CLIMATE AND ENERGY SCIENCE RESEARCH AT THE DEPARTMENT OF ENERGY

HEARING

BEFORE THE

SUBCOMMITTEE ON ENERGY

OF THE

COMMITTEE ON SCIENCE, SPACE, AND TECHNOLOGY
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C O N T E N T S

May 4, 2021

CLIMATE AND ENERGY SCIENCE RESEARCH AT THE DEPARTMENT OF ENERGY

TUESDAY, MAY 4, 2021

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

The Subcommittee met, pursuant to notice, at 11 o'clock a.m., via Zoom, Hon. Jamaal Bowman [Chairman of the Subcommittee] presiding.

COMMITTEE ON SCIENCE, SPACE, AND TECHNOLOGY
SUBCOMMITTEE ON ENERGY
U.S. HOUSE OF REPRESENTATIVES
HEARING CHARTER

Climate and Energy Science Research at the Department of Energy
Tuesday, May 4, 2021
11 a.m.

Purpose

The Subcommittee's hearing will examine two major components of the Department of Energy's Office of Science: the Basic Energy Sciences (BES) program as a whole and the Earth and Environmental Systems Sciences Division within the Office of Science's Biological and Environmental Research (BER) program. Within BES, the hearing will focus on initiatives to advance material and chemical sciences research for a broad range of energy applications. Climate and environmental systems research and its importance to understanding and reducing the threat of climate change will also be examined, including the integration of socioeconomic factors. The hearing will consider the expansion of access to user facilities, collaboration with industry, and approaches to bridging knowledge gaps to solve our nation's most pressing energy needs. Finally, the hearing will examine ways that Congress and the Administration should consider directing the activities of these programs going forward.

Witnesses

- **Dr. Kristin Persson**, Director, Molecular Foundry, Lawrence Berkeley National Laboratory
- **Dr. Fikile Brushett**, Associate Professor of Chemical Engineering, Massachusetts Institute of Technology
- **Dr. Esther Takeuchi**, Chair, Interdisciplinary Science Department, Brookhaven National Laboratory
- **Dr. Xubin Zeng**, Professor, Hydrology and Atmospheric Sciences, The University of Arizona
- **Dr. Narasimha Rao**, Associate Professor of Energy Systems, Yale School of the Environment

Basic Energy Sciences (BES) Program

The Basic Energy Sciences (BES) program in the DOE Office of Science supports research to understand, predict, and ultimately control matter and energy at the electronic, atomic, and molecular levels in order to provide the foundations for new energy technologies and to support DOE missions in energy, environment, and national security.[1] This includes a broad portfolio of research targeted to accelerate the development of advanced clean energy technologies. BES, the

[1] https://science.osti.gov/bes/About

largest program in the Office of Science, received $2.245 billion for FY 2021 to support its various activities.

BES is one of the nation's largest sponsors of research in the physical sciences. The program supports research at nearly 170 universities, national laboratories, and other research institutions nationally.[2] The expanded knowledge gained through activities and facilities supported by BES underpins the applied energy research supported by other DOE programs and by the private sector. Better characterization of materials at a molecular level and greater knowledge of chemical reactions at the atomic level are often necessary to develop new sources of energy. For example, better understanding of photochemistry and material characteristics will enable the development of more efficient photovoltaic cells and higher electricity production from solar energy. Research on the transport of electrical charge and the properties of new self-healing nanoscale materials may lead to the development of the next generation of batteries for vehicles and for large-scale use of intermittent renewable energy sources.

BES also stewards a national network of 12 major scientific user facilities based at DOE national laboratories, and approximately 16,000 scientists and engineers use the facilities yearly. The user facilities house unique instrumentation that is essential to the conduct of advanced research in the energy sciences. For example, light sources and neutron sources are used to characterize materials and examine chemical processes by observing the ways in which either neutrons or specific kinds of light waves interact with the target that a researcher wishes to study.

BES User Facilities

X-Ray Light Sources

Today's synchrotron light source facilities produce x-rays that are millions of times brighter than medical x-rays. Scientists use these highly focused, intense beams of x-rays to reveal the identity and arrangement of atoms in a wide range of materials.[3] The tiny wavelength of x-rays allow researchers to see things visible light cannot resolve, such as the arrangement of atoms in metals, semiconductors, ceramics, polymers, catalysts, plastics, and biological molecules. The current operational light source facilities are the:

- **Advanced Light Source (ALS)** at Lawrence Berkeley National Laboratory;[4]
- **Advanced Photon Source (APS)** at Argonne National Laboratory;[5]
- **Linac Coherent Light Source (LCLS)** at Stanford Linear Accelerator Center (SLAC) National Accelerator Laboratory;[6]
- **National Synchrotron Light Source (NSLS)** at Brookhaven National Laboratory;[7]
- **Stanford Synchrotron Radiation Laboratory (SSRL)** at SLAC;[8]

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[2] https://www.energy.gov/science/bes/basic-energy-sciences
[3] https://www-public.slac.stanford.edu/lcls/WhatIsLCLS_2.aspx
[4] https://als.lbl.gov/
[5] https://www.aps.anl.gov/
[6] https://lcls.slac.stanford.edu/
[7] https://www.bnl.gov/ps/
[8] https://www-ssrl.slac.stanford.edu/

Neutron Scattering Facilities

Neutrons can penetrate deep into materials to give precise information about positions and motions of atoms in the interior of a sample. Because of their unique characteristics, they are particularly well-suited to study the magnetic structure and properties of materials. They are also especially sensitive to the presence of light elements such as hydrogen, carbon, and oxygen which are found in many biological materials. The current operational neutron sources are the **High Flux Isotope Reactor (HFIR)**[9] and the **Spallation Neutron Source (SNS)**,[10] both at Oak Ridge National Laboratory.

Nanoscale Science Research Centers

The five BES Nanoscale Science Research Centers (NSRCs) are facilities in which new synthesis and processing capabilities are integrated with tools and expertise for characterization and corresponding resources for theory, modeling, and simulation. The NSRCs differ from the other BES user facilities by offering a suite of smaller, specialized tools rather than large accelerators or light sources. The centers are the:

- **Center for Functional Nanomaterials** at Brookhaven National Laboratory;[11]
- **Center for Integrated Nanotechnologies** at Sandia National Laboratories and Los Alamos National Laboratory;[12]
- **Center for Nanophase Materials Sciences** at Oak Ridge National Laboratory;[13]
- **Center for Nanoscale Materials** at Argonne National Laboratory;[14] and the
- **Molecular Foundry** at Lawrence Berkeley National Laboratory.[15]

BES Energy Innovation Hubs

The BES program funds and manages two DOE Energy Innovation Hubs that focus on collaborative research to overcome key scientific barriers for major energy challenges. The impacts of these research activities are demonstrated by development and evaluation of integrated energy systems. The Hubs bring together teams of experts from multiple disciplines to focus on two grand challenges in energy: (1) Fuels from Sunlight and (2) Batteries and Energy Storage.[16] BES's current Hubs are the:

Fuels from Sunlight Hub

The **Liquid Sunlight Alliance (LiSA)**,[17] led by the California Institute of Technology in partnership with Lawrence Berkeley National Laboratory, and the **Center for Hybrid**

[9] https://neutrons.ornl.gov/hfir
[10] https://neutrons.ornl.gov/sns
[11] https://www.bnl.gov/cfn/
[12] https://cint.lanl.gov/
[13] https://www.ornl.gov/facility/cnms
[14] https://www.anl.gov/cnm
[15] https://foundry.lbl.gov/
[16] https://science.osti.gov/bes/Research/DOE-Energy-Innovation-Hubs
[17] https://www.liquidsunlightalliance.org/

Approaches in Solar Energy to Liquid Fuels (CHASE),[18] led by the University of North Carolina at Chapel Hill, are pursuing research to produce various types of liquid hydrocarbon fuels using sunlight as the primary energy source.

Batteries and Energy Storage Hub

The **Joint Center for Energy Storage Research (JCESR)** focuses on overcoming fundamental scientific challenges to enable transformational energy storage systems beyond today's lithium-ion batteries. JCESR is housed at Argonne National Laboratory with participation from a consortium of other National Laboratories and research institutions from around the nation. [19]

Energy Frontier Research Centers (EFRC)

The EFRCs bring together creative, multi-disciplinary, multi-institutional scientific teams to tackle difficult scientific challenges preventing advances in a variety of energy technologies. They are significantly smaller in scale that the Hubs described above, with a budget of $2-4 million annually vs. $20-24 million provided annually for each Hub. These centers utilize powerful new tools for characterizing, understanding, modeling, and manipulating matter from atomic to macroscopic length scales. For example, BES has funded EFRCs to address research challenges relevant to environmental remediation, quantum information science, polymer upcycling, and microelectronics.

Most EFRCs are based at universities but feature collaboration from national laboratories and other research partners. Many serve as a platform for training the next-generation scientific workforce by supporting students and postdoctoral researchers interested in energy science. Since the program's inception, BES has funded 88 EFRCs, and the EFRC program currently supports 41 active centers across 34 states.[20]

Other Competitive Grant Funding

In addition to the center-based mechanisms above, BES supports small groups of researchers and single investigators based primarily at universities. These activities are supported through open funding calls for research ideas as well as more focused solicitations. They are critical to advancing research in materials, chemistry, geosciences, and other areas within the BES portfolio. In addition, this support helps ensure the existence of a vibrant community of researchers capable of productively leveraging the user facilities mentioned above and generating ideas that underpin future EFRCs, Hubs, and other larger scale efforts.

Earth and Environmental Systems Sciences Division, Biological and Environmental Research (BER) Program

The Earth and Environmental Systems Sciences Division (EESSD) within the DOE Office of Science's Biological and Environmental Research (BER) program carries out a broad array of

[18] https://solarhub.unc.edu/
[19] https://www.jcesr.org/
[20] https://science.osti.gov/bes/efrc

earth and climate systems research, including land, water, and atmospheric predictive and real time observations and modeling, and the complex interdependencies between human activity and the natural environment. This research is used to help determine the impacts and possible mitigation of climate change. It also supports DOE's mission by enabling better security of the nation's energy infrastructure, including by understanding subsurface biogeochemical processes. The division received "not less than" $350 million in FY 2021 appropriations.

The earth and climate systems research carried out by BER informs computational models that are used worldwide. Experimental and observational scientists perform research that ultimately results in gathering atmospheric and surface and subsurface terrestrial data, including land-water interfaces. This data is in turn used in computational models, where scientists analyze the data and further improve the experiments and models to better understand these natural processes and how humans have impacted them, including the interdependencies between the biosphere and the atmosphere. These earth and climate models can be used to predict how changes in land and water use can affect the climate and weather, from the molecular level to a global scale, which in turn can inform resource planning and policy decision-making. An example of this is in observing and modeling how particulate matter in the atmosphere impacts cloud formation, precipitation, and the Earth's surface temperature. Scientists continue to work to increase the granularity of the models which would improve our understanding of regional differences in earth and climate systems.

Another example of the research carried out by this division is regarding subsurface biogeochemical processes. The goal of this research is to understand the dynamic processes of how subsurface material moves and evolves over time, with a focus on energy-relevant materials, including contaminated materials from past nuclear weapons production. The research carried out by this division is in a constant state of iteration because of the continuously evolving interdependencies between the natural environment and the built environment by humans, and as such, this research requires interdisciplinary scientists, include social scientists who can better model socio-economic variables. DOE works alongside other relevant scientific agencies to better inform international climate models.

The Earth and Environmental Systems Sciences Division stewards two user facilities: the Atmospheric Radiation Measurement (ARM) user facility and the Environmental Molecular Sciences Laboratory (EMSL). These facilities are utilized by scientists from all over the world. These facilities are integral to carrying out experiments to obtain the observational and computational data required to inform our most advanced earth and climate models.

BER Earth and Environmental Systems Sciences User Facilities

Atmospheric Radiation Measurement (ARM) User Facility

ARM is a multi-laboratory, multi-platform facility that consists of observatories at field sites around the world. Researchers utilize these facilities to measure atmospheric phenomena from diverse regions of the Earth. The facilities allow for both in situ and remote sensing observations. The facility consists of three permanent fixtures (U.S. Southern Great Plains, North Slope of Alaska, and the Azores) and three mobile facilities which are used to research parts of the world other than the fixed sites, as well as aerial facilities which can also be used anywhere to monitor the atmosphere. The data obtained from this user facility is used to inform earth and climate models.[21]

Environmental Molecular Sciences Laboratory (EMSL) User Facility

EMSL is located at the Pacific Northwest National Laboratory in Richland, Washington. This facility provides multiple physical experimental and computational capabilities in one location that allow researchers to better understand physical processes of earth, environmental, and energy systems down to the molecular level and over precise time scales. Highly specialized instruments as well as high performance computing resources are available at the facility. Much of the subsurface biogeochemical research carried out by BER is performed at this facility.[22]

Academic and Industrial Use of Office of Science User Facilities

The DOE Office of Science's major scientific user facilities are utilized by scientists from many academic institutions and businesses across the nation and around the world. The demand for access to these facilities exceeds the time available, and management of the competing requests for time on these facilities is an ongoing challenge. DOE uses several methods to allocate time among the competing requests. The most common procedure for researchers to gain access to the facilities is through submission of a research proposal. DOE evaluates the proposals through a competitive process using standard peer-review procedures.

Industrial or academic institutions also have the option to fund the installation and maintenance of a workstation at the end of a particular beamline at some facilities. In exchange for their investment, the scientists associated with the funding institution have priority use for the majority of the time available through that workstation. Another option for industrial users who wish to maintain full intellectual property rights associated with their research project is to pay the total cost recovery of their facility use.

[21] https://www.arm.gov/
[22] https://www.emsl.pnnl.gov/

Chairman BOWMAN. This 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 virtually. I want to announce a couple of reminders to the Members about the conduct of this hearing. First, Members should keep their video feed on as long as they are present in the hearing. Members are responsible for their own microphones. Please also keep your microphones muted unless you are speaking. Finally, if Members have 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 now recognize myself for an opening statement.

Good morning, and thank you to all of our witnesses who are joining us virtually here today to discuss the importance of climate and energy science research at the Department of Energy (DOE). This hearing is one of a series on research and development (R&D) activities sponsored by the DOE's Office of Science. This office was funded at over $7 billion in fiscal year 2021, and accounts for over half of DOE's non-defense R&D budget. The energy sciences and climate research programs were each funded at over $2 billion and three quarters of a billion dollars in fiscal year 2021, respectively. Today, we will just be focusing on these two programs, though there are others that we will examine in the months ahead.

While these investments are not insignificant by any means, they are simply not enough to tackle the climate crisis. This research is not just a nice-to-have; it is a must-have for the safety, security, and future of humanity.

The Basic Energy Sciences (BES) program is one of our Nation's biggest sponsors of research in the natural sciences. This research helps us understand matter and energy down to the atomic level to ultimately inform advances in a broad range of green energy technologies. A great example of this work is battery technology development, which we will hear much more about today. Understanding the materials properties of various building blocks of batteries and being able to observe how batteries perform in real time at the molecular level, this is the kind of cutting-edge scientific research we need as we drastically reduce greenhouse gas emissions.

We should also keep in mind, however, that solving the climate crisis is not only a technological challenge. To meet our climate goals, as the Intergovernmental Panel on Climate Change has said, will take "rapid, far-reaching, and unprecedented changes in all aspects of society." And as the Biden Administration has made clear, these changes can and must lift up workers, the poor, and redlined communities of color, who are already hardest hit by the fossil fuel economy and the impacts of a warming planet.

Bold climate action can create millions of jobs, union jobs and make life better for all. And we already have the technologies we need to go all-in on the transition. Here too, research at the Department of Energy has a crucial role to play. I am pleased that we are joined today by experts who can speak to the interdisciplinary research and new kinds of collaborations we need. That includes more integration with the social sciences to help us deploy existing green technologies faster and better, in ways that promote justice and build community power. Let's learn by doing, and plug those lessons into science research and technology development as we go.

We also have distinguished witnesses present today who will discuss the climate science activities carried out by DOE's Biological and Environmental Research (BER) program. This research helps us understand complex Earth systems, the accelerating impacts of climate change, and how we can better protect people and infrastructure. It also aims to improve our understanding of regional differences in climate and Earth systems at a more granular level to help inform policymakers. This kind of data would be incredibly useful for my district, as I have seen firsthand how communities are dealing with climate impacts like flooding and extreme heat, which are compounded by failing infrastructure and other forms of environmental justice.

One of the most important features of these programs are the operation and maintenance of state-of-the-art scientific user facilities. These facilities attract some of the world's most talented researchers from academia and industry. They range from giant synchrotron light sources to nanoscale research facilities, all of which are used to imagine and understand the fundamental properties of materials and chemical processes for a wide range of clean energy, medical, and other important applications.

The Office of Science is also—also supports field observatories around the world that measure atmospheric data that feed into climate models. But the research infrastructure is not—is only one piece of the puzzle. We need people, talented and trained professionals, to perform this research and help lead us into a green, just future. And we need to increase the participation of marginalized communities, including with STEM (science, technology, engineering, and mathematics) education infrastructure and workforce pipelines that will unleash the talents of students of color who have been neglected. This is a topic that is near and dear to my heart, and I am proud that this Committee is working to make our research activities more inclusive at every level through various legislative proposals.

I want to again thank our excellent panel of witnesses assembled today, and I look forward to hearing your testimonies.

[The prepared statement of Chairman Bowman follows:]

Good morning, and thank you to all of our witnesses who are joining us virtually today to discuss the importance of climate and energy science research at the Department of Energy.

This hearing is one of a series on research and development activities sponsored by the DOE's Office of Science. This office was funded at over seven billion dollars in FY21, and accounts for over half of DOE's non-defense R&D budget. The energy sciences and climate research programs were each funded at over two billion dollars and three quarters of a billion dollars in FY21, respectively. Today we will just be focusing on these two programs, though there are others that we will examine in the months ahead.

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The Basic Energy Sciences program is one of our nation's biggest sponsors of research in the natural sciences. This research helps us understand matter and energy down to the atomic level to ultimately inform advances in a broad range of green energy technologies. A great example of this work is battery technology development, which we will hear much more about today. Understanding the materials properties of the various building blocks of batteries, and being able to observe how batteries perform in real time at the molecular level—this is the kind of cutting-edge scientific research we need as we drastically reduce greenhouse gas emissions.

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Here too, research at the Department of Energy has a crucial role to play. I am pleased that we are joined today by experts who can speak to the interdisciplinary research and new kinds of collaborations we need. That includes more integration with the social sciences, to help us deploy existing green technologies faster and better—in ways that promote justice and build community power. Let's learn by doing, and plug those lessons into science research and technology development as we go.

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One of the most important features of these programs are the operation and maintenance of state-of-the-art scientific user facilities. These facilities attract some of the world's most talented researchers from academia and industry. They range from giant synchrotron light sources to nanoscale research facilities, all of which are used to image and understand the fundamental properties of materials and chemical processes for a wide range of clean energy, medical, and other important applications. The Office of Science also supports field observatories around the world that measure atmospheric data that feed into climate models.

But the research infrastructure is only one piece of the puzzle. We need people—talented and trained professionals—to perform this research and help lead us into a green, just future. And we need to increase the participation of marginalized communities, including with STEM education infrastructure and workforce pipelines that will unleash the talents of students of color who have been neglected. This is a topic that is near and dear to my heart, and I am proud that this Committee is working to make our research activities more inclusive at every level through various legislative proposals.

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.

Chairman BOWMAN. With that, I now recognize Mr. Weber for an opening statement.

Mr. WEBER. All right. Thank you, Mr. Chairman. I appreciate that. And thank you for hosting this hearing. And we want to say thank you to our witnesses and our witness panel for taking the time to be with us today.

Passage of the *Energy Act of 2020*, comprehensive bipartisan energy legislation which became law at the end of the last Congress, was a giant leap in the right direction when it comes to updating U.S. energy policy and deploying a diverse portfolio of clean next-generation power sources. But the applied energy activities authorized by the *Energy Act* only represent, quite frankly, about half of the Science Committee's jurisdiction at DOE. The other half is the Department of Energy's Office of Science, a $7 billion, with a "B", program that oversees 10 of DOE's national labs and 28 user facilities.

Armed with the most cutting-edge tools of modern science—like advanced light sources, particle accelerators, and two of the top five fastest supercomputers in the world—the Office of Science has made invaluable contributions to the United States scientific progress. This office has repeatedly demonstrated that basic science research is the most effective way to encourage the development of those kinds of new technologies we're seeking. But as I speak here today, other countries like China are making significant investments in science and threatening our global leadership when it comes to innovation.

That is why the Department's continued investment in basic and early stage research is vital, vital to maintaining our technological edge. And I'm proud to report that we're in the middle of a bipartisan process to reauthorize the Office of Science, which will invest in the facility upgrades and basic infrastructure that attracts and retains the absolutely best scientists in the world.

As part of that reauthorization process, today, we'll focus on two specific programs within the Office of Science: Basic Energy Sciences (BES), Biological and Environmental Research (BER). At the simplest level, BES researchers discover new materials and designs new chemical processes. While this touches virtually every aspect of our energy resources, the ultimate goal of the program is to better understand the physical world and harness nature to benefit people and society as a whole. Pretty powerful stuff. BES's focus includes materials science research that leverages DOE advanced computing resources to aid in the development of novel materials used to make energy production, energy storage, and use cleaner and more efficient.

Just last Friday, I introduced H.R. 2950, the *Computing Advancements for Materials Science*, or *CAMS, Act*, which in part establishes DOE computational materials and chemistry science centers and a materials research data base. I am excited to hear from our panel of witnesses, including Dr. Kristin Persson from Lawrence Berkeley National Lab, on how applying advanced computing capabilities to materials science will accelerate our progress in developing those very exact new clean energy technologies.

The BER program, the other subject of our hearing today, is more focused on the natural world and aims to uncover nature's mysteries involving genomics, plants, ecosystems, and complex Earth science systems—or complex Earth systems rather in an effort to reengineer microbes and plants for energy, as well as other applications. In this capacity, BER also plays a unique and essential role in researching the relationship between the atmosphere, ocean, land, and us humans to improve climate and Earth system models.

I look forward to hearing from all of our witnesses on how they've utilized the many user facilities, the tools, and the collaborative resources that both BER and BES have to offer, and what groundbreaking discoveries are right around the corner as a result. We'll see if Ms. Kristin can pontificate on the future.

I'd like to take a moment to thank my friends across the aisle, Mr. Chairman, for holding this hearing and making bipartisanship a priority when it comes to this kind of legislation. It's a good thing. We appreciate that. It's been a long time coming, but I am beyond excited to think we are shaping the future of science and energy through the focus on the Office of Science.

Thank you again for all the witnesses for being here. I look forward to their testimonies. And with that, Mr. Chairman, I yield you back 2 seconds.

