BIOENERGY RESEARCH AND DEVELOPMENT FOR THE FUELS AND CHEMICALS OF TOMORROW

HEARING

BEFORE THE

SUBCOMMITTEE ON ENERGY

OF THE

COMMITTEE ON SCIENCE, SPACE, AND TECHNOLOGY

OF THE

HOUSE OF REPRESENTATIVES

ONE HUNDRED SEVENTEENTH CONGRESS

SECOND SESSION

MARCH 16, 2022

Serial No. 117–48

Printed for the use of the Committee on Science, Space, and Technology

Available via the World Wide Web: http://science.house.gov

U.S. GOVERNMENT PUBLISHING OFFICE

47–058PDF WASHINGTON : 2022

CONTENTS

March 16, 2022

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WEDNESDAY, MARCH 16, 2022

HOUSE OF REPRESENTATIVES,
SUBCOMMITTEE ON ENERGY,
COMMITTEE ON SCIENCE, SPACE, AND TECHNOLOGY,
Washington, D.C.

The Subcommittee met, pursuant to notice, at 10:30 a.m., in room 2318 of the Rayburn House Office Building and via Zoom, Hon. Sean Casten presiding.

House Committee on Science, Space, and Technology
Energy Subcommittee

Bioenergy Research and Development for the Fuels and Chemicals of Tomorrow
Wednesday, March 16, 2022
10:30AM ET

The purpose of this hearing is to examine the status of bioenergy research, development, and demonstration (RD&D) activities carried out by the U.S. Department of Energy. The hearing will also consider advancements in bioenergy research and the potential role of this resource in a cleaner energy transition. Lastly, the hearing will help inform future legislation to support and guide the U.S.'s bioenergy RD&D enterprise.

Witnesses

- Dr. Jonathan Male, Chief Scientist for Energy Processes and Materials, Pacific Northwest National Laboratory (PNNL)
- Dr. Andrew Leakey, Director of the Center for Advanced Bioenergy and Bioproducts Innovation at the University of Illinois Urbana-Champaign
- Dr. Laurel Harmon, Vice President of Government Affairs, LanzaTech
- Dr. Eric Hegg, Professor, Biochemistry and Molecular Biology, Michigan State University

Background

Previous societies have used biomass energy—energy from living organic materials—since the earliest humans made wood fires for cooking and heating. Centuries later, the first commercially used biomass gasifier was built in France in 1840, and in 1880, Henry Ford used ethanol to fuel his first automobiles, the quadricycle.[1] Today, through the advancement of biomass technologies, biomass is used to produce transportation fuels, heat, electricity, and products.[2] In the United States, 4.7% of energy consumed currently comes from this resource, making biomass the second largest source of clean energy in the nation, after nuclear energy, as well as the largest source of renewable energy.[3]

Recent Intergovernmental Panel on Climate Change (IPCC) reports conclude that bioenergy has significant potential to mitigate GHGs if resources are sustainably developed, and efficient technologies are applied.[4] The IPCC adds that through improvements of existing technologies and the development of new technologies, biomass could meet its potential as a major resource of clean energy production and thus deliver significant GHG mitigation performance at approximate 80 to 90% reduction compared to current fossil energy products. To achieve this level of mitigation performance, additional RD&D of conversion technologies and current

[1] https://www.energy.gov/eere/bioenergy/bioenergizeme-virtual-science-fair-biomass-history-timeline
[2] https://www.energy.gov/eere/bioenergy/bioenergy-basics#:~:text=Bioenergy%20is%20one%20of%20many,heat%2C%20electricity%2C%20and%20products.
[3] https://www.eia.gov/energyexplained/renewable-sources/
[4] https://www.ipcc.ch/site/assets/uploads/2018/03/Chapter-2-Bioenergy-1.pdf

feedstock systems is needed, as well as future feedstock options including perennial crops, forest products, and biomass residues and wastes.

Bioenergy may have an important role to play in enabling the clean energy transformation of hard-to-abate sectors such as cement, chemicals, aviation, and shipping. This is because biomass covers a large range of biomaterial with diverse chemical composition and properties, thus making it a highly versatile resource suitable for many applications that can be stored under multiple forms, including gaseous, liquid, or other molecules via conversion processes.[5]

Types of Biofuels

Ethanol

Ethanol is an alcohol used as a blending agent with gasoline to increase octane. The most common blend of ethanol is E10 (10% ethanol, 90% gasoline) and is approved for use in most conventional gasoline-powered vehicles up to E15 (15% ethanol, 85% gasoline). Some vehicles, called flexible fuel vehicles, are designed to run on E85 (a gasoline-ethanol blend containing 51%–83% ethanol, depending on geography and season), an alternative fuel with much higher ethanol content than regular gasoline. Approximately 97% of gasoline in the United States contains ethanol.[6]

Most ethanol is made from corn starch in the United States, but scientists are continuing to develop technologies that would allow for the use of cellulose and hemicellulose, the non-edible fibrous material that constitutes the bulk of plant matter.[7]

Biodiesel

Biodiesel is a liquid fuel produced from renewable sources, such as new and used vegetable oils and animal fats and is a cleaner-burning replacement for petroleum-based diesel fuel. Like petroleum-derived diesel, biodiesel is used to fuel compression-ignition (diesel) engines. Biodiesel can be blended with petroleum diesel in any percentage, including B100 (pure biodiesel) and, the most common blend, B20 (a blend containing 20% biodiesel and 80% petroleum diesel).[8]

Renewable Hydrocarbon "Drop-In" Fuels

Petroleum fuels, such as gasoline, diesel, and jet fuel, contain a complex mixture of hydrocarbons (molecules of hydrogen and carbon), which are burned to produce energy. Hydrocarbons are also produced from biomass sources through a variety of biological and thermochemical processes. Biomass-based renewable hydrocarbon fuels, also known as green or

[5] https://www.energy-transition-institute.com/insights/biomass-to-energy

[6] https://afdc.energy.gov/fuels/ethanol.html

[7] https://energy.wisc.edu/education/for-educators/educational-materials/why-it-so-difficult-create-cellulosic-ethanol

[8] https://afdc.energy.gov/fuels/biodiesel.html

drop-in biofuels, are nearly identical to the petroleum-based fuels they are designed to replace—thus making them compatible with today's engines, pumps, and other infrastructure.

Renewable hydrocarbon fuels are produced from non-food biomass, such as perennial grass. The processes to make these fuels are more complex and less well developed than those for first-generation biofuels (conventional ethanol and biodiesel), and often involve converting fibrous non-edible material called "cellulose" into fuel.

Types of renewable hydrocarbon biofuels include:

- Renewable diesel (differs from conventional biodiesel)
- Green Gasoline
- Sustainable Aviation Fuels

Sustainable Aviation Fuels

One area of significant promise for biofuels is within the aviation sector. Data from 2019 showed that taking a long-haul flight generates more carbon emissions than the average person in dozens of countries around the world produces in an entire year[9], and a large aircraft, such as a Boeing-747, consumes about 4 liters of aviation fuel per second.[10]

The environmental impact of continued dependence on fossil fuel-derived jet fuel has spurred international efforts in the aviation sector toward alternative solutions, most recently culminating in a pledge of the global air transportation industry to achieve net-zero emissions by 2050. The International Air Transport Association estimates that to meet this emissions reduction goal, the industry must abate a cumulative total of 21.2 gigatons of carbon between now and 2050.[11]

Given the limited options for decarbonization, sustainable aviation fuels (SAF) are viewed as one of the nearest term options for the hard-to-abate sector. SAF possesses similar properties to conventional jet fuel and, depending on the feedstock and technologies used to produce SAF, the fuel can significantly reduce lifecycle GHG emissions as compared to conventional jet fuel. Some emerging SAF pathways are even targeting a net-negative GHG footprint.[12]

SAF Pathways

There are seven SAF "pathways" or fuel categories that have been approved under the American Society for Testing and Materials (ASTM) standards. The SAF volumes of each pathway must be blended with conventional aviation turbine fuel before they are certified as being equivalent and subsequently used in aircrafts.[13]

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[9] https://www.theguardian.com/environment/ng-interactive/2019/jul/19/carbon-calculator-how-taking-one-flight-emits-as-much-as-many-people-do-in-a-year
[10] https://simpleflying.com/jet-aircraft-fuel-consumption/
[11] https://www.iata.org/en/pressroom/2021-releases/2021-10-04-03/
[12] https://www.nrel.gov/news/program/2021/from-wet-waste-to-flight-scientists-announce-fast-track-solution-for-net-zero-carbon-sustainable-aviation-fuel.html
[13] https://afdc.energy.gov/fuels/emerging_hydrocarbon.html

One noted barrier to greater SAF adoption is cost. SAF currently costs four times as much as conventional jet fuel and makes up less than one percent of fuel available in the market. Increasing its cost-competitiveness with petroleum-based fuels is seen as essential since fuel makes up about 30% of the operating cost of an airline.[14]

In response to the barriers to greater SAF adoption, DOE, DOT, and USDA created the Federal SAF Grand Challenge, a government-wide Memorandum of Understanding (MOU) that will attempt to reduce the cost, enhance the sustainability, and expand the production and use of SAF. The MOU also strives to achieve a minimum of a 50% reduction in life cycle GHG emissions compared to conventional jet fuel; and meet a goal of supplying sufficient SAF to meet 100% of aviation fuel demand by 2050.[15]

Bioproducts

In addition to fuels, biomass can be used to create valuable chemicals and materials, known as "bioproducts." Approximately 16% of U.S. crude oil consumption is used to make petrochemicals and products, such as plastics for industrial and consumer goods, fertilizers, and lubricants. According to the IEA, 2018 CO_2 emissions from the chemical sector were 1.5 gigatons or 18% of industrial CO_2 emissions.[16]

Common biobased products include:

- Household cleaners
- Paints and stains
- Personal care items
- Plastic bottles & containers
- Packaging materials
- Soaps & detergents
- Lubricants
- Clothing
- Building materials

The production of bioproducts relies on much of the same feedstocks, infrastructure, feedstock commoditization, and technologies that are central to biofuels production. Therefore, according to the Department of Energy, once technologies are proven for bioproduct applications, they could be readily transferred and greatly improve biofuel production.[17]

DOE Bioenergy R&D Programs

Bioenergy Technologies Office

[14] https://www.energy.gov/sites/prod/files/2020/09/f78/beto-sust-aviation-fuel-sep-2020.pdf
[15] https://www.energy.gov/eere/bioenergy/sustainable-aviation-fuel-grand-challenge
[16] https://www.iea.org/reports/the-future-of-hydrogen
[17] https://www.energy.gov/eere/bioenergy/bioproduct-production

The U.S. Department of Energy's (DOE's) Bioenergy Technologies Office (BETO) supports research, development, and demonstration of technologies to enable the sustainable use of domestic biomass and waste resources to produce biofuels and bioproducts.[18]

The five BETO program areas are:

- **Advanced Algal Systems** - supports research and development to lower the costs of producing algal biofuels and bioproducts.[19]
- **Conversion Technologies** - supports research and development in technologies for converting biomass feedstocks into finished liquid transportation fuels, co-products or chemical intermediates, and biopower.[20]
- **Data, Modeling, and Analysis** - supports research, analysis, and tool development to address the economic and environmental dimensions of bioenergy and bioproducts. [21]
- **Feedstock Technologies** - focuses on technologies and processes that transform renewable carbon sources into conversion-ready feedstocks.[22]
- **Systems Development and Integration program** - focuses on lowering the risk of bioenergy production technologies through verified proof of performance at the pre-pilot, pilot, and demonstration-scales. [23]

Biological Systems Science

Bioenergy research is now a principal focus in the DOE Office of Science's Biological and Environmental Research (BER) program. BER's Biological Systems Science Division's (BSSD) research focuses on integrating discovery and hypothesis-driven sciences with technology development to study plant and microbial systems relevant energy production and storage. BSSD defines systems biology as the "multidisciplinary study of complex interactions specifying the function of entire biological systems—from single cells to multicellular organisms—rather than the study of individual isolated components."[24] Research areas within the division include genome sequencing, proteomics, metabolomics, structural biology, computational models, and high-resolution imaging and characterization.

BSSD supports the Genomic Science program, considered a leading program in systems biology research, which uses genome sequences as the blueprint for understanding the common principles that govern living systems. The program supports single-investigator and team projects in research areas related to bioenergy, environmental microbiome science, and computational biology;[25] and also supports four distinct Bioenergy Research Centers to accelerate research pathways to improve and scale advanced biofuel and bioproduct production processes.

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[18] https://www.energy.gov/eere/bioenergy/beto-accomplishments
[19] https://www.energy.gov/eere/bioenergy/advanced-algal-systems
[20] https://www.energy.gov/eere/bioenergy/conversion-technologies
[21] https://www.energy.gov/eere/bioenergy/data-modeling-and-analysis
[22] https://www.energy.gov/eere/bioenergy/feedstock-technologies
[23] https://www.energy.gov/eere/bioenergy/systems-development-and-integration
[24] https://science.osti.gov/ber/Research/bssd
[25] https://science.osti.gov/ber/Research/bssd/Genomic-Science

Bioenergy Research Centers

In an effort to focus the most advanced biotechnology-based resources on the challenges of biofuel production, DOE has established four Bioenergy Research Centers (BRCs). Each center pursues research underlying a range of biological solutions for bioenergy applications to address three major challenges – the development of next-generation bioenergy crops; the discovery and design of enzymes and microbes with novel biomass-degrading capabilities; and the discovery and design of microbes that create fuels directly from biomass.[26] Advances resulting from the BRCs are providing the knowledge needed to develop new biobased products, methods, and tools that will benefit the emerging advanced biofuel industry.

- **Center for Advanced Bioenergy and Bioproducts Innovation (CABBI)**, led by the University of Illinois at Urbana-Champaign. CABBI integrates recent advances in agronomics, genomics, biosystems design, and computational biology to increase the value of energy crops, using a "plants as factories" approach to grow fuels and chemicals in plant stems and an automated foundry to convert biomass into valuable chemicals that are ecologically and economically sustainable.[27]
- **Center for Bioenergy Innovation (CBI)**, led by DOE's Oak Ridge National Laboratory. CBI conducts research to accelerate the domestication of bioenergy-relevant plants and microbes to enable high-impact, value-added coproduct development at multiple points in the bioenergy supply chain.[28]
- **Great Lakes Bioenergy Research Center (GLBRC)**, led by the University of Wisconsin-Madison in partnership with Michigan State University. GLBRC is developing scientific and technological advances to ensure sustainability at each step in the process of creating biofuels and bioproducts from lignocellulose.[29]
- **Joint BioEnergy Institute (JBEI)**, led by DOE's Lawrence Berkeley National Laboratory. JBEI utilizes advanced tools in molecular biology, chemical engineering, and computational and robotics technologies to transform biomass into biofuels and bioproducts.[30]

Joint Genome Institute

The BSSD subprogram also supports the Joint Genome Institute (JGI), established in 1997 to connect expertise and resources in genome mapping, DNA sequencing, technology development, and information sciences. JGI serves as the central source for genome sequence production capabilities for plants, microbes, and microbial communities. JGI's capabilities are instrumental

[26] https://www.osti.gov/servlets/purl/985252
[27] https://cabbi.bio/
[28] https://cbi.ornl.gov/
[29] https://www.glbrc.org/
[30] https://www.jbei.org/

to several BER programs, such as the BRCs, and the Institute's resources are available to the larger research community. JGI is currently engaged in enhancing its expertise to further support microbiome research, and production of complex plant, fungal, and microbial genomes supporting systems biology research within the BRCs and the BER portfolio.[31]

[31] https://jgi.doe.gov/about-us/

Mr. CASTEN. The hearing will come to order. Without objection, the Chairman is authorized to declare recess at any time.

Before I deliver my opening remarks, I wanted to note that, today, the Committee is meeting both in person and virtually. I want to announce a couple reminders to the Members about the conduct of this hearing. First, Members and staff who are attending in person and are unvaccinated against COVID–19 must stay masked throughout the hearing. Unvaccinated Members may remove their masks only during their questioning under the 5-minute rule. Members who are attending virtually should keep their video feed on as long as they are present in the hearing, and Members are responsible for their own microphones. Please also keep your microphones muted unless you're speaking. Finally, if Members have any documents they wish to submit for the record, please email them to the Committee Clerk, whose email address was circulated prior to the hearing.

I'd like to thank all the witnesses for joining us today to discuss the future of the bioenergy research enterprise. As some of you know, I spent 20 years in the energy industry before I came to Congress, but I'm sure all of you have read that 1998 *New York Times* bestseller *Advanced Processes for Ethanol and Electricity Coproduction from Lignocellulosic Biomass.* As I don't need to tell you, that was of course the title of my master's thesis, which caused me to spend 3 years building, operating, and modeling biofuel fermentation and energy recovery systems. And I think it's for the good of our planet and for my sanity that the technology has come a long way since then.

In fact, in December of last year I was on the first passenger flight powered by 100 percent sustainable aviation fuel (SAF) flying from the greatest city of Chicago to Washington, D.C. Although that was a historic moment, we still have some significant barriers to overcome. Cost of course remains high with sustainable aviation fuels costing about four times as much as traditional jet fuel. But in addition to that, we simply don't have enough supply. Ninety-five billion gallons of jet fuel was consumed in 2019. In that same year, less than 2 million gallons of sustainable aviation fuels was produced.

I'm encouraged by President Biden's Sustainable Aviation Grand Challenge that aims to reduce the cost, and hence the sustainability, and expand production of these fuels, which I understand LanzaJet is taking part in by pledging production of a billion gallons of these fuels per year by 2030. So I'm really looking forward to Dr. Harmon's testimony and not just because LanzaTech is headquartered in my backyard. I also really look forward to learning about the status of the technologies to create these fuels and where there are constraints and opportunities in the upstream feedstock supply.

I'm also pleased that the Department of Energy (DOE) sees this urgent need and is focusing its bioenergy research on the fuels of tomorrow. Sustainable, cost-effective feedstocks that can scale down and move refinement closer to the feedstock sources would enable a distributive model that revives local economies. As an example, the Center for Advanced Bioenergy and Bioproducts Innovation (CABBI), which also happens to be located in Illinois, works to create ecologically and economically sustainable feedstocks by using a plants-as-factories approach that prioritizes efficient land use, soil health, water health, clean air, and of course emissions reductions.

As we saw in the recent IPCC (Intergovernmental Panel on Climate Change) report, the science is overwhelmingly clear that we have to get to zero greenhouse gas emissions as quickly as possible. Sadly, as we all know in this Committee too well, what is scientifically necessary vastly exceeds what is politically on the table at the moment. And it's why I'm so proud to be on the Science Committee where we get stuff done. I hope that in convening this hearing we can ensure that our R&D (research and development) dollars are spent wisely and that we prioritize some of the less-sexy, hard-to-decarbonize industries.

Now more than ever we have to figure out how to decarbonize these hard-to-abate sectors, cement, steel, aviation, and shipping. These are sectors that use carbon and fossil fuels often not as an energy source but as a chemical reducing agent and/or they depend on liquid fuels that have the kind of mass and energy density that's very difficult to replace with other sustainable fuel stocks. Bioenergy is the unique renewable fuel source that can serve both of those needs, and I'm excited to hear from our witnesses where we can best target our research and development in this space.

The IPCC report also concluded that bioenergy has significant potential to mitigate greenhouse gases if resources are sustainably developed and efficient technologies are thoughtfully applied. If we do this right, we can pinpoint how biofuels and biobased chemicals can be utilized where they would be most effective in enabling a transition to a 100-percent clean economy.

Finally, I don't think we can emphasize enough the impacts that most Americans and indeed all of the world right now is experiencing due to our overreliance on a globally traded, geographically limited, environmentally detrimental, and ultimately finite commodity under the control of some genuinely crazy people. This is not a problem that we can drill our way out of. No amount of oil that we extract from within our shores can make a meaningful dent in the massive price spikes that always follow the kinds of geopolitical volatility that people like Mr. Putin have created. We absolutely must pursue ways to produce more sustainable and domestically grown solutions to meet our energy needs.

By doubling down on our innovation enterprise, we can electrify the bulk of many sectors and create sustainable fuels to power those otherwise hard-to-abate sectors. Knowing what we know today, we just can't keep doing more of the same and expecting a different outcome.

I want to again thank our excellent panel of witnesses assembled today, and I look forward to hear your testimony. With that, I yield back.

[The prepared statement of Mr. Casten follows:]

Thank you to all of the witnesses for joining us today to discuss the future of our bioenergy research enterprise. As some of you know I spent 20 years in the energy industry before I came to Congress. And I'm sure all of you have read the 1998 New York Times Bestseller "Advanced Process for Ethanol and Electricity Coproduction from Lignocellulosic Biomass." That, of course, was my Masters' thesis, which caused me to spend three years building, operating, and modelling biofuel fermentation and every recovery system. I'm thrilled to say we have come a long way since then. In December of last year, I was on the first passenger flight powered by 100% sustainable aviation fuel, flying from the great city of Chicago to Washington, DC. Although that was a historic moment, we still have some significant barriers to overcome. Not only is cost a prohibitive factor, with sustainable aviation fuels costing four times as much as traditional jet fuel, but we simply don't have enough supply. 95 billion gallons of jet fuel was consumed in 2019, and that same year less than 2 million gallons of sustainable aviation fuels was produced. I am encouraged by President Biden's Sustainable Aviation Grand Challenge that aims to reduce cost, enhance sustainability, and expand production of these fuels, which I understand Lanzajet is taking part in by pledging production of a billion gallons of these fuels per year by 2030. So I am really looking forward to Dr. Harmon's testimony, and not just because Lanzatech is headquartered in my back yard. But because we need to address and discuss sustainable feedstocks, and how to best increase the global supply of alternative fuels.

I am also pleased that the Department of Energy sees this urgent need, and is focusing its bioenergy research on the fuels of tomorrow. Sustainable, cost-effective feedstocks that can scale down and move refinement closer to the feedstock sources would enable a distributive model that revives local economies. For example, the Center for Advanced Bioenergy and Bioproducts Innovation - which also happens to be located in Illinois - works to create ecologically and economically sustainable feedstocks by using a "plants as factories" approach that prioritizes efficient land use, soil health, water health, clean air, and of course, emission reductions.

As we saw in the recent IPCC report, the science is clear that we must achieve zero emissions as soon as possible. What is scientifically necessary vastly exceeds what is politically on the table at the moment, which is why I'm proud to be on the Science Committee where we Get. Stuff. Done. I hope that in convening this hearing, we ensure that our R&D dollars are spent wisely, and that we prioritize these less sexy, hard to decarbonize industries. Now more than ever we must work to decarbonize hard to abate sectors, such as cement, steel aviation, and shipping. These sectors currently use the carbon in fossil fuels not as an energy source, but as a chemical reducing agent and/or depend on energy sources with the mass - and energy-density only found in liquid fuels. Bioenergy is the unique renewable fuel source that can serve both needs. I'm excited to hear from our witnesses where we can best target our research and development in this space.

The IPCC report concluded that bioenergy has significant potential to mitigate greenhouse gases if resources are sustainably developed, and efficient technologies are thoughtfully applied. If we do this right, we can pinpoint how biofuels and biobased chemicals can be utilized where they would be most effective in enabling a successful transition to a 100% clean economy.

Lastly, I don't think we can emphasize enough the impacts that most Americans, and much of the world, are now experiencing due to our over-reliance on a globally traded, geographically limited, environmentally detrimental, and ultimately finite commodity. This is not a problem that we can drill our way out of. No amount of oil that we extract from within our shores can make a meaningful dent in the massive price spikes that would always follow a world event that disrupts the global oil supply chain. This is yet another critical reason that we absolutely must pursue ways to produce more sustainable solutions, domestically-grown, to meet our energy needs. By doubling down on our innovation enterprise, we can electrify the bulk of many more sectors and create sustainable fuels to power those otherwise hard-to-abate sectors. Knowing what we know today, we just can't keep doing more of the same and expect a different outcome anymore.

I want to again thank our excellent panel of witnesses assembled today, and I look forward to hearing your testimony. With that, I yield back.

Mr. CASTEN. And the Chair now recognizes Mr. Weber for an opening statement.

Mr. WEBER. Thank you, Mr. Casten, for filling in for Chairman Bowman and for running what is our first hybrid hearing in about a year, I think. I'm glad—I, like you, am glad to see some faces here in person, although it's hard to recognize y'all without your masks.

Today, we will examine a promising clean energy technology area that should play a role in all of our above—our all-of-the-above energy strategy. Bioenergy is a broad term that refers to the use of biomass and waste resources to produce energy and related products like biofuels and biogas. The applications of bioenergy seem almost endless from sustainable aviation fuel that you talked about to recycling and waste-to-energy technologies, bioenergy has the potential to benefit not just the U.S. energy sector but a variety of industries, including manufacturing and agriculture.

