THE FUTURE OF ARPA-E

HEARING

BEFORE THE

SUBCOMMITTEE ON ENERGY

COMMITTEE ON SCIENCE, SPACE, AND TECHNOLOGY

HOUSE OF REPRESENTATIVES

ONE HUNDRED SIXTEENTH CONGRESS

FIRST SESSION

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February 26, 2019

THE FUTURE OF ARPA-E

TUESDAY, FEBRUARY 26, 2019

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

The Subcommittee met, pursuant to notice, at 10:04 a.m., in room 2318 of the Rayburn House Office Building, Hon. Conor Lamb [Chairman of the Subcommittee] presiding.

EDDIE BERNICE JOHNSON, Texas
CHAIRWOMAN

FRANK D. LUCAS, Oklahoma
RANKING MEMBER

Congress of the United States
House of Representatives
COMMITTEE ON SCIENCE, SPACE, AND TECHNOLOGY
2321 RAYBURN HOUSE OFFICE BUILDING
WASHINGTON, DC 20515–6301
(202) 225–6375
www.science.house.gov

The Future of ARPA-E

Tuesday, February 26, 2019
10:00 a.m.
2318 Rayburn House Office Building

Witnesses

Dr. Arun Majumdar, Jay Precourt Provostial Chair Professor, Stanford University

Dr. Ellen Williams, Distinguished University Professor, University of Maryland

Dr. John Wall, Retired CTO of Cummins, Member of the Committee on Evaluation for the 2017 National Academies review of ARPA-E

Dr. Saul Griffith, Founder and CEO, Otherlab

Mr. Mark P. Mills, Senior Fellow, Manhattan Institute

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

The Future of ARPA-E
Tuesday, February 26, 2019
10:00AM EST
2318 Rayburn House Office Building

PURPOSE

The purpose of the hearing is to assess the value of the role that the Department of Energy's Advanced Research Projects Agency – Energy (ARPA-E) currently plays in accelerating the development of innovative energy technologies, and to examine ways that Congress and the Administration may be able to improve ARPA-E's capabilities to spur transformational technological advances in pursuit of the agency's energy and environmental missions.

WITNESSES

- **Dr. Arun Majumdar** is the Jay Precourt Provostial Chair Professor at Stanford University and a faculty member of the Department of Mechanical Engineering. Dr. Majumdar was the founding Director of ARPA-E from 2009 to 2012. During his time at the Department of Energy (DOE) he also served as acting Under Secretary for Energy. His current research explores chemical processes in clean energy technology, next-generation materials science, and efforts to improve the efficiency of the electric grid.[1]

- **Dr. Ellen D. Williams** is a Distinguished University Professor in the Department of Physics at the University of Maryland (UMD). Dr. Williams was the Director of ARPA-E from 2014 through the end of the Obama Administration. Prior to joining DOE, she served as Chief Scientist to BP and founded the UMD Materials Research Science and Engineering Center. Her research currently focuses on surface physics and nanotechnology.[2]

[1] "Arun Majumdar Bio." Stanford University. Accessed 12 Feb 2019. https://profiles.stanford.edu/arun-majumdar
[2] "Ellen Williams Biography." University of Maryland Department of Physics. Accessed 13 Feb 2019. https://umdphysics.umd.edu/about-us/news-from-the-chair/383-ellen-williams-to-serve-as-chief-scientist-at-bp.html

- **Dr. John Wall**, now retired, served as the Chief Technology Officer for Cummins Inc. from 2000 to 2015, where he oversaw the company's worldwide commercial engine emissions reductions activities. Dr. Wall served on the Committee on Evaluation for the 2017 National Academies review of ARPA-E. Dr. Wall currently serves as a technical advisor for DOE's Joint BioEnergy Institute and as an advisor for Cyclotron Road, an energy technology incubator at Lawrence Berkeley National Laboratory[3].