[The prepared statement of Mr. Weber follows:]

Thank you, Chairman Bowman, for hosting this hearing and thank you to our witness panel for taking the time to be with us today.

Passage of the Energy Act of 2020, comprehensive bipartisan energy legislation which became law at the end of last Congress, was a giant leap in the right direction when it comes to updating U.S. energy policy and deploying a diverse portfolio of clean next-generation power sources. But the applied energy activities authorized by the *Energy Act* only represent about half of the Science Committee's jurisdiction at DOE. The other half is the Department of Energy's Office of Science, a seven-billion-dollar program that oversees ten of DOE's national labs and twenty-eight user facilities.

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Thank you again to our witnesses for being here, and I look forward to hearing each of your testimonies. I yield back the balance of my time, Mr. Chairman.

Chairman BOWMAN. Thank you. The Chair now recognizes the Chairwoman of the Full Committee, Ms. Johnson, for an opening statement.

Chairwoman JOHNSON. Thank you very much, Mr. Bowman. Good morning to all. I'm appreciative of your holding this important hearing today and want to thank all of our esteemed witnesses that are here.

Today, we meet to discuss the pioneering research supported by the Department of Energy's Office of Science, and how the national laboratories, major facilities, and cutting-edge programs that it stewards are leading our Nation to a cleaner energy future.

The Office's Basic Energy Sciences program, or BES as we call it, is one of the Nation's largest sponsors of research in the physical sciences, supporting research at nearly 170 universities, laboratories, and other research institutions throughout the U.S. The program also currently oversees 12 national user facilities, two Energy Innovation Hubs, and 41 Energy Frontier Research Centers (EFRCs) tasked with finding solutions for our Nation's greatest energy challenges.

Many significant innovations can be traced to decades of BES research and—such as the LED (light-emitting diode) lighting; efficient solar cells; better batteries; improved production processes for high-value chemicals; and stronger, lighter materials for transportation, nuclear power, and national defense applications. The program is also instrumental in fostering the next generation of scientists, which echoes the importance of our Nation's continuous support of STEM education from K–12 through the doctorate degree level.

Not to be overshadowed, the Biological and Environmental Research program, or BER, seeks to equip our leading researchers and policymakers with the knowledge and tools necessary to better understand and predict the behavior of biological, climate, and other environmental systems. BER supports atmospheric and ecosystem research at all levels, from microscopic to field-scale. This work is carried out by scientists at universities and other research institutions across the Nation and is further enabled by the two state-of-the-art user facilities, the Atmospheric Radiation Measurement facility and the Environmental Molecular Sciences Laboratory.

The research supported by BER is ultimately—provide us with a more holistic and predictive understanding of our climate and environment that accounts for regional and temporal variations and considers the complex impacts they have on human behavior. That, in turn, will enable us to better anticipate shifts in our climate and to design and develop more efficient and resilient energy generation systems and infrastructure.

Today's witnesses should know that it is a priority for this Committee to strengthen and support the scientific capabilities of our national labs and universities, so I look forward to our distinguished panelists sharing their perspectives not only on future research pathways to solve grand challenges, but also how we can expand access to the unique capabilities of these critical facilities and programs. Thank you, Mr. Chairman, and I yield back.

[The prepared statement of Chairwoman Johnson follows:]

Chairman Bowman, thank you for holding this important hearing today, and thank you to our esteemed panel of witnesses for being here.

Today we meet to discuss the pioneering research supported by the Department of Energy's Office of Science, and how the national laboratories, major facilities, and cutting-edge programs that it stewards are leading our nation to a cleaner energy future.

The Office's Basic Energy Sciences program, or BES, is one of the nation's largest sponsors of research in the physical sciences, supporting research at nearly 170 universities, laboratories, and other research institutions throughout the U.S. The program also currently oversees 12 national user facilities, two Energy Innovation Hubs, and 41 Energy Frontier Research Centers tasked with finding solutions for our nation's greatest energy challenges.

Many significant innovations can be traced to decades of BES research, such as LED lighting; efficient solar cells; better batteries; improved production processes for high-value chemicals; and stronger, lighter materials for transportation, nuclear power, and national defense applications. The program is also instrumental in fostering the next generation of scientists, which echoes the importance of our nation's continuous support of STEM education from K-12 through the doctorate degree level.

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The research supported by BER will ultimately provide us with a more holistic and predictive understanding of our climate and environment that accounts for regional and temporal variations and considers the complex impacts they have on human behavior. That, in turn, will enable us to better anticipate shifts in our climate and to design and develop more efficient and resilient energy generation systems and infrastructure.

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Chairman BOWMAN. Thank you, Madam Chairwoman.

The Chair now recognizes the Ranking Member of the Full Committee, Mr. Lucas, for an opening statement.

Mr. LUCAS. Thank you, Chairman Bowman, for hosting this hearing, and thank you to all of our witnesses for being with us today.

The Department of Energy is the largest Federal sponsor of basic research in physical sciences and is a world leader in science and technology innovation. Through its Office of Science and national laboratory system, the Department supports research across scientific disciplines and plays a lead role in U.S. research and development ecosystem.

Today, we have an opportunity to examine the activities of two of the Office of Science programs, the Basic Energy Sciences and the Biological and Environmental Research. These two programs cover a wide variety of high-priority R&D initiatives from advanced materials science in biochemistry to geoscience and climate systems modeling.

The science impact of BES and BER cannot be overstated. BES funds basic research at more than 150 U.S. academic, private-sector, and nonprofit institutions, and its user facilities support approximately 16,000 scientists and engineers each year. Over the past 40 years, BES research has led to major discoveries in solar cells, battery technology, advanced transportation materials, manufacturing processes, nuclear power, and LED lighting.

The other program we're considering today, BER, has helped redefine modern biotechnology through the Human Genome Project and since the 1950's has driven innovation in U.S. cutting-edge U.S. environmental science—systems sciences. Today, BER is accelerating the capacities of complex Earth system models using large-scale data and high-performance computing. This is the kind of fundamental research that will not only enable the development of next-generation technologies but will also support U.S. competitiveness in science and establish our global leadership in the industries of the future.

This is why my bill, the *Securing American Leadership in Science and Technology, SALSTA*, which creates a long-term strategy for investment in U.S. research and infrastructure, includes a comprehensive reauthorization of the DOE Office of Science, roughly doubling the funding for programs like BES and BER over 10 years. *SALSTA* also provides specific funding for key DOE national laboratory user facilities like the light sources and neutron sources that enable BES work. And it establishes a program for the development and construction for BER user facilities.

I'm also proud to join my colleagues on two bills to strengthen the work done by BER and BES. Last week, Randy Weber, the Ranking Member of this Subcommittee, introduced the *Computing Advances for Materials Science Act*, which will create a program at DOE to apply advanced computing practices to materials research sciences challenges. And my colleague Representative Baird of Indiana introduced a bill today to reauthorize Bioenergy Research Centers (BRCs) and create user facilities to help us address complex challenges in environmental science. These bills are important steps forward in improving our Nation's clean energy research.

This hearing comes at a critical time in our conversation on the state of our Federal R&D enterprise. Lately, we've heard a lot of talk about big investments in American innovation, but at this moment we face very real threats to our global scientific leadership. Only serious proposals can be considered. Maintaining U.S. leadership in science and technology will require a shared commitment to prioritize DOE and its Office of Science. And let me be clear, any American R&D investment plan that lacks this commitment is fundamentally flawed.

The Science Committee may not agree on everything, but we've always been united in our support of the Office of Science. This Congress, I look forward to continuing to work with Chairwoman Johnson and my friends across the aisle on bipartisan Office of Science legislation that will make a strong commitment to the success of programs like BER and BES and ensure the long-term stability of our international leadership in science.

I once again want to thank our witnesses for being here today, and I look forward to a productive discussion. Thank you, Chairman Bowman, and I yield back the balance of my time.

[The prepared statement of Mr. Lucas follows:]

Thank you, Chairman Bowman for hosting this hearing, and thank you to all our witnesses for being with us this afternoon.

The Department of Energy is the largest federal sponsor of basic research in the physical sciences and is a world leader in science and technology innovation. Through its Office of Science and National Laboratory system, the Department supports research across scientific disciplines and plays a lead role in the U.S. research and development ecosystem.

Today, we have an opportunity to examine the activities of two Office of Science programs, in Basic Energy Sciences (BES) and in Biological and Environmental Research (BER). These two programs cover a wide range of high priority R&D initiatives: from advanced materials science and biochemistry, to geoscience and climate systems modeling. The scientific impact of B-E-S and B-E-R cannot be overstated.

BES funds basic research at more than 150 U.S. academic, private sector, and nonprofit institutions, and its user facilities support approximately 16,000 scientists and engineers each year. Over the past 40 years, BES research has led to major discoveries in solar cells, battery technologies, advanced transportation materials, manufacturing processes, nuclear power, and LED lighting.

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I once again want to thank our witnesses for being here today. I look forward to a productive discussion. Thank you Chairman Bowman and I yield back the balance of my time.

Chairman BOWMAN. Thank you, Mr. Lucas.

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

At this time, I would like to introduce our witnesses. Dr. Kristin Persson is a Professor in Materials Science and Engineering at UC Berkeley with a joint appointment as Faculty Senior Scientist at the Department of Energy's Lawrence Berkeley National Laboratory where she also serves as Director of the Molecular Foundry. She has published more than 200 papers in peer-reviewed journals, holds several patents in energy applications, and is among the world's 1 percent most-cited researchers.

Dr. Fikile Brushett is an Associate Professor of Chemical Engineering and Cecil and Ida Green Career Development Chair at the

Massachusetts Institute of Technology (MIT). His research group focuses on advancing the science and engineering of electrochemical technologies needed for a sustainable energy economy. Dr. Brushett received his bachelor's in chemical engineering from the University of Pennsylvania, a master's and Ph.D. from the University of Illinois Urbana-Champaign, and was a postdoc at DOE's Argonne National Laboratory.

Dr. Esther Takeuchi is a SUNY (State University of New York) Distinguished Professor and a William and Jane Knapp Chair in Energy and Environment at Stony Brook University. She holds a joint appointment at DOE's Brookhaven National Laboratory as Chief Scientist and Chair of the Interdisciplinary Science Department. She is also a Director of an Energy Frontier Research Center funded by the Department. Dr. Takeuchi is a member of National Academy of Engineering, was awarded the National Medal of Technology and Innovation by President Obama, and was inducted into the National Inventors Hall of Fame.

Dr. Xubin Zeng is an Agnes N. Haury Chair in Environment, Professor of Atmospheric Sciences, and Director of the Climate Dynamics and Hydrometeorology Center at the University of Arizona. Through over 200 peer-reviewed papers, Dr. Zeng's research has focused on land-atmosphere-ocean interface processes, weather and climate modeling, hydrometeorology, remote-sensing, and big data analytics. He also serves on the Science Advisory Board of the DOE Pacific Northwest National Laboratories Earth and Biological Sciences Directorate and the Science Advisory Board Environmental Information Services Working Group of the National Oceanic and Atmospheric Administration (NOAA).

Last but certainly not least, Dr. Narasimha Rao is an Associate Professor of Energy Systems at the Yale School of the Environment. Dr. Rao has two decades of global experience in energy, first as an energy consultant and, for the last decade, as an academic. Dr. Rao's research examines energy systems, climate change, and human development. He is particularly interested in equity and energy transitions and the impacts of climate change and its mitigation on poverty around the world.

Thank you all for joining us today. As our witnesses should know, you will have 5 minutes for your spoken testimony. Your written testimony will be included in the record for the hearing. When you all have completed your spoken testimony, we will begin with questions. Each Member will have 5 minutes to question the panel. We will start with Dr. Persson. Dr. Persson, please begin.

TESTIMONY OF DR. KRISTIN PERSSON, DIRECTOR, MOLECULAR FOUNDRY, LAWRENCE BERKELEY NATIONAL LABORATORY

Dr. PERSSON. Thank you. Chairwoman Johnson, Ranking Member Lucas, Chairman Bowman, Ranking Member Weber, and distinguished Members of the Committee, thank you for inviting me to testify today. My testimony is my own and does not necessarily reflect the views of the U.S. Department of Energy or the University of California.

I'm an immigrant and a naturalized citizen and Basic Energy Science has touched virtually every aspect of my scientific career in the United States. My testimony is based on my leadership roles in three BES programs, the Joint Center for Energy Storage Research (JCESR), the Materials Project, and the Molecular Foundry. I also have a strong connection to industry and the applied sciences, which allows me to observe how Basic Energy Science insights translate into technological solutions.

As you know, BES provides world-leading expertise and instrumentation to advance fundamental knowledge. It also provides training of our next-generation scientists. And from my experience, BES funding provides a foundational path forward for future-looking innovation leadership, democratizing the access to knowledge and workforce development.

For example, on innovation leadership, the materials used today in lithium-ion batteries were first studied in the 1970's and 1980's at places like Bell Lab's national laboratories and universities. Today, the main question that I get from investors and EERE (Office of Energy Efficiency and Renewable Energy) is how do we deal with the mineral resource limitations? Our current lithium-ion batteries can't operate well without some of these metals, for example, cobalt. However, our most promising next-gen materials are quite different than our current ones, and these materials are directly related to strong long-term investment in the understanding of how ions arrange and how they move in battery materials.

To support future innovation, the energy storage hub at Argonne, JCESR, focuses on beyond lithium chemistries, and as one major breakthrough I can mention, JCESR has uncovered the fundamental reason why we don't have high energy density magnesium and calcium batteries like lithium. JCESR has now turned that knowledge into a discovery vehicle for the development of new materials to increase stability, and we currently hold the world record in new liquid formulations.

The Materials Project is a BES-funded Materials Genome Initiative software center, and today, it's the world-leading materials data platform. It provides a stellar example of the impact of Basic Energy Science and democratizing knowledge and accelerated learning. The Materials Project uses high-performance computing to calculate the foundational properties of materials rather than measuring them, which is so much faster and cheaper. For example, measuring even one property by traditional means across tens of thousands of materials, that would take decades and millions of dollars, and we can calculate it in a matter of weeks to months.

This high-value and precompetitive materials data is then made available free of charge to the world. Every day, tens of thousands of users, diverse minds and innovators, access this data to train machine-learning algorithms to develop novel materials that support our future energy solutions. Our audience has been growing exponentially since we started. The Materials Project is now approaching 200,000 registered users.

And finally, the Nanoscale Science Research Centers, the NSRCs, are BES-funded user facilities, one of them being the Molecular Foundry. They are knowledge-based centers for interdisciplinary research at the nanoscale where access to leading expertise is as important as access to state-of-the-art instrumentation and resources. Electron microscopy is one of those resources, and now, hopefully, thanks to the wonderful virtual format of this hearing, I'd like to take you to California.

This is the Molecular Foundry. This is the user facility where we house, for example, the TEAM (Transmission Electron Aberration-corrected Microscope) microscopes. The TEAM microscopes are a product of multi-institution industrial collaborations funded by the BES. They were the best in the world in 2009, and they're still a critical resource today. The picture you're seeing here is an iron-platinum nanoparticle where we can image exactly where each atom sets and correlate that to the knowledge of its magnetism. And this is fundamentally important for new applications in next-generation hard drives.

This is just one of the hundreds of free-of-charge capabilities that the Foundry provides, and each year, the Foundry supports roughly 1,000 users, including academics, students and training, small businesses, and 2/3 of these are early career scientists. It's a shining example of how BES-funded science democratizes both the expert knowledge, as well as high-value instrumentation, which enables a broad spectrum of today's breakthroughs and contributed to the next generation of workforce development.

These are some of the many vital roles that BES science plays in the U.S. energy ecosystem, and without sustained investment, we shortchange or stall technological advances so necessary for our future generations. Thank you for listening, and I look forward to taking any questions.

[The prepared statement of Dr. Persson follows:]

CLIMATE AND ENERGY SCIENCE RESEARCH AT THE DEPARTMENT OF ENERGY

A Hearing of the
Subcommittee on Energy
Committee on Science, Space, and Technology
United States House of Representatives

Tuesday, May 4, 2021

The Testimony of
Kristin Persson, Ph.D.
Lawrence Berkeley National Laboratory
University of California Berkeley

Chairman Bowman, Ranking Member Weber, and distinguished Members of the Committee, thank you for inviting me to testify today and for your interest in materials and chemical sciences research within the Department of Energy (DOE) Office of Science's Basic Energy Sciences (BES) program and its essential role in the development of new technologies and training our nation's scientific workforce. My name is Kristin Persson and I am a Faculty Senior Scientist at Lawrence Berkeley National Laboratory and a Professor at the University of California, Berkeley. My testimony is my own and does not necessarily reflect the views of the U.S. Department of Energy, Berkeley Lab, or the University of California.

It is my pleasure to talk about the Basic Energy Sciences program. BES has been instrumental to my scientific journey and is among the nation's and the world's premier scientific organizations focused on materials and chemical sciences research. BES develops and trains our nation's next generation of scientists by supporting fundamental research at universities across the nation; it supports fundamental science and use-inspired research hubs and science centers at our nation's national laboratories; and it builds and operates some of the world's best and most sophisticated national scientific user facilities, including the Molecular Foundry, where I am the director. The Molecular Foundry is one of five nanoscale science research centers, which are facilities that help envision and realize solutions to today's and future societal challenges by enabling imaging, manipulation and fabrication of materials and chemistry at the molecular and even atomic scale. Scientific user facilities are often large in scale and too expensive for an individual university or company to build and operate, and hence, they offer unique capabilities found nowhere else in the world. Even during a pandemic, over 12,000 researchers or "users" from academia and industry across the nation and the world, and from every U.S. federal research agency, use BES facilities to accomplish their research. Because the operation of these facilities is supported by our federal government, access to them is free of charge for researchers conducting non-proprietary work whose scientific proposals are reviewed well by their peers.

As I will testify below, BES user facilities, unique assets, and expertise are leveraged by hundreds of thousands of researchers from across the country and the world. They empower the nation's inquiry into, and accelerate technology development in, energy storage, quantum information science, transformative new materials and chemicals, artificial photosynthesis, carbon capture at scale, and more.

My personal story sets the stage and illustrates the power of BES and its place in the nation's innovation ecosystem. I immigrated to the US in 2001, and I have raised two daughters here. Today, I am proud to call this country my home as a naturalized citizen. I spent 5 years at MIT before coming to Berkeley Lab, which attracted me with its mission to bring science solutions to the world, specifically with an emphasis on team science and collaborations. This year, Berkeley Lab is celebrating its 90th anniversary and is looking forward to the next 90 with enthusiasm.

Coming to Berkeley Lab, I brought with me a vision of what high-performance computing and quantum mechanical calculations can do for materials innovation, particularly in the energy storage space. I engaged a team of enthusiastic, interdisciplinary researchers to build the first version of a materials data production and online dissemination platform. That vision carried. In 2012, I was awarded one of five DOE-BES Materials Genome Initiative software centers for the platform that my colleagues and I had created - named the ***Materials Project***. Today, the Materials Project is ***the*** world-leading materials data platform. It disseminates millions of computed, pre-competitive materials data records every day to an increasingly data-hungry community of scientists and engineers. This resource is fueling machine-assisted, accelerated learning to the discovery of novel materials with useful properties, and a deep understanding of these materials which will fuel materials design for generations to come.

Since 2012, as the only female principal investigator in the leadership team of the Joint Center for Energy Storage Research (JCESR), a BES Energy Innovation hub led by Argonne National Laboratory, I have implemented a vision of data-driven design for battery materials innovation. In 2020, I became the Director of the Molecular Foundry at Berkeley Lab, one of five DOE BES nanoscale research centers and one of five Berkeley Lab user facilities. And, through my appointment at UC Berkeley, I engage with and teach the next generation of engineers and scientists.

While nearly every aspect of my career has been supported by BES, its facilities, expertise and other research assets have enabled me and many of my colleagues to connect directly to applied sciences helping to advance technology toward applications in society. As an expert in computations, data-driven methodologies, energy storage and materials science, I am regularly called upon to inform industry on the future of battery materials and resources. I have had ARPA-E contracts, and I currently have a broad research portfolio that includes company-sponsored and DOE-EERE sponsored research. In recognition of my contributions, in 2021 DOE-EERE honored me as one of the 23 women who are making significant contributions in energy storage across the national laboratories.

The rest of my testimony will bear witness to the importance of long-term investment in basic energy science research, as a foundation and platform for:

i) Future-looking innovation leadership;
ii) Democratizing the access to knowledge; and
iii) Workforce development.

The Knowledge behind Energy Storage Today and Tomorrow

Today's energy storage technology is built on more than half a century of previous investments in basic energy sciences, which uncovered the details of how ions arrange and move in solid materials. Rechargeable battery materials, where the ions move in and out of the material without greatly changing its structure forms the basis of today's lithium ion (Li-ion) industry.

The materials used today in Li-ion batteries were first studied in the 1970s and 80s at Bell labs, national laboratories, and US universities. As an example, fundamental research to modify the properties of graphite more 50 years ago laid the basis for its uses as a universal anode for Li-ion batteries. Alloying of lithium with main group metals, such as silicon, tin, and aluminum, was investigated in the early 80s as anodes, and today silicon is the focus of major EERE programs as the next-generation anode.

Strong BES programs in materials science, combined with support for investigating the fundamental arrangement of Li ions and their transport mechanisms in solid materials more than 25 years ago, created the insights into fast charging batteries and today's most promising avenues to mitigate nickel and cobalt resource limitations: e.g. novel cation-disordered rocksalt cathodes, recently supported by EERE as an encouraging new direction. The time between fundamental research results and commercial solutions is long – often decades – but the connection is undeniable. Basic energy science research, through the Foundry, the Materials Project, the JCESR Energy Storage Hub, and sister facilities and programs, is driving down the time from discovery to useful technology.

While Li-ion technology has revolutionized our world, it may not be the endgame. To support broad implementation of sustainable energy solutions and retain international competitiveness, JCESR focuses on beyond Li-ion chemistries. Just as decades ago, fundamental research enabled the development of Li-ion batteries, there are today rich and ripe opportunities for building the knowledge at the atomic and molecular scale needed to design the next generation of electrochemical, chemical, and thermal energy storage. For example, high energy density metal-air (zinc, lithium, sodium), multivalent (magnesium^{++}, calcium^{++}, zinc^{++}) and conversion cathode (Li-sulfur) batteries can serve heavy duty and long-haul transportation.