The Department of Energy has led the way in driving U.S. innovation in bioenergy technologies, but, like most technologies we talk about here at the Science Committee, there is still work to be done and progress to be made. While some biofuels like ethanol are mature energy sources, we have just scratched the surface of what is possible when it comes to new, more efficient, advanced biofuels and bioproducts. That is what today's hearing is about, the next generation of bioenergy R&D.

Along with Chairwoman Johnson, Ranking Member Lucas, and Chairman Bowman, I was proud to lead the *DOE Science for the Future Act* and see it pass on an overwhelmingly bipartisan vote on the House floor last summer. This bill contained a comprehensive reauthorization of DOE's Biological and Environmental Research (BER) program which conducts early stage research to advance our ability to use biological systems for energy technology. This reauthorization is absolutely necessary for the success and commercialization of next-generation bioenergy technologies. Without support and updates to BER's basic research mission and facilities like the Bioenergy Research Centers (BRCs), we could be stuck with the same conventional biofuels and bioproducts that may never be cost-effective, much less widely adopted. The updated language in our bill provides guidance to DOE's activities and modernizes their research focus to align with current capabilities, needs, and demands.

DOE also conducts bioenergy research, development, and demonstration (RD&D) activities through its Bioenergy Technology Offices—Office (BETO) I should say, which is housed with the Energy Efficiency and Renewable Energy, EERE, office. While this office is focused more on mature technologies and their commercialization, it plays a valuable role in the full research and development cycle. BER in the Office of Science target the most fundamental industry-shifting breakthroughs with basic research, but BETO and EERE then help to take those breakthroughs and apply them to a technology suitable for widespread deployment. But as my colleagues have heard me say often, applied energy research on the government's dime has its limits. That's my 10 cents' worth at least. There are times when help for demonstration and commercial application makes sense, but the Federal Government has no business picking the winners and losers of the energy market.

Therefore, there comes a time when every technology, bioenergy included—pardon me—should be taken off government support and allowed to either flourish or flounder in the free market. So while I support much of the work of BETO and EERE, I don't want my words to be misconstrued as an open invitation to expand these programs irresponsibly. I believe we should start with robust funding and support for the Office of Science and then allow EERE to capitalize on their most promising breakthroughs in partnership with the private sector.

I look forward to today's hearing, too, Mr. Chairman, and learning how this basic research to commercialization cycle for bioenergy can be streamlined and improved. We have a diverse panel here with witnesses from national labs, a DOE Bioenergy Research Center, academia, as well as the private sector. Between all of those witnesses, I'm sure we'll hear about a bright future with bioenergy. So I want to thank each of them for testifying today.

And with that, Mr. Chairman, I yield back the balance of my time.

[The prepared statement of Mr. Weber follows:]

Thank you, Mr. Casten, for filling in for Chairman Bowman and running what is our first hybrid hearing in about a year. I'm glad to see some faces here in person!

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There are times when help for demonstration and commercial application makes sense, but the federal government has no business picking the winners and losers of the energy market. Therefore, there comes a time when every technology, bioenergy included, should be taken off government support and allowed to either flourish or flounder through the free market.

So while I support much of the work of BETO and EERE, I don't want my words to be misconstrued as an open invitation to expand these programs irresponsibly. I believe we should start with robust funding and support for the Office of Science and then allow EERE to capitalize on their most promising breakthroughs in partnership with the private sector.

I look forward to today's hearing and learning how this basic research to commercialization cycle for bioenergy can be streamlined and improved. We have a diverse panel here with witnesses from a National Lab, a DOE Bioenergy Research Center, academia, and the private sector. Between all of them, I'm sure we will hear about a bright future with bioenergy.

I want to thank each of them for testifying today. And I yield back the balance of my time.

Mr. CASTEN. I believe our Chairwoman is not present, so the Chair will now recognize the Ranking Member of the Full Committee, Mr. Lucas, for his opening statement.

Mr. LUCAS. Thank you, Mr. Casten. And I'd like to express my appreciation to Chairwoman Johnson and the entire majority staff for their work to hold this hearing in hybrid format. This is an exciting step toward transitioning back to in-person hearings, and I look forward to seeing the rest of my colleagues and future witnesses in our hearing room sometime soon.

Even before serving as Ranking Member of the Science Committee, I've been an advocate for an all-of-the-above approach to our energy security. Bioenergy, which is one component of that mix, carries tremendous potential as an energy resource for our country, especially given our Nation's strong agricultural capacity. However, additional research and development, particularly fundamental research and cross-sector collaboration, is needed to unlock its full potential. But that must be done in a responsible, targeted manner.

To that end, I was proud to help lead the Science Committee's bipartisan efforts to support the Department of Energy's Office of Science's Biological and Environmental Research, or BER, program by passing the *DOE Science for the Future Act* in the House last year. Among many things, this legislation modernizes the BER program and provides additional guidance for our Bioenergy Research Centers. It helps them address cutting-edge challenges for the expansion of the biofuel and biobased materials industry. We still don't have certainty on the path ahead for the *DOE Science for the Future Act.* It's been 4 months since Leader Schumer and Speaker Pelosi announced that we would go to a conference on a competitiveness legislation, and we're still waiting. The BER program is just one among many strategic and bipartisan initiatives that we in this Committee room worked on carefully together. I'd like to move it forward soon. So I look forward to working with my colleagues on both sides of the aisle and in both chambers to find a way to get this legislation across the finish line.

I want to thank our witnesses for sharing their expertise and discussing strategies to address the most critical bioenergy R&D needs. Thank you, Mr. Casten. I yield back the balance of my time.

[The prepared statement of Mr. Lucas follows:]

Thank you, Mr. Casten.

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I want to thank our witnesses for sharing their expertise and discussing strategies to address the most critical bioenergy R&D needs. Thank you, Mr. Casten, I yield back the balance of my time.

Mr. CASTEN. If there are Members who wish to submit additional opening statements, your statements will be added to the record at this point.

[The prepared statement of Chairwoman Johnson follows:]

Good morning and thank you Mr. Casten for chairing today's hearing, and for convening this excellent panel of witnesses to examine the role of bioenergy in our nation's clean energy transition.

Bioenergy is one of the world's oldest energy sources and continues to play a large and growing role in the global energy system. Today, the Department of Energy is advancing research breakthroughs in bioengineering that will significantly improve the sustainability of bio-based products, including materials, chemicals, and fuels.

Bio-based products currently displace approximately 9.4 million barrels of oil annually, and they have the potential to reduce greenhouse gas emissions by an estimated 12.7 million metric tons per year. So DOE's research in these areas will likely be critical to achieving our future climate goals.

I must also mention that my district in Dallas is a hub for domestic and international air travel, and there too, bioenergy has the potential to enable sustainable aviation. I have a vested interest in overcoming barriers to the wider adoption of these fuels, as this sector is particularly challenging to decarbonize.

Lastly, I want to again highlight our Committee's important, bipartisan work that was included in the *DOE Science for the Future Act,* the *Bioeconomy Research and Development Act,* and the *America COMPETES Act.* Amongst the many impactful science and innovation provisions in the bill, you'll find bioenergy R&D provisions that aim to ensure that the U.S. leads the bioeconomy in the 21st century. These provisions, built from the ground up with input from the stakeholder community as reflected by today's witness panel, authorize R&D in biological system science and further authorize up to six bioenergy research centers focused on research in plant and microbial systems biology, biological imaging and analysis, and genomics to accelerate the research, development, and commercial application of bioenergy sources and biobased products.

I hope today's discussion will examine how these provisions and any future legislation will help advance bioenergy's sustainability as a resource to meet the challenges of mitigating climate change while also addressing our growing energy needs. Moreover, I must note that the recent tragic events and their rippling effects across the globe have underscored the necessity for us to diversify our nation's energy supplies, not that this was a lesson that any of us would have wanted or should have needed at this point.

I thank our witnesses for being here and I look forward to your testimony.

Thank you, Mr. Chairman, and I yield back.

Mr. CASTEN. At this time, I would like to introduce our witnesses. Dr. Jonathan Male is the Chief Scientist in the Energy Processes and Materials division at Pacific Northwest National Laboratory, or PNNL. He's also an adjunct faculty member in the Biological Systems Engineering Department of Washington State University or WSU and the Co-Director of the WSU PNNL Bioproducts Institute. Previously, Dr. Male served as the Director of Bioenergy Technologies Office at the Department of Energy for over 6 years.

Dr. Andrew Leakey is the Director of the Center for Advanced Bioenergy and Bioproducts Innovation and the head of the Department of Plant Biology at the University of Illinois Urbana-Champaign. He joined the university as a Fulbright Scholar in 2002. He has received the Calvin-Benson Prize for Excellence in early career research and has been elected as a Fellow of the American Association for the Advancement of Science.

Dr. Laurel Harmon is the Vice President of Government Affairs at LanzaTech. She has over 30 years of experience in policy and technology development. In her current role, Dr. Harmon provides policy direction on legislative and regulatory matters and develops public-private partnerships to support research and demonstration projects. She also serves on the board of LanzaJet and is the Vice Chair of the Board of the Roundtable on Sustainable Biomaterials.

The Chair now recognizes Mr. Meijer for the introduction of our final witness.

Mr. MEIJER. Thank you, Mr. Casten. And it's my pleasure to introduce a fellow Michigander, Dr. Eric Hegg, the Associate Dean for Budget, Planning, Research, and Administration in the College of Natural Science at Michigan State University (MSU). Although not located directly in my district, Michigan State's research, students, and faculty all have a tremendous impact across the State when it comes to the Science Committee and national research priorities. It's always great to have Michigan and its unique skills and needs represented.

Dr. Hegg is an expert in biochemistry and molecular biology. Specifically, his research looks at how structural components of the plant cell wall can be used to form biofuels and bioproducts. And relevant to today's hearing, Dr. Hegg has served in a variety of roles within the Great Lakes Bioenergy Research Center (GLBRC) since it was first established in 2007. Most recently, he served as the MSU subcontract lead for the GLBRC before transitioning to his current role as Associate Dean. Dr. Hegg has been a Big Ten Academic Alliance Leadership Program Fellow and an Academic Advancement Network Leadership Fellow. And in 2019 he was elected a Fellow of the American Association for the Advancement of Science. His knowledge in the field of bioenergy and history with DOE's Bioenergy Research Centers are invaluable to today's discussion, and I look forward to hearing more in his testimony. Thank you, Dr. Hegg, for being with us today, for being a voice for all of Michigan. And I yield back the balance of my time.

Mr. CASTEN. Thank you all for joining us today. As our witnesses are no doubt aware, you will each have 5 minutes for your spoken testimony. Your written testimony will be included in the record for the hearing. When you've all completed your spoken testimony, we will begin with questions. Each Member will have 5 minutes to question the panel. We will start with Dr. Male. Dr. Male, please begin.

TESTIMONY OF DR. JONATHAN MALE,
CHIEF SCIENTIST, ENERGY PROCESSES AND MATERIALS,
PACIFIC NORTHWEST NATIONAL LABORATORY (PNNL)

Dr. MALE. Thank you. Good morning, and thank you, Chairman Casten, Ranking Member Weber, and Full Committee Ranking

Member Lucas and Members of the Subcommittee, for the opportunity to participate in this important hearing on bioenergy research and developing fuels and chemicals of tomorrow.

As you've heard, my name is Jonathan Male. I am a Chief Scientist for the Energy Processes and Materials at the Pacific Northwest National Lab. That's in Richland, Washington. I'm also an Adjunct Professor at Washington State University and serve as the Co-Director of the PNNL WSU Bioproducts Institute, which advances science to reduce environmental impacts of fuels and products. Previously, I served as the Director of the Bioenergy Technologies Office in the Office of Energy Renewable—Energy Efficiency and Renewable Energy.

In my testimony today I will focus on three main points about the state of bioenergy research and development and its importance to our clean energy future. First, we must expand our understanding of real-life biomass feedstocks. Second, we have a great opportunity to turn today's waste carbon streams into tomorrow's carbon resources. And third, bioenergy and bioproducts will be most important for reducing emissions in segments of our economy that are difficult to electrify such as aviation, marine, and industry.

Decades of investment in fundamental chemistry, biology, catalysis, computational modeling, and other science disciplines have positioned us to convert biomass and waste to useful fuels and products. Much of this work has depended on DOE's world-class scientific user facilities like the Environmental Molecular Sciences Laboratory (EMSL) at PNNL and the Joint Genome Institute (JGI) at Lawrence Berkeley National Lab.

To take the insights of fundamental science to scale and realize commercial impact, we must look to real biomass with all its variability and imperfections. Producing bioenergy and bioproducts at scales required to meet carbon reduction goals, bioenergy technologies must work not only for the optimal feedstocks we use in the laboratory but must be robust against variations during industrial processing.

Consider corn stover as an example feedstock. Real bales of corn stover sit out in the elements and will contain everything from soil to twine to farming tools. Bioenergy and bioproducts facilities must have resilient processes to still efficiently produce fuels and products. In demonstration and commercial scale facilities, feedstock variability has led to undesirable outcomes. DOE created the Feedstock Conversion Interface Consortium, or FCIC, to begin to scientifically understand and address critical feedstock variability issues. FCIC researchers across nine DOE national labs provided critical insights of potential methods for detailed characterization of feedstock variability and understanding key properties of feedstocks that impact facilities' performances.

To the second point, we can turn today's waste into tomorrow's carbon resources if we invest in the RD&D to characterize wastes and further develop conversion processes. DOE researchers estimate there is a potential for 1 billion dry tons of biomass to be converted to approximately 62 billion gallons of fuel annually, enough to supply all of aviation, marine, rail, and significant portion of the heavy-duty trucking. However, these analyses have assumed approximately 23 percent of those billion dry tons would be derived from woody and herbaceous energy crops, which have been slow to scale up.

If we expanded our view of renewable carbon feedstocks, we find significant additional carbon in our waste streams from municipal solid waste to food waste and waste gases to name just three. By developing science and technology to utilize these wastes, we can increase feedstock supplies, reduce landfill volumes, disposable costs, and reduce land-use impacts.

One exciting potential conversion process for waste streams is hydrogen liquefaction. It combines heat and pressure to create a biocrude. A recent analysis by PNNL and National Renewable Energy Lab showed that wet waste have potential to produce 4.5 billion gallons per year of renewable diesel.

Finally, bioenergy and bioproducts have the biggest potential to impact hard-to-electrify segments of our economy such as aviation, marine, and industry. The aviation segment remains far from viable for electrification of wide-body jets due to fuel energy density demands. There are commercially viable technologies today for converting fats, oils, and greases (FOGs) to sustainable aviation fuels, or SAFs, but 3 million gallons was made in 2019. However, the U.S. aviation sector used 26 billion gallons of jet fuel in the same year. There are not enough FOGs available as feedstocks to meet that need. Recent research has started to use waste such as carbon monoxide, hydrogen, and carbon dioxide that LanzaTech will talk about in the collaboration with PNNL have developed technologies to efficiently ferment this mixture to alcohols, which can then be taken to SAFs. The technology will help meet the DOE, DOT (Department of Transportation), and USDA's (United States Department of Agriculture's) sustainable aviation fuel grand challenge of producing 3 billion gallons to the U.S. by 2030.

In conclusion, by looking at an array of biomass and waste feedstocks, better characterizing their real-world properties, we increase potential to bring bioenergy and bioproducts to bear. We can reduce the carbon intensity of critical but hard-to-electrify segments of the economy and meet our goals for dramatic global emissions. Thank you for your time today, and I look forward to your questions.

[The prepared statement of Dr. Male follows:]

Statement of Jonathan Lloyd Male
Chief Scientist, Energy Processes and Materials
Co-director of the PNNL–WSU Bioproducts Institute
Pacific Northwest National Laboratory

Before the
United States House of Representatives
Committee on Science, Space and Technology

March 16, 2022

Good morning. Thank you, Chairman Casten, Ranking Member Weber, and Members of the Subcommittee. I appreciate the opportunity to appear before you today to discuss the state of bioenergy research and development and how Pacific Northwest National Laboratory (PNNL) and its fellow Department of Energy (DOE) national laboratories are contributing to this important enterprise.

My name is Jonathan Male, and I am chief scientist for Energy Processes and Materials at PNNL, a DOE Office of Science national laboratory located in Richland, Washington. I am also an adjunct professor in the Biological Systems Engineering Department at Washington State University (WSU) and serve as the Co-director of the joint PNNL–WSU Bioproducts Institute, which advances science that reduces the environmental impact of fuels and products while providing renewable carbon resources for sectors of the economy that are not easily electrified. Prior to my return to the Pacific Northwest National Laboratory in May 2020, I served as the Director of the Bioenergy Technologies Office (BETO), in the Office of Energy Efficiency and Renewable Energy (EERE) at DOE for over six years. As Director of BETO, I led the Office's work to lower the costs of modeled fuels and products, reduce technology uncertainty, and accelerate research and development of bioenergy and renewable chemicals technologies in the emerging bioeconomy.

In my testimony today, I will discuss the state of bioenergy research, development, and demonstration (RD&D) activities led by DOE and the great potential for advancements in bioenergy and bioproducts to help deliver a cleaner energy future. In so doing, I will address three main points:

1) We must expand our understanding of *real-life* biomass feedstocks—the raw materials to be manipulated through various technologies to create bioenergy and bioproducts—to successfully apply emerging science and technology at the scales required to meet carbon-reduction goals.

2) We have great opportunity to turn today's waste carbon streams—from municipal solid waste and landfill gases to used carbon fiber—into tomorrow's carbon resources by

expanding our RD&D agenda to increase efforts on these important potential biomass feedstocks.

3) Bioenergy and bioproducts can and should play a critical role in reducing carbon emissions particularly in sectors of our economy that are difficult to electrify, including aviation, maritime, and industry.

Background

The bioenergy and bioproduct landscape presents a rich array of RD&D challenges ripe for federal investments that target near-, medium-, and long-term opportunities. DOE programs from basic research in the Office of Science to applied research and development through BETO to the new Office of Clean Energy Demonstrations (OCED) and Loan Programs Office (LPO) are advancing technologies across the full supply chain from feedstocks to conversion technologies and from the lab bench to pilot-, demonstration-, and commercial-scales. Each of these investments is important for advancing a diverse portfolio of technology approaches we will need to meet ambitious carbon-emission reduction goals.

Thanks to decades of strategic DOE investments in basic chemistry, biology, computational modeling, and other basic science disciplines, we have more insights, tools, and technologies than ever before to address many of these challenges. Basic science efforts in the bioenergy and bioproducts area— including those supported by the DOE Office of Science's Basic Energy Sciences (BES) and Biological and Environmental Research (BER) programs—have focused largely on using pristine sugars and model compounds to thoroughly understand how conversion processes can work to transform feedstock constituents into bioenergy and bioproducts. This basic research yields important insights into the mechanisms at work in these processes.

Thousands of DOE researchers and those funded by other federal agencies rely on world-class scientific user facilities like BER's Environmental Molecular Sciences Laboratory (EMSL), located at PNNL, and its Joint Genome Institute, located at Lawrence Berkeley National Lab. Researchers at these world-class scientific user facilities characterize biomass and microbes capable of processing the biomass, as well as probe the real-time conditions of conversion processes. This research has shown that microbes can serve as cellular factories to take biomass molecules and make compounds that can be chemical building blocks to polymers, textiles, solvents, fuels, and the myriad of carbon-based materials that help us in our everyday lives. Continually developing capabilities for characterizing how microbes function in even greater detail and at greater speed and volume is critical for speeding the march of basic science advances that power bioenergy and bioproduct technology development.

We must expand our understanding of real-life bioenergy feedstocks

To take the insights of basic research to scale and realize commercial impact, we must look beyond the pristine feedstocks used in controlled experiments and look at real biomass, with all its variability and imperfections. Applied research efforts, including those supported by BETO, look at "optimal" or "average" feedstocks and have yielded critical insights into how real-world biomasses can be pre-treated to create intermediates, such as a mixture of sugars, a bio-oil, or a synthesis gas (carbon monoxide and hydrogen). To produce bioenergy and bioproducts *at scale*, bioenergy technologies must work not only for the optimal or average but must be robust against the variations to be expected in the literal tons of feedstocks they will need to process.

Consider the example of corn stover as a feedstock. Researchers have developed highly efficient conversion processes for producing bioenergy components or bioproducts from corn stover at the lab bench. And more applied work has subsequently addressed some of the important systems engineering challenges of processing "real-world" samples of corn stover. However, at the pilot- and demonstration-scales, bioenergy facilities will receive bales of corn stover collected on real farms around the country. These bales are likely to be left out in the elements for some period of time, combined with other bales, potentially from multiple locations, and shipped to a refinery over the course of many days or weeks. These real-world bales are likely to contain extraneous elements from a working farm—from soil to wildlife to farming tools—and suffer the consequences of extended exposure to the elements. A plant producing bioenergy or bioproducts at scale will need to have processes that are robust against this variability. Indeed, dealing with feedstock variability is a significant reason we see demonstration- and commercial-scale facilities fail to meet their targeted outcomes. Characterizing real-world feedstocks and understanding how conversion processes operate in the face of real-world variability is a critical area for greater investment so that we can move science insights toward commercially viable technologies at scale.

To this end, DOE recently created the Feedstock-Conversion Interface Consortium (FCIC) to begin to address these challenges. The FCIC is an integrated and collaborative network of nine DOE national laboratories with goals of; (1) developing science-based knowledge and tools to understand biomass feedstock and process variability, and (2) improving overall operational reliability, conversion performance, and product quality across the biomass value chain from harvest through preprocessing and conversion. FCIC researchers provided a critical review of advanced methods for characterizing feedstock variability; discussing advanced analytical methods that measure density, moisture content, thermal properties, flowability, grindability, rheology properties, and micromorphology; and examining methods that have not traditionally been used to characterize lignocellulosic feedstocks but have the potential to yield important insights on intrinsic biomass feedstock variability (Yan 2020).

We can turn today's wastes into tomorrow's carbon resources

DOE estimates that there is potential for a billion dry tons of biomass that could be converted to approximately 62 billion gallons of gasoline fuel equivalent annually (Brandt 2016, Rogers 2017). This would be enough gasoline equivalent fuel to completely supply aviation, marine, rail, and a significant fraction of the heavy-duty trucking market. However, these analyses have assumed that approximately 23% of those billion dry tons would be derived from woody and herbaceous energy crops, whose production has been slower to scale-up than expected.

If we expand our view of viable biomass feedstocks beyond traditional agricultural and forest residues, we find significant additional potential carbon resources in our waste streams. If we considered all forms of municipal solid waste (MSW), biosolids, food wastes, off-specification chemical streams, waste polymers, water streams with organic chemical contamination, and waste gases (biogas, methane, flue gas, landfill gas, tail gases and carbon oxides), we gain both useful carbon sources and the opportunity to solve another problem: waste disposition. By utilizing these waste streams as a carbon source, we can reduce landfill volumes, disposal costs, and land use changes needed for producing additional bioenergy crops. Waste streams also present potential advantages for the conversion to bioenergy and bioproducts in that some "pre-processing" may have already been done, whether by human and animal guts and their menagerie of microbes, or by food or chemical processing facilities.

Biomass and wastes are widely available, but no single feedstock is sufficient on its own to meet demand. We will need several different regional solutions that leverage locally available resources, which will have the co-benefit of diversifying our supply chains and increasing resilience to disruptions and affordability challenges. PNNL and the National Renewable Energy Lab (NREL) recently leveraged an existing waste-to-energy feedstock database for the conterminous United States that shows different waste streams' potential for bioenergy production on a site-specific basis. The analysis indicates that with conversion by hydrothermal liquefaction—a process that combines biomass with intense heat and pressure to create a biocrude oil, essentially a dramatically sped up version of what the earth does naturally over millions of years to create crude oil—carbon-rich waste streams have the potential to produce up to 5.9 billion gallons/year of biocrude oil that can be upgraded and refined into a variety of liquid fuels, in particular renewable diesel.

It is important to note here that current U.S. Code (42 USC 16232) states that DOE's bioenergy program may consider some waste streams, "but not including municipal solid waste, gas derived from degradation of municipal solid waste or paper that is commonly recycled." The Environmental Protection Agency (EPA) defines municipal solid waste (MSW) as consisting of everyday items we use and then throw away, such as product packaging, grass clippings, furniture, clothing, bottles, food scraps, newspapers, appliances, paint, and batteries. This comes from our homes, schools, hospitals, and businesses. As of 2012, despite efforts to increase recycling and composting, EPA estimated we still discard 164 million tons of MSW, and this MSW contains significant amounts of carbon that could be used as a resource while avoiding landfills and emissions.

Beyond conversion of biomass and wastes to bioenergy and bioproducts the repeated use of a carbon in multiple applications—not necessarily in a circular economy but perhaps more of an elliptical economy—can also provide significant carbon intensity reduction. Re-use of carbon in molecules that have embodied energy (i.e., energy was used to produce the molecules) is extremely beneficial.