- **Dr. Saul Griffith** is the Founder and CEO of Otherlab, a privately held research and development lab that develops clean energy, robotics and automation, and engineered textiles, among other technology areas. In its ten years of existence, Otherlab has been the recipient of multiple ARPA-E awards. Over the course of his career Dr. Griffith has founded a number of companies[4] and was named a MacArthur Fellow in 2007[5].

- **Mr. Mark P. Mills** is a senior fellow at the Manhattan Institute and a faculty fellow at Northwestern University's McCormick School of Engineering and Applied Science where he co-directs an Institute on Manufacturing Science and Innovation. He is also a strategic partner with Cottonwood Venture Partners, an energy-tech venture fund, and an advisory board member of Notre Dame University's Reilly Center for Science, Technology, and Values.

BACKGROUND

History

In 2005, Congress requested a report from the National Academies to identify what federal actions could "enhance the science and technology enterprise so that the United States can successfully compete, prosper, and be secure in the global community of the 21st century" [6]. The subsequent report, *Rising Above the Gathering Storm*, made a series of recommendations to enhance the nation's technological competitiveness, including the creation of a new energy agency within the Department of Energy (DOE) modeled after the Defense Advanced Research Program Agency (DARPA) within the Department of Defense[7].

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[3] "Dr. John Wall, Former Vice President and Chief Technical Officer, Cummins Inc. to Receive the Thomas W. Zosel Individual Achievement Award from the Environmental Protection Agency." BusinessWire. Published 28 June 2016. https://www.businesswire.com/news/home/20160628005254/en/Dr.-John-Wall-Vice-President-Chief-Technical

[4] "Short Bio." Accessed 13 Feb 2019. http://saulgriffith.com/

[5] MacArthur Foundation Fellows Program. Accessed 14 Feb 2019. https://www.macfound.org/fellows/825/

[6] National Academies of Sciences, Engineering, and Medicine 2007. Rising Above the Gathering Storm: Energizing and Employing America for a Brighter Economic Future. Washington, DC: The National Academies Press. https://doi.org/10.17226/11463.

[7] "ARPA-E History." Department of Energy. Accessed 7 Feb 2019. https://arpa-e.energy.gov/?q=arpa-e-site-page/arpa-e-history

In 2007, the U.S. Congress authorized such a program as a part of the America COMPETES Act, calling it the Advanced Research Program Agency-Energy (ARPA-E)[8]. ARPA-E's mission is "to overcome long-term and high-risk technology barriers in the development of energy technologies" [9]. Specifically, its goals are:

"(A) to enhance the economic and energy security of the United States through the development of energy technologies that result in—

(i) reductions of imports of energy from foreign sources;
(ii) reductions of energy-related emissions, including greenhouse gases; and
(iii) improvement in the energy efficiency of all economic sectors; and

"(B) to ensure that the United States maintains a technological lead in developing and deploying advanced energy technologies" [10].

While ARPA-E was authorized in 2007, it did not receive funding until the passage of the American Recovery and Reinvestment Act of 2009, which included $400 million to build and support the agency over a two year period[11]. Since then ARPA-E's annual budget has generally increased, despite proposals from the current Administration to eliminate the program in its FY 2018 and FY 2019 budget requests[12,13]. ARPA-E's annual budget is currently at its highest level, with $366 million appropriated for FY 2019[14].

Program Structure and Design

At the direction of Congress, ARPA-E possesses a unique structure and project management style as compared to DOE's other program offices. ARPA-E attempts to invest in projects that have a high potential for impact, but are too underdeveloped to receive sufficient investment from the private sector[15]. ARPA-E's director has considerable independence over which projects

