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

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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.

<u>CABBI's toolkit for further discovery and innovation</u>

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.