In an economy that reuses carbon, there are new ways to look at renewable products and materials especially regarding multiple uses in different applications with the need for greater industrial symbiosis. Industrial symbiosis is an approach to commercial operation which uses, recovers, and redirects resources for reuse, resulting in resources remaining in productive use in the economy for longer. This in turn creates business opportunities, reduces demands on the earth's resources, and provides a stepping stone towards creating a more circular or elliptical economy.

Take the example of carbon fiber, an extremely useful, but highly energy-intensive molecule. Carbon fiber composite has a wide variety of useful applications, each with different requirements on its properties. An elliptical carbon fiber composite economy could involve first use in aerospace, where quality requirements are highest, followed by reuse in wind turbine blades and eventually long-term use as an additive for construction beams. Multiple uses like these present important opportunities for reducing carbon intensity and waste output in sectors that are hard to decarbonize.

With biomass and waste streams there will not be just one solution. Numerous solutions will be needed across the U.S. to address the diversity in biomass and waste carbon in different geographies. Further, there is potential for a balanced portfolio of short- and longer-term use renewable products, from renewable diesel produced by hydrothermal liquefaction and consumed over the short term to cements with integrated biopolymers that improve structural properties and lock up carbon in the built environment for decades.

Bioenergy and bioproducts can play a critical role in hard to electrify sectors of our economy

To achieve a net zero carbon economy by 2050, it is necessary to pursue carbon reduction across all segments of the power, transportation, industry, commercial, residential, and agricultural sectors. Bioenergy and bioproducts can provide valuable low- or zero-carbon energy and products to many sectors of our economy, but they will be most valuable in hard-to-electrify sectors, such as aviation, maritime, and industry. These sectors also have large existing infrastructures built around the use of fossil fuels where low- and net-zero-carbon fuels derived from biomass have the potential to reduce emissions while maintaining compatibility with those existing and soon to be built facilities and processes.

Electrified aviation of wide-body jets remains far from viable despite the many real advances in battery and electric drive technologies—thanks in large part to DOE RD&D at PNNL, Argonne National Laboratory (ANL), and elsewhere. There is, however, commercially viable technology today for converting fats, oils, and greases (FOGs) of the appropriate quality to sustainable aviation fuels (SAFs), and about 3 million gallons were produced in the U.S. in 2019. However, the U.S. used 26 *billion* gallons of jet fuel in 2019 and there simply are not enough FOGs available as a feedstock to meet the needs of the aviation sector. Current and future research is needed on the utilization of other waste streams—landfill gas, biogas, renewable natural gas, carbon oxides, gasification of solids. These can each be converted to components that can be efficiently fermented to alcohols by technology developed by LanzaTech. Research developed at PNNL in collaboration with LanzaTech has shown that these alcohols can then be converted into high-quality SAFs to start to fill the void and drive towards the DOE, DOT, USDA Sustainable Aviation Fuel Grand Challenge of producing 3 billion gallons in the U.S. by 2030 and 35 billion gallons of SAF by 2050 (100% of the projected SAFs market), while achieving a minimum of a 50% reduction in life cycle greenhouse gas emissions compared to conventional fuel.

Heavy duty trucks that travel over 200 miles per day and ocean-going marine vessels are two additional examples of hard to electrify applications responsible for significant emissions today. PNNL and others have been researching the conversion of wet wastes such as biosolids, food wastes, manures, etc. using hydrothermal liquefaction to produce a bio-oil that can be upgraded to renewable diesel. PNNL researchers have shown that this sped up version of earth's natural processes for producing crude oil can efficiently produce high yields of high quality bio-oil from sewage sludge, while avoiding the expense of disposal costs.

Conclusion

While there is a scenario for a potential of one billion tons of biomass in the U.S., there is equal potential to expand the number of carbon resources considered in waste streams and biomass to mitigate concerns of scaling-up supply of feedstocks. The use of waste streams and multiple uses of carbon offer ways to be more responsible with an important resource that makes our everyday lives easier. We are increasingly gaining the scientific insights and advancing technologies capable of turning today's waste into tomorrow's carbon resource.

Introducing less carbon-intense energy into the electrical power grid will be important in decarbonizing America. However, there will be segments of the transportation, industrial, and agriculture sectors that will be hard to electrify such as: the aviation sector, the marine sector, chemicals sector, the built environment, and numerous additional applications where carbon makes our lives more comfortable. Biomass and waste streams offer a means particularly during an energy transition to leverage existing infrastructure while we seek to reduce the carbon intensity of the entire U.S. economy.

In terms of cost per unit of energy, bioenergy will continue to be more expensive than that derived from fossil fuels for the foreseeable future. We cannot overcome the fact that the earth and millennia of time provide free conversion processes for fossil fuels. However, when we account for the additional values of reducing our carbon intensity and wastes while delivering ecosystem services and beneficial coproducts, the costs can in fact be competitive. Governments can help realize these additional benefits with incentives, and corporations can value how these additional benefits advance corporate social and environmental goals.

Thank you again for the opportunity to testify on this important topic. I would be happy to answer any questions you may have.

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Proposed Jonathan's Bio for PNNL/WSU

Dr. Jonathan Male rejoined Pacific Northwest National Laboratory (PNNL) in the Energy Processes and Materials Division in May 2020 and in December 2020 became an adjunct faculty in the Biological Systems Engineering Department of Washington State University. In June 2021 Jonathan became the co-director of the WSU-PNNL Bioproducts Institute. Jonathan is interested in developing affordable technologies for the reuse of carbon.

Previously Jonathan was in the in the role of the Director of the Bioenergy Technologies Office (BETO) in the Office of Energy Efficiency and Renewable Energy (EERE) at the Department of Energy (DOE) for over six years. As Director of BETO, he led the Office's work to lower modeled costs, reduce technology uncertainty, and accelerate research and development of bioenergy and renewable chemicals technologies in the emerging bioeconomy.

Jonathan was at PNNL from 2006-2013 where he held a variety of research and management positions, including Lab Relationship Manager for Bioenergy, Management and Operational detail with the Office of Biomass Program, and Scientist with projects in aftertreatment catalysts, scintillators, and catalysts to produce renewable chemicals.

Before joining PNNL Jonathan worked at General Electric where he developed programs in heterogeneous and homogeneous catalysts at the GE Global Research Center in Niskayuna, New York.

Jonathan has more than 20 years of research experience in catalysts, inorganic materials, high throughput experimentation, greenhouse gas emissions reduction technologies, production of chemicals, and fuels. He has numerous publications, patents, and presentations in these fields.

Dr. Male received his Bachelor of Science degree in Applied Chemistry from the University of Greenwich, England, and his Ph. D. in Organometallic Chemistry at Simon Fraser University, Canada.

Mr. CASTEN. Thank you, Dr. Male. Next, we will have Dr. Leakey.

TESTIMONY OF DR. ANDREW LEAKEY, DIRECTOR, CENTER FOR ADVANCED BIOENERGY AND BIOPRODUCTS INNOVATION, UNIVERSITY OF ILLINOIS URBANA-CHAMPAIGN

Dr. LEAKEY. Acting Chairman Casten, Ranking Member Weber, and other distinguished Members of the Subcommittee, thank you for the opportunity to participate today. I am a Professor and head of the Department of Plant Biology at the University of Illinois Urbana-Champaign. Originally from Great Britain, I came to the United States in 2002 as a Fulbright Scholar. Since 2020, I have directed the Center for Advanced Bioenergy and Bioproducts Innovation, or CABBI, which is the newest of four Bioenergy Research Centers, or BRCs, that the Department of Energy is funding. CABBI is comprised of over 300 scientists from 23 institutions in 17 States.

Today, I was asked to discuss bioenergy and bioproducts research. Based on my personal experience, I aim to convey to you the need for next-generation renewable bioenergy and bioproducts, the scientific goals and progress of the BRCs, and the opportunities to train a diverse work force that can positively impact every corner of the country. I represent myself at today's hearing, and the views I express are my own.

The transportation fuels and petrochemicals sector is a global, multitrillion-dollar-per-year industry, has enormous potential to produce abundant renewable bioenergy and bioproducts from plant biomass. And this would, one, reduce reliance on foreign sources of energy and improve resiliency to international conflicts or natural disasters; two, support farming communities in developing a more sustainable and resilient agricultural system; three, develop a more just economy in which additional individuals and communities receive economic benefit from the production of fuels and chemicals, including in rural areas; and four, to reduce the greenhouse gas emissions from fossil fuels that are driving climate change.

Liquid biofuels have special potential to replace fossil fuels for modes of transportation where batteries are too heavy to store sufficient power and where charging infrastructure is not easily connected to sources of clean electricity. Sustainable biofuels for aviation, marine freight, and heavy-duty long-distance trucking are notable examples. Decarbonizing the transportation sector of the economy is important because it currently accounts for the largest fraction of U.S. CO_2 emissions. However, further research and innovation is needed for biofuels and bioproducts to meet their full potential.

The BRCs aim to provide the scientific discoveries and technologies needed to develop economically and ecologically sustainable domestic biofuels and bioproducts. This requires improved cropping systems that produce more and greater value biomass per acre while achieving sustainable greenhouse gas balances. It also includes more efficient technologies to deconstruct biomass and convert it into valuable fuels and chemicals that decarbonize our energy systems and products.

In my written testimony, I detail scientific discoveries and cutting-edge tools made by CABBI. A few highlights from the last 4 years include engineering bioenergy grasses to produce substantial amounts of oil, which can be processed into a drop-in biofuel, engineering microbes to greatly enhance conversion of plant-derived sugars into a platform chemical that can be used to make decarbonized detergents and lubricants, leveraging satellite imaging and computer simulation models to identify land that is best suited to produce bioenergy crops, accelerating research and innovation through advances in robotics and artificial intelligence (AI), as well as the sequencing and editing of plant and microbial genomes, and development of software for conducting techno-economic analysis and lifecycle assessment.

More broadly, since 2007, thousands of BRC researchers have made discoveries leading to more than 4,000 scientific publications, 670 patent applications, 280 of which have been licensed, and 15 startup companies. A focus on technology transfer and commercialization is a notable feature of the BRCs. CABBI currently has partnerships with 11 companies, allowing us to learn the challenges faced by industry and provide solutions to them. BRC work of this type is greatly aided by sustained funding for research that spans the entire value chain, thereby forming the basis of the U.S. bio economy of the future. Additional benefits come from collaboration among the BRCs and DOE's national labs, Joint Genome Institute, and Environmental and Molecular Science Laboratory.

Along with the other BRCs, CABBI is committed to training a diverse bioenergy work force. Our scientists contribute to this effort through many outreach and educational activities. I'm especially excited about our new internship program for undergraduate students from traditionally underrepresented groups.

In conclusion, I came to America because I believe we created the greatest opportunity for scientists to help tackle clean energy, climate change, and sustainable agriculture. Twenty years later, my experiences working at a top land-grant university have greatly bolstered that belief. We all have reason to be proud of this country's bioenergy research enterprise and to be optimistic about what it can do to deliver many benefits for our society.

Thank you, and I look forward to addressing your questions.

[The prepared statement of Dr. Leakey follows:]

Written Testimony of Andrew D.B. Leakey

Before the U.S. House Committee on Science, Space, and Technology Subcommittee on Energy

Hearing on "Bioenergy Research and Development for the Fuels and Chemicals of Tomorrow"

March 16, 2022

Chairman Casten, Ranking Member Weber, and other distinguished members of the Subcommittee, thank you for the opportunity to participate in this important discussion on the research and development needed to secure U.S. leadership in bioenergy. Also, thank you for your strong and consistent support for science and discovery, including your commitment to developing future generations of scientists, engineers, and educators.

I am a professor, and Head of the Department of Plant Biology, at the University of Illinois Urbana-Champaign. I am also affiliated with our Department of Crop Sciences, Institute for Genomic Biology, and Center for Digital Agriculture. Originally from Great Britain, I came to the United States in 2002 as a Fulbright Scholar to study crop responses to climate change. Today, my individual research group takes a multidisciplinary approach to study how plants interact with their growing environment and how we can develop crops that use less water, thereby protecting them from yield loss in times and places of drought. This is important for today's discussion because it would help us to produce bioenergy and bioproducts on marginal quality land, where farmers currently struggle to make a profit because growing conditions are not ideal, and where we could avoid competition between production of food and fuel. Since 2020, I have also had the privilege to lead the Center for Advanced Bioenergy and Bioproducts Innovation, or CABBI, which is the newest of four Bioenergy Research Centers (BRCs) that the Department of Energy is funding. CABBI is comprised of over 300 professors, federal scientists, postdoctoral fellows, technical staff and students from 23 institutions in 17 states. The diverse expertise of our team allows us to take a holistic approach to the study of bioenergy and bioproducts. Today, I was asked to discuss the current status of bioenergy research. Based on my personal experience, I aim to convey to you: (1) the need for next-generation bioenergy and bioproducts as part of a decarbonized economy; (2) the broad goals of the BRC program funded by the Department of Energy; (3) the scientific progress made specifically by CABBI since its inception just over four years ago; (4) the cutting-edge tools we have developed to create new opportunities for discovery and innovation in the future; and (5) the opportunities to train a diverse workforce to be leaders in a new industry that can have a positive impact in every corner of the country.

The need for next-generation bioenergy and bioproducts as part of a decarbonized economy

The transportation fuels and petrochemicals sector has become a global, multi-trillion dollar per year industry. There is enormous potential to produce abundant supplies of renewable bioenergy and bioproducts from plant biomass. This would: (1) develop a more just economy in which additional individuals and communities receive economic benefit from the production of fuels and chemicals, including in rural areas; (2) reduce reliance on foreign sources of energy and improve resilience in the face of international conflicts or natural disasters; (3) support farming communities in developing a more diverse, sustainable and resilient agricultural system; and (4) counteract the progression of climate change.

Liquid biofuels have special potential to replace fossil fuels for modes of transportation where batteries are too heavy to store sufficient power, or in times and places where charging infrastructure is not easily connected to sources of clean electricity. Sustainable biofuels for aviation, marine freight, and heavy-duty long-distance trucking are notable examples. In addition, the scarcity of raw materials used in batteries, along with the social and environmental problems associated with sourcing them, is likely to limit the full electrification of the passenger vehicle fleet. Decarbonizing the transportation sector of the economy is important because it currently accounts for the largest fraction of U.S. CO_2 emissions. And, crude oil price fluctuations resulting from natural or human disasters are felt very directly by consumers at the gas pump or airport ticket counter.

However, further research and innovation is needed for biofuels and bioproducts to meet their full potential as a renewable solution to our collectively growing demand for energy and chemical commodities.

DOE Bioenergy Research Center program goals

CABBI and the three other BRCs collectively aim to provide the fundamental scientific discoveries and technologies needed to support an economically successful and ecologically sustainable domestic biofuels and bioproducts industry. This requires improved cropping systems that produce more biomass per acre, produce biomass of greater value, and do so while achieving sustainable greenhouse gas balances. It also includes more efficient technologies to deconstruct biomass and convert it into valuable fuels and chemicals that decarbonize our energy systems and products. Since the BRC program's inception in 2007, the BRCs made numerous significant contributions to the sustainable production of valuable chemicals and transportation fuels. These advances, made by thousands of past and current researchers, are part of over 4000 publications that have been cited 200,000 times, and more than 670 patent applications that have led to 280 licenses and helped form 15 start-up companies. The strong focus on technology transfer and commercialization is a notable feature of the BRC program relative to most government grants. For example, CABBI has partnerships with 11 companies. Those relationships allow us to learn the most pressing challenges faced by industry and provide solutions to problems that we are best placed to address. I believe these efforts are greatly aided by sustained funding from DOE for our research that spans the entire value chain. This sustained support is allowing the BRCs to first identify, and then address, a series of barriers and opportunities for transitioning to a sustainable and strong U.S. bioeconomy.

CABBI's scientific approach and progress

Now in its fifth year, CABBI is organized around three themes. First, the *Feedstock Production* team develops dedicated energy crops to produce biomass and novel bioproducts including liquid fuels. Second, the *Conversion* team develops catalysts and engineers advanced microbes that can be fed plant products to produce more fuel and high value chemicals. Third, the *Sustainability* team assesses and guides the economic and environmental viability of the entire value-chain from farm field to processing plant to fuel tank. Below, I highlight examples of key discoveries made by each theme before discussing some of the cutting-edge tools that the team has established to enable future breakthroughs.

We pursue a vision of "plants as factories", in which biofuels and other chemicals are synthesized directly in grass crops. This capability can greatly increase the value of biomass, providing a strong foundation for the entire bioenergy enterprise, and directly benefiting the farming communities who produce it. It also complements the vital work being done by the other BRCs to convert the lignin and cellulose in plant biomass into fuels and bioproducts with maximum efficiency. Our *Feedstock Production* team has already engineered a 50-fold increase in the oil content of the vegetative tissues of grass crops. Minimal processing would be needed to squeeze the oil out of the plants after harvest and purify it to be a drop-in transportation fuel. Crucially, we have established an R&D pipeline that goes beyond initial proof-of-concept in greenhouse-grown plants and tests the performance of our best crops in field trials across multiple states. When combined with operation of our bioprocessing pilot plant, this demonstrated that the early versions of our "oil-grasses" can already produce as much oil per acre of land as soybean, with the potential for significant further gains in the future. In addition, our team has identified approaches to make our crops more resilient to heat, drought, cold and air pollution through both breeding and biotechnology. This will aid their deployment in locations with poor growing conditions.

Continuing along the value chain, our *Conversion* team takes plant-derived oils and sugars and upgrades them by using highly engineered microbes to produce a suite of high-value chemicals. These chemicals are the key ingredients needed to produce decarbonized plastics, adhesives, polishes, lubricants, detergents and more. For example, their engineering has modified the metabolic pathways of a specialized yeast, allowing it to produce greater amounts of a compound called triacetic acid lactone, or TAL, than ever before. TAL is a platform chemical that can be upgraded to a variety of market-relevant end products currently derived from fossil fuels, and techno-economic analysis and life cycle assessment indicates that we are already very close to making this low-carbon production system for TAL a financially viable opportunity.

That techno-economic analysis and life-cycle assessment was performed by our *Sustainability* team, as they assess and guide the economic and ecological sustainability of the production systems we develop. Their work starts with cutting-edge measurements of greenhouse gas emissions from fields of our feedstock crops. For example, they have developed new understanding of how different bioenergy feedstock crops and the soil they grow in influence the efficiency of fertilizer application and production of nitrous oxide, an unwanted and very potent greenhouse gas. They have also leveraged high-resolution satellite imaging to identify land that has historically oscillated in and out of agricultural production due to marginal profitability. This provides a new approach to identify locations that might be prioritized for bioenergy production because they are not consistently viable for profitable production of current crops. This will help avoid competition for production of food versus fuel. The team uses their unique datasets to drive simulation models of crop and agroecosystem function across the diverse growing regions of the United States. And, they have developed a ground-breaking ability to combine their predictions of crop production and greenhouse gas emissions with economic models to determine which bioenergy crops should be grown where in order to maximize farmer profits and environmental benefits. This synthesis is delivering new insights on the complex interactions among bioenergy policies, feedstock attributes, conversion technology and market conditions that will affect the both the economic and ecological sustainability of a bioeconomy.

CABBI's toolkit for further discovery and innovation

A key additional element of our mission is the development of new tools and knowledge that can solve previously intractable problems and accelerate the pace of discovery and innovation. In addition to tailor-making tools to solve challenges in bioenergy research, this work frequently has much broader impact, providing breakthroughs that have many potential applications.

Our *Conversion* team is pioneering the development of automated laboratory research with the Illinois Biological Foundry for Advanced Biomanufacturing (iBioFAB). It uses robotics and Artificial Intelligence (AI) to accelerate - by at least an order of magnitude - the scientific and engineering process for bioenergy – including designing, building, testing and learning steps. It can house tens of thousands of individual samples and use its robotics to rapidly access more than 20 instruments on the platform - including a microscope and DNA fragment analyzer - to maintain, sample and analyze them. In addition, the team has developed new AI methods that allow computers to assess myriad options for engineering an enzyme and successfully pick out only the best options for real-world testing – a huge time saver. Perhaps most radical of all, the *Conversion* team has demonstrated the ability to design enzymes that catalyze entirely new chemical reactions. This opens up extraordinary opportunities to build high-value chemicals from plant products using engineered microbes. These new tools are being directly targeted towards our bioenergy research, but have many potential spin-off applications for other elements of the bioeconomy.

Developing new feedstock crops and improving existing crops depends heavily on knowledge of the plant's genome and the ability to modify it through breeding and biotechnology. Our *Feedstocks* team has sequenced the genome of Miscanthus, one of the most promising bioenergy feedstock species in terms of greenhouse gas balance. While genome sequencing has become increasingly common, this is significant because Miscanthus is one example of a number of key crops that have exceeding genomes much more complex than humans and many other species. This made it much harder to assemble the DNA sequence into the correct order. This is crucial in the same way that the pages and chapters of a book must be in the correct order for the story to make sense. But, the team overcame that challenge, learning valuable lessons that can be applied in other important species. And, having the genome in hand opens up a suite of high-tech approaches to crop improvement that previously were unavailable. In parallel, the team has also demonstrated new capabilities in genome editing of our target crops – again a more challenging task in grasses with complex genomes, but one that creates new opportunities for producing larger quantities and a broader range of bioproducts in the plant. This work poises CABBI, and the rest of the bioenergy research community in the U.S. and around the world, to engineer bioenergy feedstocks more quickly and effectively.

The *Sustainability* team has developed a robust software platform, BioSTEAM, for conducting agile techno-economic analysis and life-cycle assessment. BioSTEAM allows for rapid evaluation of different feedstocks entering the processing plant, different conversion processes being used to produce different biofuels and bioproducts, and different configurations of the processing plant to identify financially viable opportunities, a major advance over prior, less flexible platforms. Crucially, with federal funding it is made freely available, with open-source code, unlike the less powerful commercial products that mainly preceded it. As a result, it is being widely adopted by researchers and industry. We have applied BioSTEAM to characterize the viability of liquid fuel production from CABBI feedstocks and to set research and development targets for both feedstock composition and conversion technologies, targeting the financially viable, environmentally sustainable production of a range of bioproducts.

Cutting across research in all three research themes, CABBI is developing and applying AI methods to a diverse portfolio of problems. This includes designing new enzymes and metabolic pathways, automating normally laborious and inefficient steps in genome editing, and automatically analyzing images from microscopes, drones, or satellites to much more rapidly identify which crops and locations perform best. The University of Illinois at Urbana-Champaign also recently started to lead AI Institutes funded by the U.S. Department of Agriculture and the National Science Foundation. Synergies between their work and CABBI's research will be increasingly valuable moving forward and highlights the benefits of the complementarity among federal funding agencies in the U.S.. Vitally, the same spirit of cooperation is clearly event across the research assets of the Department of Energy. The BRCs have always acted in support of one another, and over last two years we have invested significant time to identify and map out research projects that we can tackle more quickly, efficiently, and effectively through even closer collaboration. Our research is also enabled by the world-class facilities and services made available to us at DOE's National Labs, Joint Genome Institute, and Environmental Molecular Sciences Laboratory.

Training a diverse bioenergy workforce

Along with the other BRCs, CABBI is committed to training a diverse bioenergy workforce. Our scientists at all career stages contribute to this effort through participation in a wide range of outreach and educational activities. I am especially excited about our new internship program that provides summer research experiences for undergraduate students from traditionally under-represented groups. In addition to a research project, a series of seminars expose participants to career options and develop their skills in science communication and the process of applying to graduate school. We hope that these experiences, and the relationships participants build in the process, will attract help attract the students into graduate school and onto careers in bioenergy.

In conclusion, I came to America because I believed it provided the greatest opportunity of any country in the world for a scientist to help tackle the grand challenges of clean energy, climate change, and sustainable agriculture. Twenty years later, my experiences working at a top land-grant university that partners with other academic institutions, federal agencies, diverse industries, and farmers have greatly bolstered that belief. The privilege of leading a Department of Energy BRC is arguably the most complete expression of this opportunity. Everyday involves learning something new and it is impossible not to be inspired by the work of the team around me. I hope I have helped you understand why we all have reason to be proud of this country's bioenergy research enterprise and to be optimistic about what it can deliver in the future for the benefit of everyone in our society.

Andrew David Bazett Leakey
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I. NARRATIVE BIOGRAPHY

Dr. Leakey received his B.Sc. in Plant Sciences in 1998 and his Ph.D. in Tropical Tree Physiology and Ecology in 2003, both from the University of Sheffield, UK. He moved to the University of Illinois at Urbana-Champaign, USA as a Fulbright Scholar in 2002. Staying at Illinois he was a post-doctoral scientist in the Department of Plant Biology and then Research Fellow at the Institute for Genomic Biology, before joining the faculty as an Assistant Professor in 2007. He was promoted to Associate Professor in 2013 and Professor in 2018. He has received the Calvin-Benson Prize for excellence in early-career research on photosynthesis and been elected as a Fellow of the American Association for the Advancement of Science. He is currently the Director of the Center for Advanced Bioenergy and Bioproducts Innovation (CABBI) and the Head of the Department of Plant Biology.