JCESR focuses on these future technologies and uncovers the fundamental bottlenecks in their current state: whether they be limited electrolyte stability or transport limitations in the solid state. The resulting design rules – why certain materials and chemistries work better than others – inform future technological solutions. JCESR leverages BES-funded user facilities such as the Advanced Photon Source (APS) at Argonne, the Advanced Light Source (ALS) at Berkeley Lab, the Molecular Foundry and the Stanford National Accelerator Center (SLAC) to synthesize novel membranes for selective ion transport, and to understand the chemistry of how liquid electrolyte components form clusters which impacts stability and transport. Our ability to 'see' and understand these processes at the molecular and atomic level enables us to devise improvements. One particular limitation comes from the electrochemical stability window of the electrolyte, which impedes the development of high-voltage calcium or magnesium-ion batteries. Because of the sustained and forward-looking investments in JCESR and in other similar basic science programs, ***JCESR has uncovered the fundamental reason why so few calcium and magnesium electrolytes work well, and has now turned that knowledge into a discovery vehicle for the development of new electrolytes with increased stability. We now hold the world record in magnesium and calcium electrolyte formulations.***

The history of fundamental science investments and its connections to today's battery science illustrates the long-term impact of BES science and how it sets the foundation for future technologies.

The Materials Project; Democratizing Pre-competitive Materials Data and Machine Learning

The Materials Project aims to accelerate innovation by removing the guesswork from materials design. Its mission is to compute properties of all known inorganic materials, and beyond, and use structure-chemistry correlations to inspire and design novel materials for applications such as better batteries, affordable carbon capture at scale, and advanced medical diagnostics. Leveraging Office of Science computing and networking resources at the National Energy Research Scientific Computing Center and the Energy Sciences Network, both at Berkeley Lab, we deliver this data to the broad, global community of scientists and engineers using modern web-delivery methods, similar to those used by Google and Amazon. Imagine that Google was more than a sophisticated search engine, collecting, organizing and delivering third-party data. Imagine that it also physically measured, for example, all the traffic, commercial, social, and weather data it showed. That would be the Materials Project; we produce all of our data, organize it, disseminate it, and showcase the design of novel materials for energy applications.

This free access to an enormous and constantly expanding amount of materials data is a new and unprecedented resource. To give an example, the measured elastic tensor, a critically important property for any technology that involves materials, describes how a material deforms under external strain and stress. Any structural design, from bridges to durable solar cells, requires such information. Despite its importance, the complete elastic tensor can be found for only a few hundred materials in the open literature. Using computations and supercomputers, the Materials Project has calculated over 14,000 elastic tensors, which would have taken decades and millions of dollars by traditional synthesis and measurement techniques. The elastic data alone have enabled our own scientists as well as community scientists to use machine-learning algorithms to correlate crystal structure and chemistry to extraordinary elastic behavior, resulting in novel waste-heat capturing materials, super-strong materials, and sound-absorbing materials that could be used in better transportation, building, and energy-saving technologies. The elastic tensor data set shows the impact of allowing free access to the data from ***one*** materials property across structure and chemistry. The Materials Project allows access to millions of such property data points, from materials stability to battery and capacitor metrics such as voltage, energy density and ionic mobility. As a result, novel materials are being realized, aided and accelerated by this novel resource, and every day, one paper is published mentioning the Materials Project and machine learning.

By all metrics, the Materials Project has been a tremendous success. Our audience has been growing exponentially since 2012, and is now approaching 200,000 registered users. Even more importantly, up to 45 million data records are requested and delivered daily, and tens of thousands of community researchers login to the site every day. Allowing free access to high-value, pre-competitive materials data enables diverse minds and innovators across the world to train machine learning algorithms and develop novel materials for sustainable energy production and storage, for climate change mitigation, for waste heat recovery, for energy-smart building materials and more.

The Materials Project represents an example of how BES science democratizes knowledge, data and accelerates learning across communities, without borders.

The Molecular Foundry; a knowledge-based user facility

I am also tremendously proud to represent the Molecular Foundry, home to one-of-a-kind instruments and world-class experts that span the broad field of nanoscale science. As mentioned earlier, the Foundry is one of five BES Nanoscale Science Research Centers. In the simplest terms, nanoscale science is the study of the very small. Because it involves interacting with the world atom by atom, it encompasses every field of science and its impacts are found in every corner of modern-day life. Unlike other facilities centered around billion-dollar machines, the NSRCs are knowledge-based centers for interdisciplinary research at the nanoscale, where access to leading expertise is as important as access to state-of-the-art instrumentation.

Being a user facility, the broad collection of elite capabilities at the Foundry and other NSRCs enable user-driven science that has and will continue to change the world. Our users are visiting researchers who apply to the Foundry through our peer-reviewed proposal process. They come to us from across the country and around the globe, to use our tools and collaborate with our staff. We partner with these users to enable and amplify the impact of their research. Imagine a highly creative early career professor at a remote teaching college or a startup company developing a high-tech device. In both these cases, their great ideas may be hampered by insufficient access to cutting edge scientific tools and world-class experts. At the Molecular Foundry we provide these critical resources, free of charge, to ensure that every good idea has a chance to be explored to the benefit of these researchers, the broader scientific community, and the nation.

Each year, the Foundry supports roughly 1,000 users. They include academics and national laboratory scientists, but also a significant number of industry researchers, most of whom are at small businesses, who use our research infrastructure to de-risk their ideas and build a stronger scientific foundation for their companies. On average, after just a year with us, these industrial users each report that their work at the Foundry results in 1.2 pieces of IP, 3.3 jobs created, and nearly $2M raised.

To illustrate the broad and long-lasting reach of our user model, I will describe some discoveries involving electron microscopy, which is just one of the many areas of expertise found at the Molecular Foundry. In the field of electron microscopy, the

Molecular Foundry's elite tools and expertise provide world-leading capabilities to the scientific community and the nation. The Foundry's TEAM microscopes are two of the most powerful electron microscopes in the world and their development ushered in a new era of science by allowing researchers to study the world atom by atom. The TEAM 0.5 microscope is the product of a multi-institution, industrial collaboration funded by BES. It was the first microscope capable of imaging individual atoms with the resolution of half an Ångstrom, which is the size of the radius of a single hydrogen atom. It was the best microscope in the world when it was completed in 2009, and today, over a decade later, it remains a critical resource for the scientific community. Through the Molecular Foundry's user program, researchers benefit from access to the actual microscope as well as the scientists who are experts at operating it. The unprecedented detailed information of materials has helped unlock fundamental understanding that is critical for future advancement in a range of areas, everything from quantum technologies to learning about the origins of the universe. In the following, I will provide a few examples illustrating the broad and diverse scientific impact of electron microscopy at the Foundry.

Recently, researchers funded by the Toyota Research Institute came to Berkeley Lab with the goal of scanning an entire working battery at the atomic scale. They sought to use the TEAM 0.5 microscope and the 4DCamera, a recently invented camera for electron microscopes that can take pictures at nearly 100,000 frames per second. Using a technique called 4D-STEM, they were able to get atomic scale clarity of the arrangement of atoms inside a battery before, during, and after battery cycling. After the researchers obtained their structural information from the Foundry, they literally walked their samples over to the Advanced Light Source, another BES-supported user facility at Berkeley Lab, and used the X-ray beamlines there to image the distribution of lithium inside them. The synergy of expertise at these two co-located BES user facilities afforded the researchers a complete picture of how the structure of the battery material responds to the movement of lithium ions, which in turn tells us the long-term degradation of these materials, and therefore the battery performance.

A different group of users funded by the U.S. Office of Naval Research accessed a suite of advanced electron microscopes at the Foundry, to understand the role of impurities in titanium for transportation and infrastructure applications. Titanium has the highest strength to weight ratio of any element, but one of the limiting factors for its more widespread use in aerospace, naval and other structural applications is its sensitivity to impurity elements, especially oxygen. Minute amounts of oxygen as low as 0.1 atomic percent can have a profound impact on titanium's structural properties, and minimizing oxygen during processing of titanium is the main driver of its relatively high cost. Using the Molecular Foundry's expertise and advanced imaging techniques, the researchers identified the origins of the profound oxygen poisoning effect, which has also led to identification of mitigation approaches including processing and the addition small amounts of other elements, such as aluminum. Over the years, this project has involved the training and education of multiple generations of graduate students and postdoctoral researchers from different parts of the country, many of whom have now moved on to industry and academia.

These two examples show what world-unique microscopes can do in two dimensions, but we can also image and map atoms in 3D using a special holder that can rotate the sample 180 degrees left and right. It works like a medical CAT scan, taking pictures of a material from multiple angles, that can be stitched together into a 3D image. In 2017, a research team that included UCLA, Oak Ridge National Laboratory, and the United Kingdom's University of Birmingham used the TEAM microscope to image every single atom in an iron-platinum nanoparticle, a material that is magnetic. The ability to create a 3D image of the particle allowed the researchers to explore the different atomic arrangements and thus, different amounts of magnetism. Applications like next-generation hard disk drives for data storage need materials that are highly magnetic. What the TEAM microscope showed was that this material is only 60% magnetic, which is insufficient for this application, but you would not know about the problem without looking at the material atom-by-atom. Now that we can image where all the atoms are and can correlate that to how the material performs, we can work with our chemists to optimize the chemical composition to maximize the ideal atomic arrangement for maximum performance.

The Molecular Foundry exemplifies how BES-funded science democratizes both expert knowledge and high-value instrumentation enabling a broad spectrum of today's breakthroughs and contributing to the next-generation workforce development.

I hope these examples illustrate the many vital roles that BES science plays in the US innovation ecosystem. Without sustained investment in basic materials and chemical sciences, I believe we shortchange and stall technological advances so necessary for our future generations. In my career, I have witnessed the translation of basic research into the applied sciences and further onto viable technologies. BES science creates a fertile platform for exploratory, pre-competitive scientific knowledge, which can be shared and discussed across diverse interest spheres, people and outlooks. The BES-funded user facilities welcome anyone with a great idea to come and work together to solve our current challenges in global warming, sustainable energy production and storage, fresh-water and energy equity. Passionate students, small-businesses, Fortune 500 companies, and academics from every part of the US and beyond, join us, share their knowledge, learn and become part of the global scientific and engineering community striving to improve our world.

Thank you for inviting me to testify. I look forward to answering any questions that you may have.

Kristin Persson obtained her Ph.D. in Theoretical Physics at the Royal Institute of Technology in Stockholm, Sweden in 2001. She is currently a Professor in Materials Science and Engineering at UC Berkeley with a joint appointment as Faculty Senior Scientist at the Lawrence Berkeley National Laboratory where she also serves Director of the Molecular Foundry. Her expertise is materials informatics, specifically pursuing novel and optimized materials for clean energy applications. She has published more than 200 papers in peer-reviewed journals, holds several patents in energy applications, and is among the world's 1% most cited researchers. She is most known for her stewardship of the Materials Project (www.materialsproject.org); one of the most visible of the Materials Genome initiative (MGI) funded programs attracting >180,000 users worldwide with more than 10,000 unique users accessing the site every day. She is a leader in the MGI community, and she serves as an Associate Editor for Chemistry of Materials, on advisory boards of a number of organizations such as NanoHub, FAIRMat, Q4Climate, and various journal editorial boards. She has received the 2018 DOE Secretary of Energy's Achievement Award, the 2017 TMS Faculty Early Career Award, the 2020 Falling Walls Science and Innovation Management Award, the LBNL Director's award for Exceptional Scientific Achievement (2013) and she is a 2018 Kavli Fellow.

Chairman BOWMAN. Thank you, Dr. Persson. Dr. Brushett, you are now recognized.

TESTIMONY OF DR. FIKILE BRUSHETT,
ASSOCIATE PROFESSOR OF CHEMICAL ENGINEERING,
MASSACHUSETTS INSTITUTE OF TECHNOLOGY

Dr. BRUSHETT. Thank you. Chairman Bowman, Chairwoman Johnson, Ranking Member Weber, Ranking Member Lucas, distinguished Members of the Subcommittee, I'm honored to testify before you here today at this hearing. My name is Fikile Brushett, and I'm an Associate Professor of Chemical Engineering at the Massachusetts Institute of Technology. I'm also a contributor to the Joint Center for Energy Storage Research, JCESR, an Energy Innovation Hub sponsored by the Department of Energy's Basic Energy Sciences program.

My research program at MIT focuses on advancing the science and engineering of electrochemical technologies needed for a sustainable energy economy. My principal research interest has been the development of redox flow batteries, which have the potential to enable such a transition by facilitating the integration of intermittent resources like wind and solar into the electric grid, as well as by optimizing existing grid infrastructure. While state-of-the-art redox flow batteries have achieved niche successes, present embodiments are too expensive for ubiquitous adoption. We are vigorously pursuing opportunities for transformative advancements that will change these economics. My group, along with others, are searching for inexpensive electrolyte formulations, developing high-performance electrochemical reactors, and working to establish manufacturing capabilities for battery systems and the materials and components they are made of.

We work on these important problems with other academics, with national laboratories, and with industry. JCESR has truly served as a hub for these collaborations, without which I would have sought other, safer directions, and my group's progress in flow batteries would have been slower and ultimately our work less impactful.

So let me tell you how BES has supported the career development path I've taken. When I finished my graduate thesis at the University of Illinois at Urbana-Champaign, I knew I wanted to apply my training to problems in energy storage. An appointment at the—as a Director's Postdoctoral Fellow at Argonne National Laboratory provided a rapid entrance into my newly chosen field. There, dozens of research professionals with diverse scientific backgrounds were working in the battery group addressing an interconnected set of problems for modeling the chemistry inside an electrochemical cell at the atomistic level to building and breaking large battery packs. I was immersed in battery science and engineering and learned much from this vibrant research community surrounding me.

I also had easy access to experts at Argonne's cutting-edge facilities. I could grab coffee with a beamline scientist at the Advanced Photon Source (APS) or have lunch with a synthetic chemist from the Center for Nanoscale Materials. I learned new science, expanded my research skills, and was inspired to explore new research directions.

Beyond research, I was also able to develop other important skills essential for running a successful group, things like project management, scientific leadership, and best practices in environment, health, and safety. My postdoc at Argonne also provided an opportunity to participate in writing what would become the winning proposal for an Energy Innovation Hub focused on energy storage, JCESR. Thus, when JCESR ramped up at the same time I started at MIT, I was able to secure research funding for my group, pursue ideas that I had helped to develop, and gain immediate visibility both at MIT and within the energy research community.

My own experience at Argonne, first as a postdoc and now as a JCESR researcher and team leader, opened my eyes to educational and scientific opportunities that DOE offers young scientists and engineers through the national laboratories, opportunities I now often suggest to undergraduate students, graduate students, and postdoctoral associates I mentor at MIT.

In conclusion, while I have undoubtedly benefited from the rich research environment at MIT in terms of student education, faculty mentoring, fundraising, and fruitful collaborations, my engagement with JCESR has added another dimension, accelerating my career growth as a scientist, as a teacher and mentor, and as a leader.

Thank you for the invitation to testify before this Senate—this Subcommittee. I would be happy to answer any questions you or other Members of the Committee may have. Thank you.

[The prepared statement of Dr. Brushett follows:]

Written Statement of

Fikile Brushett
Associate Professor of Chemical Engineering
Massachusetts Institute of Technology

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

Hearing on:
Climate and Energy Science Research at the Department of Energy

May 4, 2021

Introduction

Chairman Bowman, Ranking Member Weber, and Members of the Subcommittee, thank you for the opportunity to participate in today's discussion on *Climate and Energy Science Research at the Department of Energy*.

My name is Fikile Brushett and I am an Associate Professor of Chemical Engineering at the Massachusetts Institute of Technology (MIT) where I hold the Cecil and Ida Green Career Development Chair. I am also a contributor to the Joint Center for Energy Storage Research (JCESR), an Energy Innovation Hub sponsored by the Department of Energy (DOE), Office of Basic Energy Science (BES) in the Office of Science. In JCESR, I currently serve as the Research Integration co-Lead and as a member of the Executive Committee.

My comments to the Committee will focus on my career development and the important role that science, technology, engineering, and mathematics (STEM) education and research opportunities, enabled by BES support of universities and national laboratories, have played in my growth as a scientist, mentor, and leader.

The Brushett Research Group

To provide some context to my testimony, let me briefly describe my educational background and current research activities.

I received my undergraduate degree in Chemical and Biomolecular Engineering from the University of Pennsylvania in 2006 and my graduate degree in Chemical Engineering from the University of Illinois at Urbana-Champaign (Illinois) in 2010. My doctoral thesis, under the supervision of Professor Paul J.A. Kenis, focused on microfluidic fuel cells as portable power sources and diagnostic platforms for analyzing the performance of catalysts and electrodes. From 2010-2012, I was a Director's Postdoctoral Fellow at Argonne National Laboratory (Argonne) in the Electrochemical Energy Storage Group working under the supervision of Dr. John T. Vaughey. I began my independent career in the Department of Chemical Engineering at MIT in 2012, rising from an assistant professor (2012 – 2018) to an associate professor without tenure (2018-2020), to now an associate professor with tenure (2020 – present).

The objective of my research program is to advance the science and engineering of electrochemical technologies, such as advanced batteries, needed for a sustainable energy economy. My group seeks to understand and control the fundamental processes that govern the performance, cost, and lifetime of present day and next-generation electrochemical systems for energy storage and conversion. Our approach combines synthesis and characterization of redox active materials, design and engineering of electrochemical reactors, and techno-economic modeling of electrochemical systems. We place a strong emphasis on connecting system-level performance and cost goals to materials-level property requirements and on leveraging this knowledge to guide exploration of new chemistries and reactor designs. Ultimately, we aim to develop robust and portable guiding principles for the design of materials, processes, and devices that harness electrochemical phenomena. Pursuant to this goal, I have established and continue to grow a diverse and innovative research portfolio. The students and postdoctoral associates in my group, together with JCESR colleagues and other collaborators, are tackling important challenges in grid energy storage and environmental stewardship. We are also expanding our work to include the role of electrochemical processes in manufacturing to reduce energy use and to enable transformations infeasible via traditional methods. My teaching and service contributions focus on educating and empowering engineers to conceive, develop, and implement electrochemical solutions to critical global energy and sustainability challenges.

During my pre-tenure career, the bulk of my research activities focused on the development of redox flow batteries (RFBs) for stationary energy storage. In brief, electrochemical energy storage has the potential to play an important role in enabling a sustainable, resilient, and cost-effective electric power system by facilitating the integration of intermittent renewable resources (e.g., wind, solar) as well as by extending the lifetime and improving the efficiency of existing grid infrastructure. Redox flow batteries are rechargeable batteries where the charge-storing materials (redox species) are dissolved in liquid electrolytes which are stored in external tanks and pumped to a power-converting reactor where they are oxidized and reduced to alternately charge and discharge the battery. As compared to other rechargeable batteries (e.g., lithium(Li)-ion batteries), RFBs have several key advantages that are particularly relevant for grid energy storage including independent power (reactor size) and energy (tank size) specification, long operational lifetimes and easy maintenance, simplified manufacturing, and improved safety characteristics. While state-of-the-art RFB technologies have achieved success in niche applications, present embodiments are too expensive for ubiquitous adoption. In general, these limitations arise from a combination of high materials costs and low cell voltages, due to the small electrochemical stability window of aqueous electrolytes. Opportunities exist for transformative advancement through the discovery of inexpensive redox couples and associated electrolyte formulations, the development of high-performance electrochemical reactors, and the establishment of manufacturing capabilities for charge-storing materials and battery systems. To date, my research activities have focused on the former two.

Without my postdoctoral experience at Argonne National Laboratory, my collaborations with other academics, national laboratories, and industry enabled by DOE BES funding, my progress in this area would have been significantly slower and I would have sought other “safer” but less impactful research directions closer to my graduate training.

Postdoctoral Research at Argonne National Laboratory

As I neared the completion of my Ph.D. at Illinois, I realized that I wanted to learn more about energy storage, in particular rechargeable batteries. In searching for a postdoctoral position that would allow me to do that, I considered working under the supervision of a leading battery scientist at a top-tier academic institution, but ultimately decided to pursue an opportunity in the Electrochemical Energy Storage group in the Chemical and Engineering Sciences Division at Argonne. There were several professional and personal reasons for this decision. I will limit my comments to the former.

From the professional development perspective, Argonne offered a rapid and broad introduction to the battery field. At an academic institution, there are typically 1-2 faculty studying energy storage, each typically pursuing fundamental research on a narrow aspect of a particular battery system. Thus, while I would have had an opportunity to learn from a leading expert, the breadth of knowledge to be gained was limited. In contrast, the battery research group at Argonne was composed of dozens of professional researchers of diverse scientific backgrounds pursuing a wide variety of interconnected problems in battery systems, ranging from modeling atomistic phenomena to "building-and-breaking" battery packs. This breadth of research activities within a single group provided an opportunity for a neophyte like me to immerse in battery science and engineering. Furthermore, Argonne offered access to cutting-edge science tools and facilities (e.g., Advanced Photon Source, Center for Nanoscale Materials) which could not be housed at research universities. As a postdoctoral associate I had easy, informal access to experts within the laboratory (e.g., grabbing a coffee with a beamline scientist). These engagements both strengthened my existing research activities and inspired exciting new scientific directions. Finally, working within a professional research environment gave me an opportunity to develop important non-research-related skills that have served me well in my faculty career including project management, environment, health & safety management, and laboratory hazard assessment.

My postdoctoral appointment was supported by a Director's Postdoctoral Fellowship from the Division of Education (now, Educational Programs and Outreach) at Argonne. This funding allowed me to do exploratory research that diverged from the group's primary focus on lithium (Li)-ion batteries. It was through this opportunity that I starting studying RFBs, trying to translate knowledge gained from and materials developed for Li-ion batteries to high-voltage, high-efficiency flow batteries. This became the foundation of my research as an independent faculty member at MIT, and led directly to my engagement with BES funded programs through JCESR. In addition, my knowledge of the educational and scientific opportunities DOE offers within Argonne and other national laboratories has informed my mentoring of undergraduate, graduate, and postdoctoral associates at MIT. This includes recommending that undergraduate students apply to the science undergraduate laboratory internship (SULI) program and other lab-specific opportunities as well as advising graduate students of the benefits of career trajectories that pass through the national laboratories.

Career development enabled by BES-funded programs

Toward the end of my postdoctoral appointment at Argonne, BES announced the competition for an innovation hub focusing on energy storage. I had the opportunity to participate in the writing process for what became the winning proposal, JCESR. Specifically, I was a key writer for the nonaqueous redox flow thrust, one of three discovery science thrusts in the proposal. I developed the scientific narrative for that thrust and coordinated with other writers, typically tenured faculty at academic institutions. When JCESR ramped up around the same time I started at MIT, I was able to secure research funding for my group, pursue research activities that I had helped to develop, and gain immediate visibility both at MIT and within the energy research community.

While I have undoubtedly benefitted from the MIT community in terms of student education, faculty mentoring, research funding and fruitful collaborations, among many other things, my engagement with JCESR has accelerated my career development. JCESR has been my primary source of DOE BES-funding to date and, hence it is the focus of my testimony. Below I will try to emphasize the unique benefits for a junior faculty member of working in a hub, and how this funding modality has influenced my own research directions and those of the broader community. For interested Committee members, I have provided a more extensive overview of JCESR at the end of this document as an appendix.