[8] America COMPETES Act. Pub. L. 110-69. 121 Stat. 621. 9 Aug 2007.
[9] National Academies of Sciences, Engineering, and Medicine 2017. An Assessment of ARPA-E. Washington, DC: The National Academies Press. https://doi.org/10.17226/24778
[10] America COMPETES Act. Pub. L. 110-69. 121 Stat. 621. 9 Aug 2007.
[11] "ARPA-E History." Department of Energy. Accessed 7 Feb 2019. https://arpa-e.energy.gov/?q=arpa-e-site-page/arpa-e-history
[12] Department of Energy FY 2018 Congressional Budget Request. https://www.energy.gov/sites/prod/files/2017/05/f34/FY2018BudgetVolume3_0.pdf
[13] Department of Energy FY 2019 Congressional Budget Request. https://www.energy.gov/sites/prod/files/2018/03/f49/FY-2019-Volume-3-Part-2.pdf
[14] "ARPA-E Budget." Department of Energy. Accessed 12 Feb 2019. https://arpa-e.energy.gov/?q=arpa-e-site-page/arpa-e-budget
[15] "ARPA-E About." Department of Energy. Accessed 13 Feb 2019. https://arpa-e.energy.gov/?q=arpa-e-site-page/about

are funded, the funding levels of projects, and the hiring of program managers, who are not subject to civil service hiring laws[16]. Program managers typically come from highly technical backgrounds and work for ARPA-E on short, three year cycles. Program managers have autonomy to rapidly begin projects, monitor them closely, and terminate funding if specific milestones are not reached[17]. According to a 2017 review of ARPA-E by the National Academies, discussed further below, this allows the agency to manage projects at a speed and risk-level not found in other DOE research and development activities[18]. The awarded projects are organized into programs based on specific technology themes. There are currently 38 distinct ARPA-E programs, with projects ranging from advanced nuclear energy modeling to plant driven carbon sequestration[19]. ARPA-E also provides technical and commercialization assistance to all projects that are selected for funding.

Performance

Since 2009, ARPA-E has provided $1.8 billion in R&D funding to over 660 projects. Of these projects, 71 have led to the formation of new companies, 109 have partnered with non-DOE government agencies, and 136 have attracted over $2.6 billion in private sector follow-on funding. ARPA-E projects have also produced 245 U.S. patents and 1,724 peer reviewed journal articles.[20]

Included in ARPA-E's initial authorization was a requirement that it receive an independent evaluation from the National Academies of Science after its first 4 years.[21] The National Academies of Science conducted this review beginning in 2015, and published its results in *An Assessment of ARPA-E*, in 2017. In summary, the report concluded that ARPA-E was making significant, unique contributions to the U.S.'s energy research and development enterprise.[22]

[16] America COMPETES Act. Pub. L. 110-69. 121 Stat. 623. 9 Aug 2007.
[17] "Frequently Asked Questions." Department of Energy. https://arpa-e.energy.gov/?q=faq
[18] National Academies of Sciences, Engineering, and Medicine 2017. An Assessment of ARPA-E. Washington, DC: The National Academies Press. https://doi.org/10.17226/24778
[19] "ARPA-E Programs." Department of Energy. Accessed 12 Feb 2019. https://arpa-e.energy.gov/?q=program-listing&term_node_tid_depth=All&field_program_tid=All&field_program_status_value=1&sort_by=title&sort_order=ASC
[20] "ARPA-E Impact." Department of Energy. Accessed 14 Feb 2019. https://arpa-e.energy.gov/?q=site-page/arpa-e-impact
[21] America COMPETES Act. Pub. L. 110-69. 121 Stat. 624. 9 Aug 2007.
[22] National Academies of Sciences, Engineering, and Medicine 2017. An Assessment of ARPA-E. Washington, DC: The National Academies Press. https://doi.org/10.17226/24778

LOOKING AHEAD

Recently, several bipartisan and non-partisan energy and technology focused organizations, including the Information Technology & Innovation Foundation (ITIF)[23] and the American Energy Innovation Council (AEIC)[24], released reports advocating for substantial funding increases to ARPA-E. Notably, the AEIC's 2018 report titled, *Energy Innovation: Fueling America's Economic Engine*, calls for an annual budget of $1 billion for ARPA-E, close to three times its FY 2019 budget. These reports highlighted ARPA-E's unique structure and management, and recommend expanding these qualities to other DOE research and development programs.

Acknowledging these recommendations, this hearing will examine the potential for improvements to the operations and impact of ARPA-E. In particular, the hearing will explore how ARPA-E can best leverage additional funding, whether by expanding its current portfolio of programs, establishing a scale-up program for select, well-reviewed projects previously supported by the agency, or other options.