Dr. Leakey's research group at the University of Illinois aims to help improve the productivity, resource use efficiency and stress resilience of food and fuel crops. To do this we integrate genetic, molecular, biochemical, physiological, agronomic, imaging and machine learning tools. Our current focus is to holistically understand the mechanisms controlling stomata, rooting and water use efficiency. Our work to develop crops that use less water aims to protect them from yield loss in times and places of drought. This is important because drought already limits agricultural production in many parts of the world and will do so increasingly as the climate continues to change. In addition, water use efficient crops would help us to produce bioenergy and bioproducts on marginal quality land, where farmers currently struggle to make a profit because growing conditions are not ideal, and where we could avoid competition between production of food and fuel.

II. PERSONAL HISTORY AND PROFESSIONAL EXPERIENCE

A. Educational Background

University of Sheffield, U.K., B.Sc., Department of Animal and Plant Sciences, 1998
University of Sheffield, U.K., Ph.D., Department of Animal and Plant Sciences, 2003

B. Academic Positions

2002-2003	Fulbright Scholar, Department of Plant Biology, UIUC
2002-2004	Postdoctoral Research Associate, Department of Plant Biology, UIUC
2004-2007	Research Fellow, Institute for Genomic Biology, UIUC
2007-2013	Assistant Professor, Department of Plant Biology, UIUC
2007-2013	Assistant Professor, Institute for Genomic Biology, UIUC
2013-2018	Associate Professor, Department of Plant Biology, UIUC
2013-2018	Associate Professor, Institute for Genomic Biology, UIUC
2013-2018	Associate Professor, Department of Crop Sciences, UIUC
2016-2017	Visiting Scientist, Carnegie Institute for Plant Biology, Stanford, CA
2018-	Professor, Department of Plant Biology, UIUC

2018-	Professor, Institute for Genomic Biology, UIUC
2018-	Professor, Department of Crop Sciences, UIUC
2019-2020	Acting Head of Department, Department of Plant Biology, UIUC
2019-2020	Theme Leader, Feedstock Production, CABBI
2019-	Professor, Center for Digital Agriculture, UIUC
2020-	Head of Department, Department of Plant Biology, UIUC
2020-	Director, Center for Advanced Bioenergy & Bioproducts Innovation, UIUC

C. Other Professional Employment

2013 Consultant to Koch Fertilizer

D. Honors, Recognitions, and Outstanding Achievements

1998 J.G. Boswell Prize for B.Sc. in Plant Sciences, University of Sheffield
1999 Scurfield Bursary for Overseas Ph.D. Research, University of Sheffield
2002 Fulbright Scholar
2007 Teacher Ranked Excellent by Students (*Plants & Global Change*)
2008 Dean's Teaching Fellow, College of Liberal Arts & Sciences, UIUC
2008 Teacher Ranked Excellent by Students (*Global Warming, Biofuels, Food*)
2009 Teacher Ranked Excellent by Students (*Plants & Global Change*)
2010 Faculty Fellow, Environmental Change Institute, UIUC
2011 Beckman Fellow, Center for Advanced Studies, UIUC
2011 Teacher Ranked Excellent by Students (*Plants & Global Change*)
2013 I.C. Gunsalus Fellow, College of Liberal Arts and Sciences, UIUC
2013 Arnold O. Beckman Research Award
2015 Teacher Ranked Excellent by Students (*Plants & Global Change*)
2016 Calvin-Benson Award for outstanding early career research, International Society of Photosynthesis Research
2017 University Scholar, Office of the President, University of Illinois System
2018 Teacher Ranked Excellent by Students (*Plants & Global Change*)
2019 Elected Fellow of the American Association for the Advancement of Science (AAAS)
2020 Martin & Ruth Massengale Lecturer, Crop Science Society of America Annual Meeting.
2020 Teacher Ranked Excellent by Students (*Plants & Global Change*)
2021 Arnold O. Beckman Research Award

E. Invited Lectures and Invited Conference Presentations

1. How will the major agricultural ecosystem of the U.S. respond to global climate change in 2050? (2003) *Fulbright Commission Lecture, Astra-Zeneca HQ, UK.*
2. How will leaf respiration respond to future CO_2-rich atmospheres? (2004) *Department of Ecology and Evolutionary Biology, University of Kansas.*
3. How will leaf respiration respond to future CO_2-rich atmospheres? (2004) *Department of Crop Sciences, UIUC.*
4. Measuring diurnal courses of gas exchange and chlorophyll fluorescence in the field. (2005) *International Workshop on Photosynthetic Gas Exchange and Chlorophyll Fluorescence Measurement, Universidad Autonoma de Nuevo Leon, Mexico.*

5. Microarray analysis of gene expression responses in soybean to growth at elevated [O_3]. (2006) *USDA NE1013 National Program Workshop, UIUC.*

6. Food for thought: crop responses to climate change in the 21st century. (2006) *Natural Science Colloquia, Illinois Wesleyan University.*

7. Ecological genomics: new insights from microarray analysis of soybean responses to elevated CO_2 and O_3 under Free-Air Concentration Enrichment. (2006) *Department of Ecology and Evolutionary Biology, University of Colorado.*

8. Food for thought: Crop responses to climate change in the 21st century. (2006) *International Education Symposium, Hathaway Brown School, Shaker Heights, OH.*

9. Plant responses to global change and a new genomic ecology approach.(2006) *Department of Plant Biology, UIUC.*

10. Elevated CO_2 does not stimulate C_4 photosynthesis directly, but impacts water relations and indirectly enhances carbon gain during drought stress in maize (*Zea mays*) grown under free-air CO_2 enrichment (FACE). (2006) *Crop Science Society of America Annual Meeting, Indianapolis, IN.*

11. Ecological genomics: new insights from microarray analysis of soybean responses to elevated CO_2 and O_3 under Free-Air Concentration Enrichment. (2006) *Department of Molecular Genetics and Microbiology, University of Florida.*

12. Plant responses to global change and a new genomic ecology approach. (2007) *Division of Biology, Imperial College, London, UK.*

13. How will the gene expression profile, biochemistry and physiology of soybean leaves respond to growth at elevated [CO_2] under open-air field conditions? (2007) *Institute for Genomic Biology Fellows Symposium, UIUC.*

14. Using microarrays to reveal the mechanism of crop responses to global climate change under field conditions. (2007) *International Rice Research Institute Workshop – Cool Rice for a Warmer World, Huazhong Agricultural University, Wuhan, China.*

15. Functional genomics and field ecology: Mechanistic insights from microarray analysis of soybean responses to elevated [CO_2]. (2007) *Ecological Society of America Annual Meeting, San Jose, CA.*

16. Design and analysis of microarray experiments for global change research. (2007) *Workshop on Statistical Analysis and Data Integration in Plant Genomic Ecology Research, UIUC.*

17. Physiological, biochemical and molecular analysis of the coordinated up-regulation of photosynthetic, respiratory and biosynthetic metabolism in soybean leaves under Free-Air CO_2 Enrichment. (2007) *14th International Congress of Photosynthesis, Glasgow, UK.*

18. Food (and fuel) for thought: Plant responses to climate change. (2008) *National Climate Change Teach-In, Urbana Free Library, Urbana, IL.*

19. Genomic Ecology of soybean responses to elevated [CO_2] and drought. (2008) *Facing the future, International Joint Workshop of AspenFACE, SoyFACE and SFB projects, Rhinelander, WI.*

20. Food (and fuel) for thought: Plant responses to climate change. (May 2008) *Earth Day Lecture, Students for Environmental Concerns, UIUC.*

21. Corn and soybean responses to climate change (May 2008) *Monsanto Headquarters, St Louis.*

22. Lecture to High School Science Teachers conference on The Global Demand for Biofuel (June 2008), titled, "*The Ecology of Biofuels*".

23. Lecture to Middle School Girls attending summer science camp, Girls Adventures in Math, Engineering and Science (GAMES; July 2008), titled *Climate Change and Food.*

24. The Genomic Basis of stimulated respiration by plants growing under elevated carbon dioxide. (Aug 2008) *Gordon Research Conference, Photosynthesis: from genome to biome.*

25. Lecture to visiting delegation from AAPRESID, the Argentinean No-Till Farmers Association (Sept 2008), titled *Food (and fuel) for thought: plant responses to climate change.*

26. Genomic ecology of soybean responses to elevated [CO_2]. (Nov 2008) *UIUC Keck Center for Comparative and Functional Genomics Microarray Workshop.*

27. Crop responses to climate change (March 2009) *A New Green Revolution Meeting Global Food and Energy Demands. A Joint Area Centers Symposium.*

28. Genomic, Physiological & Ecological Responses of Soybeans to Elevated [CO_2]: A Case Study from SoyFACE (March 2009) *Ecological Society of Japan, Annual Meeting.*

29. Genomic, physiological and ecological responses of soybean to free-air CO_2 enrichment (March 2009) *500th seminar at National Institute for Agro-Environmental Sciences, Tsukuba, Japan.*

30. Genomic, physiological and ecological responses of soybean to free-air CO_2 enrichment (March 2009) *National Agricultural Research Center for Tohoku Region, Morioka, Japan.*

31. Genomic Ecology of Global Change (April 2009) *National Evolutionary Synthesis Center Workshop, Toward A New Synthesis of the Evolutionary History and Ecology of C_4 Grasses, Durham, NC.*

32. Transcriptional reprogramming of leaf metabolism under elevated CO_2 stimulates respiration in soybean (May 2009) *International Conference for Plant Mitochondrial Biology.*

33. Lecture to Middle School Girls attending, Girls Adventures in Math, Engineering and Science summer science camp at UIUC (July 2009), titled *Climate Change and Food.*

34. Lecture to visiting delegation from AAPRESID, the Argentinean No-Till Farmers Association (Sept 2009), titled *Food (and fuel) for thought: plant responses to climate change.*

35. Food for thought – crop responses to climate change (October 2009) Meeting of *Students for Environmental Concerns, UIUC.*

36. How will elevated CO_2 impact photosynthesis of tropical plants? (November 2009) *23rd New Phytologist Symposium Carbon Cycling in Tropical Ecosystems, Guangzhou, China.*

37. The Environmental Change Biology Podcast Project (December 2009) *Environmental Change Institute Annual Symposium, UIUC.*

38. Transcriptional reprogramming of leaf carbon metabolism in plants growing at elevated [CO_2] (March 2010) *Kansas State Functional Genomics Consortium Symposium, Manhattan, KS.*

39. Global environmental change impacts on plant function and agroecosystem services (April 2010) *Geography Department Seminar, King's College London, UK.*

40. The elevated CO_2 by drought interaction: a saviour or false hope for future food production? (April 2010) *Stockholm Environmental Institute Seminar, University of York, UK.*

41. The elevated CO_2 by drought interaction: a saviour or false hope for future food production? (April 2010) *Department of Animal and Plant Sciences Seminar, University of Sheffield, UK.*

42. Rising atmospheric CO_2 and the future of C_4 crops for food and fuel (August 2010) *Symposium on C_4 Plant Biology, CAS-MPG Partner Institute for Computational Biology, Chinese Academy of Sciences, Shanghai, China.*

43. Crop adaptation for an elevated [CO_2] world (August 2010) *Royal Society International Scientific Seminar, Atmospheric CO_2 and green evolution, Kavli Royal Society Center, UK.*

44. Genomic ecology of plant responses to global environmental change (November 2010) *Using Functional Genomics to Harness Adaptive Traits in Australian Native Plants Workshop, University of Western Australia, Australia.*

45. What will be the effect of the climate change on crop production (November 2010) *Environmental Change Institute Annual Symposium, UIUC.*

46. Do we really need more experiments to understand how vegetation change is driven by rising atmospheric CO_2 concentrations? (January 2011) *South African CO_2 and Vegetation Consortium Workshop, Grahamstown, South Africa.*

47. Soybean and maize responses to global environmental change at SoyFACE (March 2011) *CO_2 Symposium, Smithsonian Tropical Research Institute, Panama.*

48. Transcriptional reprogramming of respiration to optimize plant metabolism in response to stress and resource availability (May 2011) *Institute for Genomic Biology Fellow's Symposium, UIUC.*

49. Transcriptional reprogramming of respiration in response to global environmental change (May 2011) *Penn State Plant Biology Symposium.*

50. Rising atmospheric CO_2 and the future of C4 crops for food and fuel (July 2011) *International Botanical Congress, Melbourne, Australia.*

51. Transcriptional reprogramming of respiration under elevated CO_2 and elevated O_3 (July 2011) *International Botanical Congress, Melbourne, Australia.*

52. Non-optimal responses to drought stress of soybean grown at elevated CO_2 in the field (July 2011) *International Botanical Congress, Melbourne, Australia.*

53. New rice for an elevated CO_2 future (Nov 2011) *International Rice Research Institute, Philippines.*

54. Climate-proofing rice for farmers in the tropics (December 2011) *Environmental Change Institute Annual Symposium, UIUC.*

55. Environmental change impacts on soybean rooting, food production and ecosystem function (Dec 2011) *Environmental Change Institute Annual Symposium, UIUC.*

56. Climate change and crops (Jan 2012) Lecture to Mahomet Junior High School Students

57. Transcriptional reprogramming of respiration in response to global environmental change (March 2012) *Okazaki Biology Conference 8, Japan.*

58. Plant interactions with the atmospheric CO_2 pool – a phytocentric view of the global carbon cycle (April 2012) *Department of Geology, UIUC.*

59. Should the paradigm of reduced plant drought stress under elevated [CO_2] be hung out to dry? (May 2012) *Lancaster Environment Center, University of Lancaster, UK.*

60. Data and models for predicting water processes in rainfed agriculture – the plant scale (June 2012) *Water in Bioenergy Agroecosystems Workshop, Chicago, Energy Biosciences Institute.*

61. Next-generation elevated CO_2 experiments for climate-proofing crops (July 2012) *World Crop FACE Workshop, Tsukuba, Japan.*

62. SoyFACE overview (July 2012) *World Crop FACE Workshop, Tsukuba, Japan.*

63. Should the paradigm of reduced plant drought stress under elevated [CO_2] be hung out to dry? (July 2012) *World Crop FACE Workshop, Tsukuba, Japan.*

64. Integration of physiology, genomics and genetics to understand nad improve crop productivity in a changing world (July 2012) *CSIRO, Canberra, Australia.*

65. Integrating transcriptomics and physiology (September 2012) *SEB Plant Environmental Physiology Group, Ecophysiology Techniques Workshop, Lisbon, Portugal.*

66. Acclimation of stomatal function to elevated O_3 (September 2012) *White Rose Workshop on Regional Scale Ecosystem Model Development, University of York, UK* (presentation via video conference)

67. Plants iView: a plug-n-play outreach program for Plant Biology (March 2013) *Department of Plant Biology Colloquium, UIUC.*

68. A universal playbook for stomata in C_3 plants: fact or fiction? (April 2013) *Department of Plant Biology Colloquium, UIUC.*

69. Should the paradigm of reduced plant drought stress under elevated [CO_2] be hung out to dry? (May 2013) *Interdisciplinary Plant Group Symposium on Roots, University of Missouri, Columbia, MO.*

70. Transcriptional reprogramming of plant metabolism in response to global environmental change (May 2013) *Beijing Genome Institute-Institute for Genomic Biology Workshop, UIUC.*

71. Corn (June 2013) *Workshop on for Champaign Unit 4 High School Teachers.*

72. Elevated CO_2 ameliorates stress under mild drought but exacerbates stress under severe drought in soybean (July 2013) *American Society of Plant Biologists Annual Meeting, Providence, RI.*

73. SoyFACE: a field laboratory for adaptation of C_4 (and C_3) crops to global environmental change (August 2013) *International Symposium for C_4 and CAM Plant Biology, UIUC.*

74. Have we been ignoring physiological plasticity and genetic variation in stomatal function as a significant source of error in models of water and carbon fluxes? (August 2013) *International Photosynthesis Congress, St Louis, MO.*

75. A universal playbook for stomata in C_3 plants: fact or fiction? (August 2013) ATMS571 *Department of Atmospheric Science, UIUC.*

76. Plants iView: a plug-n-play outreach program for Plant Biology (September 2013) *Purdue University.*

77. Elevated CO_2 ameliorates stress under mild drought but exacerbates stress under severe drought in soybean (October 2013) *Physiological and Molecular Plant Biology Seminar, UIUC.*

78. Should the paradigm of reduced plant drought stress under elevated [CO_2] be hung out to dry? (January 2014) *Department of Plant Biology Seminar, Carnegie Institute, Palo Alto, CA.*

79. Should the paradigm of reduced plant drought stress under elevated [CO_2] be hung out to dry? (February 2014) *Department of Plant Sciences Seminar, UC Davis, CA.*

80. Should the paradigm of reduced plant drought stress under elevated [CO_2] be hung out to dry? (February 2014) *Hydrosystems Group Seminar, UIUC.*

81. Should the paradigm of reduced plant drought stress at elevated CO_2 be hung out to dry? (March 2014) *MEPS Symposium, Texas A&M, College Station, TX.*

82. Should the paradigm of reduced plant drought stress under elevated [CO_2] be hung out to dry? (April 2014) *Monsanto, St Louis, MO.*

83. Targets for improving simulation of plant carbon-water interactions in earth system models (April 2014) *New Phytologist Workshop on Representation of Photosynthesis in Earth System Models, Montauk, NY.*

84. Crop Adaptation & High-Throughput Field Phenotyping (June 2014) *Monsanto-Illinois Meeting on Crop Nutrient Management, Institute for Genomic Biology, UIUC.*

85. Elevated CO_2 ameliorates stress under mild drought but exacerbates stress under severe drought in soybean (July 2014) *Society for Experimental Biology Annual Meeting, Manchester, UK.*

86. A universal playbook for stomata in C_3 plants: fact or fiction? (July 2014) *American Society of Plant Biologists Annual Meeting, Portland, OR.*

87. Using genomic tools to understand crop responses to a future, elevated [CO_2] world (July 2014) *Genomics for Teachers Workshop, Institute for Genomic Biology, UIUC.*

88. Measurement, analysis and interpretation of A/c_i curves to evaluate the factors limiting photosynthetic CO_2 fixation (Sept 2014) *SEB Plant Environmental Physiology Group, Ecophysiology Techniques Workshop, Lisbon, Portugal.*

89. Crop responses and adaptation to climate change (Oct 2014) *UK-US Taskforce on Resilience of the Global Food Supply Chain to Extreme Events, Willis Tower, Chicago, IL.*

90. The future of crops with global environmental change (Dec 2014) *Chambana Science Café, Pizza M, Urbana, IL.*

91. How much will elevated CO_2 offset crop yield losses in a hotter, drier future? (December 2014) *Departmental Seminar, Penn State University, PA.*

92. Genomic Solutions for Adapting Crops to Global Change (Feb 2015) *Osher Life Long Learning Institute, Champaign, IL.*

93. SoyFACE: A field laboratory for study of crop global change biology (March 2015) *Visit of ARPA-E panel managers to UIUC, Institute for Genomic Biology, UIUC.*

94. My teaching and research with LAS students (repeated 3 times, March and April 2015) *Admitted Students Day, LAS, UIUC.*

95. How much will elevated CO_2 offset crop yield losses in a hotter, drier future? (May 2015) *UGA Plant Center Symposium, University of Georgia, GA.*

96. Modification of the response of photosynthetic productivity to drought by elevated CO2 concentrations – has its significance been misunderstood? (June 2015) *School of Biological Sciences, University of Essex, UK.*

97. Measurement, analysis and interpretation of leaf gas exchange (July 2015) *The Flux Course, Rocky Mountain Research Station, CO.*

98. Genetic and genomic approaches to understand and improve maize responses to ozone (Sept 2015) *NSF Plant Genome Research Program PIs Meeting, Washington DC.*

99. Adapting crops to climate change – a 21st century science problem (Sept 2015) *LAS Recruitment Event, UIUC.*

100. Adapting crops to climate change – a 21st century science problem (Sept 2015) *Looking in the Right Direction: Carl Woese and the New Biology, IGB, UIUC.*

101. A rapid optical profilometry and computer vision method for phenotyping leaf epidermal structure applied to genetic and environmental control of stomatal patterning in the model C4 species maize and setaria (Nov 2015) *Workshop on Plant Development and Drought Stress, Asilomar, CA.*

102. Adapting Crops to Climate Change (Nov 2015) *The IGB Fellows Alumni lecture, IGB, UIUC.*

103. Rapid optical profilometry and computer vision of leaf epidermal structure applied to genetic and environmental control of stomatal patterning in model C_4 species (Jan 2016) *The Plant and Animal Genome Conference, San Diego, CA.*

104. High fidelity-rapid phenotyping in field experiments to advance adaptation of crops to global change (Apr 2016) *Collaboration Symposium, Donald Danforth Plant Science Center, St Louis, MO.*

105. High fidelity-rapid phenotyping in field experiments to advance adaptation of crops to global change (Apr 2016) *Department of Plant Biology Colloquium, UIUC.*

106. Targets for Crop Adaptation Discovered in Free-Air CO_2 Enrichment (FACE) Field Experiments (May 2016) *Adaptation Futures 2016 – practices and solutions, Rotterdam, The Netherlands.*

107. SoyFACE: A field laboratory for study of crop global change biology (May 2016) *Visit of Provost Delegation from Birmingham University, UK to UIUC.*

108. High fidelity detection of QTL for biomass production from rapid imaging of a C4 grass crop in the field (July 2016) *American Society of Plant Biologists Annual Meeting, Austin, TX.*

109. Improving drought tolerance and water use efficiency in C4 crops (Aug 2016) *Agronomy Day, Illinois Experimental Research Farm, UIUC.*

110. Rising [CO_2] as a benefit and challenge to improving crop photosynthesis (Aug 2016) *Plenary lecture for Calvin Award, International Congress on Photosynthesis Research, Maastricht, The Netherlands.*

111. Vertically integrating analyses of plant carbon, water and nutrient relations to understand and improve crop performance (Oct 2016) *Seminar, Department of Global Ecology, Carnegie Institute for Science, Stanford, CA.*

112. Water Efficient Sorghum Technologies (Nov 2016) *ARPA-E TERRA and OPEN program PIs meeting, Phoenix, AZ.*

113. High fidelity phenotyping of productivity, WUE and drought traits in the model C4 grasses maize, sorghum and setaria (March 2017) *Seminar, International Rice Research Institute, Philippines.*

114. Development and application of novel phenotyping techniques to understand the genetic control of productivity and drought traits in the model C4 grass Setaria (Feb 2017) *Plenary talk, 2nd International Genetics Conference, Donald Danforth Plant Science Center, St Louis, MO.*

115. Stomata and water use efficiency at the core of plant-environment interactions (Apr 2017) *Seminar, School of Plant Sciences, University of Arizona, AZ.*

116. Water Efficient Crop Technologies (Sept 2017) *Value Proposition, Ag Innovation Showcase, St Louis, MO.*

117. Phenomics of stomata and water use efficiency in model C4 crops (Feb 2018). *Phenome 2018, Tucson, AZ.*

118. Phenomics of stomata and water use efficiency in model C4 crops (March 2018). *UIUC Department of Plant Biology Departmental Colloquium.*

119. High-throughput Phenotyping of Leaf Traits to Understand Plant Carbon, Water and Nitrogen Relations (April 2018). *Plant Phenomics Symposium, University of Nebraska.*

120. Academic Highlights – The Illinois campus as an inventor's workshop for the crops of the future (Sept 2018). *University of Illinois Board of Trustees Meeting.*

121. Stress tolerant crops for the future (Oct 2018) *Presentation to UIUC Alumni and Donors, World of Genomics, St Louis Science Center.*

122. Phenomics of stomata and water use efficiency in model C4 crops (June 2018). *American Society for Plant Biology Annual Meeting, Montreal, Canada.*

123. Plant science for sustainability and resilience to climate change (April 2018) Agriculture and Consumer Economics Library, UIUC.

