in (1) high-yielding, robust feedstocks, (2) lower capital and processing costs via consolidated bioprocessing to specialty biofuels, and (3) methods to create valuable byproducts from lignin residues.

Great Lakes Bioenergy Research Center (GLBRC), led by the University of Wisconsin-Madison and Michigan State University

Developing sustainable ways to produce the transportation fuels and products that are currently derived from petroleum is among society's greatest challenges. GLBRC envisions a future in which specialty biofuels and bioproducts derived from dedicated bioenergy crops can provide alternatives to those produced today. This approach will provide substantial environmental benefits and expanded economic opportunities for biofuel refiners, farmers, and communities. GLBRC will help realize this vision through research to address identified knowledge gaps in the production of specialty biofuels and bioproducts from dedicated bioenergy crops that are grown specifically on marginal, non-agricultural, lands.

Joint BioEnergy Institute (JBEI), led by DOE's Lawrence Berkeley National Laboratory

The vision of JBEI's follow-on phase is that bioenergy crops can be converted into economically viable, carbon-neutral biofuels and renewable chemicals currently derived from petroleum, and many other bioproducts that cannot be efficiently produced from petroleum. Providing a new source of domestic energy and feedstock chemicals from U.S. crops would further expand and diversify the US energy portfolio. JBEI's mission is to establish the scientific knowledge and new technologies in feedstock development, deconstruction and separation, and conversion needed to transform the maximum amount of carbon available in bioenergy crops into biofuels and bioproducts. When fully scaled, JBEI's technologies will enable the production of replacements for petroleum-derived gasoline, diesel, jet fuel, and bioproducts.

Center for Advanced Bioenergy and Bioproducts Innovation (CABBI), led by the University of Illinois at Urbana-Champaign

CABBI's vision is founded on the "plants as factories" paradigm, in which biofuels, bioproducts, and foundation molecules for direct application or conversion are synthesized directly in plant stems. CABBI will develop the predictive capability to determine which feedstock combinations, regions and land types, market conditions, and bioproducts have the potential to support diverse and ecologically and economically sustainable displacement energy options. CABBI represents a transformative research model designed to accelerate bioproduct development while retaining the flexibility to assimilate new disruptive technologies — whatever their source.

BIOREFINERIES OF THE FUTURE

In much the same way that petroleum refineries are situated where crude oil is either imported or produced in the United States, biorefineries could one day sit in rural areas, providing vital economic growth and a clean, reliable, supply of fuels and other useful products for the nation.

In this reality, fields and forests of specialty, nonfood crops are planted on underutilized lands—even lands deemed unsuitable for food crops. Farmers grow and harvest the crops, which are transported to nearby biorefineries where workers oversee modern, efficient methods to break down and process 100% of that biomass into bioproducts. There are no leftovers; even residues are converted to valuable specialty chemicals. Pipelines, trucks, and railroads transport biofuels to existing infrastructure where they are either blended with other fuels or distributed for direct use in vehicles and power plants.

Non-fuel bioproducts are likewise shipped to companies eager for new sources of specialty chemicals to meet the demand for high-value downstream products like electronics, polymers, and cosmetics. Robust, domestic production of specialty biochemicals means companies no longer must move overseas to access cheap petroleum-based feedstocks.

At ORNL, we are working to enable this diverse energy future by demonstrating more uses for bioproducts. Already, we have successfully used plant-based material developed at the lab to demonstrate advanced manufacturing using 3D printing of complex structures. For example, we have demonstrated that lignin and other bioderived materials can be converted directly into carbon fiber or its chemical precursors, which could then be used in applications such as lighter components for more fuel-efficient cars and airplanes.

CLOSING REMARKS

Federal leadership in scientific research has resulted in substantial progress toward a better understanding of the fundamentals behind the biofuels production process. That progress will continue with the new generation of BRCs, focused on new bioproducts and advanced biofuels. We have demonstrated that improvements in plants, microbes, and processes can lead to more efficient production of domestic biofuels, further diversifying the nation's portfolio of reliable, clean energy and making possible a new menu of bioproducts.

Currently, the U.S. is the leader in both research, development and deployment of the rural bio-based economy. However, others are accelerating their efforts. Together, we can succeed in bringing the best of our nation's scientific understanding and engineering prowess to bear on deploying the next generation of bioproducts and clean energy technologies for strengthening our economic foundation, U.S. competitiveness, and our way of life.

Thank you again for the opportunity to provide this briefing. I welcome your questions on this important topic.