[23] Hart, David. Kearney, Michael. "ARPA-E: Versatile Catalyst for U.S. Energy Innovation." Information Technology & Innovation Foundation. Published Nov 2017. http://www2.itif.org/2017-arpae-energy-innovation.pdf
[24] "Energy Innovation: Fueling American's Economic Engine." American Energy Innovation Council. Published Nov 2018. http://americanenergyinnovation.org/wp-content/uploads/2018/11/Energy-Innovation-Fueling-Americas-Economic-Engine.pdf

Chairman LAMB. This hearing will come to order. Without objection, the Chair is authorized to declare a recess at any time.

Good morning, everybody. Welcome to today's hearing, which is entitled, "The Future of ARPA-E." I'd like to thank our panel of expert witnesses for appearing with us today.

In my district, and in many around the country, the topic of today's hearing, which is energy and energy research, means cutting-edge science, but it also means jobs that support entire families. We must make sure that the United States remains a leader in this industry, and I look forward to working with Members from both parties to do that.

And in fact, today, we are here to discuss a great bipartisan success, which is the future of the Advanced Research Projects Agency-Energy, or ARPA-E. I think it's helpful for us to look at how this program was started. Almost 15 years ago, a bipartisan group of Members from the House and Senate were worried that the United States' competitiveness in science and technology might be falling behind, so they did a smart thing, which is they commissioned a report from the National Academies to suggest how the Federal Government could continue to maintain leadership in these areas. The report was called, "Rising Above the Gathering Storm: Energizing and Employing America for a Brighter Economic Future," and it did show that we were quickly losing our scientific and technological advantages.

One of the major recommendations was the creation of a new program within DOE (Department of Energy), which became ARPA-E. It was modeled on DARPA (Defense Advanced Research Projects Agency) from the Department of Defense, which has been essential to revolutionary technologies like GPS (global positioning system) and the internet. So we created ARPA-E with that same program in mind. We did something that people may think we in Washington don't know how to do, which is to double-down on a government success, but that's what we're doing and that's what we're trying to do here again today. We need to encourage innovation and paradigm-shifting discoveries in all sectors of our economy but especially energy. The United States has consistently demonstrated throughout its history that our greatest resource is its people and ability to innovate and lead, and we view that ARPA-E is a critical component of spurring that type of innovation.

Congress first authorized this program in 2007, and I've been told that it was largely due to the hard work of one person, who we are lucky enough to have in the room today, which was the Chairman of this very Committee at the time, Bart Gordon, who is sitting back and to my left. Chairman Gordon, thank you very much for your efforts and for being with us here today. Since then, ARPA-E projects have led to 71 new companies, 109 projects partnered with other government agencies, and 136 projects that have garnered more than $2.6 billion in private-sector funding. And as we're going to talk about today, that is more than the government has spent on ARPA-E in that time.

Among these projects is one that I'm very proud of. It's located in my district at the historic Westinghouse Corporation in Cranberry Township. And what this project aims to do is to innovate in the nuclear power industry by continuing to provide carbon-free,

reliable electricity through a microreactor made of advanced materials that can be modeled and component samples can be fabricated and tested with the ultimate goal of reducing the cost and making these plants more available worldwide. I'm very pleased with the progress of this project, but I know it's expensive and difficult and they might not be able to pursue it without the help of a program like ARPA-E.

So now I look forward to the testimony of our witnesses, the opening statements of other Members to learn what else we can do to improve this great program.

[The prepared statement of Chairman Lamb follows:]

Chairman Lamb Opening Statement for Hearing on the Future of ARPA-E

Good morning. I'd like to thank this panel of expert witnesses for being here today. I'd also like to welcome the other members of this subcommittee to our first hearing. In my district, and many around the country, energy means cutting-edge science and family-supporting jobs, and there is much work to be done to ensure the U.S. remains a leader in this industry. I look forward to working with members from both sides of the aisle to do just that.