124. Water Efficient Sorghum Technologies (Oct 2018) *ARPA-E TERRA and OPEN program PIs meeting, San Francisco, CA.*

125. Studying climate change on the farm: free-air CO_2 enrichment experiments (Oct 2018) *ARPA-E TERRA and OPEN program PIs meeting, San Francisco, CA.*

126. Phenomics of stomata and water use efficiency in model C4 crops (September 2018). *Bayer Crop Science Seminar, St Louis, MO.*

127. 25 years of FACE experiments – evidence for or against elevated CO_2 reducing evapotranspiration and ameliorating plant drought stress? (August 2018) *Ecological Society of America Annual Meeting, New Orleans, LA.*

128. Phenomics of stomata and water use efficiency in model C4 crops (August 2018). *University of New Mexico Department of Biology Departmental Colloquium.*

129. High-throughput Phenotyping of Leaf Traits to Understand Plant Carbon, Water and Nitrogen Relations (September 2018). *SEB Plant Environmental Physiology Group, Ecophysiology Techniques Workshop, Lisbon, Portugal.*

130. Phenomics of stomata and water use efficiency in model C4 crops (March 2019). *UIUC Center for Digital Agriculture Kickoff Event.*

131. Phenomics of stomata and water use efficiency in model C4 crops (May 2019). *UIUC Physiological and Molecular Plant Biology Seminar.*

132. Addressing the challenge of climate change for crops (June 2019). *Bayer Crop Science Fellows Colloquium, St Louis, MO.*

133. Phenomics of stomata and water use efficiency in model C4 crops (November 2019). *Purdue University Seminar.*

134. Using computer vision to relieve the crop phenotyping bottleneck (February 2020). *UIUC Center for Digital Agriculture Symposium*

135. Progress toward the "plants as factories" paradigm for bioenergy in grasses (February 2020). *DOE Genomic Science Program Annual PIs meeting*

136. The Phenomics of Stomata and Water Use Efficiency in C4 crops (December 2020). *ARPA-E TERRA Program PIs Meeting*

137. The Phenomics of Stomata and Water Use Efficiency in C4 crops (October 2020). *Martin and Ruth Massengale Lecture to the Annual Meeting of the Crop Science Society of America*

138. The Phenomics of Stomata and Water Use Efficiency in C4 crops (Feb 2021). *University of Missouri Interdisciplinary Plant Group seminar*

139. The Phenomics of Stomata and Water Use Efficiency in C4 crops (March 2021). *UIUC Department of Plant Biology colloquium*

140. The Phenomics of Stomata and Water Use Efficiency in C4 crops (April 2021). *DOE BRC Sorghum workshop*

141. Overcoming bottlenecks in field-based root phenotyping using thousands of minirhizotrons (May 2021). *11th Symposium of the International Society of Root Research and Rooting 2021*

142. Phenotyping stomatal anatomy and function (Sept 2021) *Society for Experimental Biology Environmental Physiology Group, Virtual Workshop on Field and Laboratory Techniques*

143. Lessons on G x E from a phenomics approach to studying stomata and water use efficiency in C4 crops (Oct 2021) *Purdue Graduate Student Plant Science Symposium*

F. Offices Held in Professional Societies

2018 – 2019	Convener, Crop Molecular Genetics Group, Society for Experimental Biology, UK
2019 – present	Convener, Photosynthesis Group, Society for Experimental Biology, UK

G. Editorship of Journals or Other Learned Publications

2009 – 2017	Editor, *Photosynthesis Research*
2012 – 2016	Editor, *Food and Energy Security*
2013 – 2018	Editorial Review Board, *Plant Cell & Environment*
2017 – 2020	Guest Editor, *The Plant Cell*
2017 – 2020	Academic Editor, *Plant Direct*
2019 – present	Associate Editor, *Plant Cell & Environment*

H. Grants Received

CURRENT PROJECTS

I Baxter, A Cousins, J Dinneny, A Kausch, **ADB Leakey**, T Mockler, S Rhee, D Voytas; *Using systems approaches to improve photosynthesis and water use efficiency in sorghum*, DOE Biosystems Design, 09/2017 – 09/2022, $ 16,067,714 ($2,127,099 to UIUC).

ADB Leakey, EH DeLucia, SP Long, S Moose, H Zhao, M Khanna, ME Hudson, C Rao, W Yang, V Singh, *et al.*; Center for Advanced Bioenergy and Bioproducts Innovation, DOE Bioenergy Research Center, 12/2017 – 11/2022, $104M.

V Adve et al. (**ADB Leakey senior personnel**); *Artificial intelligence for future agricultural resilience, management, and sustainability*, USDA-NIFA Artificial Intelligence Institute, 09/01/2020 – 08/31/2025, $19,998,045 (approx $350,000 to Leakey).

ADB Leakey, I Baxter, J Dinneny C Pignon; *Transcriptomics of water use efficiency traits in sorghum and setaria*, Joint Genome Institute Community Sequencing Project, 2018-2024.

JC Mortimer, F Brandizzi, **ADB Leakey**, H Scheller, D Ware, Z Xin; *Sequencing of sorghum EMS mutants*, Joint Genome Institute Community Sequencing Project, 2018-2021.

ADB Leakey, W Yang; *Revealing root system interactions with shoots and microbes as drivers of bioenergy feedstock productivity and sustainability*, CABBI Postdoc Integration Project, 2019-2021, $250,000.

ADB Leakey, EA Ainsworth; *Using high throughput phenotyping to assess the leaf economics spectrum of C4 bioenergy crops*. Arnold O. Beckman Research Award, UIUC, 2021, $29.848.

A Jones, **ADB Leakey**, C Jones; *Collaborative Research: RoL – Rules for Dynamic-Light Environmental Sculpting of Genomes*. NSF Rules of Life, Integrative Organismal Systems; 06/2021 - 06/2025, $1,212,609 to UIUC.

PAST PROJECTS

ADB Leakey; *Astra-Zeneca Fulbright Scholar*, Fulbright Commission, 07/2002 - 07/2003, $22,000.

EH Delucia, EA Ainsworth, M Berenbaum, **ADB Leakey**, DR Ort, A Zangrel; *Genomic Regulation of the Response of an Agroecosystem to Elements of Global Change*, Department of Energy, 01/2009 – 12/2009, $250,000.

SP Long, **ADB Leakey**, EH DeLucia, DR Ort; *How will productivity, evapotranspiration & insect herbivory of the Midwest agroecosystem respond to the combined drought and elevated [CO2] anticipated for 2050?* DOE National Institute for Climate Change Research, 07/2007 - 06/2010, $368,648.

ADB Leakey, EA Ainsworth; *Integrated Enhancement of Global Change Biology Classes*, Environmental Change Institute - UIUC, 06/2009 – 05/2010, $4,880.

TE Twine and **ADB Leakey**; *Agroecosystems: Effects of changes in climate, carbon dioxide, and ozone over the central United States*, DOE National Institute for Climate Change Research, 05/2008 - 04/2011, $360,717.

EA Ainsworth, CJ Bernacchi, EH Delucia, **ADB Leakey**, DR Ort; *ECI Student Ambassadors for SoyFACE*, Environmental Change Institute - UIUC, 06/2009 – 05/2011, $25,000.

ADB Leakey; *ECI Faculty Fellowship*, Environmental Change Institute - UIUC, 06/2010 – 05/2011, $10,000.

ADB Leakey, DR Ort; *Altered Root-To-Shoot Signaling and Osmotic Adjustment as Key Determinants of Soybean Stress Tolerance Under Drought and Elevated [CO_2]*, USDA NIFA, 01/2010 – 12/2012, $349,266.

ADB Leakey; *Environmental Change Impacts on Crop Rooting, Food Production and Ecosystem Function,* Environmental Change Institute - UIUC, 06/2010 – 05/2012, $24,790.

ADB Leakey; *Plants iView – An After School Program in Plant Biology*, American Society of Plant Biologists Education Foundation, 10/2011 – 9/2012, $19,919.

ADB Leakey; *Testing Setaria drought response under Midwest U.S. field conditions*, Donald Danforth Plant Science Center, 10/2011 – 12/2012, $99,828.

ADB Leakey; *Plants iView – An After School Program in Plant Biology,* Office for Public Engagement, UIUC, 01/2012 – 12/2012, $19,744.

ADB Leakey; *Global Environmental Change Outreach Project*, UIUC Center for Global Studies, 1/2013 – 12/2013. $3000.

ADB Leakey; Arnold O. Beckman Research Award, UIUC, 2013, $30,000.

ADB Leakey; *Meeting: C4 + CAM Plant Biology 2013*, NSF IOS, 4/2013 – 3/2014, $12,800.

ADB Leakey; C_4 and CAM Plant Biology Symposium 2013, DOE, 6/2013-5/2014, $9,420.

ADB Leakey; *EBI 2011: Sustainability of Woody Biofuel Feedstocks*, Energy Biosciences Institute, 1/2012 – 12/2014, $602,931.

ADB Leakey; *Sustainability of Woody Biofuel Feedstocks*, Energy Biosciences Institute, 1/2015 – 12/2015, $101,401.

I Baxter, A Cousins, J Dinneny, **ADB Leakey**, T Mockler, S Rhee, Voytas; *A systems-level analysis of drought and density response in the model C4 grass Setaria viridis*, DOE Biosystems Design, 10/2012 – 8/2018, $ 12,140,437 ($1,997,547 to UIUC).

EA Ainsworth, **ADB Leakey**, P Brown, L McIntyre; *Genetic and Genomic Approaches to Understand and Improve Maize Responses to Ozone* , NSF Plant Genome, 1/2013 – 12/2019, $5,733,823.

EA Ainsworth, **ADB Leakey**, D Bush; *Phloem Loading as a Driver of Plant Photosynthetic Responses to Carbon Supply*, USDA-AFRI, 1/2015-12/2018, $474,099.

ADB Leakey; *Student Ambassadors of System Biology for Sustainable Food and Energy,* Department of Ed. Title VI National Resource Center in Global Studies, 2014-2018 $40,000.

ADB Leakey, CJ Bernacchi, PJ Brown, E Buckler, J Burke, T Clemente, M Gore, SP Long, DR Ort, E Spalding ; *Novel Technologies to Solve the Water Use Problem of High Yielding C4 Bioenergy and Bioproduct Feedstocks*, Advanced Research Projects Agency – Energy, 4/2016-9/2019, $4,995,967.

C Topp, I Baxter, N Goldenfeld, **ADB Leakey**; *An integrated phenomics approach to identifying the genetic basis for maize root structure and control of plant nutrient relations*, NSF Plant Genome, 2016-2020, $3,930,496. ($1,768,240 to UIUC)

ADB Leakey, TAM Pugh; Leading the way to a new global consensus on carbon dioxide impacts on crops and forests, BRIDGE Seed Fund Grant, 2017-2018, $4,400.

ADB Leakey, N Ahuja, J Hart; *Using Computer Vision to Relieve the Crop Phenotyping Bottleneck*, UIUC Center for Digital Agriculture Seed Grant, 2019-2020, $50,000.

Manuel Garcia, **ADB Leakey**; *Novel Deep Learning Methods for In Situ Fine Roots Measurements*, DOE SBIR Phase I Grant in collaboration with UHV Technologies, Inc., 2/18/2020 - 10/18/2020 ($60,000 to Leakey)

Andrea Pearce, **ADB Leakey**; *Progressive Automation of Minirhizotron Root Image Analysis through Advanced Contextualization and Machine Learning*, DOE SBIR Phase I Grant in collaboration with Transcend Engineering, 2/18/2020 - 10/18/2020 ($29,991 to Leakey)

I. Review Panels (e.g., for Governmental Agencies, Educational Institutions)

2008 Panel member evaluating proposals to the Midwest Region of DOE's *National Institute for Climate Change Research*.

2009 Panel member evaluating proposals to the European Commission's 7th Framework program on *Forest Ecosystem Genomics*.

2012 Panel member evaluating proposals to the American Society of Plant Biologists Summer Undergraduate Research Fellowship (SURF) program.

2014 Panel member evaluating proposals to UC Davis' *Signature Research in Genomics* program.

2015 Panel member evaluating proposals to NSF's *Integrated Environmental Physiology* program.

III. Publications and Creative Works

A. Doctoral Thesis Title

Photosynthetic and growth responses of dipterocarp tree seedlings to dynamic irradiance

B. Chapters in Books

1. DR Ort, EA Ainsworth, M Aldea, DJ Allen, CJ Bernacchi, MR Berenbaum, GA Bollero, G Cornic, PA Davey, O Dermody, FG Dohleman, JG Hamilton, EA Heaton, **ADB Leakey**, J Mahoney, TA Mies, PB Morgan, RL Nelson, A Rogers, AR Zangerl, X-G Zhu, EH DeLucia & SP Long (2006) SoyFACE: The effects and interactions of elevated [CO_2] and [O_3] on soybean. In: *Managed ecosystems and CO_2: Case studies, processes and perspectives* Ed: J Nösberger *et al.* Ecological Studies Series. Springer Verlag, pp. 71-86.

2. SP Long, EA Ainsworth, CJ Bernacchi, PA Davey, GJ Hymus, **ADB Leakey**, PB Morgan & CP Osborne (2006) Long term responses of photosynthesis and stomata to elevated [CO_2] in managed systems. In: *Managed ecosystems and CO_2: Case studies, processes and perspectives* Ed: J Nösberger *et al.* Ecological Studies Series. Springer Verlag, pp. 253-270.

3. **ADB Leakey**, EA Ainsworth, CJ Bernacchi, X Zhu, SP Long & DR Ort (2012) Photosynthesis in a CO_2 rich atmosphere. In: *Photosynthesis: A Comprehensive Treatise Physiology, Biochemistry, Biophysics and Molecular Biology.* 34: 733-768. Eds: JJ Eaton-Rye and BC Tripathy. Springer.

4. **ADB Leakey** (2012) Biogeochemical cycles and the flow of energy in the earth system. *Sustainability: A comprehensive foundation* Eds. T Thesis and J Tomkin. Online, open source textbook - http://cnx.org/content/col11325/latest/

5. **ADB Leakey** (2014) The Anthropocene: Plants in a New Environmental Domain. In: *The Plant Sciences*. In press. Ed: RK Monson. Springer. DOI 10.1007/978-1-4614-7612-2_6_1

C. Articles in Journals

1. **ADB Leakey**, MC Press, JD Scholes & JR Watling (2002) Relative enhancement of photosynthesis and growth at elevated CO_2 is greater under sunflecks than uniform irradiance in a tropical rain forest tree seedling. *Plant, Cell & Environment* 25: 1701-1714.
2. **ADB Leakey**, MC Press & JD Scholes (2003) Patterns of dynamic irradiance affect the photosynthetic capacity and growth of dipterocarp tree seedlings. *Oecologia* 135: 184-193.
3. **ADB Leakey**, JD Scholes & MC Press (2003) High temperature inhibition of photosynthesis is greater under sunflecks than uniform irradiance in a tropical rain forest tree seedling. *Plant, Cell & Environment* 26: 1681-1690.
4. **ADB Leakey**, CJ Bernacchi, FG Dohleman, DR Ort & SP Long (2004) Will photosynthesis of maize (*Zea mays*) in the U.S. Corn Belt increase in future [CO_2] rich atmospheres? An analysis of diurnal courses of CO_2 uptake under Free-Air Concentration Enrichment (FACE). *Global Change Biology* 10: 951-962.
5. **ADB Leakey**, JD Scholes & MC Press (2005) Physiological and ecological significance of sunflecks for dipterocarp seedlings. *Journal of Experimental Botany* 56: 469-482.
6. SP Long, EA Ainsworth, **ADB Leakey** & PB Morgan (2005) Global food insecurity. Treatment of major food crops with elevated carbon dioxide and ozone under large-scale fully open-air conditions suggests models may seriously overestimate future yields. *Philosophical Transactions of the Royal Society* 360: 2011-2020.
7. **ADB Leakey**, M Uribelarrea, EA Ainsworth, SL Naidu, A Rogers, DR Ort & SP Long (2006) Photosynthesis, productivity and yield of *Zea mays* are not affected by open-air elevation of CO_2 concentration in the absence of drought. *Plant Physiology* 140: 779-790.
8. SP Long, EA Ainsworth, **ADB Leakey**, J Nosberger & DR Ort (2006) Food for thought: Lower than expected crop yield stimulation with rising carbon dioxide concentrations. *Science* 312: 1918-1921.
9. **ADB Leakey**, CJ Bernacchi, DR Ort & SP Long (2006) Long-term growth of soybean at elevated [CO_2] does not cause acclimation of stomatal conductance under fully open-air conditions. *Plant, Cell & Environment* 29: 1794-1800.
10. CJ Bernacchi, **ADB Leakey**, LE Heady, PB Morgan, A Rogers, SP Long & DR Ort (2006) Hourly and seasonal variation in photosynthesis and stomatal conductance of soybean grown at future CO_2 and ozone concentrations for three years under fully open air conditions. *Plant, Cell & Environment* 29: 2077-2090.

11. SP Long, EA Ainsworth, **ADB Leakey**, DR Ort, J Nosberger & D Schimel (2007) Crop models, CO_2, and climate change – Response. *Science* 315: 460-460.

12. EA Ainsworth, A Rogers, **ADB Leakey**, LE Heady, Y Gibon, M Stitt & U Schurr (2007) Does elevated [CO_2] alter diurnal C uptake and the balance of C and N metabolites in sink and source soybean leaves? *Journal of Experimental Botany* 58: 579-591.

13. SD Wullschleger, **ADB Leakey** & SB St Clair (2007) Functional genomics and ecology – a tale of two scales. *New Phytologist* 176: 735-739.

14. EA Ainsworth, **ADB Leakey**, DR Ort, SP Long. (2008) FACE-ing the facts: Inconsistencies and interdependence among field, chamber and modeling studies of elevated [CO_2] impacts on crop yield and food supply. *New Phytologist* 179: 1-5.

15. EA Ainsworth[¶], A Rogers[¶], **ADB Leakey**[¶] (2008) Targets for crop biotechnology in a future high-CO_2 and high-O_3 world. *Plant Physiology* 147: 13-19. [¶]these authors contributed equally to this work. *** This paper was amongst the top 10 "most read" articles in *Plant Physiology* in November and December 2008 ***

16. EA Ainsworth, C Beier, C Calfapietra, R Ceulemans, M Durand-Tardif, GD Farquhar, DL Godbold, GR Hendrey, T Hickler, J Kaduk, DR Karnosky, BA Kimball, C Korner, M Koornneef, T Larfarge, **ADB Leakey**, KF Lewin, SP Long, R Manderscheid, DL McNeil, TA Mies, F Miglietta, JA Morgan, J Nagy, RJ Norby, RM Norton, KE Percy, A Rogers, J-F Soussana, M Stitt, H-J Weigel and JW White (2008) Next Generation of elevated [CO_2] experiments with crops: a critical investment for feeding the future world. *Plant, Cell and Environment* 31: 1317-1324

17. P Li, EA Ainsworth, **ADB Leakey**, A Ulanov, V Lozovaya, DR Ort, HJ Bohnert (2008) Arabidopsis transcript and metabolite profiles: ecotype-specific responses to open-air elevated [CO_2]. *Plant, Cell and Environment* 31: 1673-1687

18. QS Qiu, JL Huber, FL Booker, V Jain, **ADB Leakey**, EL Fiscus, PM Yau, DR Ort & SC Huber (2008) Increased protein carbonylation in leaves of *Arabidopsis* and soybean in response to elevated [CO_2] and [O_3]. *Photosynthesis Research* 97: 155-166.

19. **ADB Leakey**, F-Xu, K Gillespie, J McGrath, EA Ainsworth, DR Ort (2009) Genomic basis for stimulated respiration by plants growing under elevated carbon dioxide. *Proceedings of the National Academy of Sciences* 106: 3597-3602 *** This paper was highlighted on F1000***

20. **ADB Leakey**, EA Ainsworth, SM Bernard, RJC Markelz, DR Ort, S Placella, A Rogers, MD Smith, E Sudderth, DJ Weston, SD Wullschleger, S Yuan (2009) Gene expression profiling – opening the black box of plant ecosystem responses to global change *Global Change Biology* 15: 1201-1213.

21. **ADB Leakey** (2009) Rising atmospheric carbon dioxide concentration and the future of C_4 crops for food and fuel. *Proceedings of the Royal Society B: Biological Sciences* 276: 2333-2343.

22. **ADB Leakey**, EA Ainsworth, CJ Bernacchi, A Rogers, SP Long & DR Ort (2009) Elevated CO_2 effects on plant carbon, nitrogen and water relations: six important lessons from FACE. *Journal of Experimental Botany* 60: 2859-2876.

23. FG Dohleman, EA Heaton, **ADB Leakey**, SP Long (2009) Does greater leaf-level photosynthesis explain the larger solar energy conversion efficiency of Miscanthus relative to switchgrass? *Plant, Cell & Environment* 32: 1525-1537.

24. A Rogers, EA Ainsworth, **ADB Leakey** (2009) Will elevated carbon dioxide concentration amplify the benefits of nitrogen fixation by legumes? *Plant Physiology* 151: 1009-1016.

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D. Bulletins, Reports, or Conference Proceedings (in print or accepted)

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IV. UNIVERSITY TEACHING

A. Classroom teaching

2007-present	Undergraduate and graduate class – “Plants and Global Change”
2008-2013	Undergraduate class – “Global Warming, Biofuels and Food”
2015	Undergraduate and graduate class – “Ecosystem Ecology”
2016	Undergraduate class – “Environmental Biology”
2017-2019	Undergraduate class – “Ecology”

B. Research Mentorship

Supervisor to 2 M.Sc. students

Supervisor to 11 Ph.D. students

Supervisor to 15 postdoctoral scholars

Supervisor to 4 international visiting scientists

Member of examination committee for 17 graduate students

Mentor to >50 undergraduate researchers

Mr. CASTEN. Thank you, Dr. Leakey.

Dr. Harmon, you are now recognized for 5 minutes.

TESTIMONY OF DR. LAUREL HARMON,

VICE PRESIDENT, GOVERNMENT AFFAIRS, LANZATECH

Dr. HARMON. Thank you, Acting Chairman Mr. Casten, Ranking Member Mr. Weber, and Members of the Subcommittee. I really appreciate this opportunity to share LanzaTech's experience and our perspectives here today.

LanzaTech is a carbon capture and transformation company headquartered in Illinois with offices around the world. Our goal is to replace virgin fossil carbon with carbon from wastes, creating what we call a circular carbon economy. Because even in a decarbonized world, most of the products in our daily lives from clothes to jet fuel need carbon.

Our technology uses a biocatalyst, a bacteria or microbe, like beermaking except we use bacteria and waste carbon instead of yeast and sugar. With this biocatalyst, we can turn all kinds of carbon-rich waste streams into products from the industrial emissions you heard earlier like steel mill off-gas to solid waste, including biomass residues and municipal waste.

This technology is operating commercially in two plants today, producing ethanol from industrial emissions, and several other plants are in design and construction around the world. We have created custom microbes using technologies as you've just heard described, which are capable of producing over 100 different molecules.

Taking a step back, to advance bioenergy, we need a robust bioeconomy, which includes biological processes like ours, the use of biobased feedstocks, and hybrid pathways such as Mr.—Dr. Male described that combine biochemistry and thermochemistry to maximize carbon efficiency. The bioeconomy can free us from virgin fossil carbon and also from the massive, centralized refinery model on which we rely today.

Production facilities that are matched to the scale of waste feedstocks can be located throughout the country. This means they could be located in heavy manufacturing centers that can be located in rural communities or in urban centers. These improve the local environment, as well as creating high-quality jobs.

LanzaTech has partnered with the Department of Energy in projects from basic research from BER, for example, through process optimization and scale up in BETO and the Advanced Manufacturing Office. I provided many examples in my written testimony, but here, I want to highlight DOE's role in developing collaborations. You've heard that touched on already.

DOE has allowed LanzaTech to collaborate with world-class universities and with the national labs, and these collaborations are developing new basic insights. They're developing new computational and experimental tools that accelerate discovery. They're expanding feedstocks to new materials like waste CO_2 or waste plastics. They are also intensifying the conversion processes themselves to increase energy and carbon efficiency and scaling them up to enable commercial implementation.

One example is the alcohol-to-jet or ATJ technology that Dr. Male referenced, developed initially at PNNL, converts ethanol into sustainable aviation fuel and renewable diesel. After initial proof of concept, BETO funded a project for a pathway to show that sustainable aviation fuel could be produced from biomass using our gas fermentation and the ATJ process. BETO also supported PNNL to produce fundamental data that catalyzed additional investments by LanzaTech and industry partners to scale up the process and produce thousands of gallons of fuel. Some of that fuel, made using ethanol that came directly from steel mill emissions, was used in a transatlantic commercial passenger flight with Virgin Atlantic, a 747 flying across the ocean on steel mill emissions, a great demonstration of the circular carbon economy.

The DOE partnership continues in a project to support a 10 million gallon-per-year facility in Georgia, and in 2020, we formed a spinout company—LanzaJet—to commercialize this technology with support from Mitsui, Shell, LanzaTech, Suncor, and British Airways. This is a great example of DOE engagement throughout all stages of technology development and deployment.

In closing, I'd like to emphasize three main points. DOE's RD&D programs must be technology and feedstock agnostic to advance all technically, economically, and sustainably viable pathways. DOE funding is, as I've emphasized before, needed not just for R&D but also for demonstration and deployment to ensure plants get built and are built where they are needed. And the expansion—the bioenergy concept needs to be expanded to chemicals and materials that require carbon and are made from petroleum today.

Finally, I would like to emphasize that the DOE needs support also for the staff and the systems that it—will enable the Department to accelerate the selection and execution of these projects.

Thank you again. I look forward to responding to the Members' questions.

[The prepared statement of Dr. Harmon follows:]

Statement of Laurel Harmon
Vice President, Government Relations
LanzaTech, Inc.