Scientific Development:

The collaborative environment established by the hub allowed me to rapidly expand my breadth of expertise in energy storage, to develop differentiating skills through engagement with experts in academia, national labs, and industry, and, ultimately, to pursue research activities I could not have achieved as an individual PI in an academic environment. Further, JCESR provides access to frontier tools and facilities within the member national laboratories (e.g., Argonne, Lawrence Berkeley, Pacific Northwest, and Sandia) including advanced light sources, leadership computing, nanoscience centers, and other state-of-the-art facilities. Engagement with these cutting-edge resources not only accelerates research progress but also promotes education and development for academics along with their graduate students and postdoctoral associates. Below, I provide two examples of this drawing from my own experiences.

As a first example, my postdoctoral work in RFBs was focused on the discovery of new redox species and associated electrolytes. At the time, our approach was to page through the chemical catalogs to identify small molecules with aromaticity and heteroatoms, purchase what seemed promising and evaluate the compound in a set electrolyte. At the onset of JCESR, organic chemists and electrochemists, who did not necessarily have a background in RFB science but possessed deep knowledge of molecular design and functionalization, joined the efforts. They allowed us to rapidly expand the materials design space by leveraging years of prior knowledge and chemical intuition obtained in different fields. However, we soon found that experimental screening for redox materials was limited by throughput. We could not mine the vast chemical design space without advanced computing tools, which could screen thousands of materials and make connections between seemingly-disparate molecular structures that would be challenging to realize through intuition, experience, or experiment alone. To this end, the Electrolyte Genome Project at Lawrence Berkeley National Laboratory, which was developed to search for better liquid electrolytes for battery systems, allows us to streamline the discovery / screening process by evaluating thousands of materials by simulation on the computer and choosing only the most promising few to synthesize and test in the laboratory. Today, such advances have enabled the identification, synthesis, and testing of several valuable molecular families for charge storage in RFBs. Emerging machine learning and artificial intelligence tools have the potential to further refine computational materials discovery.

As a second shorter example, prior to JCESR, I had no knowledge in techno-economic modeling of electrochemical systems, and while I recognized the importance of those activities, the topic was distinct enough from my academic training that I would have hesitated to pursue it as a pre-tenure faculty member. Through JCESR, I was able to collaborate with and learn from leading experts at Argonne National Laboratory and United Technologies Research Center, and later to apply my new-found capabilities to a range of problems in my own research. Indeed, the uniqueness of my expertise in techno-economic modeling of electrochemical systems was a foundational piece of my successful tenure case at MIT.

Student Mentorship:

For a junior faculty member, successfully recruiting and mentoring students can be challenging. New faculty are almost always inexperienced in research and personnel management. Their scientific direction and funding are uncertain. JCESR provided my students with a community, a professional network of graduate students, postdoctoral researchers, scientists, and faculty from diverse institutions working on battery-related energy science. Instead of having a single mentor (myself), my students benefitted from multiple supportive voices and, at times, I was able to lean on the expertise or experience of others. This environment allowed my students to address research problems which would have been unsolvable in my own laboratory, by leveraging expertise and capabilities of JCESR colleagues and by making use of frontier facilities and tools at partner institutions. For example, I have had students leverage the Electrochemical Discovery Laboratory at Argonne (which houses specialized equipment featuring simultaneously chemical and electrochemical measurements) to analyze complex and transient electrolyte transformations that we cannot interrogate either in my own laboratory or through standard equipment in shared facilities at MIT. Finally, the multi-year JCESR funding provided support and stability for student growth and development as well as the pursuit of more complex high risk-high payoff research problems which require time to unravel.

Leadership development:

Beyond advancing technical skills, the hub environment offered opportunities to learn scientific leadership and project management under the mentorship of senior personnel. Since the outset of JCESR, I have held various leadership roles, with increasing responsibility, including "Solutions Group" leader within the Nonaqueous Redox Flow thrust (01/13 – 11/14), Cell Design & Prototyping Principal Investigator (03/14 – 06/15), and Grid Arc Lead Technologist (06/15 – 06/18). Since the renewal (06/18-present), I have served as the Research Integration co-Lead and a member of the Executive Committee. The knowledge gained and lessons learned from these experiences have extended to my service and leadership at MIT.

Thank you for the invitation to testify to the Subcommittee on Energy. I would be happy to answer any questions you or other members of the Committee may have.

Appendix: An Overview of the Joint Center for Energy Storage Research

JCESR is led by Argonne National Laboratory, whose mission is to accelerate science and technology that drives U.S. prosperity and security. At its core, JCESR is comprised of 19 leading battery research and development institutions, including national laboratories, universities, and industry. These institutions have been working collaboratively to create the battery science and technology needed to enable deep decarbonization of the electricity grid, automotive transportation, and aviation. Such a breadth and diversity of talent cannot be found in any single institution. The battery challenge requires a major effort, combining the frontiers of electrochemistry, high-performance computing, atomic-level materials characterization, and advanced discovery and synthesis of new materials. Each of these frontiers has its own group of specialized techniques and leading researchers. Bringing them all together in a single collaborative organization is the only way to make the rapid progress needed in battery technology to avoid the worst consequences of climate change.

From the outset, JCESR determined to work in the "beyond-lithium (Li)-ion" space, meaning we focus on inventing and enabling technologies that can surpass the limits inherent to today's Li-ion batteries. This approach is important because, although revolutionary, Li-ion batteries alone cannot meet all of the required applications of energy storage, such as powering heavy trucks and long-duration storage of renewable energy for grid firming. It is also important because Li-ion battery production is firmly established overseas, and teams like JCESR foster the ingenuity required for America to capture the next generation of battery manufacturing leading to new jobs, economic growth and energy security.

JCESR First Five Years

In its first five years, JCESR's vision was to transform transportation and the electricity grid with high performance, low cost energy storage. The mission was to deliver electrical energy storage with 5× the energy density and $1/5^{th}$ the cost of 2012 commercial batteries within 5 years. The three legacies were (1) to establish a fundamental science library of the materials and phenomena of energy storage at atomic and molecular levels; (2) to deliver two prototypes, one for transportation and one for the electricity grid, that, when scaled up to manufacturing, have the potential to meet JCESR's transformative goals; and (3) to demonstrate a new paradigm for battery research and development that integrates discovery science, battery design, and research prototyping and manufacturing collaboration in a single highly interactive organization [1].

JCESR introduced comprehensive techno-economic models which quantify and compare the performance and economic potential of the diverse set of established and conceptual grid and automotive battery systems. This modeling framework was used across JCESR in three ways: (1) to "back-translate" from system-level performance and price goals to materials and component-level targets, (2) to "forward evaluate" the challenges, costs, and ultimate performance of different technology approaches, and (3) to chart progress and allocate limited resources most effectively. Further, JCESR advanced computer simulation of battery materials to a new level permitting comprehensive atomic- and molecular-level prediction of capacity, voltage, and mobility of ions in solid electrode and liquid organic electrolytes. For example, JCESR simulated 1800 combinations of working ions and cathodes for a magnesium battery, finding five promising candidates which were synthesized and proven to work in the laboratory. Exploring this many combinations of materials could never have been achieved in the laboratory alone without computer simulation, even with an army of graduate students solely dedicated to the task. JCESR's high-throughput computer simulation dramatically accelerated the pace of materials discovery.

Highlights of JCESR's many other significant advances include:

- invention of inexpensive nanoscale polymer membranes that selectively transmit or block organic molecules on the basis of size,
- introduction of the Electrolyte Genome, a comprehensive database of predicted properties of liquid organic molecules for next-generation batteries,
- development of the concept of redox active polymers or "redoxmers" for a new kind of high-performance, low-cost flow battery,
- discovery of high mobility pathways for doubly charged ions, such as magnesium in crystalline electrodes and electrolytes, and
- pursuit of a promising new direction for lithium-air batteries with high energy density and low cost.

At the end of five years, JCESR delivered four prototypes, two for transportation and two for the grid. For the former, we demonstrated innovative batteries based on magnesium, zinc, and calcium, each of which carries two charges instead of the single charge on lithium, doubling the energy stored or released per ion on each charge or discharge cycle. We also developed the concept of sparingly solvating lithium-sulfur batteries to raise their energy density while prolonging their cycle life. For the latter, JCESR's new concept of redox-active polymers or "redoxmers" promises flow batteries with low cost, high capacity, and self-healing properties to extend their life. JCESR's invention of inexpensive aqueous air-breathing sulfur batteries for long duration storage fills a long-standing and challenging gap in grid storage technologies.

JCESR spun out three startups in its first five years. Blue Current is pursuing solid state electrolytes. Sepion Technologies is commercializing inexpensive size-selective polymer membranes. Form Energy is commercializing JCESR's long-duration inexpensive flow battery based on sulfur, water, and oxygen. Working together, JCESR and Form Energy took the idea of an aqueous, air-breathing sulfur battery for long duration storage from initial concept to commercialization in less than five years.

At the end of its first five years, JCESR won the Secretary of Energy Achievement Award for its development of new strategic and operational concepts for large collaborative projects, such as Energy Innovation Hubs. This confirmation of our success inspired us to push our research boundaries even more aggressively going forward.

JCESR Renewal

In September 2018, the Office of Basic Energy Science in DOE renewed JCESR for a second five-year term. In the renewal, JCESR shifted its focus from particular battery systems to transformational battery materials, chemistries and architectures. Towards the end of the first term, we realized that even if all four of our prototypes were commercialized, this would not come close to satisfying the urgent need for a diversity of new batteries to match a diversity of emerging applications in the electricity grid, automotive transportation, and electric flight. Moreover, while techno-economic modeling provides insight to what materials property sets are desirable, the discovery, synthesis and validation of these materials is typically the roadblock in creating new battery technologies. To address these challenges, JCESR shifted its focus in its renewal to transformational battery materials, chemistries and architectures for electrodes, electrolytes, and interfaces that will enable a diversity of purpose-designed batteries for a diversity of uses [2].

JCESR's renewal introduces a new approach to transformational battery innovation: building batteries "from the bottom up", atom by atom and molecule by molecule, where each atom or molecule plays a prescribed role in achieving targeted overall materials behavior. This kind of atomic- and molecular-level materials design would not have been possible ten years ago because our knowledge of the atomic and molecular origins of electrochemical behavior was incomplete. The advanced atomic-level computer simulation and experimental characterization of battery materials in JCESR's first five years are part of the foundation for our new bottom-up materials design approach. Introducing such innovative approaches is critical to secure America's energy future and deliver economic—and scientific—competitiveness and growth.

JCESR's renewal provides a natural platform for strengthening broader research alignment among its partner institutions. JCESR's partners are working to ensure that their broader lab strategies and capabilities beyond the JCESR program are complementary and closely aligned with long-term DOE goals, such as research challenges for future U.S. battery manufacturing needs. This fostering of research alignment raises the effectiveness of the labs as a whole, collectively champions engagement with U.S. industry, and serves as a role model for cooperation across the national lab and university systems.

Overall, JCESR's short-term strategy is to significantly advance our atomic and molecular understanding of battery phenomena to enable rapid new materials discovery in liquid and solid electrolytes, redoxmers, and multivalent electrodes, electrolytes and interfaces. JCESR's long-term strategy is to initiate strategic new directions with the promise of disruptive impact that will set ten-year directions for energy storage and lay a firm foundation for the research community to grow and prosper in energy storage after JCESR ends. These short- and long-term strategies will ensure that America regains the international leadership in next generation battery innovation, manufacturing and marketing.

JCESR's Impact on Workforce Development

Since its inception, JCESR has made important contributions to developing the US workforce including the publication of >680 high-quality, high-visibility battery science papers in peer-reviewed journals, 59 total patent applications and 26 total issued patents, the education of >200 early career scientists, and the nucleation of three start-up companies.

JCESR is also actively engaging with the research community by hosting workshops (in person and, due to the pandemic, virtual) to discuss important research activities including artificial intelligence and machine learning for energy materials discovery, synthesis, and characterization, as well as computational and experimental techniques to study battery interfaces, the origin of many battery degradation processes. These workshops enable workforce development by bringing a multidisciplinary lens to pivotal research challenges to inspire scientists and engineers beyond JCESR's core team. In addition, JCESR is working to connect external graduate students to member national laboratories through mentorship webinars and panel discussions regarding career trajectories and guidance on applying to postdoctoral openings. This concept was piloted in April 2021 and we are gathering feedback from graduate student attendees to inform future events for HBCUs and minority-serving institutions.

Within the hub, the development of early- and mid-career scientists at member institutions is furthered in several meaningful ways. Junior researchers benefit from nurturing, mentoring, and collaborating with many of the world's preeminent battery and electrochemical scientists. This environment offers opportunities to expand their technical skills but also to learn scientific leadership and project management. Further, JCESR provides access to frontier tools and facilities within the national laboratory system including advanced light sources, leadership computing, nanoscience centers, and other state-of-the-art laboratories. Engagement with these cutting-edge resources and their associated research staff promotes education and development for not only academics but their graduate and postdoctoral students. The culture of innovation and critical thinking fostered by JCESR drives rapid advancement and refinement of ideas from inception to publication. Finally, the visibility and credibility of the JCESR "brand" in the global research community provides platforms for dissemination (e.g., papers in high-impact journals, invited presentations at prestigious conferences). Importantly, the knowledge gained and lessons learned from working with JCESR extend to other areas of our professions including scholarship in non-JCESR-related areas, teaching and mentorship of undergraduates, graduates, and postdoctoral associates, and service and leadership at our individual institutions.

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Research Summary

The objective of my research program is to advance the science and engineering of electrochemical technologies (e.g., batteries, electrolyzers) needed for a sustainable energy economy. My group seeks to understand and control the fundamental processes that govern the performance, cost, and lifetime of present day and next-generation electrochemical systems for energy storage and conversion. Our approach combines synthesis and characterization of redox active materials, design and engineering of electrochemical reactors, and techno-economic modeling of electrochemical systems. We place a strong emphasis on connecting system-level performance and cost goals to materials-level property requirements and on leveraging this knowledge to guide exploration of new chemistries and reactor designs. Ultimately, we aim to develop robust and portable guiding principles for the design of materials, processes, and devices that harness electrochemical phenomena. Pursuant to this goal, I have established a diverse and innovative research portfolio consisting of projects tackling important challenges in grid energy storage, environmental stewardship, and the role of electrochemical processing in chemical manufacturing. My teaching and service contributions focus on educating engineers to develop electrochemical solutions to critical global energy and sustainability challenges.

Education and Training

University of Pennsylvania	Chemical & Biomolecular Eng.	B.S.E., 2006
Univ. of Illinois at Urbana-Champaign	Chemical Engineering	M.S., 2009
Univ. of Illinois at Urbana-Champaign	Chemical Engineering	Ph.D., 2010
Argonne National Laboratory	Electrochemical Energy Storage Group	Postdoc, 2010-2012

Graduate Advisor: Paul J.A. Kenis, University of Illinois at Urbana-Champaign

Postdoctoral Advisor: John T. Vaughey, Argonne National Laboratory, Chemical Sciences Division

Select Awards and Honors

NESACS/NENOBCChE Henry A. Hill Lecturership	2021
NOBCChE Lloyd N. Ferguson Young Scientist Award for Excellence in Research	2020
ECS Supramaniam Srinivasan Young Investigator Award	2018
U.S. Department of Energy, Secretary of Energy Achievement Award	2018
Chemical and Engineering News Talented 12 Chemist	2017
Scialog Fellow for Advanced Energy Storage	2017
C. Michael Mohr Outstanding Faculty Award, MIT	2014, 2017
Director's Postdoctoral Fellowship, Argonne National Laboratory	2010
GEM Fellowship for Ph.D. in Engineering	2006

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Professional Membership: ECS, AIChE, ACS, NSBE, NOBBChE

Chairman BOWMAN. Thank you, Dr. Brushett. Dr. Takeuchi, you are now recognized.

TESTIMONY OF DR. ESTHER TAKEUCHI, CHAIR, INTERDISCIPLINARY SCIENCE DEPARTMENT BROOKHAVEN NATIONAL LABORATORY

Dr. TAKEUCHI. Good morning. Chairman Bowman, Ranking Member Weber, Chairwoman Johnson, Chairman Lucas, Committee Members, thank you very much for the opportunity to speak with you today. I draw on my experience of several decades in industry leading a research and development group in battery manufacturing, as well as my current position where I'm a joint appointee at Stony Brook University as a faculty member and a member of the Brookhaven National Lab.

Let me start with a few words about the energy landscape. It really is imperative to rapidly change the energy landscape in order to address not only resiliency but environmental sustainability. The two opportunities that I want to describe for you today are electrification of transportation and broadening adoption of renewable energy into the electric grid, and both of those opportunities depend on energy storage.

Specifically, I'm going to talk about batteries. What batteries do is take chemical energy and reversibly allow electricity to be delivered. When I was in industry, I developed the battery for the implantable cardiac defibrillator. While that battery works very well for its application, it's entirely different than the batteries in our laptop computers, the batteries in electric vehicles that are much larger, and now we're talking about even larger batteries for the grid that must last 10 or 20 years, so lifetimes and size keep both increasing.

In terms of research and development structure, complex problems such as energy storage are best addressed in teams. I'm the Director of an Energy Frontier Research Center funded by BES. This is a vehicle that has allowed me to pull together a team of highly talented researchers on their own and focus them collectively to address items that they could not address singly. From 2014 to 2018, we probed the question of the balance of batteries delivering electricity and heat. If we can minimize heat, they become more efficient, and now we're looking into the fundamental science of making batteries big and scalable.

Researchers, talented researchers need tools. When I started my career, the best way to figure out what was happening in a battery was to test it, cut it open, and look at the pieces. Today, I can go to facilities such as the National Synchrotron Light Source II at Brookhaven National Lab. I can probe a working battery using high-energy x-rays strong enough to visualize what's taking place inside a sealed battery in real time. This information really accelerates ability to develop and visualize next-generation batteries because we have unprecedented information.

Our findings in the EFRC have also led us to be able to work with more applied programs in the Department of Energy. Some of the materials findings we're working with the Office of Electricity to probe whether these ideas are relevant to large-scale batteries with water-based electrolyte or working with the Vehicle Technologies Office, part of EERE, to investigate fast charge, a 10-minute charge of vehicle batteries. That technology approach we patented, and now we have follow-on funding from the Technology Commercialization Fund to demonstrate that approach at scale.

Workforce development and interacting directly with next-generation scientists is one of the major drivers for me to leave industry and move to academics to be able to shape and inspire the next generation of scientists and leaders. The EFRCs provide a venue where young investigators can be supported, gain insight into national lab, academic, and collaborative research, and frame their careers for the future.

So, in closing, I want to highlight that availability of clean, reliable energy directly correlates with standard of living and the quality of human life. We must ensure that this is the case. Transformation of our energy landscape is an imperative. That's why the investments by DOE and BES are so critical. Let me be clear. This is a race. There are significant global investments, and these investments over the next several years will determine not only the energy landscape but whether the United States maintains an opportunity to lead.

Thank you very much for your time, and I look forward to questions.

[The prepared statement of Dr. Takeuchi follows:]

Testimony of Dr. Esther S. Takeuchi
SUNY Distinguished Professor, William and Jane Knapp Chair in Energy and the Environment
Stony Brook University
Chief Scientist, Department Chair, and Joint Appointee, Interdisciplinary Sciences Department
Brookhaven National Laboratory

Before the
Committee on Science, Space, and Technology
Subcommittee on Energy

At the Hearing on
Climate and Energy Science Research at the Department of Energy

May 4, 2021

This statement is from Esther S. Takeuchi, SUNY Distinguished Professor, William and Jane Knapp Chair in Energy and the Environment, Stony Brook University; Co-Director, Institute for Electrochemically Stored Energy at Stony Brook University; Director, Center for Mesoscale Transport Properties, a Department of Energy funded Energy Frontier Research Center; Chief Scientist, Department Chair and Joint Appointee, Interdisciplinary Science Department, Brookhaven National Laboratory.

Energy Landscape. The energy landscape must rapidly change to address the urgent needs for environmental sustainability and greater resiliency of our energy infrastructure. Two major opportunities are electrification of transportation and integration of renewable forms of energy generation into the electric grid. Both of these changes depend on energy storage. Electric vehicles require high power portable energy where drive distance, charge time, lifetime, safety, and vehicle cost are all considerations. The broad implementation of renewable energy sources such as solar and wind is challenged by their intermittency. Thus, methods to reliably and safely store the energy and allow later release are needed to enable integration of renewables into the electric grid.

Energy Storage. Batteries function by taking chemical energy and turning it into electrical energy and serve key functions as sources of portable power. As applications evolve, new batteries must be invented or adapted to meet the needs of the new use condition. For example, while in industry, my main project was the development and launch of the battery for the implantable cardiac defibrillator. The battery that we developed was the first that provided the needed power and longevity with the requisite safety and reliability to make the device clinically viable and thus, it enabled the widespread deployment of implantable defibrillators. These devices are life-saving as they can respond quickly if the patient has onset of ventricular fibrillation that is often fatal without intervention.

As a second example, lithium ion batteries were critical to the widespread adoption of portable electronics such as laptop computers and cell phones, due to their high energy content and lightweight. This application demands batteries that may last 3-5 years as the devices become obsolete quickly. In contrast, electric vehicles demand batteries that are much larger and last up to 10 years so that they do not need to be changed for the life of the car. Considering grid level storage, the desired lifetimes are 10-20 years such that the installed infrastructure does not need to be changed frequently. These differences in lifetime as well as specifics in function require that new generations of batteries be developed. It is the evolution of the applications that are motivating the investigation and development of new generations of batteries.

Research and Development Structure. Complex problems, such as energy storage systems, are best addressed by teams of people from different backgrounds brought together for a purpose. An example I use here is the structure of the Energy Frontier Research Centers (EFRCs), funded by the Basic Energy Sciences program in the Department of Energy (DOE) Office of Science. With funding of approximately $2-4 million per year and a term of 2 to 5 years, each Center provides a vehicle to assemble scientists, talented in their own right, to focus on issues beyond the ability of one scientist to deliver on their own, bringing experts from universities and national laboratories together. When led by visionary and insightful leaders the outcomes can be remarkable. As an analogy from the Arts, imagine a symphony orchestra. Each musician is a virtuoso, with distinct talent and expertise. Brought together by a knowledgeable conductor who understands the music a grandeur of sound results beyond that possible from an individual. This holds for science as well when the leader has the deep knowledge and understanding of the problem and the opportunity to bring the collective solutions forth from synergistic engagement of the participants, remarkable scientific and technical achievements can result.