Today, we are here to discuss the progress and future of the Advanced Research Program Agency-Energy, or ARPA-E. To understand the success of this program, I think it's helpful for us to better understand how it started. Almost 15 years ago, a bipartisan group of Members from the House and Senate, worried that the U.S.'s competitiveness in science and technology development might be falling behind, commissioned a report from the National Academies to provide suggestions to the federal government on how to maintain its leadership in these critical fields. The report, entitled Rising Above the Gathering Storm: Energizing and Employing America for a Brighter Economic Future, indicated that the U.S. was quickly losing its scientific and technological advantages.

One of its major recommendations was the creation of a new program within the Department of Energy modeled after the Defense Advanced Research Program Agency (DARPA) within the Department of Defense, whose work was essential to the development of revolutionary innovations like GPS and the Internet. And so, ARPA-E was born – to ensure that the U.S. maintains its global competitiveness by pursuing high-risk, high-reward energy technology research and development projects. Our country's heritage of innovation does not exist in a vacuum. We need to encourage innovation and paradigm-shifting discoveries in all sectors of the economy – and especially in energy. Or as the National Academies put it: "Throughout history, the United States has consistently demonstrated that its greatest resource is its people and their talent for innovation and leadership. There has never been a greater need or opportunity for American leadership than that posed by the challenge of achieving dramatic innovations in energy technology." ARPA-E is a critical component of spurring that type of innovation.

Since Congress first authorized this program in 2007, largely due, I understand, to the hard work of this Committee under its Chairman at the time, Bart Gordon, ARPA-E projects have led to 71 new companies, 109 projects partnered with other government agencies to further development, and 136 projects that have garnered more than $2.6 billion in private sector funding.

Among these exciting projects is one right in my district at Westinghouse, located in Cranberry Township. This project aims to address known issues that face the nuclear power industry today to ensure that this valuable resource continues to provide carbon-free, reliable electricity to the grid. A micro-reactor design made of advanced materials will be modelled and component samples will be fabricated and tested with the ultimate goal of significantly reducing the costs and schedule for building a new plant.

I am pleased with the progress of this project and many others supported by ARPA-E, and I look forward to the testimony from our witnesses here today to discuss issues and ideas Congress should consider as we aim to further the success of this program.

Chairman LAMB. The Chair now recognizes Mr. Weber for an opening statement.

Mr. WEBER. Thank you, Mr. Chairman. Thank you all for all being here today.

Today, we are going to hear from our panel of experts on the status of the Department of Energy's Advanced Research Projects Agency-Energy (ARPA-E) and discuss how Congress can effectively evaluate and reform this fundamental science program.

Created in 2007, as noted by the Chairman, DOE's ARPA-E program was modeled after the Department of Defense's DARPA program. The agency was intended to provide finite R&D funding for innovative projects that could have disruptive impact on critical American economic, environmental, national security, and energy-sector challenges. Specifically, ARPA-E was tasked by Congress to reduce reliance on foreign sources of energy and energy-related emissions, and to improve energy efficiency in all economic sectors.

ARPA-E was intended to be unique among DOE's applied research programs. The agency aims to achieve its goals by funding the highest-risk, highest-reward fundamental science, the transformative research that industry will not pursue.

But today, it's unclear if ARPA-E remains true to this inspiring mission. While there are examples of truly groundbreaking research like the project exploring unique fusion reactor designs, there are also a large number of programs that actually overlap with DOE's applied energy offices. For example, today, ARPA-E has funding announcements or active programs supporting research in wind energy technologies, advanced nuclear technology, and energy storage systems for the electric grid, all areas of research that receive—already receive funding through other DOE programs.

Industry already has an interest in developing incremental improvements to today's energy technology. We cannot afford to spend limited Federal resources on duplicative, late-stage programs that compete with private-sector investment. Instead, we should refocus the ARPA-E program on its original purpose, taking fundamental science discoveries and applying them to our biggest technology challenges. This approach could provide solutions across the Department's diverse mission space, including areas like nuclear waste management and national security. With the agency's unique expertise, I believe that this program is capable of supporting a new generation of scientific breakthroughs. But that won't happen without real reforms to prevent duplication and refocus ARPA-E on the greatest technology challenges.