Before the
United States House of Representatives
Committee on Science, Space and Technology

"Bioenergy Research and Development for the Fuels and Chemicals of Tomorrow

March 16, 2022

Good morning Mr. Chairman, Mr. Ranking Member and Members of the Subcommittee. Thank you for providing LanzaTech the opportunity to participate in this important hearing on "*Bioenergy Research and Development for the Fuels and Chemicals of Tomorrow*. I appreciate the opportunity to share our experience in bioenergy technology development and commercialization, as well as a perspective on the unique and important role that the U.S. Department of Energy can play in accelerating the transition to a clean energy future.

Introduction

LanzaTech is a carbon capture and transformation company, headquartered in Skokie, Illinois, with offices in the UK, Europe, India, and China. The company was founded 17 years ago with the goal of eliminating the need for virgin fossil carbon by changing the way the world sources and uses carbon. Fossil carbon is in everything we use in our daily lives. It is not just in fuels and power, but in our clothes, cosmetics, toys and home goods. All of these products start life in a refinery based mostly on petroleum or natural gas. Unfortunately, in 2022 this carbon economy is not sustainable given our current understanding of the impact of emitted and waste carbon on our environment and climate. We absolutely must stop putting carbon into our atmosphere and to do that we need to change our entire carbon economy.

LanzaTech is a business that enables a closed loop, circular carbon economy where carbon is reused rather than wasted. Through technology designed to touch all points of carbon use we believe we can offer a profitable solution to decarbonizing carbon intensive businesses, while providing sustainable raw materials to make the things we use in our daily lives.

We do this using biotechnology based on nature that mimics the original carbon recyclers – trees. Nature served as the inspiration for the amazing idea that became LanzaTech. We use a biocatalyst – a bacteria or microbe - which metabolizes carbon and produces useful chemicals. We often use an analogy which compares our process to making beer via fermentation. Rather than using yeast, we use bacteria and instead of sugar, we use waste carbon.

The beauty of this process is that it is based on biology, which is inherently flexible. The flexibility allows us to use a variety of different waste streams, from industrial emissions to solid waste, including biomass residues and municipal solid waste. Over the past 17 years, we've developed the bacteria, or biocatalysts, the bioreactor and refined and scaled the technology. We have proven the entire process at scale, with two commercial plants operating today and several others in various stages of design and construction. In addition, our continued R&D innovations have enabled us to create custom microbes capable of producing new, differentiated products for our customers with a pipeline of over 100 molecules.

Our focus is on substituting carbon from wastes for fresh fossil resources and on directing that carbon to applications where it will continue to be needed even as power becomes increasingly carbon free. While there are many ways to make renewable or carbon-free power, jets will continue to need energy-dense liquid fuels and our clothing will still require carbon-based textiles. Therefore, when we think about "bioenergy", we think about all the aspects of a bioeconomy that can enable the transition from fresh fossil to waste or recycled carbon that has already seen a primary use.

From that vantage point, the bioeconomy includes biological processes, such as LanzaTech's, that can be used to transform essentially any carbon waste, such as emissions created during the steel making process that would traditionally be emitted into the atmosphere as CO_2 or carbon found in solid waste streams like our daily trash and the landfill gases formed at municipal solid waste sites. It also includes the myriad pathways, biological and not, that transform biological feedstocks such as agricultural and forestry wastes, into sustainable fuels and chemicals. Furthermore, it includes hybrid pathways, combining the best technology at each step along the way. The key to a successful energy transition is maximizing carbon efficiency during transformation of waste carbon into final products.

The bioeconomy not only allows us to move away from virgin fossil carbon but also allows us to move away from today's paradigm of massive, centralized, refining facilities. The scales of biotechnology and of waste and residue feedstocks can be matched to allow production facilities to be located near heavy manufacturing to utilize industrial emissions, in communities where municipal wastes are creating environmental hazards, and in rural communities where biomass residues are plentiful. In each instance, transforming waste carbon into products improves the local environment while creating new local cleantech jobs.

LanzaTech's experience during our 17-year journey from an idea to a new carbon capture and transformation industry offers unique insights into the importance and role of Research and Development at all stages of technology development and deployment. I will begin with comments derived from our work with the U.S. Department of Energy during development of our gas fermentation technology and then focus on a case study: development and commercialization of technology to produce Sustainable Aviation Fuel from ethanol in partnership with the DOE's Pacific Northwest National Laboratory (PNNL).

Role of R&D: From Concept to Commercial

The U.S. DOE will be crucial to not only enable but, more importantly, to accelerate the transition to a clean energy future. DOE has a critical role to play at all stages of the development of new technology, from basic research to scale up and commercialization. I will offer some examples from LanzaTech's experience to illustrate the importance of DOE support at different stages:

- **Understanding of basic biological mechanisms** leading to core knowledge which can lead to new biomanufacturing processes. One example is funding from EERE-BETO (Bioenergy Technologies Office) of a collaboration between LanzaTech and Oak Ridge National Laboratory

(ORNL) to develop a new biosynthetic route to acetone, an important platform chemical, from syngas. LanzaTech has subsequently scaled up a process from gas to acetone building on the basic knowledge developed during the project.

- **Sophisticated computational tools for machine learning and modeling** related to organisms, systems, and processes. The EERE-BETO Agile Biofoundry Program supports a number of collaborative projects between industry and National Laboratories to develop new tools to address computational problems identified by industry.
- **Experimental platforms to accelerate discovery** of new organisms and processes. As an example, the DOE Office of Science (SC) is supporting a collaboration between Northwestern University and LanzaTech to develop a biofoundry for high-throughput discovery of new biocatalysts combining computational modeling, systems-level analysis, and cell-free engineering.
- **Diversification of the bioenergy feedstock pool.** EERE-BETO has funded a variety of projects to develop and demonstrate syngas as an intermediate that can be produced from cellulosic residues, municipal wastes, and waste plastics via gasification; the syngas can then be converted to fuels and chemicals via biological methods, like LanzaTech's gas fermentation, or thermochemical techniques. Both SC and EERE-BETO have supported collaborations between LanzaTech and electrolysis partners to develop and validate methods to convert CO_2 to CO as a feedstock for gas fermentation. EERE's Advanced Manufacturing Office (EERE-AMO) is supporting a collaboration between LanzaTech, Lululemon, Waste Management and InEnTec to develop a pathway for producing plastics using non-recyclable textiles and non-recyclable plastics from municipal wastes. EERE-BETO is supporting projects to produce ethanol feedstocks for Sustainable Aviation Fuel from landfill gas/biogas and from waste CO_2 coupled with renewable H_2.
- **Process intensification** to improve carbon, water, and energy efficiency. The Advanced Research Project Agency - Energy (ARPA-E) supported initial prototype development and piloting of LanzaTech's next generation bioreactor which reduces energy requirements and increases reaction rates; the technology is now being scaled up in partnership with Emissions Reduction Alberta.[1] EERE-BETO has also supported collaborations with PNNL and Oregon State University to develop microchannel reactor technology for converting ethanol to hydrocarbon products.
- **Integration and scale up.** EERE-BETO's Systems Development and Integration Program, formerly known as the Advanced Development and Optimization Program, offers cooperative funding for scale up including pilot and pre-commercial demonstration plants (see Case Study below). The purpose of scale up projects should be to identify and address key elements that require attention, which is typically specific to conversion technology and feedstock.
- **Deployment at scale.** While not necessarily falling under the "Research and Development" umbrella, it is vitally important that the DOE support be used to reduce investment risk for first commercial implementations of new technologies. This is where the mission offices interface with the Loan Programs Office.

The examples above also illustrate an important but often overlooked role for DOE: catalyzing collaborations among universities, national laboratories, and industry. Industry partners, even in early-

[1] https://eralberta.ca/projects/details/carbon-sequestration-via-next-generation-bioreactor-technology/

stage R&D projects, can provide feedback regarding industrial relevance and the likelihood that the research will ultimately lead to commercial implementation and real-world impact.

Case Study: Sustainable Aviation Fuel

The ethanol-based LanzaJet™ Alcohol-to-Jet (ATJ) Sustainable Aviation Fuel (SAF) technology is an excellent illustration of the role that DOE can and needs to play in advancing new technologies. The ATJ pathway is also a good example of a hybrid biological-thermochemical process: 1) ethanol is a platform chemical that can be produced readily from a wide variety of feedstocks using **biochemical** processes but is difficult to produce using thermochemistry; 2) ethanol is **thermochemically** converted to the long-chain hydrocarbons required for aviation fuel, which is extremely difficult biochemically.

LanzaTech developed the ethanol-based ATJ technology platform in collaboration with PNNL. Starting in 2010, PNNL researchers demonstrated that ethanol could be used as a feedstock for preparing an all-hydrocarbon jet fuel blendstock that met ASTM International specifications for jet. After initial proof of concept at PNNL, LanzaTech and PNNL were awarded cost-shared funding from EERE-BETO to develop a hybrid pathway from biomass to jet by combining biomass gasification to syngas (thermochemical), syngas fermentation to ethanol (biochemical), and ethanol conversion to jet (thermochemical).

PNNL worked with LanzaTech to develop laboratory and small pilot-based conversion of the ethanol into a renewable "drop in" jet fuel blendstock that will work in today's existing aircraft. With DOE funding, PNNL researchers demonstrated catalyst lifetime and process performance for the key process steps extensive time on stream at the bench and small pilot scales.

With internal funding and support from HSBC and Virgin Atlantic, LanzaTech scaled up the ATJ process developed by PNNL to demonstration scale and produced 4,000 gallons of jet fuel blendstock and 600 gallons of diesel from waste gas-derived and grain-derived ethanol, demonstrating that the process was independent of ethanol source.

In April 2018, ASTM International published the revision of ASTM D7566 on its website, including the approved ethanol based ATJ pathway, based on the Research Report **RR D02:1884**[2] led by LanzaTech and submitted to ASTM which contained detailed data measured by Air Force Research Labs (AFRL), Southwest Research Institute (SwRI) and University of Dayton Research Institute (UDRI) on ethanol-based ATJ produced using the LanzaTech-PNNL technology. As a result, ethanol-based ATJ is qualified for use in commercial aviation at up to a 50% blend with conventional jet.

A portion of the fuel was used in a transatlantic commercial passenger 747 flight with Virgin Atlantic in 2018, a transpacific flight 777-300 ER with ANA in 2019, as well as numerous flights by the National Research Council Canada measuring contrail and emissions data.[3] In addition, the fuel was used in the FAA Continuous Lower Energy, Emissions, and Noise (CLEEN II) Technologies Program.[4]

In 2017, LanzaTech was selected for cost-shared funding from EERE-BETO to support construction of an ethanol to jet facility, called "Freedom Pines Fuels", with a total production capacity of 10 million gallons

[2] https://www.astm.org/Standard/researchreports.html

[3] https://nrc.canada.ca/en/stories/national-research-council-canada-investigates-aircraft-contrails-sustainable-aviation-fuels

[4] https://www.faa.gov/about/office_org/headquarters_offices/apl/research/aircraft_technology/cleen

per year, located at LanzaTech's Freedom Pines Biorefinery in Soperton, Georgia. In 2020, LanzaTech formed a spinout company, LanzaJet,[5] to commercialize the ATJ technology. LanzaJet's investors include LanzaTech, Shell, Mitsui & Co, Suncor Energy, and British Airways. Development of Freedom Pines Fuels ATJ has continued to advance with both DOE and private sector support, including financing from the Microsoft Climate Innovation Fund recently announced by LanzaJet.[6]

The case study illustrates the importance and value of DOE R&D investment at all stages in the development and deployment of a new technology. DOE partnership with industry has led to a Sustainable Aviation Fuel technology that is now being rapidly commercialized around the world through LanzaJet and LanzaTech.

Closing Remarks

In closing, I would like to highlight a few observations and recommendations regarding the future of Bioenergy Research and Development within and supported by the Department of Energy.

First, all waste carbon must be brought to the table to replace fresh fossil inputs. Furthermore, all technically- and economically-viable pathways to produce chemicals and fuels from waste carbon will be needed, if we are to achieve our objectives for a clean energy future. Therefore, DOE programs should be technology- and feedstock-agnostic. This may in some instances require legislative corrections to remove outdated constraints on the scope of DOE funding.

Second, DOE funding is needed throughout the technology development timeline – from basic research through commercialization. While DOE has a strong history of supporting early-stage research, the urgency of meeting U.S. climate objectives, and doing so in a just and equitable fashion, means that DOE must expand its support for at-scale deployment, creating more flexibility regarding scope and scale in its R&D-pilot-demonstration paradigm, and with increasing attention to pre-commercial demonstration facilities. We cannot afford long project development timelines due to perceived risks in building first of a kind (or even first few of a kind) commercial plants. DOE support is also needed to ensure that plants, to the extent possible, are built in underserved and/or economically depressed locations.

Third, a clean energy transition must include replacement of fresh fossil carbon in both fuels and in chemicals ("products"). Thus far EERE has limited demonstration projects to fuels for the aviation and marine sectors. This focus should be expanded to include chemicals and materials that require carbon. In many cases, such products have a different and longer CO_2 cycle than fuels which are designed to be immediately combusted, therefore offering enhanced carbon reduction potential.

Finally, DOE needs to be provided the necessary tools to accelerate the pace of project selection and execution. Such tools include expansion of program staff and streamlining of procedures to enable projects to move forward at a pace consistent with the timeframes required to address climate change, and coordination across EERE and the DOE Loan Programs Office regarding due diligence.

I would again like to thank the Subcommittee for the invitation to testify today and look forward to Members' questions.

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[5] https://www.lanzajet.com/

[6] https://www.lanzajet.com/lanzajet-secures-industry-leading-innovative-financing-with-microsoft-climate-innovation-fund-to-construct-the-worlds-first-commercial-alcohol-to-jet-sustainable-fuel-plant/

Dr. Laurel Harmon
VP Government Relations, LanzaTech

Dr. Harmon provides policy direction and leadership on international legislative and regulatory matters and develops public-private partnerships to support collaborative research and demonstration projects. LanzaTech is the global leader in gas fermentation technology, offering novel and economic routes to a variety of products, including aviation fuel, from waste carbon streams, including industrial emissions. LanzaTech's carbon capture and transformation technology enables recycling of carbon to mitigate carbon emissions from industry without adversely impacting food or land security. LanzaTech's unique process, currently protected by over 1115 granted patents, enables a closed loop, circular carbon economy where carbon is reused rather than wasted, so that products such as sustainable aviation fuel and platform chemicals can be produced from carbon that has already served a primary purpose. Dr. Harmon received her Ph.D. in Physical Chemistry from the University of Michigan and has over 30 years of experience in policy matters and technology development. She serves on the Board of LanzaJet and is Vice Chair of the Board of the Roundtable on Sustainable Biomaterials.

Mr. CASTEN. Thank you, Dr. Harmon.

And finally, we have Dr. Hegg. You are recognized for 5 minutes.

TESTIMONY OF DR. ERIC HEGG, PROFESSOR, BIOCHEMISTRY AND MOLECULAR BIOLOGY, MICHIGAN STATE UNIVERSITY

Dr. HEGG. Acting Chairman Casten and Ranking Member Weber, thank you. Thanks also to Representative Meijer for your introduction and to Representative Stevens for giving me my first opportunity to testify back in 2019. It is my honor to be here today. I am representing myself, and the views I express are my own.

I am a Professor at Michigan State University and Associate Dean for Research in the College of Natural Science. Previously, I was the MSU Subcontract Lead for the Great Lakes Bioenergy Research Center. In all of these roles, I have experienced the critical partnerships that exist between the Federal Government and universities.

Several Federal agencies have funded my research, including NIH (National Institutes of Health), NSF (National Science Foundation), USDA, and three different agencies within the DOE, BES (Basic Energy Sciences), BER, and BETO. My research focuses primarily on bioenergy and environmental research, and I am an inventor of bioenergy and bioproducts technology. It is within this context that I provide today's testimony.

Federal support for interdisciplinary centers is critical to addressing society's grand challenges. Centers bring together researchers from disparate fields, stimulate innovation, and tackle complex problems in ways not possible with smaller projects. For bioenergy, this includes bringing together scientists from agronomy, genetics, and plant biochemistry to develop dedicated bioenergy crops; biogeochemistry and microbial ecology to understand nutrient flow; and microbiology, chemistry, and engineering to convert the biomass into biofuels and bioproducts. Overarching is the work of computational scientists who ensure that the strategies identified are economically and environmentally sustainable. Without large centers, new technologies developed in one area might not integrate across the entire pipeline. Centers are therefore essential to identifying sustainable and holistic solutions.

At the same time, however, it is critical to maintain and even increase funding for creative individual research projects, hallmarks of U.S. innovation. Smaller projects often adapt more quickly to unexpected results, thereby opening new avenues of inquiry. These individual breakthroughs can themselves become the basis for integrated research. Single investigative projects are therefore vital to the success of large centers, as well as to the entire scientific enterprise. Examples relevant to bioenergy are found across the entire pipeline.

In addition, discoveries made in one field can unexpectedly benefit other research areas, often years later. It is therefore nearly impossible to overestimate or predict the full impact of basic research. Once promising technologies are shown to be compatible in an integrated system, they must then be scaled. Technologies established at the bench, however, often encounter unanticipated challenges as they move to the industrial scale. Demonstrating they can be overcome is key to obtaining industrial investment.

BETO has been important to my own research, enabling us to optimize our technology and begin the scaling process. The work has led to a new patent and an additional patent application and a potential industrial partner. To take full advantage of Federal investments in basic research, BETO and similar programs should be continued.

Critical to the bioenergy research process is developing the work force needed for scientific breakthroughs to maintain U.S. leadership. Large integrated centers are ideal environments for educational development. They provide cutting-edge research experiences while exposing students to multidisciplinary teams vital to industrial research. Authentic laboratory experiences also reinforce concepts learned in the classroom, teach critical thinking, and encourage creativity. Because many undergraduates must work to afford tuition, paid research programs improve diversity, equity, and inclusion, thereby significantly impacting the quality, quantity, and diversity of the future work force. Opportunities such as NSF's REU (research experiences for undergraduates) program and the DOE's internship program are hugely successful. Competition for these and related programs is often intense, and additional funding to expand them would significantly—would have a significant impact on the future work force pipeline.

In the coming decades, there are opportunities for growth that will increase the impact of Federal investment in bioenergy research ranging from expanding long-term studies to increasing coordination among the agency—under the agencies under the purview of this Committee, including the DOE and NSF. This coordination would be especially powerful if expanded to include other agencies supporting bioenergy research, including the USDA. These proposed steps would ensure highly integrative and synergistic research that avoids duplication and promotes coordination in tackling society's complex grand challenges.

Thank you for inviting me to testify and address any questions that you may have.

[The prepared statement of Dr. Hegg follows:]

Witness Testimony of Eric L. Hegg

Michigan State University (MSU)
Professor of Biochemistry & Molecular Biology
Associate Dean for Budget, Planning, Research, and Administration
College of Natural Science

Before the House Committee on Science, Space, and Technology
Subcommittee on Energy
Hearing titled
Bioenergy Research and Development for Fuels and Chemicals of Tomorrow
March 16, 2022

Acting Chair Casten and Ranking Member Weber, thank you for the invitation to testify today. I am grateful to Rep. Meijer for his leadership and generous introduction. Also, I would like to thank Subcommittee member Rep. Stevens and full committee member Rep. Kildee, for their guidance of innovation in this critical area. I would like to commend the committee for its drafting of the DOE Science of the Futures Act and its inclusion into the America Competes Act. I understand that it authorizes two new Bioenergy Research Centers. Thank you for your leadership on this topic and for your continued advocacy as you go to conference with the Senate. It is my great pleasure to contribute to the ongoing discussion of the opportunities, challenges, and current status of bioenergy research, and how this research leads to both new technologies and a workforce prepared to address emerging grand challenges. I look forward to today's review of how current and future advancements in bioenergy and bioproduct research will help the United States and the world transition to cleaner forms of energy. I am representing myself at today's hearing. The views I express are my own. To best serve the goals of the subcommittee, I have broken my written testimony into four key sections — (1) my professional experience and interest in bioenergy research; (2) the importance of supporting individual science projects, research centers, and scale-up and/or commercialization projects; (3) science and technology workforce development; and (4) opportunities for growth to improve the impact of future investment.

1. Overview of my professional experience and my interest in bioenergy research

I serve as both a Professor in the Department of Biochemistry & Molecular Biology at Michigan State University (MSU) and as the Associate Dean for Budget, Planning, Research, and Administration in the College of Natural Science. Prior to assuming my administrative duties in 2020, I was the MSU Subcontract Lead for the DOE-funded Great Lakes Bioenergy Research Center (GLBRC). In all three of these roles, I have observed and experienced the critical collaborative partnerships that exist between the federal government and universities. MSU ranks first nationally in Department of Energy (DOE) expenditures and ninth nationally for National Science Foundation (NSF) expenditures according to the NSF Higher Education Research and Development (HERD) 2020 data. Support from the DOE and the NSF each comprise approximately 25 percent of MSU's total federal research funding, while the United States

Department of Agriculture (USDA) accounts for an additional 10 percent (https://research.msu.edu/facts-figures). Together, these funds provide vital support for cutting-edge fundamental research, for the training of the future workforce and leaders in science and technology, and for the development of new sectors of our economy. Michigan State University is part of the University Research Corridor, an alliance between MSU, the University of Michigan, and Wayne State University, whose mission is to promote innovation and economic growth in Michigan. Together, these three institutions – one of the top eight academic clusters in America – contributed an estimated $19.3 billion to our state's economy in 2019 (https://www.urcmich.org/reports/urc-universities-contribute-193-billion-michigans-economy).

My personal research focuses on the role of metal ions in biological systems, and more specifically, on understanding how nature uses metal ions to perform difficult and important chemical transformations. Because of their unique ability to attract, store, and transfer electrons, metal ions are vital in a number of biological pathways, including respiration, photosynthesis, carbon fixation, and nitrogen fixation, to name just a few. Obtaining a deeper understanding of the strategies used by nature may enable us to replicate these strategies and produce better catalytic systems for a variety of industrial processes.

Over the years, I have used this approach to study cellular respiration, oxygen (O_2) activation, biological hydrogen (H_2) production, biological global nitrogen cycling, and biomass deconstruction and conversion into biofuels and bioproducts. Several federal agencies have funded my research, including the National Institutes of Health (NIH), the NSF, the United States Air Force (AFOSR), the USDA, and three different agencies within the DOE, including Basic Energy Sciences (BES) and Biological and Environmental Research (BER) from the Office of Science, and the Bioenergy Technologies Office (BETO) from the Office of Energy Efficiency & Renewable Energy. I am grateful to these funding agencies, and the societal contributions I have made in my research is a direct result of the financial support of these agencies.

Much of my research has focused on bioenergy and environmental research. I have been fortunate to work with the MSU Technologies office, which facilitates commercialization of faculty members' research with the goal of moving new technologies out of the lab and into the marketplace. Relevant to this hearing today, I am an inventor of patented technologies to (a) deconstruct biomass and separate the plant cell walls into their core components for conversion into biofuels and bioproducts, (b) depolymerize lignin (one of the key structural components found in plant cell walls) into its monomeric constituents, and (c) employ lignin in polyurethane applications. I am hopeful that these technologies will ultimately supply farmers and growers with additional revenue streams, provide industry with new or improved products, contribute to the strengthening of the Michigan and U.S. economies, and enable an environmentally and economically sustainable bioeconomy.

2. Importance of supporting large multidisciplinary research centers, individual science projects, and scale-up and/or commercialization projects

Center-level funding. Federal support of large, interdisciplinary research centers is critical to addressing society's grand challenges, including the transition from an economy based heavily on fossil fuels to a cleaner, more sustainable bio-based economy. Large research centers, such as the Bioenergy Research Centers, are uniquely positioned for this task. They bring together researchers from multiple fields to tackle complex and challenging problems in ways that are simply not possible with single-investigator or small group projects.

In the case of bioenergy research, this includes bringing together scientists from agronomy, genetics, plant biology, and plant biochemistry to develop and produce dedicated bioenergy crops with improved traits such as increased carbon fixation and greater biotic and abiotic stress tolerance. Simultaneously, soil scientists, biogeochemists, hydrologists, entomologists, and microbial ecologists are needed to understand the flow of nutrients and plant-microbe interactions, both of which are critical to plant and soil health as well as environmental sustainability. The expertise of microbiologists, synthetic and computational biologists, biochemists, chemists, and engineers are also required to deconstruct the biomass and convert it in an atom and energy efficient manner into biofuels and bioproducts. Overarching these areas is the work of computational modelers and those performing life-cycle analysis and techno-economic analysis to ensure that the strategies identified to generate biofuels are both economically and environmentally sustainable.

Finally, it is key to remember the human element. The best scientific solutions are useless if we ignore the key stakeholders. It is crucial for agriculture and economic extension services to engage with and obtain buy-in from landowners, farmers, industrial partners, and consumers to ensure that the solutions identified can be employed in the real world.