As a specific example, I direct the EFRC, The Center for Mesoscale Transport Properties. Over the first fours years 2014-2018, our mission was to establish a comprehensive understanding of ion and electron transport mechanisms over multiple length scales in energy storage systems. To reach our goals, the center investigators included experts in materials synthesis, characterization over multiple length scales from the atomic scale to the full battery, electrochemistry, and multilength scale theory and modeling. Through effective interaction, the center was highly effective at determining transport limitations at the atomistic, particle, aggregate, electrode, and system levels. This information provides the fundamental insights needed to move toward optimal design and synthesis of active materials, formulation and processing of electrodes, and battery design. From 2018-2022 our mission is to build the scientific knowledge base necessary to enable future creation of scalable electrochemical energy storage systems. Existing materials and electrode constructs suffer transport limitations that inhibit design of scalable electrodes necessitating compromise of either energy content or power delivery. Thus, we are considering the constructs needed for deliberately scalable architectures as well as materials suitable for low cost and safe large-scale energy storage.

Knowledgeable leadership and a talented team also require cutting edge instruments and tools to be successful. Historically, batteries were developed using an Edisonian approach based on trial and error. New successful battery types are not introduced often as the changes and implementation of new designs, materials, and manufacturing processes may take decades. Even after the batteries are deployed in the marketplace, full understanding of how they work lags behind. Only 10-15 years ago the best way to understand the function of the battery was destructive analysis - to test it then cut it open and examine the parts. The limitation is that the battery components may change significantly, limiting the usefulness of the resulting data. Today, synchrotron devices such as the National Synchrotron Light Source II at Brookhaven National Laboratory supported by the DOE's Basic Energy Sciences program provide high energy x-rays that can be tuned to very small beams, often smaller than the diameter of a human hair. These x-ray beams are powerful enough that they can penetrate battery housings, including special configurations and commercially built batteries. The x-ray beams are then used to follow the reactions of the battery as it is working. This can be done in real time to capture time-dependent mechanisms and it can also be done where spatial location or mapping are conducted to determine the location of the reaction or the transformation. These operando measurements conducted on functioning batteries are allowing unprecedented insight into mechanisms that are taking place. Thus, we can now deliberately design the next generation of battery based on the knowledge that we have gained through the ability to track its internal function. We can move ahead in a more deliberate way based on the insights that were obtained.

The fundamental insights provide a path by which the knowledge can be used to advance product development. The concepts first demonstrated in the laboratory can then be targeted to the specific needs of the applications. The information then becomes relevant to the private sector where adoption for commercialization can proceed.

I elaborate here three categories of the impact of scientific research. The first is the scientific impact as it lays the foundational understanding needed for new energy technologies. The second is broader scientific impact where the fundamental scientific findings foster interest and interaction beyond basic science and the third is impact beyond the research arena where benefits to society can be realized. I provide several examples from our own research. Research as part of our EFRC demonstrated that synthetic control of material physiochemical properties can have significant impact on the resultant electrochemistry. As a result of our findings, we were able to initiate a program with the Department of Energy Office of Electricity Delivery and Energy Reliability through Sandia National Laboratory to exploit synthetic material tuning in systems directly applicable to large scale storage. The second example is an outgrowth of our demonstrated ability to modify material surfaces to favorably influence their electrochemistry. Based on the insights, we attracted funding from the Vehicle Technology Office of the Department of Energy's Energy Efficiency and Renewable Energy organization to enable fast charge, less than 10 minutes, of lithium ion electric vehicle batteries. Based on our patented approach, we were then able to attract funding from the Office of Technology Transfer through the Technology Commercialization Fund to demonstrate the process at scale. A third example stems from our EFRC findings where we demonstrated the ability to measure the heat generated by an active battery to probe reactions of electrolyte at the electrode surface as a function of the battery voltage. These sensitive and precise measurements were recognized as industrially relevant where we could understand material and battery stability in a relatively short timeframe compared to many months or years of testing. We are pursuing this topic more expansively funded by an electric vehicle company for systems relevant to their application.

Workforce development. The time that I spent in industry was highly rewarding as the battery that powered implantable cardiac defibrillator devices has saved millions of lives. However, my direct interaction with those that were impacted was limited. One of the motivations in my transition from industry to academics was the ability to impact the next generation of scientists and leaders more directly. The graduate students and post-doctoral researchers in our research group represent the future. They are diverse in terms of scientific, cultural, gender, and ethnic backgrounds. They leave our research group well educated and have moved to a variety of careers including faculty at universities and colleges, scientists at National Laboratories, and Industrial scientists and engineers. They will contribute to solving the issues of the future.

The structure of the EFRCs also provides a venue for young investigators to participate in addressing significant and complex science questions. In the Center that I direct, the young investigators interact with the established scientists, gain exposure to both academic and national laboratory research environments, and witness first-hand the benefits of research conducted in a cohesive collaborative manner. These young investigators gain the needed skills to become the scientists and leaders of tomorrow.

Importance of the Field. In many ways, the pursuit of technology relevant to the energy sector is a race where the entire energy landscape will change quickly over the next 10-20 years. This is recognized internationally and thus, there is significant investment taking place worldwide. It is known that access to reliable energy is directly tied to standard of living and quality of human life. It is also recognized that unlimited burning of fossil fuels cannot continue forever. Thus, transformation of how energy is generated, stored, and used is imperative. Decisions in this arena will determine who leads and who follows in the new global energy economy.

Summary. The funding for the Department of Energy Basic Energy Science has proven to be critical on multiple fronts. The research support has proven exceptionally valuable to gain fundamental scientific insights. The support of young investigators as part of the research initiatives is imperative to ensure the availability of an educated workforce. Further, Department of Energy Basic Energy Science funded research facilities are enabling unprecedented insights into energy related systems. Thus, the funding remains critical for the talent development, research, and facilities/tools that will help the nation realize if not lead the energy revolution through many diverse applications of energy storage and batteries.

Biosketch

DR. ESTHER S. TAKEUCHI

Dr. Esther S. Takeuchi is a SUNY Distinguished Professor and the William and Jane Knapp Chair in Energy and the Environment at Stony Brook University. She holds a joint appointment at Brookhaven National Laboratory as Chief Scientist and Chair of the Interdisciplinary Science Department. She is Director of an Energy Frontier Research Center funded by the Department of Energy. Prior to her academic appointments, she was employed at Greatbatch, Inc., where her achievements in lithium battery research, particularly for implantable applications, led to several technological innovations. Her work was instrumental in the successful development of the lithium/silver vanadium oxide (Li/SVO) battery, the power source of life-saving implantable cardiac defibrillators (ICDs). Dr. Takeuchi is a prolific inventor with > 150 patents.

Dr. Takeuchi's accomplishments have been widely recognized. She is a member of National Academy of Engineering, was awarded the National Medal of Technology and Innovation by President Obama, inducted into the National Inventors Hall of Fame, a member of the American Academy of Arts and Sciences, and is a Charter Member of the National Academy of Innovation. She received the E. V Murphree and Astellas Awards from the American Chemical Society and the Electrochemical Society (ECS) Battery Division Technology award. She is a Fellow of the ECS, the American Institute of Medical and Biological Engineering, and the American Association for the Advancement of Science. She received the 2018 European Inventor Award for non-EPO countries. In 2019, she received the Walston Chubb Innovation Award from Sigma Xi and an honorary Doctorate in Engineering from Notre Dame University and the Edward G. Acheson award from the Electrochemical Society in 2020. She is past president of the Electrochemical Society.

Dr. Takeuchi received a BA from the University of Pennsylvania with a double major in chemistry and history and a Ph.D. in chemistry from the Ohio State University.

Chairman BOWMAN. Thank you, Dr. Takeuchi. Dr. Zeng, you are now recognized.

TESTIMONY OF DR. XUBIN ZENG, PROFESSOR, HYDROLOGY AND ATMOSPHERIC SCIENCES, THE UNIVERSITY OF ARIZONA

Dr. ZENG. Chairman Bowman, Ranking Member Weber, Chairwoman Johnson, Ranking Member Lucas, and the Members of the Subcommittee, thank you for the opportunity to be here today to discuss climate and the environmental science research at the Department of Energy or DOE.

Starting this week, I begin to co-chair the Scientific Steering Group of the Global Energy and Water Exchange Project, which is one of the major international programs on climate and water sciences. My testimony today draws on my extensive leadership experiences and a publication record of over 200 peer-reviewed papers.

I will briefly cover four topics: current status of the DOE research, unique aspects, major challenges, and future directions.

For the current status, DOE programs support three primary research activities on the atmospheric system, environmental system, and the Earth and the environmental systems modeling. This portfolio also supports true scientific user facilities, the Atmospheric Radiation Measurement facility and is an Environmental Molecular Sciences Laboratory. In particular, the modeling program supports the development of the DOE energy exascale Earth system model.

To illustrate the success of these activities, here, I share just one example. DOE's [inaudible] model version I was released in 2018, including a unique capability to zoom in for a closer look of the particular regions such as the United States. More recently, a new global cloud-permitted modeling capability of a 2-mile grid spacing has been developed, making this model the world's highest resolution climate prediction capability.

Regarding the uniqueness, four unique aspects of DOE's research efforts can be identified. First, DOE climate model stands out for being the first Earth system model of its kind to be drawn on the ultrafast supercomputers, that is exascale computers developed by DOE.

Second, DOE emphasized the extreme weather under global warming and a geographic domains that exist—exhibit sharp gradients such as coastlines and complex terrain over Western United States.

Third, DOE is integrating its human system model with its climate model. This represents the world's first attempt to develop a fully coupled human-Earth system model to make more consistent and realistic predictions.

Finally, DOE's user facilities are world-leading in relevant fields. For instance, the comprehensive observatory approach using ground and airborne measurements is now widely adopted by other national and international programs.

But at the same time DOE's research faces several major challenges in integrating Earth system modeling with exascale computing, the understanding of predictability of the fully coupled human-Earth system and in keeping up with new observing technologies for the user facilities.

Based on these discussions, the future directions include several areas. First, global cloud-permitting model with a grid spacing of 2 miles should continue to be developed for exascale computers. Also needed is the use of innovative artificial intelligence (AI) for coupled human and natural system modeling and uncertainty quantification, computational efficiency, and the model process representation.

Second, closer collaborations with DOE applied programs are needed to assist in the planning of our Nation's energy and related infrastructure. In particular, this planning can be assisted by tradeoff and scenario analyses using full coupled human-Earth system modeling.

Third, DOE user facilities need to keep up with new capabilities, and enhanced better service is needed to expand the user base and to help convert data into knowledge. DOE also needs to proactively reach out to minority-serving institutions and historically Black colleges and universities.

Besides interagency collaborations, the coupled human-Earth system modeling capabilities can also assist the private sector on topics like extreme events under climate change.

Finally, DOE can benefit from and contribute to the new initiative of the World Climate Research Programme on Digital Earth, which is a dynamic representation of the Earth system based on optimal blending of models and observations.

Thank you.

[The prepared statement of Dr. Zeng follows:]

WRITTEN TESTIMONY OF

Dr. Xubin Zeng
Agnese N. Haury Chair and Professor,
Department of Hydrology and Atmospheric Sciences,
University of Arizona, Tucson, Arizona

BEFORE THE HOUSE COMMITTEE ON SCIENCE, SPACE, AND TECHNOLOGY SUBCOMMITTEE ON ENERGY

Climate and Energy Science Research at the Department of Energy

May 4, 2021

Introduction

Chairman Bowman, Ranking Member Weber, and members of the Subcommittee, thank you for the opportunity to be here today to discuss climate and environmental science research in the Biological and Environmental Research (BER), Office of Science, Department of Energy (DOE).

My name is Xubin Zeng and I am the Agnese N. Haury Chair in Environment, Professor of Atmospheric Sciences, and Director of the Climate Dynamics and Hydrometeorology Center at the University of Arizona. I am also an affiliated professor of the Applied Mathematics, Global Change, and Remote Sensing and Spatial Analysis Interdisciplinary Programs. I am an elected fellow of both the American Meteorological Society (AMS) and American Association for the Advancement of Science. I served on the Governing Board of AMS and its Executive Committee, and received the AMS Charles Franklin Brooks Award for Outstanding Service to the Society in January 2021. I also received the Special Creativity Award from the National Science Foundation (NSF), the Outstanding Faculty Award from the University of Arizona's Asian American Faculty, Staff and Alumni Association, and the Colorado State University Atmospheric Science Outstanding Alumni Award.

Relevant to the topic of today's hearing, starting this week, I begin to co-chair the Scientific Steering Group of the Global Energy and Water Exchange (GEWEX) Project – one of the major international programs on climate and water science. I also serve on the Science Advisory Board of the Earth & Biological Sciences Directorate of DOE Pacific Northwest National Laboratory, and the Science Advisory Board Environmental Information Services Working Group of the National Oceanic and Atmospheric Administration (NOAA). In the past decade, I co-chaired the National Aeronautics and Space Administration (NASA) Earth Science Community Workshop and White Paper on future directions in the Weather Focus Area, chaired the Community Workshop and White Paper on lower-atmosphere observing facilities for climate studies for the NSF Division of Atmospheric and Geospace Sciences, chaired the NOAA white paper on the use of observing system simulation experiments which was forwarded to the U.S. Congress, and served on the National Academies Board on Atmospheric Sciences and Climate and the NASA/NOAA/USGS Earth Science Decadal Survey Weather and Air Quality Panel.

My testimony today draws on my above experiences and my publication record of over 200 peer-reviewed papers on land-atmosphere-ocean interface processes, weather and climate modeling, hydrometeorology, remote sensing, nonlinear dynamics, and big data analytics. In particular, it draws on my research and my extensive interactions with DOE and other scientists on the science and user facilities related to the topic of today's hearing.

This testimony is organized into four brief sections: 1) current status of DOE's climate and environmental systems research, 2) unique aspects of these research efforts, 3) major challenges, and 4) future directions.

1) What is the current status of DOE's climate and environmental systems research?

DOE Office of Science manages its research portfolio through six program offices, including Biological and Environmental Research (BER). BER has two divisions, including the Earth and Environmental Systems Sciences (EESS) Division. The EESS Division supports fundamental science and research capabilities that enable major scientific developments in Earth system-relevant atmospheric and ecosystem process and modeling research in support of DOE's mission goals for transformative science for energy and national security. All of DOE's climate science research is housed within the EESS Division which supports three primary research activities:

- Atmospheric System Research Program addresses a main source of uncertainty in Earth system models: the interdependence of clouds, atmospheric aerosols, and precipitation that in turn influences the Earth's radiation balance. This Program works closely with the Atmospheric Radiation Measurement (ARM) user facility in support of its activities.
- Environmental System Science Program supports research to provide an integrated, robust and scale-aware predictive understanding of environmental systems, including the role of hydro-biogeochemistry from the subsurface to the top of the vegetative canopy. Experimental and modeling research is supported in part by capabilities at the Environmental Molecular Sciences Laboratory (EMSL).
- Earth and Environmental Systems Modeling Program supports three areas:
    - to develop physical, chemical, and biological model components, as well as fully coupled Earth System Models;
    - to develop multi-sector (e.g., energy, water, agriculture) dynamics models for human system and integrated human-Earth system modeling; and
    - to enhance a predictive understanding of variability and change within the Earth System through modeling and data analysis.

  In particular, the first program area supports the Energy Exascale Earth System Model (E3SM), which is a world-class, variable-resolution climate model that is run on DOE's Leadership Computing Facility supercomputers.

In addition, the EESS Division supports two scientific user facilities:

- ARM provides unique, multi-instrumented capabilities for continuous, long-term observations and mobile facilities as well as model–simulated high resolution information to improve understanding and test hypotheses involving the role of clouds and aerosols on the atmosphere's solar and terrestrial radiative balance over a variety of spatial scales; and

- EMSL provides world-class laboratory equipment and integrated experimental and computational resources to extend understanding of the physical, biogeochemical, chemical, and biological processes that underlie DOE's energy and environmental mission.

To illustrate the success of these activities, here I provide three examples. First, E3SM version 1 was released in 2018, including a unique capability of regional refinement in all of its components for high resolution modeling. E3SM results at both low (~100 km) and high (~25 km) resolutions are used in the Intergovernmental Panel on Climate Change (IPCC) Sixth Assessment Report (AR6). More recently, a new global cloud-permitting modeling capability at 3 km grid spacing has been developed and demonstrated through participation in an international effort to intercompare global cloud-permitting simulations, making E3SM the world's highest resolution climate prediction capability. These simulations show substantial improvements in addressing longstanding model biases (with a grid spacing of ~100 km) such as the diurnal cycle of precipitation – which is the focus of an international project led by a DOE E3SM scientist.

ARM developed and implemented the LES (Large-Eddy Simulation) ARM Symbiotic Simulation and Observation (LASSO) workflow. LASSO uses ARM observations to constrain and evaluate LES simulations to provide high-resolution (100 m grid spacing), three-dimensional datasets for studying atmospheric processes. Besides the LES simulations of shallow cumulus clouds over the Southern Great Plains ARM site, LASSO has recently been expanded to study deep convection and heavy precipitation in conjunction with a major ARM field campaign in Argentina and to study marine stratocumulus clouds, which is crucial for the Earth's radiation balance, at the Eastern North Atlantic atmospheric observatory established by ARM.

As part of the Earth and Environmental Systems Modeling Program, the multi-sector dynamics program area has been further developed in order to extend beyond the more constrained emphasis on Integrated Assessment Modeling. This (MultiSector Dynamics) program area has launched a Community-of-Practice to explore the co-evolution of human and natural systems over time and to build the tools that bridge across sectors (energy, water, land, economy) and scales (spatial, temporal). Furthermore, the Global Change Analysis Model (GCAM), which represents many of the interactions among human and Earth system, has been in continuous development by this program area and is currently being incorporated into E3SM. Given this, E3SM is the only climate model that includes details on the human component (i.e., infrastructures, economics, land use, etc.) that is built within the prediction modeling framework.

2) What is unique about these research efforts?

Research efforts supported by the BER EESS Division are part of the interagency U.S. Global Change Research Program (USGCRP), that in turn is comprised of 13 federal agencies that conduct or use research on global change and its impacts on society, in support of the Nation's response to global change. Here I identify four unique aspects of DOE's climate and environmental systems research.

First, there are ~50 Earth system models in the world. E3SM stands out for having a close integration with DOE's world-leading high-performance computing. Indeed, "exascale" computing is even included in the name of E3SM. While supercomputer speed can be measured and benchmarked, the actual speed realized in modeling strongly depends on the model architecture and software. By optimizing the E3SM code for DOE's advanced computers, DOE not only maximizes its ability to leverage its own resources but is also developing new knowledge and best practices that will improve other models worldwide. E3SM is the first model of its kind to be run on the ultra-fast supercomputers, i.e., exascale computers, developed by DOE.

Another unique aspect is DOE's heavy emphasis on extreme events (e.g., hurricanes) and geographic domains that exhibit sharp gradients (e.g., coastlines and complex terrain over western U.S.) in the context of larger-scale and longer-term changes such as the global warming and other climate changes induced by greenhouse gas increases and other human activities. This is done, for example, through E3SM's unique capability of regional refinement in all of its components for high resolution modeling. Recent progress in the development of a GPU (graphics processing unit)-enabled, rather than the traditional CPU (central processing unit)-based, version of the E3SM global cloud permitting model, will further enhance E3SM's ability to resolve extreme events and tight spatial gradients in the context of a global Earth system model that can simulate multi-decadal changes. Complementing the modeling of these complicated regions, DOE also supports long term field experiments such as in the Arctic, Tropics, and mid-latitude U.S. sites, to calibrate, validate, and test predictive models with a focus on characterizing and reducing prediction uncertainty.

GCAM is one of only a handful of integrated human-simplified Earth system models that has contributed scenarios (e.g., Representative Concentration Pathways and Shared Socioeconomic Pathways) to drive climate model simulations in all of the IPCC's major assessment reports, including AR5 and AR6, as well as other important community activities such as the Coupled Model Intercomparison Projects (CMIP5 and CMIP6). One weakness of current approaches used by most climate modeling centers is that the greenhouse gas concentrations at the end of 21st Century from these scenarios would be different from those using Earth system models with the same natural and anthropogenic emissions. To avoid this inconsistency, GCAM is being integrated into E3SM, which represents the world's first attempt to develop a fully coupled human-Earth system model to make more consistent and realistic predictions.

Both ARM and EMSL are world-leading user facilities in the relevant fields. For instance, ARM provides the world's most comprehensive, continuous, and precise observations of clouds, aerosols, and related meteorological information. This is done through a combination of ground-based measurements and aerial measurements with piloted aircraft, unmanned aerial systems and tethered balloon systems. This comprehensive "supersite" observatory approach is now widely adopted by other national and international programs. Besides supporting BER atmospheric sciences and Earth system modeling research, the ARM facility freely provides key information to other agencies; e.g., for calibration and validation of space-borne sensors at NASA.

3) What are the challenges for DOE's climate and environmental systems research?

To continue DOE's leadership in climate and environmental systems research, several major challenges will need to be addressed.

First, to further enhance the integration of Earth system modeling with exascale computing, there are a number of scientific and software engineering challenges. For instance, while the numerical solution of partial differential equations for atmospheric dynamics (e.g., for the movement of water vapor by wind in the atmosphere) has been traditionally emphasized, the numerical solution of physical, chemical, and biological processes (e.g., aerosols, clouds, precipitation, radiation, turbulence), interactions among these processes, and their interaction with atmospheric dynamics have not received enough attention. Additionally, there is an urgent need to develop approaches that take maximum advantage of both GPU- and CPU-based computing, which is a paradigm shift for many Earth system modelers, who have traditionally emphasized CPU-based architectures. These challenges can be addressed through the Scientific Discovery Through Advanced Computing (SciDAC) Program jointly supported by BER and DOE's Office of Advanced Scientific Computing Research and through DOE Office of Science's Graduate Student Research Program (to develop the future pipeline in this area).

Understanding Earth system predictability (which represents the upper bound of prediction using physics-based equations) is already recognized as a multi-agency grand challenge in the U.S. It is even more challenging to understand the predictability of the fully coupled human-earth system. New understanding is urgently needed through innovative theoretical studies, global data analysis, and global modeling of human, natural, and coupled human-natural systems. It is unclear if current global models are adequate for predicting extreme events, as such models may contain numerical and spurious chaos and may dampen extreme events. Also needed is the use of innovative Artificial Intelligence (AI)/Machine Learning (ML) approaches to address predictability issues in both human and natural systems, such as the prediction of extreme events as the climate evolves.