We also can't just assume that big increases in spending will magically appear in the budget. If ARPA-E's budget is increased, we will inevitably have to make tough choices and cut spending elsewhere in the Department.

In preparation for this hearing, I thought about what breakthrough energy technologies look like, and I was reminded of how hydraulic fracturing and horizontal drilling revolutionized the global energy market. Research at our national labs laid the groundwork, and American industry picked up and harnessed those discoveries to change the world. We need to focus agencies like ARPA-E on applying DOE's basic science discoveries. With this approach,

I believe that American industry can capitalize on that research and revolutionize the energy industry once again.

I want to thank the Chairman for holding this hearing today and the witnesses for coming in to provide their testimony, and I'm looking forward to a productive discussion about ARPA-E's future today.

Mr. Chairman, I yield back.

[The prepared statement of Mr. Weber follows:]

Opening Statement of Ranking Member Randy Weber at Energy Subcommittee Hearing on ARPA-E

Feb 26, 2019
Opening Statement

Today, we will hear from a panel of experts on the status of the Department of Energy (DOE)'s Advanced Research Projects Agency – Energy (ARPA-E) and discuss how Congress can effectively evaluate and reform this fundamental science program.

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I want to thank the Chairman for holding this hearing today and the witnesses for providing their testimony, and I'm looking forward to a productive discussion about ARPA-E's future today.

Chairman LAMB. Thank you. The Chair now recognizes Chairwoman Johnson for an opening statement.

Chairwoman JOHNSON. Thank you very much and good morning, and good morning to our witnesses.

Thank you, Chairman Lamb, for holding this timely hearing to review the impressive performance of ARPA-E to date and to explore new ways that this vital program might accelerate America's transition to a clean energy future.

About 12 years ago, since this agency was first authorized by this Committee, and 10 years since it was finally funded thanks to the *American Recovery and Reinvestment Act*, ARPA-E now plays a critical role in maintaining America's economic competitiveness by advancing high-risk concepts that previously lacked Federal or private-sector support that could have significant impacts on the ways we produce and use energy.

Thus far, 71 ARPA-E projects have led to the formation of new companies, 109 have partnered with other government agencies for further development, and 136 have attracted over $2.6 billion in private-sector follow-up funding.

This clear record of accomplishment is why I was proud to introduce the *ARPA-E Reauthorization Act* in 2017 in the last Congress, which had 39 cosponsors including 11 Republicans. That bill was endorsed by an incredibly broad coalition of stakeholders, including the U.S. Chamber of Commerce, the National Association of Manufacturers, the American Council on Renewable Energy, the American Petroleum Institute, the Nuclear Energy Institute, the Alliance to Save Energy, the Bipartisan Policy Center, and the Energy Sciences Coalition, just to name a few. And I think we can do better this year.

I was also very proud to cosponsor the *ARPA-E Act of 2018* introduced by then-Vice Chairman Lucas, and I look forward to continuing to work with him and my colleagues on both sides of the aisle to enable this agency to be as effective as it can be in achieving its mission.

Before I'll—before I close, I'll note that over the last few years this program has been the subject of several overwhelmingly positive assessments by widely respected, bipartisan and nonpartisan institutions like the National Academies, the American Energy Innovation Council, and most recently by the Breakthrough Energy. And in Secretary Perry's own address to ARPA-E Energy Innovation Summit last March, he said, and I quote, "ARPA-E is one of the reasons DOE has had and is having such a profound impact on American lives." I couldn't have said it better myself. So I certainly hope that in its next budget request, this Administration will reconsider its previous and fortunately doomed proposals to eliminate ARPA-E altogether.

I thank you again for holding this hearing, and I look forward to the dialog with the excellent panel of witnesses and thank them for being here. I yield back.