It is important to reiterate that in bioenergy research, small or even mid-sized projects cannot fully address the interdependent and expansive areas of feedstock production, sustainability, biomass deconstruction, and conversion into fuels and chemicals. Scientific breakthroughs and paradigm-shifting discoveries in one area can greatly impact both the challenges and solutions in other areas. In the absence of large, integrated centers, the new technologies and approaches developed for one area might not integrate across the entire pipeline, thus restricting their adoption and the creation of a sustainable bioeconomy.

As an example, new bioenergy crops designed for desirable characteristics such as altered lignin content can impact both the reaction conditions for the ideal biomass deconstruction process and some of the products that are formed. At the same time, deconstruction conditions affect the quality and quantity of the structural sugars and other cell wall components that are released during processing. Meanwhile, the microbial and chemical conversion of these biopolymers into biofuels and bioproducts can be significantly influenced by the specific composition of the solution following deconstruction. In addition, the biotic and abiotic stresses that the plants experience (*e.g.*, pathogens, pests, drought, nutrient deprivation, etc.) impact not only the biomass yield and composition, but also the range of plant secondary metabolites produced, all of which can dramatically impact downstream processes. In the absence of a large, integrated research center, it would be exceedingly difficult to identify and efficiently share solutions that can work together in a holistic, robust, and sustainable manner.

Funding for individual research projects. While large centers are essential to address today's societal grand challenges, it remains critical that we maintain and even increase funding for individual research projects. Single-investigator or small-group research projects encourage the essential creativity that has been the hallmark of U.S. innovation leadership and can lead to profound and unexpected breakthroughs. Although large centers also perform basic, transformative research, even large centers cannot have expertise and visionary insight in all relevant areas. In addition, smaller projects often adapt more quickly to changing conditions and exciting or unexpected results, thereby opening new avenues of inquiry. In fact, these individual breakthroughs are often the basis for the integrative research performed by the centers. Single-investigator projects are therefore vital to the success of the scientific enterprise and, indeed, to the success of large research centers.

For example, pioneering work elucidating the pathways of lignin biosynthesis has led to the design and production of plants with altered lignin composition and more amenable to processing. This cutting-edge research has been incorporated into some of the bioenergy research centers, and these plants with unique traits are an important component of the research pipeline. In addition, the technology has been licensed to the private sector. Highlighting the complexity of integrating such developments into bioenergy solutions, this technology is first being applied in the pulp and paper industry, where it is expected to lower both energy and chemical usage.

As another example of the importance and creativity of small research projects, much of the essential biomass deconstruction research in the centers, including work in my own lab, is related either directly or indirectly to breakthroughs achieved as a result of single-investigator or small group projects.

Finally, it is imperative to remember that in basic research, discoveries made in one field can provide profound and unexpected benefits in other research areas, often many years later. It is therefore nearly impossible to overestimate or predict the full impact of basic research on the economy or quality of life.

Scale-up and/or pre-commercialization projects. Once promising new technologies have been proven to be compatible in an integrated system, they must then be scaled-up and de-risked to make them attractive to industry, especially when these new technologies are competing with established and highly optimized existing technologies. There are a number of federal programs and resources focused on this endeavor including, but not limited to, the Bioenergy Technologies Office (BETO) within the DOE Office of Energy Efficiency & Renewable Energy (EERE), the SCALEUP program (https://arpa-e.energy.gov/technologies/scaleup) initiated by the DOE's Advanced Research Projects Agency – Energy (ARPA-E), and the multiagency Small Business Innovation Research (SBIR) and Small Business Technology Transfer (STTR) programs. Key resources for scale-up demonstration include the DOE Advanced Biofuels and Bioproducts Process Development Unit (ABPDU) at Lawrence Berkeley National Laboratory (https://abpdu.lbl.gov/) and resources at the National Renewable Energy Laboratory (NREL).

Promising technologies established at the bench scale often encounter unanticipated challenges (*e.g.*, issues associated with mass flow and heat/chemical transfer) when they are moved to the industrial scale. Demonstrating that these challenges can be overcome is often key to obtaining significant industrial investment for disruptive technologies. In my own personal experience, BETO has been an important partner in advancing our deconstruction technology that was developed within the Great Lakes Bioenergy Research Center (https://www.glbrc.org/). With BETO funding, we have both optimized the technology and scaled the process from the initial bench scale by over a factor of 1000. The work has led to an additional patent and patent application, and an industrial partner is potentially interested in collaborating on further scale-up, de-risking, and expanded application of the technology. BETO funding was crucial in developing potential corporate interest despite the many advantages of our deconstruction process, and my experience with the challenges encountered at this stage of technology development is not unique. Thus, to take full advantage of federal research investment and ensure that new technologies can move from the bench into the private sector, BETO and similar scale-up and de-risking programs and resources should be continued and, as appropriate, expanded.

3. Workforce development in science and technology

Established in 1855 as the nation's first agricultural college, MSU proudly carries its responsibilities as a public, research-intensive, land-grant university. In addition to (a) conducting the research and outreach required to expand human understanding, (b) identifying solutions that positively impact society both locally and globally, and (c) serving as an engine for economic development, MSU is also deeply dedicated to "providing outstanding undergraduate, graduate, and professional education to promising, qualified students in order to prepare them to contribute fully to society as globally engaged citizen leaders" (https://trustees.msu.edu/about/mission.html). In the context of bioenergy research, this includes developing the workforce needed to support the growing bioenergy research and economic sector, thereby enabling the scientific breakthroughs and deployment needed for the United States to maintain its leading role in this area and to diversify its energy options.

At Michigan State University, and at many universities throughout the country, interest in science, technology, engineering, and mathematics (STEM) fields has risen considerably over the past 15 years. Authentic laboratory experiences that provide students the opportunity to participate in cutting-edge research to solve real-world problems are key components to preparing them to become practicing scientists. Opportunities such as the NSF's Research Experiences for Undergraduates (REU) program (https://www.nsf.gov/crssprgm/reu/) and the DOE's Science Undergraduate Laboratory Internships (SULI) program (https://science.osti.gov/wdts/suli) have been hugely successful and popular. In fact, competition for these summer research programs is typically intense. For many programs, there are often far more qualified applicants than there is funding to support them. To help balance this mismatch, additional federal funding to support these and new undergraduate research programs would have a significant impact.

Meaningful research experiences that employ the scientific method reinforce key concepts, teach critical thinking, and encourage creativity, thereby laying the groundwork for the skills and training needed for scientists, technicians, and engineers at all levels. Further, because many undergraduate students must choose between meaningful research experiences and working to afford tuition and/or living expenses, paid internships and summer research programs positively impact diversity, equity, and inclusion. As a result, investing in these relatively inexpensive summer research programs can significantly impact the quality, the quantity, and the diversity of the future workforce engaged in the bioenergy economy.

In addition to specialized undergraduate and post-baccalaureate research programs, students at all levels can also gain invaluable experience in the laboratory by participating in federally-funded research projects. Thus, investing in university-led research not only advances the scientific mission of the funding agencies, it also provides crucial educational opportunities and technical training.

Large integrated endeavors such as the Bioenergy Research Centers are especially ideal environments for educational development. Not only do they provide experience in cutting-edge research focused on real-world problems, they also expose students to integrative and multidisciplinary teams that are so vital in today's industrial research enterprise. To be optimally impactful, researchers need to communicate effectively with scientists outside of their specific discipline as well as to the broader public. Exposing undergraduates, graduate students, and postdoctoral students to the integrative environments found in large research centers prepares them for this important challenge.

4. Opportunities for growth to improve the impact of future investment

As we move forward in the coming decade, there are opportunities for growth that will increase the impact of federal investment in bioenergy research. The first of these is continued and/or expanded support for long-term studies. The significance of historical long-term data and its impact on multiple research areas cannot be overstated. An example directly relevant to bioenergy is NSF's Long-Term Ecological Research (LTER) program. MSU's LTER site (https://lter.kbs.msu.edu/) at the Kellogg Biological Station (KBS) was established in 1987 and provides critical data to understand the interactions among plants, microbes, and insects in cropping systems appropriate to the Midwest, including candidate bioenergy crops and their potential positive environmental impacts. The recently established Long-Term Agroecosystem Research (LTAR) site at KBS (https://www.canr.msu.edu/ltar/), funded by the USDA, is anticipated to provide synergistic insights to enhance the agricultural sector. Studies co-developed with stakeholders will provide farmers new approaches for sustainably intensifying the production of food and bioenergy while simultaneously delivering ecosystem services such as climate mitigation, clean water, and pollination.

A second potential growth area is increased coordination among the agencies under the purview of the House Science, Space, and Technology Committee, including the DOE and NSF. This coordination could be especially powerful if expanded to include other federal agencies that fund bioenergy related research, including the USDA.

One way to achieve improved inter-agency coordination is to increase funding for the development of large-scale centers that are supported by multiple agencies. Potential centers could be reviewed by and report to teams representing all of the participating funding agencies. Successful centers, by their very nature, would be interdisciplinary and cross-cutting as they must address key aspects of each agency's mission. This process would ensure highly integrative and synergistic research, reduce duplicative efforts, and promote coordination in tackling society's difficult and complex grand challenges.

Thank you for inviting me to appear before the Subcommittee. I welcome the opportunity to address any questions you may have.

Eric Hegg obtained his B.A. from Kalamazoo College and his Ph.D. from the University of Wisconsin under the direction of Professor Judith Burstyn. It was during his time at Wisconsin that he became interested in metalloenzymology, studying the role of metal ions in enzymes that hydrolyze DNA, RNA, and proteins. After receiving his Ph.D., Eric joined Larry Que's group at the University of Minnesota as an NIH postdoctoral fellow where he studied non-heme iron dioxygenases and established his long-standing interest in understanding how nature synthesizes and activates small molecules such as H_2 and O_2. Following his postdoctoral work, Eric and his family moved to Salt Lake City where he joined the faculty of the University of Utah and began his independent research career. He received a Cottrell Scholars Award in 2002 and a National Science Foundation Career Award in 2004. When the opportunity arose, Eric and his wife eagerly returned to the northern Midwest to join the faculty at MSU, where Eric is a Professor in the Department of Biochemistry & Molecular Biology. Eric has served a variety of roles within the Great Lakes Bioenergy Center since its founding in 2007, and he served as the MSU Subcontract Lead for the GLBRC from 2013 through the end of 2019. In January 2020, Eric accepted the position to become the Associate Dean for Budget, Planning, Research, and Administration in the College of Natural Science. Eric has participated in two leadership activities at MSU; in 2016, he was a Big Ten Academic Alliance Leadership Program Fellow, and in 2017-2018 he was an Academic Advancement Network Leadership Fellow. In 2019, Eric was elected a Fellow in the American Association for the Advancement of Science (AAAS).

Research in the Hegg lab focuses on elucidating how microbes perform environmentally important reactions. In particular, they are studying various enzymes critical to the global nitrogen cycle, including an enzyme that converts the environmental contaminant nitrite into ammonia as well as enzymes that produce the potent greenhouse gas N_2O. The Hegg lab also studies how microbes break down biomass to release the sugars and lignin from the plant cell wall, and how these structural components of the plant cell wall can be used to form biofuels and bioproducts. Ultimately, they are interested in applying the knowledge gained from these studies to address real-world problems.

Mr. CASTEN. Thank you to all of our witnesses. At this point, we will begin our first round of questions. And I will recognize myself for 5 minutes.

Dr. Harmon, the recent report entitled "Sustainable Aviation Fuel: A Review of Technical Pathways" funded by the Department of Energy finds that the United States' refinery production of renewable diesel exceeds 300 million gallons, but only 2 million gallons of sustainable aviation fuels made with the same technology were produced. The report does say that there's sometimes that is a difference in production costs, but it says that the difference in renewable diesel production and sustainable aviation fuels is primarily driven by policy. Can you give us a little understanding of what those policies are and what policies we would need to get greater sustainable aviation fuel production?

Dr. HARMON. Thank you for that important question. The first priority I think is to recognize that road transport has benefited from a long history of incentives to which sustainable aviation or SAF has not really been privy. Even when the California low-carbon fuel standard (LCFS) was developed, aviation fuel was not a compliance mechanism. And what that meant is that even though most technologies to produce SAF also produce diesel, industry focused on production of diesel, and much of that was provided to the California market. When the LCFS was opened up to SAF, then SAF production increased, including the attraction of imports.

What I would also like to add is that what we do not have today are policies that selectively promote aviation fuel, and an example which is on the table would be the SAF blenders tax credit. And that's something that I would be happy to follow up or my colleagues would be happy to follow up with the Committee on.

Finally, I would note that there are fuel policies which don't selectively discriminate against SAF but the RFS (renewable fuel standard), for example, is quite limited in the pathways that are acceptable. And so many waste feedstocks are actually not acceptable under the RFS and that expanding the RFS to include waste such as industrial emissions, waste CO_2, would also have the benefit of accelerating production of SAF.

Mr. CASTEN. So I'd love to follow up on that feedstock question. We've got this 95 billion gallons a year of jet fuel production and 2 million—with an M—gallons of SAF. With current production technologies that you have, how much could you ramp up before you would be completely maxed out on current feedstocks? And what technologies would you need to develop or they already exist—I know Dr. Male had talked about carbon monoxide, but I'm assuming that's produced from something else upstream. What does the technology look like, and what does the feedstock look like in a feedstock-unconstrained world?

Dr. HARMON. All right. So I'll speak to alcohol-to-jet because the intermediate use by alcohol-to-jet is ethanol. Ethanol could be produced using many different technologies from a huge array of feedstocks. Very specifically, for example, using our technology, we can take carbon monoxide-rich steel mill emissions, making ethanol, turn that into SAF. That production of that ethanol is immediately commercial today and operating. We've produced—I'm not going to quantify, but we've produced millions of gallons of ethanol from steel mill emissions.

Municipal waste is another example. Gasification of municipal waste can feed into our process and then produce ethanol, which goes into SAF. As we look farther out, CO_2, coupled with the hydrogen produced from renewable energy, is also a SAF feedstock, again, by production of ethanol and then transformation into SAF using the alcohol-to-jet pathway. So there's almost no limit to the feedstocks that can be applied to the SAF market using existing technology.

Mr. CASTEN. Thank you, Dr. Harmon. With the time I got left, I want to just pivot to Dr. Hegg. And I have tremendous appreciation for what BETO does and the pain of that valley of death that you have talked about, you know, getting from lab scale to industrial scale. I wonder if you could speculate a little bit. Some of those projects get all through that, they get scaled up, all the bugs are ironed out and they still aren't economic. I'm a market guy, and I also serve on the Climate Committee. And one of the things we keep coming back to on that Committee is this International Monetary Fund report that says that the United States subsidizes the fossil fuel industry by $650 billion a year. I don't like picking winners and losers, but my goodness, if we keep subsidizing an industry that needs $650 billion a year to stay competitive doesn't sound like we're picking the winners.

Do you have some sense, Dr. Hegg, of how many of the technologies that come out that we deem to be economically uncompetitive we only deem because the other technology is so heavily subsidized? How much would come forward if we took off those subsidies? Can you even guess at that?

Dr. HEGG. That's a great question, and unfortunately, no. I mean, I simply don't have the data available to me to be able to speculate. But I think one of the other critical issues here is not only sort of the subsidizing that may occur but also this issue of ensuring that technologies fit through the entire pipeline. And so not just, you know, solving one—not just solving one problem while forgetting how that solution integrates into the entire system. But related directly to your question, I'm sorry, I simply don't have those numbers available.

Mr. CASTEN. Well, maybe we could follow up off-line. I'm out of my time. I will now recognize Mr. Weber for 5 minutes.

Mr. WEBER. Thank you, sir. We had a hearing many years ago in 2017 that was focused specifically on biofuels. One of our witnesses was from the University of Michigan. So, Dr. Hegg, let's see if you agree or want to stoke up the rivalry with your institution. When talking about the billions of dollars spent on DOE's bioenergy research, development, and deployment efforts, he said, quote, "None of the promised cellulosic fuels have become commercially viable even with subsidies amplified by mandates," end quote.

As I mentioned in my opening statement, I think the Office of Science and the discoveries that originate there played a large role in the ultimate success of EERE. So, Dr. Hegg, can you give us an updated opinion on DOE's bioenergy research efforts and how the BER and the Office of Science can accelerate the overall development of biotechnologies? And, as part of that update—no pressure here. As part of that update, could you provide an example or a success story from your days at Great Lakes Bioenergy Research Center or a project you were part of that started at the basic research level and is working toward being commercially viable? Dr. Hegg?

Dr. HEGG. Sure. So I think one excellent example is when you think about designing dedicated bioenergy crops. And so at the basic research level, you can begin to design them for specific traits that make them specifically available—especially appropriate for bioenergy. In one classic example, researchers in the Great Lakes Bioenergy Research Center, not myself, worked out a system to make lignin, which is a structural component of the plant cell wall, degrade more easily. All right. So they were able to do that on the plant side. And then, again, thinking about this idea of the pipeline, though, you have to think not just about the plants but about the deconstruction.

And so I was involved with a team sort of analyzing the impact of this new plant technology for how that it—how it might degrade more easily. And by performing this research, we were able to identify that in fact we could use lower chemical inputs to degrade the biomass into the structural components, specifically the sugars, so that they could be used downstream, and then of course, again, thinking of this pipeline, having a group of people that can then take that—the structural components that have been separated and turn them into biofuels and bioproducts.

Overlaid on all of this and one of the challenges for a long time has been what to do with the lignin, again, this important structural component, which can be approximately 20 percent of the total biomass but upwards of sometimes 40 percent of the energy content and figuring out how you can turn that into useful fuels and/or chemicals.

And so I would say that a decade ago the technology simply wasn't there to be able to effectively use that lignin. It was the old adage the only thing good to do with lignin was to burn it. But we know that's not true, and we know that given the right sorts of scientific breakthroughs, we can in fact turn that lignin into useful fuels and chemicals. And in fact we're working to do that across all of the centers. And we are in fact making great strides. So I think you'll see a big change once we stop throwing away an important component of that plant biomass.

Mr. WEBER. All right. Well, thank you. I appreciate that, Dr. Hegg. I want to move to Dr. Male now.

Dr. Male, this Committee is a big supporter of the national labs, including PNNL. We've heard a lot about the Bioenergy Research Centers, but let's not forget there are so many different centers and projects and things going on at the national labs, the Environmental Molecular Science Laboratory, EMSL, the Joint Genome Institute, and Energy Frontier Research Centers (EFRC) all come to mind. So I want to give you a chance, Dr. Male, to talk about the end-to-end research collaboration. How does PNNL try to shape some of the activities that might not seem directly connected to bioenergy, especially those at EMSL to assist the BRCs. Or, alternatively, how does PNNL work with the JGI and EFRCs to identify shared goals and mutual benefits? You got about 30 seconds, no pressure.

Dr. MALE. So an example would be Joint Bioenergy Institute, JBEI, which is a BRC. They've done some phenomenal work on driving synthetic biology. And this is directly fed into BETO, which is doing the Agile BioFoundry, looking at synthetic biology for specific targets. JBEI has also had successes that have been gone on to the advanced biofuels, bioproducts process development unit, which is a pre-pilot process development unit, and so that has been a real stimulant in the bay area for new startup companies coming in with their ideas and ideas germinating at JBEI and beginning to get them from microliters up to 100 liters. So you can start to go——

Mr. WEBER. I hate to cut you off, but I appreciate you. You're pretty knowledgeable on that and thank you. I yield back.

Mr. CASTEN. Ms. Stevens, you are now recognized for 5 minutes.

Ms. STEVENS. Well, thank you, Mr. Acting Chair. What a treat to have you chair today's hearing. And as a Michigan native, of course it is a real pleasure again to welcome Dr. Eric Hegg from Michigan State University. I'm wearing my green for you today, sir, as—and that's for the Committee for us here today.

And so, Dr. Hegg, you discussed the importance of advancing technology beyond the lab bench. I'll just tease at that a little bit more. How does this work effectively within the Great Lakes Bioenergy Research Center? What have been your own experiences?

Dr. HEGG. That's a great question. So at the Great Lakes Bioenergy Research Center, individual researchers work directly with their respective technologies office at their respective universities. And so once we have a nice technology at the lab scale that we think might be scaled up, we put out an invention disclosure. It is reviewed by the technology office, and if it's deemed to be interesting, important, and promising, then it moves on to file patent application and hopefully, obviously, then ultimately, a patent.

Now, once we have a patent, it's important to note that all of the technologies offices within the various universities at the Great Lakes Bioenergy Center work together. And the importance of that is that an industry can come in and they don't have to deal with multiple technology offices. They can work it with one center basically and then pass the technologies that perhaps were developed at individual universities back and forth or sometimes——

Ms. STEVENS. Yes.

Dr. HEGG [continuing]. Jointly between universities.

Ms. STEVENS. Yes. And so let me try and get both of you in here, too, because obviously, you know, we want to kind of talk about how critical it is that researchers from multiple fields tackle the R&D, the bioenergy enterprise. And so anything you can say on that would be important. And then tucked in that, I'd like to add that, you know, Department of Energy has significantly grown its footprint in the area of artificial intelligence. And this Committee, the Science Committee, has been highly supportive of that expansion. And, for example, we led on the *National Artificial Intelligence Initiative Act,* which was enacted in late 2020—this was last term—to authorize the DOE to support efforts in artificial intelligence that cut across multiple missions. So anything that you could also speak to on the Bioenergy Research Centers as a platform for exploring how artificial intelligence can be used to advance DOE's goals in bioscience would be much appreciated. So I sort of started with a macro question and then tucked in a micro one there, too.

Dr. HEGG. OK. So getting to the first question, I think it's really critical to understand the interdisciplinary nature of course of bioenergy research. And I think all of the centers do a great job. I mentioned just some of the fields that come—have to come together within the Great Lakes Bioenergy Research Center. And in fact at MSU there's almost 30 different faculty involved in the Great Lakes Bioenergy Research Center, which together they constitute about 12 different departments and five different colleges. So it's really a huge group of people that is bringing—that is being brought together to ensure that you have this integrated process. Solving—you know, finding a solution in one area can in fact translate across the entire pipeline.

So getting to your second question about the importance of computational work and especially artificial intelligence, it's outside my direct area of research——

Ms. STEVENS. OK.

Dr. HEGG [continuing]. By actually a long way, but I would echo what you said, which is the absolute importance of this type of research, really any—or I should say this type of capability in really any sort of research project which deals with large and complex data sets, which in fact bioenergy research does. Being able to make sense out of this very complex, rich source of data, which comes from land management or genomics or looking at product analysis or looking at microbial pathways is really invaluable. And taking all the data sets which are available throughout the literature and somehow combining them in a meaningful way is absolutely critical.

But I can—if you're interested in more, I can sort of work with my colleagues——

Ms. STEVENS. Yes, I mean, this is something we're going to continue to kind of tease out, too, on this Committee, and we're obviously running on the short of my 5 minutes of time, but that was a really helpful start. And with that, Mr. Chair, I'll yield back.

Mr. CASTEN. The Chair now recognizes the gentleman from Indiana, Dr. Baird, for 5 minutes.

Mr. BAIRD. Thank you, Mr. Chairman. I appreciate that, and I appreciate this Subcommittee hearing on energy. And, you know, I have in my district one of the laboratories for renewable resource engineering, as well as the Center for Direct Catalytic Conversion of Biomass to Biofuels. And so it's an exciting time in my opinion to be looking for some of these alternative energy sources.

And so, Dr. Hegg, you mentioned lignin. Would you care to elaborate on that a little bit? Because I think the forestry industries, which is a real carbon sink, the trees I'm talking about, and so I would really appreciate if you could elaborate just for another moment on the lignin if we can use that for a source of energy. What is the—what stage is that in, and how far along are we or——

Dr. HEGG. So I think exactly the state of it depends on sort of what direction you'd like to take it. So one direction you can take the lignin, which, again, is this complex biopolymer that's an important structural component of the plant cell wall, and you can sort of extract it and you can use it I'll say more or less directly as a polyol replacement. In other words, it's got a lot of alcohols on it, which can make it useful in certain applications such as various types of polyurethanes. And so that is a market which actually already has a lot of industrial interest and in fact one of my colleagues in the forestry department here at Michigan State University, Mojgan Nejad, collaborate quite a bit with a number of industries all over the Nation. And so that is—I wouldn't call it a mature technology, but it is already sort of on that road to being able to make an important contribution to the overall bioeconomy.

Now, another thing that you can do with that lignin is depolymerize it into its constituent monomers and then use those monomers either as a fuel directly or to be built up into other types of useful bioproducts. That technology is coming along. It is still much more nascent. It's challenging. It's challenging to break apart lignin into monomers and to keep those and to then separate those monomers and stop them from reacting with each other in a sort of uncontrolled way. And so that's the challenge. Chemists are learning to do that, and they've made great strides over the last, you know, I would say 5 years. There's a long way to go, but they are really making great, great progress. So I think that's—you know, I think that will get to the same technology level in the next 5 to 10 years. At least I'm hopeful it will.