A major goal of BER's modeling efforts is to help examine the resilience of our Nation's infrastructure, especially energy infrastructure and its interaction with other sectors such as water systems and land use changes, and to help inform energy infrastructure investment decisions and national security. This requires smaller horizontal model grid spacing (e.g., using the global cloud-permitting model at 3 km grid spacing), better representation of important processes (e.g., cloud-aerosol, water cycle, biogeochemistry, and the cryosphere) assisted by ARM and EMSL user facilities, better understanding of how human activities influence and are influenced by climate change, and quantification and possible reduction of key uncertainties, based on integration of AI/ML with physics-based approaches. Also needed are the close interactions between BER activities and DOE's applied energy programs.

To continue the leadership of the ARM and EMSL user facilities, the challenge is to keep up with new observing technologies, develop new capabilities, and provide better user support to enhance the user base and scientific and societal impacts. For example, the newly acquired manned aircraft significantly enhances ARM's aerial capabilities. The ARM data center currently holds over 2 Petabytes of data from over 11,000 datasets and these numbers are steadily increasing. While ARM is doing an excellent job in access and stewardship, the challenge is on data discovery, visualization, and tailored needs of users.

4) What are the future directions of DOE's climate and environmental systems research?

Based on the above discussions, the future directions include:

Coupled model development. A GPU-enabled version of the E3SM global cloud-permitting model (with a grid spacing of 3 km) should continue to be developed for exascale computers. Scale-aware parameterizations of physical, chemical, and biological processes need to be developed for a unified model applicable and skillful at resolutions ranging from 3 – 100 km. In addition, GCAM at even higher resolution should be further integrated into E3SM. Currently, the primary interactions between the two codes are with respect to biogeochemistry and land surface changes, but more complete integrations (e.g., water demand from GCAM influencing water availability in E3SM) are needed.

To further accelerate coupled human-earth system modeling, AI/ML approaches should be explored:

- to improve the representation of both natural processes and human systems, including human decision-making and other social science-oriented aspects (e.g., to explore the potential of developing a hybrid modeling system with both AI/ML and traditional modeling components);
- to better quantify uncertainty in future climate projections (e.g., for energy infrastructure design and resilience assessment);
- to make the modeling more efficient computationally (e.g., for downscaling to local information); and
- to study coupled human-Earth system predictability (e.g., to understand if the predictability of extreme events is higher than that for the normal conditions and if model deficiencies decrease the predictability of the coupled system).

These AI/ML applications require customized solutions for domain-specific problems, and they can be achieved only through better collaborations between Earth scientists and AI/ML experts.

Model application to energy security. One key application of the coupled human-earth system modeling capability on DOE's exascale computers is to address science questions relevant to energy security, in the broad sense. With this, the new science derived from Earth observations and model-generated data can be used to achieve broad benefits ranging from informing the design of robust resilient energy infrastructures to risk analysis involving natural disaster impact mitigation to natural resource management and environmental stewardship. BER should work more closely with DOE applied energy programs and Office of Energy Policy and Systems Analysis to assist in the planning of our Nation's energy infrastructure and in the assessment and mitigation of potential damages to, e.g., energy and related infrastructures. In particular, this planning can be assisted by tradeoff and scenario analyses using fully coupled human-Earth system modeling along with exascale computing. For this purpose, the framework widely used in making major observing system decisions would be very valuable: the Observing System Simulation Experiment (OSSE) which is a modeling experiment used to evaluate the value of a new observing system when actual observational data are not available.

ARM and EMSL user facilities. These observing facilities provide the backbone to test and improve models, and they need to keep up with new capabilities (e.g., phased-array radar and a variety of edge computing technologies for ARM). Tighter integration across BER's observing and modeling platforms is also needed. For instance, LASSO should be further expanded by working with modeling groups to develop (or expand) frameworks for data-model integration at even fine resolutions. To expand the user base and help convert data into information and then into knowledge, enhanced data service is needed for data discovery, visualization and animations, and tailored needs of users. For instance, with the expansion of ARM data volume for data sets from instruments such as scanning radars or LASSO simulations, local computing at the ARM Data Center becomes necessary for some users.

Outreach and Partnership. Recognizing the lack of under-represented researchers in the relevant field, DOE's climate and environmental systems research projects and programs should proactively reach out to colleges and universities with a focus on Minority-Serving Institutions and Historically Black Colleges and Universities (e.g., through summer internship, summer school, developing training materials, building modules to apply observational and model data in the classroom). The results from multi-sector dynamics modeling (e.g., on economics, population, land use, and climate drivers for coastal development and engineering) are directly relevant to the study of environmental equity and justice, and hence outreach to relevant communities is needed and collaborations should be pursued.

In the U.S., interagency collaborations (e.g., through the USGCRP) should be strengthened. For instance, the collaboration between ARM and NASA-supported scientists leads to the use of ARM data for the calibration and validation of satellite remote sensing retrievals and data. As another example, further interagency collaborations could be pursued to study the water cycle (e.g., precipitation, snowpack, evaporation, soil moisture, river streamflow, and lake water levels) over the U.S. through the USGCRP's Integrated Water Cycle Group. Besides these interagency collaborations, the coupled human-Earth system modeling capabilities will also allow potential partnerships with the private sector on topics like extreme events under climate change (e.g., relevant to the insurance and reinsurance industry).

Internationally, E3SM has participated in the CMIP6 model intercomparison activities for the IPCC AR6, GCAM has contributed scenarios that drive CMIP5 and CMIP6, and ARM has a close collaboration with the GEWEX Global Atmospheric System Studies Panel in data archive and in organizing a competition of early-career researchers (including graduate students) in using the ARM data for atmospheric process understanding. A new opportunity is the World Climate Research Programme's lighthouse initiative on Digital Earth - a dynamic representation of the Earth system founded on an optimal blend of models and observations. With the development of the E3SM global cloud-permitting model (with a grid spacing of 3 km) for exascale computers, DOE should actively participate in this international activity and take leadership where appropriate. These and other international collaborations can benefit DOE and the Nation, and can be used to continuously monitor the health of the Earth, study the effects of climate change and the state of the oceans and cryosphere, and improve modeling and predictive capabilities around extreme weather events and over heterogeneous or high gradient regions (e.g., urban, coastal).

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Starting in May 2021, he begins to co-chair the Scientific Steering Group of the Global Energy and Water Exchange (GEWEX) Project – one of the major international programs on climate and water science. He also serves on the Science Advisory Board of DOE Pacific Northwest National Laboratory Earth & Biological Sciences Directorate and the Science Advisory Board Environmental Information Services Working Group of the National Oceanic and Atmospheric Administration (NOAA). In the past decade, he co-chaired the National Aeronautics and Space Administration (NASA) Earth Science Community Workshop and White Paper on future directions in the Weather Focus Area, chaired the Community Workshop and White Paper on lower-atmosphere observing facilities for climate studies for the NSF Division of Atmospheric and Geospace Sciences, chaired the NOAA white paper on the use of observing system simulation experiments which was forwarded to the U.S. Congress, and served on the National Academies Board on Atmospheric Sciences and Climate and the NASA/NOAA/USGS Earth Science Decadal Survey Weather and Air Quality Panel.

Chairman BOWMAN. Thank you very much, Dr. Zeng. Dr. Rao, you are now recognized.

TESTIMONY OF DR. NARASIMHA RAO, ASSOCIATE PROFESSOR OF ENERGY SYSTEMS, YALE SCHOOL OF THE ENVIRONMENT

Dr. RAO. Chairman Bowman, Chairwoman Johnson, Ranking Member Weber, Ranking Member Lucas, distinguished Members, I'm honored to have the opportunity to address you today.

I was asked to speak about the social sciences and climate research and specifically about the benefits of integrating socioeconomic aspects into climate models. First, as a matter of clarification, the models that I address are those that project greenhouse gas emissions from human activities and simulate policies and actions to reduce these emissions. I would like to make the case today that we need more social science research to understand how different communities around the country may be impacted by and respond to climate policies. These energy and climate models can support the design and implementation of climate policies by incorporating insights from such research into realistic projections of emissions reductions so that we can more accurately assess progress and the best path forward to achieve our targets.

Our energy systems are embedded in social institutions with changes implied by our targets are potentially far-reaching across society involving not only how we produce and deliver energy but also how we use energy. These changes may affect our homes, how we get around, as well as how we organize our lives Achieving the scale of transformation in society requires turning knowledge into action, action by government, organizations, and individuals, and understanding the social processes by which these actions can lead to transformative change is the domain of social sciences.

My focus today is specifically on households, how energy climate models represent household consumption behavior and their response to policies. The motivation for my focus is twofold. First, there is wide recognition that climate change is a matter of social justice and equity. We know that low-income communities globally are likely to face a disproportionate burden of climate change and of efforts to mitigate its effects. Racial and income inequalities and energy burdens in the United States are already stark. Low-income Black communities spend more than double the share of their income on transport as the average American, while 1/3 of them have no vehicular and poor transit options. Mortality during heat waves is higher in low-income communities very likely due to lower use of air-conditioning.

The social sciences offer a rich understanding of poverty and structural inequality. We can draw from these insights and research approaches to better understand energy burdens on which we will impose new policies and technologies.

My second motivation for focusing on households is that climate researchers have identified many changes in our lifestyles that would improve our well-being such as health and reduce emissions. For instance, walking or cycling to work, riding transit in cities, reducing waste, using products longer with more care can reduce overall material use and free up societal resources to improve our lives in different ways. However, we need more research in the social sciences to examine the scope and feasibility of these changes and realize the potential benefits.

Let me speak specifically of the models. Energy climate models have been instrumental in getting us to this point. They have helped us understand how human systems drive emissions growth, the portfolio of technologies we need to mitigate climate change and the pace of decarbonization required to avoid the worst effects of climate change. These models are widely used by different communities, including policymakers, the finance community, development agencies, and researchers who want to understand what to expect from future climate policies.

However, these models have simplistic representation of households. For instance, they typically model single representative households per region. As we move to implementing policies, it is critical that we disaggregate households based on structural differences such as income, contextual factors such as the people live in cities or suburbs or rural areas, and assess noneconomic considerations such as health, all of which influence decisions.

Household decisions in these models also neglect social norms, peer effects, and various constraints that shaped decisions. For instance, homes located near those that have rooftop solar panels are more likely to invest in them themselves. Financial constraints, the digital divide, poor electric charging infrastructure may all be barriers to widespread adoption of new electric mobility options. And making these effects more explicit in models can enable more realistic assessment of technology adoption.

Energy services are instrumental to meet other needs. Poor transit limits job opportunities, access to nutritious food, and the scope for other activities. Our energy use impacts others' well-being such as through air pollution. New electric mobility options could reduce local air pollution, but they may increase pollution from power plants, which can affect other communities.

So, in conclusion, with more social science research, we can develop a more systematic understanding at a local level of the impacts of future policies on our climate goals, on equity, and on our overall well-being. And by integrating this research into climate models, we can link local policies and responses to national and global emissions targets, we can assess the broader social impact of an energy transition, and more realistically track progress in achieving our long-term climate goals. Thank you for listening. I look forward to your questions.

[The prepare statement of Dr. Rao follows:]

Congressional Testimony of

Narasimha D. Rao
Associate Professor of Energy Systems
Yale School of the Environment

Before the

Subcommittee on Energy
House Committee on Space, Science and Technology
U.S. House of Representatives
Hearing: *Climate and Energy Science Research at the Department of Energy*
May 04, 2021

Chairman Jamaal Bowman, distinguished members of the committee, I am honored to have the opportunity to offer my views on the energy science research needs to improve our energy systems and combat the threat of climate change. I bring two decades of experience in the energy sector, including a decade of interdisciplinary academic experience in understanding the role of energy in society and development. I have examined the energy needs of people, communities and nations, and the threats posed by climate change and its mitigation to human wellbeing. Drawing on this experience, I have focused my comments on the importance of integrating socio-economic factors into energy and climate models ("E-C models") to better project how different communities may be impacted by and respond to climate policies. The models that I address are those that project greenhouse gas (GHG) emissions from human activities and simulate policies and actions to reduce these emissions. This includes the global Integrated Assessment Models (IAMs) as well as national energy-economy models. In my view, E-C models can support the implementation of climate policies by better representing society and the social processes that influence household behavior. I describe why it is important to build stronger bridges between social science research and E-C models and then provide suggestions for future research in this direction.

We are at a critical juncture in human history. National governments are preparing to ramp up their pledges to the Paris Agreement to accelerate decarbonization and achieve net-zero emissions by 2050. The changes implied by these targets are potentially far-reaching, involving not only how we produce and deliver energy, but also how we use energy, both directly, such as to heat our homes, and indirectly, through the manufacturing of products that we purchase and use. These changes may affect our homes, how we get around, how and where we work, what we eat, how we engage with each other and with technology, how we organize our lives, and how we shape our future physical environment.

Translating aspirations into policies that can achieve this scale of transformation in society requires turning knowledge in many disciplines, including the social sciences, into action. Scientists have identified many avenues for social science to support global environmental change research[1]. Indeed, there has long been a trend in research to integrate social and biophysical sciences. The number of social science publications in global environmental research grew from just a handful of studies in 1990 to over 3,500 articles per year[2] by 2011. Just in the context of climate mitigation, social science can help understand the social processes that drive our energy and emissions growth, the behavior of institutions that make and implement policy, and the processes by which transformative change can take place. My focus in these comments is specifically on households — how E-C models represent households' consumption behavior and their response to policies. The motivation for this focus is twofold: first, there is increasing recognition in the U.S. by policymakers and scientists of the need to view climate change as a matter of social justice and equity[3]; second, there is growing recognition among climate researchers that E-C models under-represent the opportunities for behavioral change that can enhance the quality of our lives in a low-carbon society[4].

E-C Models have been instrumental in getting us to this point. E-C models have helped us understand how human systems drive greenhouse gases (GHG) and climate change, how climate change would in turn impact us, and what changes in our energy system would be required to mitigate climate change. We have learned about the pace of decarbonization required to avoid the worst effects of climate change, the portfolios of technologies that could get us there, and potential impacts of decarbonization on the economy and the environment. E-C models also shed insights on the potential trade-offs and synergies between different choices for reducing emissions. The IAM scenarios of climate stabilization feature in the Intergovernmental Panel on Climate Change's (IPCC) periodic reports on the state of science. These scenarios are used widely by different communities, including policymakers, finance, development agencies, and researchers who want to understand what to expect from future climate policies. As we move towards designing and implementing effective policies, we need to better understand how individuals and societies across the United States will respond to energy/climate policies. The E-C models can play an important supporting role to anticipate these responses, assess the impacts of policies on different social objectives, and track their collective progress in reducing emissions.

I now lay out some of the research challenges for enhancing E-C models to (1) address equity and social justice; and (2) expand opportunities for identifying wellbeing-enhancing and GHG-reducing consumption.

Addressing Equity and Social Justice

The IPCC has repeatedly emphasized that low-income communities globally are likely to face a disproportionate burden of climate change and of efforts to mitigate its effects. Events such as Hurricane Katrina have shown us that this applies to disadvantaged communities in the U.S., particularly people of color. The social sciences offer a rich understanding of the structural and environmental conditions that perpetuate poverty and inequality. Racial inequalities in energy burdens in the U.S. are stark. Low-income Black communities spend more than double the share of income on transport as the average American, while a third of them have no vehicle and poor transit options. Mortality during heat waves is higher in low-income Black communities, very likely due to lower use of air conditioning.

Studies that examine the limitations of E-C models in representing poverty and inequality show that there are many aspects to improving E-C models[5]. One prerequisite step in this direction is for E-C models to incorporate more detailed representation of households. This includes: disaggregating households based on structural differences; incorporating social and contextual factors into how people make decisions; broadening model outcomes to include non-economic dimensions such as health.

E-C models mostly rely on single 'representative' households in regions, with the assumption that, in aggregate, differences within regions balance out. However, policymakers may want to target subgroups for social protection or support for green investments. Without proper social protection, green investments can worsen poverty by increasing energy prices, or be out of reach for low-income households. For example, low-income households or those with senior citizens in hot climates may need financial support to run air conditioning if energy prices increase. Contextual conditions such as whether they live in cities, or socio-demographic characteristics, can also influence the scope for new technology adoption. For instance, electric scooters and car-sharing options may have greater potential in cities where more people can access them. Policies for energy efficiency retrofits may have to be designed differently for homeowners in the suburbs and rental units in multi-rise buildings. Few E-C models have started segmenting households based on income. Models could incorporate other structural factors to reflect different needs and likely responses to climate policies.

Household decisions in E-C models typically represent individual preferences and responses to price changes. The social sciences offer insights on how social norms, neighbors' actions and various constraints can shape individual decisions. For instance, homes located near those that have rooftop solar panels are more likely to invest in it themselves. On the other hand, the 'digital divide' may be a barrier to widespread adoption of new electric mobility options and 'smart' devices in homes that require the use of smart phones and the Internet. Making these effects more explicit in models can enable more realistic assessments of technology adoption. Further research is required to examine specifically the adoption of new green technologies, which may present opportunities and risks to new users.

The energy services we enjoy have far-reaching impacts on our health and wellbeing and on that of others. Economic indicators, such as households' energy expenditures, typically measure the financial burden households bear for these services. However, expenditure shares may mask different levels of service if people forego services that they cannot afford. For instance, heating and cooling our homes provides comfort and protection from extreme climates only if we turn devices on. Energy services may be instrumental to meet other needs. How much time and money people spend on transport influences their job opportunities, access to nutritious food, and the scope for other activities. Making these connections requires developing new indicators of energy services besides economic costs. We would also learn of the inter-dependence of people's wellbeing through the byproducts of their energy use. Automobiles cause air pollution that affect public health. On the other hand, new electric mobility options reduce local air pollution but may increase pollution from power plants, which disproportionately harm communities located near them.

Opportunities for Wellbeing-enhancing Mitigation

Household consumption choices may affect wellbeing and cause GHG emissions in less direct ways. Research in the social sciences shows that beyond a point increasing material consumption adds less and less to our wellbeing. Climate researchers have identified many wellbeing-enhancing changes in consumption patterns that would reduce GHG emissions, such as reducing beef consumption[4]. Even more profound changes in our lifestyles, such as reducing waste, shifting to shared mobility options, using products longer through better care and maintenance, can reduce material use and free up societal resources to improve our lives in different ways. The resulting reduction in material and energy demand from these lifestyle shifts can ease the burden on the pace of future decarbonization of energy supply. However, we need more research in the social sciences to examine the feasibility of these changes and realize these potential benefits.

New research in wellbeing assessment over the last couple of decades offers new data and insights on different dimensions of wellbeing in communities across the United States. However, we lack a systematic understanding of how different lifestyles and consumption patterns contribute to wellbeing in different communities and contexts. Bringing together research in wellbeing and consumption in the social sciences with climate research may reveal new opportunities to pursue consumption choices that reduce GHG emissions and improve wellbeing.

Way Forward

The above comments aim to identify the potential for E-C models to support the pursuit of equitable and wellbeing-enhancing climate mitigation policies by deepening how they model households' characteristics, decisions, and wellbeing. There is considerable knowledge from past research in the social sciences that can be harnessed, but new research and data will also be required.

One could identify at least two approaches to moving forward — one that involves continuing to improve the models themselves; another is for social scientists to critically interpret decarbonization pathways generated by E-C models to assess their feasibility and consonance with knowledge in their disciplines. Both approaches will likely require significant commitment to interdisciplinary research, and collaborations across diverse disciplines within the social sciences and modeling communities. Based on my knowledge of ongoing research in the climate modeling community in Europe, including my own research, there has been significant funding and research into building more realism in E-C models through collaborations with social scientists.

As mentioned, one important step in this direction is to develop a finer-scale disaggregation of households in E-C models to better characterize their energy service conditions. The E-C models are already setting up for this. With the promulgation of the Sustainable Development Goals (SDGs), and the increase in the number of climate pledges at various levels of government, there has been growing interest to apply E-C models to include more fine-grained analysis at smaller spatial scales and shorter time horizons, while also addressing broader social objectives[6]. However, there are still large knowledge gaps and methodological challenges in this research direction. Moving from global and regional to local within models may be burdensome and present computational challenges. Alternative approaches need to be assessed, such as coupling local and regional models.

There exists already a wealth of data in the U.S. from national household surveys by various government agencies that periodically collect information on different aspects of household characteristics (e.g., the American Communities Survey, American Housing Survey, Residential Energy Consumption Survey, Survey of Consumer Finances, and numerous others). These data would be a valuable starting point. It is also likely that new data would need to be collected through new surveys and community engagement to identify disadvantaged communities that are under-sampled in these surveys.

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Dr. Narasimha D. Rao is an Associate Professor of Energy Systems at the Yale School of the Environment. He also serves as a Senior Research Scholar at the International Institute for Applied Systems Analysis. Dr. Rao has two decades of global experience in energy, first as an energy consultant and for the last decade as an academic. Dr. Rao's research examines energy systems, climate change and human development. He is particularly interested in equity in energy transitions, and the impacts of climate change and its mitigation on poverty around the world. He is a contributing author to the IPCC's Sixth Assessment Report. He was a recipient of the European Research Council (ERC) Starting Grant for a project entitled Decent Living Energy – which examines the energy and climate impacts of poverty eradication in emerging economies. He was recently featured as a climate visionary in the New York Times. He received his PhD from Stanford University in Environment and Resources, and has two Masters from the Massachusetts Institute of Technology in Technology Policy and Electrical Engineering. His CV and further information can be found here.

Chairman BOWMAN. Thank you, Dr. Rao.

At this point we will begin our first round of questions. The Chairman recognizes himself for 5 minutes.

Dr. Rao, thank you for your fascinating testimony. I wanted to follow up on your comments about climate policy focused on well-being. I believe we need to break out of the simplistic economic assumptions that too often shape the parameters of policy, and your remarks underscored that for me. In a country where the rich have massively higher carbon footprints, achieving a fairer distribution of wealth is a matter of climate policy. Giving people more time to care for and enjoy their loved ones is a matter of climate policy, too, because we need to shift away from harmful kinds of consumption and toward an abundance of the things that genuinely improve quality of life.

If we went big on investing in the modeling improvements you described and integrated cutting-edge social science, can you say more about the different kinds of possibilities that might be opened up? Would that kind of modeling allow us to demonstrate how climate action and building a better society can go hand-in-hand?

Dr. RAO. Yes, sir. I do believe there are many opportunities that are opened up to seek a more equitable society from pursuing climate policies that we assess in models that assess a wide range of impacts besides economic impacts.

So I'd like to classify them into two types of opportunities. One of them is to be able to alleviate some of the existing burdens that people already face from their energy situations. So, for instance, if we think about people who live in inner cities who don't have access to transit today, they may not have vehicles, and the existing options may be too cumbersome for them to really travel outside their neighborhoods in order to seek employment opportunities or seek places where they can buy nutritious food. New mobility options such as car-sharing options or introducing new routes, electric buses, for example, these could potentially fill a gap in the existing services that they receive today.