Mr. BAIRD. Super. I'm glad to hear that. So would you have any further comments about the Centers for Direct Catalytic Conversion of Biomass just to give you the opportunity to make a comment about those centers—those C3Bios?

Dr. HEGG. Yes, unfortunately, I don't have enough of experience with them to be able to speak with a great degree of authority.

Mr. BAIRD. Dr. Leakey, do you have any comments on either one of the questions that I asked?

Dr. LEAKEY. So the CABBI research portfolio focuses heavily on a——

Mr. BAIRD. Yes.

Dr. LEAKEY [continuing]. Complementary approach——

Mr. BAIRD. Yes.

Dr. LEAKEY [continuing]. To the work that Dr. Hegg described on lignin, and so we focus largely on producing oils within the plant that can be easily extracted as a drop in biofuel that increases the value of the biomass per acre. So that would complement the approaches that you described.

Mr. BAIRD. Well, the advances we've made in biotechnology in recent decades are tremendous, and it really enhances our ability to provide food and fiber and mitigate some of this climate change. So anyone else have a comment? If not, I thank you, and I yield back, Mr. Chairman.

Mr. CASTEN. We are going to continue with the Ph.D. caucus. And Dr. McNerney from California is now recognized for 5 minutes.

Mr. MCNERNEY. I thank the Chairman for that recognition and the hearing, and I thank the witnesses. This is really interesting and important, and I'm glad to be a part of it.

Dr. Leakey, you discussed how artificial intelligence can be used to increase efficiencies in the traditionally laborious RD&D processes, so I'm going to follow up on Ms. Stevens' question. How is AI beneficial to bioenergy research and development and how can the government support further use of this technology?

Dr. LEAKEY. Sure, thank you very much. Yes, so scientists within CABBI are using machine learning to help address a very broad range of questions and accelerate our research progress. To give you some flavor for it, this includes designing new enzymes and metabolic pathways, automating normally laborious and inefficient steps in genome editing, as well as automatically analyzing images from microscopes, drones, and satellites to much more rapidly identify which crops and locations bioenergy would be—would perform best for bioenergy production.

I will say that there are some—this is a good example of there being some valuable interactions with Federal funding agencies beyond DOE, so the University of Illinois, for instance, leads two artificial intelligence research institutes, one funded by USDA, one funded by the National Science Foundation. And I'm pleased to say that even though those are just over a year old, we have got significant overlap in scientists between this project and CABBI and real valuable relationships building there. And we have some examples of AI accelerating progress particularly on our microbial platforms by up to an order of magnitude. So I think it's a really——

Mr. MCNERNEY. It sounds like it's not only a research tool, but it's a collaboration tool, so I'm glad to hear that.

Dr. LEAKEY. Yes.

Mr. MCNERNEY. Dr. Male, the climate benefits of bioenergy are still widely debated with different conclusions about the carbon intensity of biomass feedstocks. Do you think there are gaps in the lifecycle assessments of biomass feedstocks?

Dr. MALE. The lifecycle assessment modeling is still an evolving field. I'll give you an example. Particularly where products are perhaps used multiple times, we have not seen that really come to the fore. And there's a real opportunity to actually be more transparent and have discussions about what are the assumptions in anyone's models, the boundary conditions in the models, and how it leads to a certain conclusion. And it's OK to have discourse. That stimulates overall for the entire community of lifecycle assessment modeling and land-use change modeling to actually move forward.

Mr. MCNERNEY. Well, what barriers are remaining for conducting the kind of research—for creating partnerships for commercial development projects?

Dr. MALE. Barriers for commercial—oh, with regard to the lifecycle assessments or with regard——

Mr. MCNERNEY. Right.

Dr. MALE [continuing]. Or just to commercialization in general?

Mr. MCNERNEY. Well, let's talk about the lifecycle assessments.

Dr. MALE. With regard to lifecycle assessments, looking at it more holistically, that is, not just about greenhouse gas emissions, it's a myriad of other metrics of sustainability or sustainability indicators such as water, the quality of the soil, how that is treated, just to give you two examples. And so it is a multifaceted challenge, and you are doing tradeoffs across these numerous facets or success metrics.

Mr. MCNERNEY. Thank you.

Dr. MALE. So having a program where you can put forth in a transparent manner how you assessed what your crop did in the field and the water usage and the energy usage in your process and engage people like the Roundtable for Sustainable Biomaterials is an excellent way to go forward.

Mr. MCNERNEY. OK, thank you. I believe I'm about out of time, so I'm going to yield back to the Chair.

Mr. CASTEN. I'm looking for Mr. Meijer, and I don't see him, so the Chair will now recognize Mr. Obernolte from California.

Mr. OBERNOLTE. Thank you very much, Mr. Chairman, and thank you to the witnesses for a very fascinating hearing.

I'd like to ask a couple questions about the need to increase feedstock supplies because that's been kind of a recurrent theme in our hearing today. And as a Representative from California, as I note that the Chairman is, it's no surprise that we've had a couple of worst years of wildfires in the entire State's history. And one of the things that's been discovered is that our traditional approach to forest management is insufficient and we're going to have to pay a lot further attention to things like fuels reduction in the future if we hope to tame this activity.

So, you know, I'm interested in the fact that when we do fuel reduction in the forests, we come up with a lot of biomass but we really don't have anything to do with them. You know, we try and create energy from them, but that creates a lot of soot. It's very inefficient. That process requires government controls.

I'm wondering if that can't have—that biomass supply can't have a role to play in maybe the production of aviation fuel through the processes that we've been talking about? So let me start with Dr. Male since you had mentioned, you know, the need for expansion of the feedstock supply. Is there some kind of process that this forest-based fuels reduction biomass can be used for that purpose?

Dr. MALE. There is, and particularly if you look at managed forests. And a key aspect, though, is you always have to bear in mind the accessibility to that particular resource. So if you're doing thinning or putting in fire corridors, getting that resource from that site has traditionally been—if you have logging roads, that's fine. If you don't, it's a challenge. And so that has pushed the research on can we have systems that are modular and can be distributed to those locations to make an intermediate that can then subsequently be taken from there that doesn't create the soot that you mentioned?

Mr. OBERNOLTE. Right. Yes. I mean, obviously, that's going to be a recurrent theme no matter what use you put that biomass to, but, you know, given the fact that that's a problem we have to solve anyway, I'm kind of optimistic that maybe, you know, a pathway can be found there.

And Dr. Leakey, you also brought this up in your testimony. Do you think that that—that the use of this forest-based biomass might be kind of a substitute for actual food stock crops?

Dr. LEAKEY. So the work within CABBI focuses specifically on the use of grasses as our feedstock, and so I can't testify directly to the use of woody feedstocks.

Mr. OBERNOLTE. OK. Dr. Male, going back to you, you were talking about how difficult it is to create an industrial process to make a feedstock-based fuel that allows for variability in the feedstock. And obviously, if we're talking, you know, with fuels that have been reduced from forests, there's a lot of variability there. What do you think we can do to overcome that particular problem?

Dr. MALE. I think what we can do is recognize the issue that there is clearly—if you think about Gaussian distributions, take any parameter of a feedstock like particle size. There is a particle size distribution. And it's not good enough just to sit on top of the mean particle size. It shows you a technical feasibility of the process. But really you want to go out—perhaps if you want to be 95 percent sure you can deal with all the variability in that wood, you can go out two sigma either side of that mean to look at the tails of that distribution where the quality varies greatly and show that your process is both resilient and robust. And then that will allow your process to transition to industry with a greater certainty.

Mr. OBERNOLTE. Right. OK. Well, thank you. You know, it's—I'm really happy that we're having this discussion because we have a big problem with fuels reduction in the Western United States and what to do with that biomass because if we—I mean, we can burn it, which will just the de-sequester the carbon that's stored in it. We can let it decompose, but that over a longer amount of time also de-sequesters the carbon. Or we can figure out some way of making productive use of that carbon that is—results in avoided carbon through other channels. And I think that turning that into a feedstock for an organic-based fuel is a really good solution, so I'd love to see more attention paid to that. I'd love to see some more research. And I'm very happy that this Committee is taking a leadership role in that.

Mr. Chair, I yield back.

Mr. CASTEN. Thank you. And not seeing Mr. Lamb, the gentlelady from North Carolina, Ms. Ross, is now recognized for 5 minutes. Oh, and before I introduce her, I apologize for not recognizing the other Member of our Ph.D. caucus, Dr. Obernolte. So apologies for the missed—Ms. Ross, you're now recognized.

Ms. ROSS. Thank you, Mr. Chairman. And I'm a member of the lawyer caucus. I want to thank Chairman Bowman for holding this meeting. And as a member of the lawyer caucus, I represented several different bioenergy clients in North Carolina, including those who used wood waste, those who turned hog poop into power, and I also represented people who dealt with municipal waste and turned that into energy.

And I'm very interested to hear the insights from our panelists and the status and the pace of DOE bioenergy research. And obviously, more research and development coupled with environmental justice and economic considerations are needed to ensure that we can maximize the use of bioenergy to our benefit.

And as I said, I did represent a client that dealt with wood waste. And wood waste has been both a positive and a controversial issue in North Carolina. And the production particularly of wood pellets has created some environmental justice concerns that need to be considered as we move forward. Specifically, some of the wood pellet plants in North Carolina and across the United States are located in rural and low-income and predominantly minority areas. And the plants can produce fine particle pollution, carbon monoxide, and can degrade the local air quality. These effects disproportionately harm minority and disadvantaged communities given their proximity to the plants, putting them at higher risk of suffering from health consequences.

And so to all of our panelists, are there best practices that can prevent environmental injustices such as these, and are there immediate steps we can take to reduce the increased health risks associated with these plants? Anybody?

Dr. MALE. You should be able to readily address the particulate matter if you have any particulate matter coming off, and there are regulations on volatile organic compounds coming off from the production of, say, a roasting, like in torrefaction or in the production of pellets, that those volatile organic compounds should be combusted prior to going up a stack. And the EPA (Environmental Protection Agency) has guidelines on both to help all communities.

Ms. ROSS. OK. Does anybody else have anything to add? I have a second question.

Also, the selling or moving of bioenergy in existing pipelines, so I'm talking about what is referred to as renewable natural gas, requires negotiation with pipeline owners, and this requires coordination and careful attention to the movement of other gases in order to avoid dangers in combustion. And the North Carolina Utilities Commission is dealing with this right now and has several pilot programs for bioenergy moving through natural gas pipelines.

Dr. Harmon, how do we ensure that the Pipeline and Hazardous Materials Safety Administration, PHMSA's regulation of these transactions balance the safety risks without being over-restrictive on something that can be a positive industry?

Dr. HARMON. So, first, I have to acknowledge I have no expertise in natural gas pipelines or the complexity that you describe. What I would say is that if we think about renewable natural gas as something that can be used closer to its source in conversion facilities that make, for example, sustainable aviation fuel or make chemicals from that resource, in that way we would obviate the need for some of the complexity that you describe.

Ms. ROSS. Yes. Yes, that is a great point, and actually those projects are moving forward much more seamlessly. Interestingly in North Carolina our utilities get credit—get credits for using renewable natural gas, and so that's raised this issue with the pipelines. But hopefully, we can submit some other questions and get answers to those. Thank you so much, Mr. Chair, and I yield back.

Mr. CASTEN. It appears that we have no more Republicans on the panel, so we will now turn to Dr. Foster from Illinois for 5 minutes. To our distinguished panel, we've got you tied. We've got four doctors to your doctors. We'll see if you raise us on the next round. Dr. Foster, you're recognized.

Mr. FOSTER. Well, I think that probably the thing that trumps this is the Ph.D. from the University of Wisconsin that Dr. Hegg has, and so as a graduate of Wisconsin myself, I think that we can all acknowledge that that probably trumps everything.

But one of the big knocks against biofuels in the early days had to do with the fact that it was unclear that things like corn ethanol were even carbon neutral. And there at the time were very large fossil fuel inputs to making, well, corn ethanol, for example. And so the two big things that have been talked about to eliminate those are the ability to eliminate ammonia fertilizer, and there are various biological approaches to that. I think Pivot Bio and some other companies are actually—and so I was wondering if you could sort of give a quick status report on that.

The other thing that seemed promising is there's a company called ClearFlame I think that apparently has cracked the code on how to make diesel engines work with full thermodynamic efficiency and very low soot emissions using, for example, corn ethanol, methanol, or a variety of other. So apparently that, you know, required some bright new ideas from a startup that's just gotten a lot of follow-on funding. They're driving trucks around with corn ethanol at full thermodynamic efficiency.

And so I was wondering what you think the promising ways are—you know, how far along are we, and what is the promising road ahead for further reducing the carbon footprint used to produce biofuels? Dr. Male, do you want to have a shot at that?

Dr. MALE. Yes. Thank you for bringing up that topic. There has been a lot of progress in introducing sustainable practices or best land management practices and utilization of lignin and other practice and going toward extracting corn oils and extracting fiber that have driven down—or, sorry, increased the greenhouse gas reductions. You've seen them march from a 20 percent reduction initially for corn ethanol to when you have other processes on the site going to around 45 percent.

You're right about there are different ways of utilizing organic fertilizer. There's a terrific opportunity that DOE and USDA are looking at, and there's a lot of science that is needed to look at the interaction of fertilizer, the soil bacteria communities, the root system of plants, and the interaction between those and the species and the transports and keeping it on the field. Farmers pay for their fertilizer. They do not want it leaving the field, and so there are opportunities where you can use energy crops or perennials with a deeper root system perhaps on the drainage from your field or the edge of your field so that you keep your fertilizer in the field while preventing your fertilizer from going into streams that can then go downstream and effect, well, organisms like microalgae to give you a harmful algal bloom.

Mr. FOSTER. Yes. Dr. Leakey, did you have any comments on——

Dr. LEAKEY. Yes, I could certainly contribute to that conversation. So within CABBI, reducing the greenhouse gas emissions in the form of nitrous oxide and maximizing the efficiency with which plants use nitrogen in the soil is of strong interest. As with a number of other aspects of this problem, I think it's best addressed with next-generation bioenergy feedstocks. And our team is working on that in a variety of ways.

Actually having feedstocks which are perennial themselves is exceedingly valuable because they recycle the nutrients from 1 year to the next. And similar to what Dr. Male just mentioned, our theme is also really actively working on understanding how microbial partners in the soil and in some cases the chemicals released from the roots of these crops influence that cycling of nitrogen and how we can manage them optimally to retain most of that nitrogen in the plant.

And then last but not least we can actually engineer the plants themselves to try to use the nitrogen more efficiently. So there's a number of strands of research on the topic.

Mr. FOSTER. Now, do you anticipate that within a small number of decades we'll be able to essentially eliminate the need for ammonia-based fertilizer? Is that a realistic hope?

Dr. LEAKEY. I think we can realistically hope to substantially reduce its use. Whether we get to a total elimination or not is hard to say.

Mr. FOSTER. All right. Thank you. My time is up and yield back.

Mr. CASTEN. Thank you to all of our witnesses. Before I bring the hearing to a close, well, I'd like to thank all of our witnesses for testifying today. I have a statement for the record from the Biotechnology Innovation Organization, which I would move to be incorporated into the record. So ordered.

The record will remain open for 2 weeks for additional statements from the Members and for any additional questions that the Committee may ask of the witnesses. The witnesses are excused, and the hearing is now adjourned.

[Whereupon, at 11:51 a.m., the Subcommittee was adjourned.]

Appendix I

ANSWERS TO POST-HEARING QUESTIONS

ANSWERS TO POST-HEARING QUESTIONS

Responses by Dr. Jonathan Male

U.S. HOUSE OF REPRESENTATIVES
COMMITTEE ON SCIENCE, SPACE, AND TECHNOLOGY

"Bioenergy Research and Development for the Fuels and Chemicals of Tomorrow"

Questions for the Record to:
Dr. Jonathan Male
Chief Scientist, Energy Processes and Materials
Pacific Northwest National Laboratory
Submitted by Representative Donald Norcross

1. High-ethanol blend fuels are not always compatible with existing infrastructure. What current efforts to convert or build new infrastructure that can handle high-ethanol blend fuels do you believe are most promising, and what challenges and opportunities do they bring? What role do you think Congress should play in this space?

In September 2019 DOE released the Top Ten Blendstocks for Turbocharged Gasoline Engines which looked at biofuel derived blendstocks which could be blended with gasoline up to 30% in boosted spark ignition engines and could increase the fuel economy of light duty vehicles 10% beyond current technology.[1] Ethanol was one of the six candidates determined to have the fewest barriers to adoption and use. "*The Co-Optimization of Fuels and Engines (Co-Optima) initiative identified a number of outstanding challenges for the most promising blendstocks. First and foremost, only three (ethanol, isobutanol and di-isobutylene) are currently allowed in market fuels. Any new blendstocks would have to go through the normal fuel certification process. Second, the production cost of all of blendstocks identified is significantly higher than fuels on the market today; finding ways to value the enhanced fuel properties could help, along with process improvements. Third, fuel system and infrastructure compatibility, emissions impacts, and health and safety impacts would have to be determined to be acceptable prior to the fuel certification process. Finally, the efficiency and environmental impacts must be confirmed in engine tests and more detailed analyses, along with opportunities for refinery integration.*"

In December 2020 the U.S. Department of Agriculture (USDA) announced it intended to make up to $100 million available in new funds for biofuels infrastructure, such as blender pumps through the Higher Blends Infrastructure Incentive Program (HBIIP) for Fiscal year 2021.[2,3] The funding was to provide grants to refueling and distribution facilities for cost of installation, retrofitting or otherwise upgrading of infrastructure required at a location to ensure the environmentally safe availability of fuel containing bioethanol blends of E-15 and greater or fuel containing biodiesel blends B-20 and greater. In August 2021 USDA awarded $26 million for higher-blend biofuel infrastructure in projects in 23 states to install pumps, tanks, and other equipment for selling higher-blend biofuels and potentially increase capacity by 822 million gallons annually in the 23 states.[4]

We are surrounded by molecules containing carbon that enable our everyday lives such as textiles, carpets, casings, packaging of consumer goods, and even liquid fuels. We have segments of the U.S. economy that are hard to electrify. As Pacific Northwest National Laboratory (PNNL) and others have noted ethanol can be used as a renewable building block for fuels and chemicals.[5] PNNL has developed a two-step oligomerization process that produces primarily iso-paraffin hydrocarbons, forms minimal aromatics, facilitates efficient conversion of high carbon fractions to distillate-range fuels, and minimizes formation of naphtha-like compounds by efficient intermediate product recycling. This technology was demonstrated at scale by LanzaTech and its' spin-off, LanzaJet which is looking at utilizing all forms of ethanol to make sustainable aviation fuel. Additional research at PNNL is currently looking at how to convert ethanol to other chemical products such as alkenes and renewable diesel for other applications that would leverage existing infrastructure.

Ethanol produced from corn grown using existing agricultural practices is less carbon-intensive than petroleum gasoline, the greenhouse gas profile of U.S. corn ethanol, is on average 39% lower than that of gasoline.[6] With reduced tillage, smart farming, intercropping, renewable energy, increased corn yields, and cover crops, could reduce greenhouse gas emissions of corn ethanol between 47 and 70% relative to gasoline with options to go further with renewable energy, electrical- and biological-synthesis of nitrogen fertilizers. Congress may wish to be briefed by DOE and USDA on recent and proposed future research to reduce the carbon and resource intensity of agriculture.

References

1 Gaspar, Daniel. 2019. Top Ten Blendstocks For Turbocharged Gasoline Engines: Bioblendstocks With Potential to Deliver the for Highest Engine Efficiency. PNNL-28713, Pacific Northwest National Laboratory. https://www.osti.gov/servlets/purl/1567705

2 https://www.usda.gov/media/press-releases/2021/12/07/usda-make-800-million-available-provide-economic-relief-biofuel#:~:text=USDA%20intends%20to%20make%20up,availability%20in%20the%20retail%20market.

3 USDA Rural Development, Higher Blends Infrastructure Incentive Program https://www.rd.usda.gov/hbiip

4 USDA invests $26 million in biofuel infrastructure to expand availability of higher-blend renewable fuels in 23 states https://www.usda.gov/media/press-releases/2021/08/19/usda-invests-26-million-biofuel-infrastructure-expand-availability

5 Robert Dagle, Austin Winkelman, Karthikeyan Ramasamy, Vanessa Lebarbier Dagle, Robert Weber (2020) Ethanol as a renewable building block for fuels and chemicals, Ind. Eng. Chem. Res. 59, 4843-4853, https://doi.org/10.1021/acs.iecr.9b05729

6 Jeffrey Rosenfeld, Diana Pape, Tommy Hendrickson, Kirsten Jaglo, Katrin Moffroid (2020) The greenhouse gas benefits of corn ethanol – assessing recent evidence, Biofuels, 11:3, 361-375, DOI: 10.1080/17597269.2018.1546488.

Appendix II

Additional Material for the Record

LETTER SUBMITTED BY REPRESENTATIVE SEAN CASTEN

Biotechnology Innovation Organization
1201 Maryland Avenue SW
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March 16, 2022

The Honorable Jamaal Bowman
Chairman
Subcommittee on Energy
Committee on Science, Space
and Technology
U.S. House of Representatives
2321 Rayburn House Office Building
Washington, DC 20515

The Honorable Randy Weber
Ranking Member
Subcommittee on Energy
Committee on Science, Space,
and Technology
U.S. House of Representatives
2321 Rayburn House Office Building
Washington, DC 20515

Dear Chairman Bowman, Ranking Member Weber, and Members of the Subcommittee:

The Biotechnology Innovation Organization (BIO) is pleased to submit a statement for the record to the to the United States House of Representatives Committee on Science, Space, and Technology Subcommittee on Energy hearing entitled, *Bioenergy Research and Development for the Fuels and Chemicals of Tomorrow*.

Introduction

BIO[1] represents 1,000 members in a biotech ecosystem with a central mission – to advance public policy that supports a wide range of companies and academic research centers that are working to apply biology and technology in the energy, agriculture, manufacturing, and health sectors to improve the lives of people and the health of the planet. BIO is committed to speaking up for the millions of families around the globe who depend upon our success. We will drive a revolution that aims to cure patients, protect our climate, and nourish humanity.

Research and Development Fostering Innovation

BIO welcomes the subcommittee holding a hearing on the need for research and development of sustainable fuels and chemicals. We are pleased the subcommittee invited Dr. Laurel Harmon from our member company LanzaTech to serve as a witness for the discussion.

Congressional support of federal research and development of bioenergy is critical part of a larger strategy to grow the bioeconomy. As the country emerges from the COVID-19 pandemic and confronts rising energy prices driven by conflict in Ukraine, we must invest in a sustainable and resilient economy, with innovation at its core.

Biotechnology is enabling a dramatic paradigm shift in the production of fuels and chemicals. Modern biorefineries are converting domestic sources of renewable biomass, wastes, and residues into sustainable low carbon fuels, chemicals, and products. In turn, the sector creates high paying jobs,

[1] https://www.bio.org/

particularly in rural parts of the country where renewable biomass is grown and in manufacturing communities where carbon can be captured and utilized. Developing and employing domestic feedstocks will help reduce the United States' dependence on foreign energy and create an energy sector that reduces greenhouse gas emissions and enhances human health through improved air quality.

Economic Benefits of Research and Development

Federal programs that foster research, development, demonstration-scale activities, and deployment of renewable, low-carbon energy technologies send positive signals to the investment community. Private sector funding is critical to accelerate innovation, create a more resilient economy, and grow jobs for years to come.

A 2020 Breakthrough Energy report[2] prepared by PricewaterhouseCoopers LLP showed that federally funded research and development catalyzed hundreds of billions in added economic value in 2018, and that every job supported with federal research and development investment added almost three additional jobs to the U.S. economy. Looking specifically at energy, the same study found that $9.5 billion in energy research and development and associated infrastructure investments in 2018 supported more than 112,000 American jobs, while also contributing $9 billion in labor income, $2.8 billion in tax payments, and $14 billion in value added to the economy.

For investments made by the U.S. Department of Energy's Office of Energy Efficiency and Renewable Energy (EERE), the economic benefits have far exceeded the cost of the R&D investments. A total taxpayer investment of $12 billion (inflation-adjusted 2015 dollars) in EERE's research and development portfolio yielded more than $388 billion in net economic benefits to the United States[3].

Conclusion

Policies supporting research and development of sustainable fuels and chemicals will allow us to build a biobased economy and workforce. BIO is committed to working with Congress in a forward-looking manner to foster pioneering technology breakthroughs and science. Doing so will bolster our economic and energy independence and set us on a path to better health and prosperity.

Sarah Gallo
Vice President, Agriculture and Environment
Biotechnology Innovation Organization

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[2] https://www.breakthroughenergy.org/-/media/files/bev/bepwcreport09162020.pdf
[3] https://www.energy.gov/sites/prod/files/2017/11/f46/Aggregate%20ROI%20impact%20for%20EERE%20RD%20-%2010-31-17%20%28002%29%20-%2011-17%20%28optimized%29.pdf