And so if we can understand with social science research these vulnerabilities that people have in different parts of the country, understanding the actual energy burdens they face, not only economic but actual deprivations of energy services, we may find ways that these new abilities, these new options could actually meet some of these needs that aren't being met today.

Another example might be heat stress. We—if we understand better the extent to which people are not using equipment today in order to keep their homes cool in summer or warm in winters, we can potentially think about upgrades to buildings that can offer new technologies that could alleviate problems such as respiratory illnesses due to mold, it can make sure that they have the ability to afford to heat their homes as well or cool them in summer. So these are some of the options that we can exploit with these new technologies, and social science can help us understand the potential for that.

There also are other range of opportunities that we open up in thinking about well-being when you consider our broader consumption. So, for example, we may think about the fact that we waste a quarter of our food supply, and that has an impact on greenhouse gas emissions. We have a lot of congestion and air pollution from our use of private vehicles in cities. If we introduce policies that can encourage people to use transit, to share vehicles, we can reduce air pollution, which may affect particular communities, and we may raise the overall level of resources that are freed up by reducing waste and channel them to improving our well-being overall. So those are some examples.

Chairman BOWMAN. Thank you, Dr. Rao. I wanted to try to squeeze in one more question.

Dr. Takeuchi, thank you for your testimony as well. I want to zoom in on what you said about training the next generation of scientists and leaders and ask if you have further reflections on that subject. I may be biased, but as a former teacher and principal, I tend to think that education is the answer to everything and particularly more equitable education so that we are tapping into the potential of communities that have seen decades of disinvestment. We've had several discussions on this Committee about the role of education in preparing our young people for the green energy transition. Given what you've told us about the importance of interdisciplinary research and collaboration across different aspects of a scientific problem, do you see ways that we can infuse those principles into STEM education more broadly, particularly at the K to 12 level?

Dr. TAKEUCHI. Thank you, Chairman. I'm going to have to speak quickly here. I think part of the key is to making sure that everyone is included. I'm extremely proud of our own research group that is highly diverse not only in ethnic and cultural background but gender as well. The FRC team that I assembled is also highly diverse, and I think demonstrating to people that everybody counts is a key aspect of showing people that there's an opportunity for them so they don't feel left behind or excluded.

Chairman BOWMAN. Thank you. I now recognize Mr. Weber for 5 minutes. Oh, excuse me.

Mr. WEBER. I'm here. I'm here.

Chairman BOWMAN. Disregard. Who's next in line to ask questions? My apologies.

STAFF. Mr. Weber is next.

Chairman BOWMAN. Thank you.

Mr. WEBER. If I can figure out how this machine works, I can do this. Can you all hear me? Mr. Chairman? OK, thank you.

Dr. Persson, in your opening—like I mentioned in my opening statement, I recently introduced the *CAMS Act*, which I think you will—I hope you will agree really touches in a good way on a critical area of research in addition to establishing computational materials in chemistry science and in materials research data base. My bill aims to improve materials science research by applying advanced computing practices to emerging chemistry and materials science challenges. It did not escape me that one of the other witnesses—I think it was—is it Dr. Takeuchi—said that we are in a race, and boy, she's right about that.

Anyway, Dr. Persson, you said in your testimony that 45 million data records are requested and delivered daily, and tens of thousands of community researchers log into the materials data base every single day. If you could quantify it, how much or what percentage of that data is being fed into advanced computers or artificial intelligence algorithms, No. 1, first question? No. 2, how unique are DOE's computing resources and knowledge and how would they help improve your particular materials research? And I'll stop for your answers.

Dr. PERSSON. Thank you for that question. I—indeed, I am passionate about this subject. This is the foundational work that the Materials Project relies on and hopes to bring to the future.

Your question goes first about how much or the percentage of the data that gets fed into AI and machine learning, the best answer I can give to that is that every day a paper is published using Materials Project data that uses also the word machine learning. It's hard for us to track exactly how people use data, but that is one way. We can use natural language processing to look into papers rapidly, even though so many are published every day, and literally say, OK, they've mentioned the materials part and they've mentioned machine learning. Every day a paper is published doing that.

We have seen a tremendous increase of the number of data points the Materials Project delivers—is requested and delivers every day. From the last couple of years with the acceleration of machine learning as being such a popular and powerful way to address materials innovation and design, the—being the only data base that gives this many properties for materials available, this is why we're seeing such a tremendous increase.

Your question—the second question was on the DOE computers. The—they're amazing. We would never be able to do what we do today without them. I have had tremendous support from—for example, from NERSC (National Energy Research Scientific Computing Center) and Berkeley Lab but also from places like NREL (National Renewable Energy Laboratory) and Argonne in terms of using their computers.

There are different kinds of computers useful for different things. If you're doing climate modeling or social sciences modeling or materials research modeling, and the one thing I would say is that we need the diversity of computing architectures to address all of those different kinds of computing needs. And I'm really happy to see that those are being met at different kinds of computing centers in the United States.

Mr. WEBER. So do you go onsite to use those computers? How often do you interface with those computers?

Dr. PERSSON. We run 24/7. I don't—thankfully, I don't have to go there in person. We are scripts and our algorithms run every day 24/7 as long as they have up time. Sometimes they go down for maintenance, but that is the only time we don't run.

Mr. WEBER. And you say there's many, many papers every day published. You're right, this is absolutely fascinating. Who keeps up with those papers? How do you talk to your colleagues? Who decides what papers, what's the best article? I know you're limited by time.

Dr. PERSSON. No, that's a great question, too, and we are struggling with out. There's no researcher today that can physically read every paper that's produced, so we're actually starting to use automated ways to analyze which papers to read and how to read them.

So, like I mentioned, natural language processing is a way for machines to read papers and to extract the knowledge from them.

Actually, we have to—in my opinion, papers are wonderful, they're storytelling vehicles, but we also need to actually get the data out of them more quickly. That's one way of doing it. But if we were better at putting the data in places like data bases like the Materials Project, we would have to go back and actually extract different papers. So in my opinion we should do better.

Mr. WEBER. Well, hence the need for advanced supercomputing in a major way. And I have a lot more questions, but I'll yield back. Thank you, Mr. Chairman.

STAFF. Ms. Johnson is next.

Chairwoman JOHNSON. Thank you very much, Mr. Chairman.

Oftentimes when people think of climate science research they think of NOAA, the EPA (Environmental Protection Agency), NSF (National Science Foundation), and understandably so because they may forget about the vital work of DOE and what they do in this space such as contributions to the national climate science and modeling efforts to the U.S. Global Change Research Program and the international level through contributions of the Intergovernmental Panel on Climate Change.

I'd like to ask Dr. Zeng, can you discuss what makes—I'm sorry. Can you discuss what makes the Department of Energy uniquely qualified among the Federal Government science agencies to conduct climate science research? And then to what extent do these agencies currently collaborate on climate science research?

Dr. ZENG. Thank you for the question. Among the different Federal agencies, when I think of DOE, I can think of a few unique aspects. The first one is DOE's climate model is optimized for the fastest computers in the world. This is super fast exascale computing. It is a big deal because the hardware speeds of the supercomputers can be ranked and benchmarked, but what's equally important is what's the percentage of those capabilities actually used? This is related to architectural and the software engineering of the climate model. And the DOE is moving very rapidly in that direction. The lessons learned and the best practices of DOE can be followed and will be used by other agencies and worldwide.

The second unique aspect is about the coupled human-Earth system model. There are around 50 Earth system models, and there are around 10 human system models in the world. And only DOE is in the process to bring them together. So with limited time I just give you those two examples.

And in terms of the multiagency collaborations, there are already some interactions of different levels. Scientists supported by different agencies are talking with each other all the time, and the program managers from different agencies are talking with each other. Even today, we are having our scientific steering group meeting, so I escape from that meeting, come here to testify. And it's there we have managers from different agencies in the United States and worldwide. There is cross-agency collaboration mechanism such as the U.S. Global Change Program. But I still—more can be done, particularly on big projects.

I'll give you an example. If you cannot balance your checkbook, you don't feel good. But if we ask we cannot balance our water for major basins for Mississippi, for Colorado, as scientists, we do not feel good either. In other words, we don't know exactly how much water go to the Colorado River Basin, how much water come out and where are the sources and the sinks. And the community wants to have big projects working together with different agencies to solve this kind of grand challenge.

I will stop here. Thank you.

Chairwoman JOHNSON. Thank you very much. One other question. In developing legislation to reauthorize activities of the Biological and Environmental Research, the BER program within the Office of Science, we've heard from stakeholders that there is a gap in research funding mechanisms. I understand that this program funds large-scale experiments and the user facilities we've heard a lot about in this hearing and also small individual research grants, but there is no in-between. So do you think that the BER program could benefit from having a midscale funding mechanism to fund research that would be carried out by multiple institution research centers, similar to the Office of Science's Basic Energy Sciences program that supports the Energy Frontier Research Centers?

Dr. ZENG. Making it simple, it's a great idea. I just hope at one more point these university partners should also include the involvement of underrepresented groups such as students from minority-serving institutions and historically Black institutions and universities. Thank you.

Chairwoman JOHNSON. Thank you very much. I yield back, Mr. Chairman.

STAFF. Ranking Member Lucas is next.

Mr. LUCAS. Thank you, Mr. Chairman. And I would address my questions, my inquiries to all the witnesses.

As I mentioned, *SALSTA* doubles our investment in basic research in the Department of Energy over the next decade. What role do you think of DOE's Office of Science and its national laboratories play or perhaps I should say should play in enhancing our competitiveness with other nations in science and technology? And while you're thinking about that, what if anything should we be doing to enhance DOE's role in our Federal research enterprise as we seek an edge over international competition? And I throw that open to the entire panel.

Dr. TAKEUCHI. Let me just make a few opening comments. I think——

Mr. LUCAS. Please.

Dr. TAKEUCHI. [continuing]. BES investment is really critical because it does lay all of the foundational science, and I think that the continued DOE investments in the more applied offices are also critical because we need that translational infrastructure to ultimately end up in the private sector as well. So the way I see it that there's really four circles. Academics, national labs, industry, and let me add policy all need to work together to advance the field to accomplish what you're talking about in having international competitiveness.

Mr. LUCAS. Anyone else care to touch on that?

Dr. ZENG. Yes. From the——

Mr. LUCAS. Please.

Dr. ZENG [continuing]. Our sides, there is substantial competition from our partners in Europe. They are very aggressive in terms of supporting big science. And our hope is that we want to maintain our leadership. In terms of the coupled human-Earth system modeling, the integration of modeling with exascale computing and our observing user facilities in each area, OK, even today, we are having the international steering committee meeting. You can see there are very ambitious projects supported by E.U. And on the American side, the DOE is always about the big projects. Besides the small and now we talk about midsize, we need those ambitious big size projects to maintain our leadership.

Mr. LUCAS. Anyone else care to touch on that subject matter, the question?

Dr. PERSSON. I'd be happy to. I completely agree with the latest comments. I have collaborators and colleagues in Europe and also in Asia, and what I can see, for example, the Materials Project funding, they are getting funding that are four times that. They're still behind us because, quite honestly, American innovativeship—innovativeness is hard to beat, and we're also the first ones to do what we did. But in the end funding will matter, so that is the one big vehicle.

I also—I see the tremendous passion that the scientists at the Molecular Foundry and the NSRCs and the labs have for working with our community. Doing that better, being vehicles—bringing in vehicles that allows, for example, professors and graduate students and postdocs to travel from the rest of the country to be part of the knowledge sharing and the ideas that we leverage to solve our future problems, that would be a big deal for the user facilities and for our communities in general.

Mr. LUCAS. Anyone else?

Dr. RAO. Sure. I'd just add one small point here.

Mr. LUCAS. Please.

Dr. RAO. I wanted to mention that the European Research Council, I've recently seen their strategic plan over the next 5 years for research and they've allocated $15 billion toward climate. And one of the main elements of that strategic plan is to have social science and humanities research be a core part of every single cluster that they have announced. And so I think, you know, interdisciplinary collaborations within the sciences and social science to really understand how we can have widespread adoption of these technologies I think would be also valuable.

Mr. LUCAS. In my few remaining seconds, and I have to ask from both perspectives, what if anything we should not be doing, we should not be doing? And you don't have to answer, but your insights are appreciated.

Dr. ZENG. Yes, I do have one comment here. I don't have a direct answer, but I feel accountability and a metrics for success is crucial.

Mr. LUCAS. Fair enough, Doc. With that I see the balance of my time is expiring. Thank you, Mr. Chairman, and I thank all the witnesses for their insights today.

STAFF. Ms. Bonamici is next.

Ms. BONAMICI. Thank you so much. Thank you, Chair Bowman, Ranking Member Weber. Thank you especially to our witnesses for your expertise. This is an excellent discussion this morning.

I represent northwest Oregon, and here, the climate crisis is not a distant threat; it's really a reality. We see it in many ways. And the need for robust climate science will only grow as our communities and our economy experience the increasing effects of the climate crisis.

I'm honored to serve on the Select Committee on the Climate Crisis. Last year, we released our bold, comprehensive, science-based climate action plan to reach net zero emissions no later than midcentury and net negative thereafter. And we acknowledge that we need high-quality, peer-reviewed climate science to serve as the foundation for our efforts to solve this crisis. Our plan calls for robust climate science research, observations, monitoring, and modeling activities, including support for Earth observations, climate model development, international collaboration, and improvements in data and computing infrastructure.

And I know certainly on this Science, Space, and Technology Committee we have a lot of support for quantum computing and we've shown that over the years.

Dr. Zeng, I'm the Co-Chair of the bipartisan House Oceans Caucus, so I'm particularly interested in your research on the land-atmosphere-ocean interface processes in the Earth system. How can efforts through the Biological and Environmental Research program within the Office of Science better inform our understanding of sea level rise and other effects of the climate crisis on coastal communities?

And following that, Dr. Rao, how can we make sure that this research better integrates the socioeconomic modeling to support frontline communities in those coastal regions?

Dr. Zeng?

Dr. ZENG. Yes. You know, you pick up all those crucial topics. Actually, DOE's climate modeling at this time has three focus areas. One of them is cryosphere in terms of the Antarctic and Greenland ice sheets melts, how does that affect sea level rise? For Oregon, of course, as a coastal state, and DOE just initiated a new program on the coastal study for the interaction between ocean, lands, and atmosphere.

So, obviously, DOE research and the results will directly benefit States like Oregon. Even from my own research is directly relevant to say our Nation's weather forecasting, my group has contributed the software developments for the weather forecasting every single day over ocean and over land, of course, including Oregon.

Now, in terms of the social sciences sides, DOE does have a multisector dynamics program that's about human system modeling. There, human activities are included, things like urbanization, irrigation, agriculture, deforestation, for example. And the socioeconomical projects are also included. What has not been treated well is about the human behavior. We are human beings. We have a lot of complicated decisionmaking process. Those are the processes——

Ms. BONAMICI. And, Doctor, I don't want—mean to cut you off, but I want to ask a Dr. Rao that question as well and then I have one more question I wanted to try to get in. Dr. Rao, can you add anything to the social services—or, excuse me, social sciences aspect of the ocean and economic model?

Dr. RAO. Yes, thank you very much. Just to build on what Dr. Zeng was saying, which I agree with, we need a deeper representation of households, which includes looking at the spatial regularity, so understanding what populations are located on the coast, what are their characteristics in terms of income and other attributes. We need to understand the physical infrastructure around them in order to assess the vulnerability to sea level rise and other impacts. We need to think about migration, migration into coastal areas and away from coastal areas and what—under what conditions people are amenable to that. And there are models that are trying to look at that in terms of climate resilience and adaptation, but we need a lot more granularity to really understand and make them responsive to future conditions.

Ms. BONAMICI. Thank you. I'm going to get one more question in. Dr. Takeuchi, in your testimony you talk about the importance of teamwork, working in partnership to develop new generations of battery and energy storage. As a longtime advocate for integrating the arts into STEM education, I truly appreciate your arts analogy of a symphony orchestra bringing together—you know, with a conductor bringing together everyone. You talk about that in your collaboration potential of the Energy Frontier Research Centers.

So recognizing that the existing lithium-ion batteries will not meet the growing need for more complex energy storage challenges like electric vehicles or a clean energy grid, how can the Basic Energy Sciences program better support that type of collaboration to accelerate the development of clean energy technologies and energy storage?

Dr. TAKEUCHI. I do think that the program such as the Energy Frontier Research Center and the hubs are really outstanding vehicles to bring together teams of scientists and technologists and engineers to focus on kind of mission-driven science questions. So I think that those vehicles should be maintained, expanded where possible because they are outstanding concepts that allow addressing exactly the point that you're making.

Ms. BONAMICI. Thank you so much. I yield back. Mr. Chairman, I wish we had 5 hours per Member instead of 5 minutes. Thank you. I yield back.

STAFF. Mr. Baird is next.

Mr. BAIRD. Thank you, Mr. Chairman and Ranking Member Weber. I appreciate this opportunity, and I really appreciate the insight from the witnesses that we have here today.

As Ranking Member Lucas mentioned, I introduced the Department of Energy's *Biological Innovation Opportunities*, the *BIO Act* today, and it is to support DOE's biological research infrastructure initiative, which would include reauthorization of DOE's Bioenergy Research Centers and establish a program for the construction of Biological and Environmental Research user facilities.

And one example we've talked about across various disciplines in our discussion here this morning, there are multiple benefits for society that are derived from the Department of Energy's Office of Science basic research. And we are constantly looking for sustainable domestic biofuels and bioproducts that are derived from nonfood lignocellulose plant biomass. And for those of you that might be interested, lignocellulose is the most abundant biological material on Earth, and it's most often contained in plant cell walls. It's made up of long, tightly bound chains of sugars, polysaccharides, that can be either converted to biofuels and bioproducts by microbes. And so I am making the connection here because of agriculture and the role they might play or it might play in this energy solution.

But my question really deals with knowing the importance of this interdisciplinary Office of Science research and how important that can be, my question to the witnesses is how your perspective, what opportunities there are for additional BER user facilities? So I really want to focus on those user facilities, what we might derive from expanding and increasing the number of those. So, Dr. Zeng, would you care to express an opinion on that?

Dr. ZENG. Regarding biofuel or crops, the good news is that DOE climate model actually includes the treatment of biofuel crops in the model, so that means we can look at the potential impacts in the modeling system. For the biofuel itself, that's not really my research area. Probably I should not say anything I don't understand.

Mr. BAIRD. How about any of the other witnesses? Do you care to address that question about biofuels and the importance of research and the interdisciplinary connectivity?

Dr. TAKEUCHI. Representative Baird, I wanted to comment on your question regarding research facilities and infrastructure, and I wanted to point out that, for example, the synchrotrons are used very often in biological and pharmaceutical and clinical-type investigations. So I think that the fundamental infrastructure in terms of both the nano centers and the large-scale synchrotron facilities are also highly relevant to the questions that you're asking regarding biofuels and understanding the fundamental physiology and mechanism of plants.

Mr. BAIRD. Anyone else care——

Dr. PERSSON. I——

Mr. BAIRD. Go ahead.

Dr. PERSSON. I'll just add that even though this is not my core expertise either, the beauty of the NSRCs is that we have many different floors and many different expertise, and one of our floors in the Molecular Foundry is the bio floor. They work very closely in partnership with the JGI, the Joint Genome Institute, that actually works on biofuels.

So the number of user facilities that work together from the characterization of the light sources to the nano centers to the BER user facilities, they're all actually—that's part of the teamwork, too, that we have discussed previously and I would like to highlight it. It's a vital part of that innovation.

Mr. BAIRD. Very good. Anyone else have a comment? If not, I yield back the balance of my time, and thank you, Mr. Chairman. I yield back.

STAFF. Mr. McNerney is next.

Mr. MCNERNEY. Well, I thank the Chairman, and I thank the witnesses. This is a great subject. I majored in chemical engineering, and then switched to mathematics at some point in my career, but I really appreciate the testimony.

Dr. Zeng, cloud aerosol research and computing seem to help us understand some of the key climate challenges, but uncertainty on how aerosols impact on the clouds seem to hinder our ability to determine climate sensitivity to greenhouse gas levels. Reducing this uncertainty will improve our ability to forecast weather and climate. How critical is increasing investment in the modernization and acceleration of the Energy Exascale and Earth Systems Model program? Dr. Zeng?

Dr. ZENG. Yes. I'm thinking of two things. One is the research, and one is the application. On the research side, for example, I mean, a couple of weeks ago, news media asked me about hurricane activities because there are above average hurricane activities 5 years in a row. This year, we predict an above average hurricane activity. How can we predict hurricane activities in the future if we use today's climate model, the grid size is 50 miles. We cannot even see the eyes. What we need would be at least the 5 miles grid spacing and a DOE computer. And the climate model can do that to help the fundamental understanding.

And for the application sides and thinking about the DOE climate model can be used for the planning to assist in the planning of our Nation's energy and its related infrastructure, scenario analysis and risk analysis and about working with applied programs of the DOE.

Mr. MCNERNEY. Well, you mentioned a 2-mile resolution, so we have a little ways to go on that then. A 2-mile resolution is the—is what you'd prefer. How essential is artificial intelligence to climate models?

Dr. ZENG. It's crucial because the data volume becomes huge. Frankly, we human beings don't even know how to handle them anymore, so we need artificial intelligence from different perspectives, first help us to save computer time. Second, help reformulate the model processes and third, help us to do that uncertainty quantification and wherever possible, uncertainty reduction.

Mr. MCNERNEY. Thank you. Dr. Brushett, in November of 2020 the *Wall Street Journal* published an article in which Dr. George Crabtree, Director of the Office of Science's Joint Center for Energy Storage Research, discussed the crucial role that AI plays in the battery materials discovery process. What roles do emerging technologies such as AI and robotics play in battery storage in AI development and battery storage technology development?

Dr. BRUSHETT. Thank you for this question, and I think also Dr. Persson can also answer this, but I'll give you a first pass. I think AI and machine learning dramatically accelerate critical activities like materials discovery and material synthesis, which are two vexing bottlenecks in the development of new technologies. They do so by finding sort of hidden correlations between desired performance metrics, which we could calculate, and actually then finding the structure and composition of materials that would be able to meet those desired performance metrics. These correlations can then define new classes of materials that will likely exhibit those desired properties and performance. It's tens to hundreds of times faster than searching for new materials by laboratory sort of brute force computation. Long used in drug discovery, I think that this is the next way for discovery for energy storage materials and materials science in general.

Mr. MCNERNEY. Thank you. And I was going to follow up with Dr. Persson on the same question. I'm interested in AI. I am Chairman—Co-Chairman of the AI Caucus in Congress and the use of AI in battery development and the researcher's ability to interact with the AI-driven insights. Could you discuss that a little, please?

Dr. PERSSON. Absolutely. Thank you so much for your support of science in Berkeley lab in particular.

So materials science is not like the social sciences or like they can leverage Google. We're actually data-poor in many cases, which is so important to also have a vehicle for harnessing our data or where it comes from, from experiments, from computations so that you can actually train machine-learning algorithms on top of that data.

So the first part—and I always liken this to like you—machine algorithms are a Ferrari but you need fuel, the data, to actually run it. The automation—and I know I'm over time—is a really critical aspect to it, too. If we have more time later on, I'll be happy to elaborate on what that's needed to close the loop between the modeling, the synthesis, and the characterization faster.

Mr. MCNERNEY. Thank you. And I'll be visiting the Molecular Foundry sometime as soon as I can.

Dr. PERSSON. Fantastic.

Mr. MCNERNEY. I yield back.

STAFF. Mr. Feenstra is next.

Mr. FEENSTRA. Thank you, Chairman Bowman and Ranking Member Weber. Thank you to each of the witnesses for their testimony and sharing their extensive research and opinions with us.

The research and collaboration lead by the Department of Energy's Office of Science is crucial for the future of American energy. I represent Iowa's 4th District, a leader in wind energy, so I am thankful for the ongoing research into new energy storage technology and critical materials that are important for renewable energy. And with our State being a leader in clean-burning biofuels and other forms of bioenergy, I appreciate the work being done at the Office of Science and Biological and Environmental Research programs.

I have a question for Dr. Takeuchi. I was pleased to read about your research about leadership at one of the Energy Frontier Research Centers. It truly is a unique model that you pointed out that is similar to a conductor who understands an orchestra's music results from just one person and all the orchestra pieces playing together. Your specific EFRC focuses on scalable electrochemical energy storage systems, which are crucial as we grow wind energy in my district and across the country.

Elsewhere in the Office of Science and Biological and Environmental Research programs are the Bioenergy Research Centers. And in my district, Iowa State University is a partner in one of these BRCs called the Centers for Advanced Bioenergy and Bioproducts Innovations, which focuses on increasing the value of energy and crops and converting biomass into valuable chemicals.

So this is my question. My question to you is at what level of interaction do EFRCs have with any of the Bioenergy Research Centers, and what role do Bioenergy Research Centers play in being part of this group of people aiming for this common goal? Is increasing collaboration something that I could or we in general could assist on moving forward? Could you comment on that?

Dr. TAKEUCHI. Thank you very much for your question. I just have to say really quickly I understand your interest in wind energy. I live on Long Island, and soon, we will have some of the greatest offshore wind energy in the entire country, so we will face similar challenges for integration.

One of the things that DOE does very effectively is bring together the different Energy Frontier Research Centers in things called principal investigator meetings where the different centers focused on different areas come together and share their research and findings to facilitate interaction among the different groups. And I think that could be readily expanded to not only include BES but BER as well where cross-population and cross-fertilization of ideas and findings could really be facilitated, and by sharing the findings, the different groups can then internalize how those findings would be relevant to their specific areas of research even though the specific thing that they are researching is different. And that can be a really effective way to kind of fertilize that interaction and make sure those communications take place.

Mr. FEENSTRA. Thank you, Doctor, for that answer and those comments. I have one other question for everyone. One of the newer technologies that I have heard promised about is in regard to fuel cells. As you know, fuel cells can use a variety of fuels, including bio-based fuels, which is of particular interest in Iowa. In fact, Dr. Persson of Lawrence Berkeley National Laboratory has been awarded funding to conduct research into metal-supported solid oxide fuel cells for vehicles that could be used as part of the rapid start fuel cell system that uses the liquid bioethanol as a fuel. This is just one example of how biofuels could fit into future fuel technologies that dramatically lower our transportation sector carbon footprint.

An open question to all witnesses, do you think we should drive more research into renewable fuel technology as an alternative to petroleum?

Dr. PERSSON. Maybe I'll start. I think that it's—one of the beauties of biofuel is that we already have an infrastructure for liquids, and it nicely also ties into our climate mitigation. If we could harness CO_2 and turn that into viable products, which is something that we work on from LiSA (Liquid Sunlight Alliance), which is the continuation of JCAP (Joint Center for Artificial Photosynthesis), of one of the innovation hubs, of how actually to turn CO_2, and that is also a materials problem, right? You have to actually come up with the catalyst that helps you to turn CO_2, which is an extremely stable molecule, into a liquid fuel that you can burn and become carbon neutral.

At the Foundry, we also have several users that come to the Foundry with exactly that dream. They come from places like Houston in Texas or out in California with—and having seen their environment where they grew up and the climate impact on that environment, then they bring that passion and they bring their ideas to places like the NSRCs. And we work together with them to find solutions. We have startup companies that work with CO_2 capture and turning that into actually a viable fuel.

So that is a similar problem, but I'm going to turn it over to others.

Mr. FEENSTRA. Well, thank you so much, and I yield back. I ran out of time, but thank you so much.

STAFF. Mr. Casten is next.

Mr. CASTEN. Thank you so much. The—this panel is—I don't mean to get all scientific, but you guys are awesome. I'm learning so much here. I really appreciate it.

I got concerned several years ago that the—as we are deploying increasing volumes of intermittent renewables on our grid, we have the potential to start seeing increased CO_2 emissions, not because the renewables are generating CO_2 but because the only tool grid managers have is really inefficient partially loaded but quickly ramping gas cycles that ramp up and down to balance. And we started seeing some evidence of that in the Midwest where I'm from in Illinois a couple years ago. And it was really—and that was really what drove me to introduce the *Grid Energy Storage Act* last term, which worked with Congressman Foster, became the *BEST Act*, which was signed into law by the prior Administration to put about $1 billion into research, development, and deployment of grid energy storage because, of course, we're going to do grid energy storage or transmission to solve that problem. There's—there are not a lot of other solutions to it. Hopefully, we will get that appropriated shortly and it will help support some of the research that all you people are doing here.

But I want to start with you, Dr. Takeuchi, given your expertise on grid energy storage systems. Can you give us some sense of where are we at best-in-class right now especially around, you know, energy density and cost per kilowatt hour, and where do we need to get to before we're really going to have viable—commercially viable grid energy storage systems to start to balance out some of those imbalances in our system?

Dr. TAKEUCHI. Thank you very much for the question. You know, in terms of energy density, my own personal belief is that for installed systems, the energy density itself is a little bit less critical than in applications like vehicles or portable power because most of the time it doesn't have to move. You know, we put it in place and it sits there.

I think that the two critical things really are longevity and cost and they're related. Longevity is extremely important because then you can amortize the cost over a longer time. If the thing can last longer, you don't have to replace it as often. So I think we're still a distance away in terms of the cost targets that the utilities would like to see. I interact with many utilities in the Northeast to understand their needs and concerns.

And I think another area that's really critical is the understanding and the education and the interaction with the ultimate customer, meaning the utility and the ultimate user, to make sure that the energy storage technologies that are deployed are deployed in an effective way such that their longevity, their lifetime, and their efficiency is maximized through the use profiles.

So we're developing modeling systems on that integration question to make sure that when the energy storage is integrated, that it's integrated in the best place, best location, and with the best usage profile to, let's say, optimize the cost deployment profile.

But the amount of research dollars that has been invested in grid scale storage is still far, far, far less than things like vehicle technology, et cetera, so there's still work definitely that needs to be done.

Mr. CASTEN. Well, thank you. And I could ask Dr. Brushett or Dr. Persson the next question, but I'm going to go with Brushett only because I started my career at Arthur D. Little in Fresh Pond, and we cross-pollinated with a lot of your folks at—over at MIT. And of course now Argonne National Lab is just south of my district.

The Advanced Photon Source, which of course is part of the BES program, has done all sorts of just fascinating things to develop some of these advanced battery chemistries. In the minute or so we have left, can you maybe just share with us some of the tools that we can use through that APS program to help develop these larger scale—particularly in the energy grid storage batteries?

Dr. BRUSHETT. Thank you. I'll do my best in the time that remains, and if you would like some more information, we can certainly follow up.

So I think one of the things that Professor Takeuchi mentioned was lifetime associated with grid scale batteries and understanding how those batteries might decay over the lifetime and establishing mitigation strategies early on to allow them to last for longer and to allow us to use cheaper materials. A lot of the phenomena that we need to see our atomistic changes in catalysts or in electrode-type materials within that battery, and being able to see those often requires resources that you need to penetrate into an operating battery and see how the dynamic processes are occurring on that interface. It's not possible to do that at top-tier research facilities like MIT. You really need synchrotron resources and those powerful x-rays to peer inside the battery and understand where decay mechanisms are coming from. And so that's how we've been using it to understand how we can extend lifetime of these new materials.

Mr. CASTEN. Thank you so much. I'm out of time and yield back. Dr. Persson, I'm sorry I didn't get to you, but if you do have more comments, please feel free to follow up with our office. Thank you.

STAFF. Mr. Gimenez is next.

Mr. GIMENEZ. Thank you, Mr. Chairman. And it's been really fascinating listening to all the experts on the questions. I share my colleague's fascination with fuel cells and think that that is a viable alternative to large-scale batteries on transportation simply because of the refueling time and the impact that actually if we moved everything into electric vehicles, the impact that's going to have on the grid. And also how do we dispose of these batteries at the end of their useful life? I don't think we have a great answer for that.

So—but regardless of that, my first question I guess is to Dr. Persson. And where do you think the United States lies right now in terms of computing power? Are we No. 1, are we No. 2, and is the world catching up with us?

Dr. PERSSON. That's a good question. I think the way I would see it—so I—there's competitiveness out there. I don't—I'm not entirely sure we're No. 1. But the No. 1 question is a multifaceted question. Is it really just the exascale, like how fast? Is it really just how many CPU (central processing unit) hours you're getting? It's—or how many of those processes do you have? The important part is that we invest in the computing that will drive our innovation forward.

So I'll give you an example. Some of our computing centers are particularly well-suited for certain algorithms. Some algorithms that I run can only run on other computing systems, so it's important to ask the question maybe what computing do we need to solve today's and maybe the next decade's problems? So, for example, machine-learning algorithms run on certain computers. The kind of algorithms that materials scientists run, run on other kinds of computers. And I do think in terms of those, we're leading.

Mr. GIMENEZ. How fast is the world catching up to us, and who is our leading competitor? I already know the answer, so go ahead and answer.

Dr. PERSSON. I would venture to guess that China is our competitor when it comes to the computing.

Mr. GIMENEZ. OK. In terms of artificial intelligence because I think that's the great leap that we have—we have to win the race to artificial intelligence. Once we do that, then I think that, you know, the knowledge that we have and the ability to take unlike concepts and put them together and come up with something revolutionary is just going to take off. And so where are we in terms of the development of true artificial intelligence? And again, how close is our nearest competitor or are we lagging behind right now in achieving that?

Dr. PERSSON. So there are two aspects to artificial intelligence. It's the data part, and it's the machine-learning part, the algorithm part. The machine-learning algorithm part is very tightly integrated with our ability to compute fast and efficiently in certain ways, so, for example, quantum computing is one of those avenues toward actually making artificial intelligence a reality.

If I were to bring that back to my field because I would have to refer to experts in computing architectures to really truly talk about that aspect, if I bring it back to my field, quantum computing is inherently tied to materials. We don't have the materials today that can realize quantum computing in a cost-efficient way that operate with higher coherence that can actually like have those electrons talk to each other without losing signal across information flow. That is a materials problem, and that's one of the problems that we work on as materials scientists to try to enable the materials that can do that kind of talking lightning fast.

Mr. GIMENEZ. Is that a material——

Dr. PERSSON. Yes.

Mr. GIMENEZ. Is that a material problem just for the United States or is it a material problem that the world has?

Dr. PERSSON. Everywhere. Everywhere. That is a fundamental global and I would say precompetitive problem in the sense that the mechanisms for decoherence, for losing that signal strength is a precompetitive problem that BES funding is coming into. The actual material that eventually will go into a quantum computer, a truly successful one, that is more of the sort of more proprietary pathway.

Mr. GIMENEZ. What can we do as a government in order to help you? I know it's going to be money, but what else can we do to help you to achieve—for the United States to be the leader in artificial intelligence and computing and maintain its leadership?

Dr. PERSSON. So I would say that, again, going back to those two pillars, right, the computing, the materials aspect, and the data, we need data to actually train the machine-learning algorithms. They don't work—they don't—they cannot operate without huge amounts of data to train them. We are not leveraging the data that's already being produced today in our user facilities, in our basic research programs because it's such huge amounts, right? And that's great, that's awesome. That means our scientists are immensely productive. But imagine now that you harnessed all that data and you learned from it more than just reading an article, which is hard enough to keep up with. If we harnessed our data in a more efficient way today, we cannot only turn machine-learning algorithms, we would be much more efficient in using the knowledge for [inaudible].

Mr. GIMENEZ. Thank you so much, and I guess I'm out of time and I yield back. Thank you.

STAFF. Mr. Lamb is next.

Mr. LAMB. Thank you all for hanging in there with us and for appearing today and sharing all the information that you have.

I wanted to ask—I think maybe this is a question for Mr. Brushett, but I'll leave it open to anybody. With respect to the state of things today for grid scale battery storage, is it correct to say that in the United States the length of time that any grid scale battery installation lasts is somewhere around 4 to 6 hours at most? Is that like an upper limit of where we are today?

Dr. BRUSHETT. In terms of how you might want to use that application, yes. Most of the applications would require 4 to 6 hours of storage or less. Is that what you intended to say, Mr. Lamb?

Mr. LAMB. I think what I mean is just in practical terms if we lose power generation at 10 o'clock at night, is there anywhere that lasts beyond 4 a.m. the next morning? That—my understanding was that that was the roughly the limit of where we are now in terms of intermittency and the ability to cover that period.

Dr. BRUSHETT. Yes, I understand, and that is a correct understanding. Most of the backup battery installations that exist in the United States are designed for 4 to 6 hours largely for at time of energy management, so shifting energy from one part of the day to the other.

Mr. LAMB. OK. And do either you or Ms. Takeuchi or anybody, do you guys have a sense of the time it will take us from today to transcend that in a meaningful way, you know, to get to not just 10 hours but to 100 hours with specifically batteries? I know there's other storage technologies and everything but just kind of the outlook for battery R&D?

Dr. BRUSHETT. So that's happening right now. There is ongoing research in long-duration energy storage that extends to, we'll say, multiple—a daylong worth of storage all the way out to a couple of days to, say, cover an outage that lasts for a week or a few days. Some of that work is sponsored within JCESR. One example is Form Energy, which is focused on, as you mentioned, a 100-hour battery, but some of that research nucleated in JCESR looking at long-duration energy storage with ultracheap materials and then ultimately spun off as a startup that became Form Energy.

There's also increasing research within JCESR and other parts of the DOE as well on redox flow batteries. I mentioned a little bit earlier in my oral testimony, and these systems are designed for that 6 hours plus, right? The reason you want to go to a system like that is because, as it scales out in terms of time, the cost of the installation reduces per-unit energy based upon the system architecture. And so there is—but people are also looking into that as well.

As was mentioned I think a little bit earlier, the amount of investment as compared to the investment in energy storage for transportation applications is decidedly less, and that's an area that I think is going to become increasingly important as more and more locally available renewable resources come onto the grid and we wish to utilize those. We're going to have to think about ways to store that energy and deliver it in a dispatchable way.

Mr. LAMB. Yes, that's an important point, and thank you for emphasizing it.

I know this is always a hard question to answer, but from what you know of the state of the research now, is it at all possible to forecast whether you think there would be a demonstration project of longer duration storage within the next 5 years, 10 years, 15 years? Do you have any idea what kind of timescale we're talking about there?

Dr. TAKEUCHI. I personally am pretty optimistic. I'm not going to point to a specific example, but I think within the next 5 to 10 years—I'll put it this way—I think not only will it happen, I think it has to happen. So I think that's where the—you know, let me just echo what [inaudible] that, you know, the investment in long-duration or large-scale energy storage I think has been, you know, too low to be blunt, and I think that there is huge opportunity that—and a lot of insight that can be tapped to get us where we need to be.

Mr. LAMB. Great. Thank you all. I'm out of time, Mr. Chairman. I yield back.

STAFF. Ms. Ross is next.

Ms. ROSS. Thank you, Mr. Chairman. This has been a wonderful Subcommittee meeting. And I really thank all of the folks who have come to testify.

My question initially is for Dr. Rao, but if other people want to pipe in after he's answered it, please feel free.

So I'm from North Carolina. I'm from the Research Triangle area, and I've done some work with renewable energy and with integrated resource plans. And North Carolina was the first State in the Southeast to adopt a renewable energy portfolio standard. And in addition to adopting that standard, it created incentives for the regulated utilities to encourage conservation because, as we know, if we conserve energy, then we don't have to produce as much, right?

And so because you are working in multidisciplinary areas and trying to reach communities that might not be like the techie community I live in that looks at their smart meter and tries to figure out how to peek shave and do all of this, how can we use research and in particular behavioral research to encourage conservation? And what else should be added to enable communities that don't traditionally think about conservation to see it both as cost-saving and a way to improve our planet?

Dr. RAO. Thank you so much for that question. That's a really important dimension. One aspect of this is involving customers more directly in reducing load, and that involves potentially using new technologies, smart appliances, smart devices, potentially having to be much more involved in your energy conditions or thinking about energy costs if you have a smart meter that tells you more information about your real-time prices and how you respond to them. We need to understand if people are able and willing to engage that much more in the effort to try and save energy. So I think we can do a lot of research on the customer side to understand behaviorally what will incent customers to really engage, and we need more research that's qualitative fieldwork to talk to people, engage stakeholders. That's one aspect.

I think we also need institutional research and understanding how we provide the incentives to utilities and to other agencies and to State governments to provide the kind of support that we need both to prepare the grid in order to deliver those—that information to people, to understand the physical conditions of buildings to know where we can maximize or get the most bang for the buck in terms of a shell, building shell improvements, for example, and also making sure that you have the right set of incentives for coordination amongst different players to make sure that all these end up leading to significant long-term investments in efficiency because, as you already rightly said, the more we invest in conservation, the less we have to invest to a greater extent in supply of energy.

Ms. ROSS. And just one part of my question was for less-educated and low-income communities who traditionally do not live places where it's easy to conserve energy and don't come from a culture where that's something that's valued or it's complicated to figure—you know, my mother couldn't figure out how to use an AMI (Advanced Metering Infrastructure) meter. So what can we do to bridge that gap? Because not only will that help our environment, but it will lower their energy costs.

Dr. RAO. Yes, I absolutely agree. There is a digital divide in some sense. There's an information gap. We know some things about it. What can we do about it? We can ask people. I think we need strong stakeholder engagement to understand what it will take for people to engage, and that's really what I think is the first step.

I'd also mention we have a lot of publicly created data from national surveys that starts to hint a little bit at some of these conditions, people's education level, people's engagement with other technologies, that we can use as a starting point. But we definitely need to ask people. That's my main message.

Ms. ROSS. I only have a couple seconds left, so if anybody else wants to pipe in, please do so. Otherwise, I'll yield back.

Dr. TAKEUCHI. I just wanted to comment that, you know, at Brookhaven we created a department that I chaired that brings together energy efficiency, integration, and grid modeling, as well as energy storage because, as you so correctly said, all of those questions are interrelated. Thank you.

STAFF. Ms. Stevens is next.

Ms. STEVENS. Thank you, Mr. Chair Bowman, Dr. Bowman. This is just a real honor to be with my Chair of the Energy Subcommittee on House Science and all of our fantastic witnesses and also my colleague, the previous questioner, also from the freshman class of the 117th Congress, along with Chair Bowman, Congresswoman Deb Ross. This is just, you know, one of the examples of how fantastic this Science Committee is and the type of Members that come onto it and help lead the charge. And of course we're doing this work alongside the researchers and the experts and the doctorates, all of you who provide [inaudible].

I think Mr. Casten reflected on just the level of detail and expertise that you all have brought to today's hearing, which, again, is a part of Chair Bowman's effort to reauthorize some of the basic research funding in the Department of Energy, you know, part of the reauthorization that we're doing with DOE.

And one of the things I wanted to ask about with Dr. Zeng. And, again, I'm holding your testimony, clutching it because I loved it. I loved all of your testimonies but I'm really like—can't take notes fast enough and all this great stuff that you covered. But I wanted to ask a higher level question just to level set what we're up to here today, which is about the role of climate science research and the role of the Department of Energy. And if you could articulate how that operates, you know, what that looks like here. We're doing climate research. This is a major topic. There's a lot to delve into. You know, we've got—obviously, you've got NOAA, which is in the Department of Commerce. I guess some people are wondering about why, but NOAA is in the Department of Commerce, and they do a lot of this atmospheric work. But how are you using the Department of Energy and their basic research for climate science?

Dr. ZENG. Yes, I'll give you two examples. First one, earlier, we discussed about the supercomputers. OK. For the speed of supercomputers you can rank who is No. 1, No. 2. But that is not the most important factor. What's most important is what the actual capability used by the end user for this case by the climate models. Why the DOE has done a great job is to recognize what you need, the hardware. You also need the scientific computing office and to work with many scientists for this case climate modelers to bring them together to get at the best computing capability out of the hardware. That's what DOE does very well. That's something we'll have, help other agencies and help that the science overall worldwide. That's what I think.

The second is about extreme events under climate change. DOE does not work on tomorrow's extreme weather over any parts of the Nation. That's a job for NOAA. But the DOE's focus is about extreme events for the future with climate change. How do we prepare our national energy infrastructure for the future extreme events? What I want to see is closer interactions between the climate research and the applied energy research within DOE so that they can talk more with each other and that use those knowledge for the actual planning of our Nation's energy infrastructure for the future.

Ms. STEVENS. Thank you. Well—and I know we've also touched on the grid. Obviously, the supercomputer consideration is major because of the cost. And, you know, it's expensive to access these supercomputers. And I know the Chair has been touching on this, too, which is the human capital considerations and the research opportunities. But do you feel, Dr. Zeng, that we are able to cover enough of the research with a—either the flow of applications coming in or the dollars coming in? And is there any confusion by—of what the DOE does as compared to other agencies that are also covering basic research? Do we have to deal with any confusion? And, as usual, 10 seconds left so maybe I can take that to a written one, but if you have anything before we have to close.

Dr. ZENG. You know, there is no confusion. Part of the competition for DOE research dollars is too fierce to the degree sometimes it's discouraging to the university investigators.

Ms. STEVENS. Great. Well, thank you all. Thank you for the whole panel. And again, to my Chair, Dr. Bowman, I yield back.

Chairman BOWMAN. Thank you so much. Before we bring the hearing to a close, I want to thank our witnesses for testifying before the Committee today. The record will remain open for 2 weeks for additional statements from the Members and for any additional questions the Committee may ask of the witnesses.

The witnesses are excused, and the hearing is now adjourned. Thank you all so much. Have a great day.

[Whereupon, at 1:01 p.m., the Subcommittee was adjourned.]

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