[The prepared statement of Chairwoman Johnson follows:]

OPENING STATEMENT

Chairwoman Eddie Bernice Johnson (D-TX)

House Committee on Science, Space, and Technology
Subcommittee on Energy Hearing
"The Future of ARPA-E"
February 26, 2019

Good morning and welcome to our witnesses. Thank you, Chairman Lamb, for holding this timely hearing to review the impressive performance of ARPA-E to date and to explore new ways that this vital program may accelerate America's transition to a clean energy future.

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Thank you again for holding this hearing, and I look forward to the dialogue with this excellent panel of witnesses on the future of ARPA-E.

I yield back.

Chairman LAMB. Thank you, Chairwoman Johnson.

The Chair now recognizes Ranking Member Lucas for an opening statement.

Mr. LUCAS. Thank you, Chairman Lamb. And I would like to congratulate you on your new position as Chairman of the Energy Subcommittee, and thank you for holding this hearing today. And I also appreciate your acknowledging the former Chairman Gordon in attendance with us today. I've had the privilege of serving with five of the previous Chairmen whose portraits are on this wall, and I look forward to the inevitable day when we have the first lady portrait hanging, which is now inevitable, too. That will be a good day.

That said, ARPA-E was created to help the U.S. energy sector maintain its competitive edge in developing advanced energy solutions. The program was established to jumpstart technologies that were too-early stage to attract private-sector investment but could have a significant impact on the energy market. In order to accomplish this, ARPA-E was given a unique management structure, with the flexibility to start and stop research projects based on performance. Program managers have expedited hiring and firing authority to make sure that ARPA-E staff can adequately select and support.

Today, ARPA-E supports fundamental research over a wide range of cutting-edge energy technology areas, including bioenergy, battery technology development, and advanced nuclear. But despite some fascinating areas of research, ARPA-E is not without controversy. For example, many ARPA-E programs have significant overlap with programs' goals of DOE's applied energy research programs. We'll hear testimony today supporting big increases in spending for ARPA-E. But with $6 billion in annual spending already devoted to applied research elsewhere in DOE, ARPA-E, and any increased spending for it, is redundant if it's not refocused on more innovative research.

Now, that brings us to the second problem. We've heard concerns over the years that ARPA-E isn't meeting its intended goal—to fund the kind of technologies that are so pioneering they would never attract private-sector investment but instead, providing funding to big companies with access to capital markets or funding research that's already succeeding in the private sector.

ARPA-E is a program that can and has had tremendous impact on the development of new energy technologies, but we must address these concerns and refocus the agency on funding the most innovative research. That's why I, too, introduced a bill to reform ARPA-E in the last Congress, which passed the House in a—with bipartisan support. This legislation expanded the mission of ARPA-E to include the full DOE mission and empowered the agency to promote science- and technology-driven solutions to DOE's broader goals.

My bill also included important direction to prevent the duplication of research across DOE and ensure that the limited taxpayer dollars are spent on the most transformative technologies, not in competition with the private sector.

I hope that we can work together to include those reforms in any reauthorization of ARPA-E this Congress.

It is our job to be good stewards of the taxpayers' resources of course, and with the right mission goals and commonsense conservative management, I believe ARPA-E's innovative approach can build on the basic science and early-stage research at the Department. We can help fast-track new technologies that will grow our economy, stabilize our environment, and maintain U.S. leadership in science and technology around the world.

I want to thank our witnesses for being here today, and I look forward to a productive discussion this morning.

I yield back, Mr. Chairman.

[The prepared statement of Mr. Lucas follows:]

Opening Statement of Ranking Member Frank Lucas at Energy Subcommittee Hearing on ARPA-E

Feb 26, 2019
Opening Statement

Thank you, Chairman Lamb. I would like to congratulate you on your new position as Chairman of the Energy Subcommittee and thank you for holding this hearing today.

ARPA-E was created to help the U.S. energy sector maintain its competitive edge in developing advanced energy solutions. The program was established to jumpstart technologies that were too early-stage to attract private sector investment but could have a significant impact on the energy market.

In order to accomplish this goal, ARPA-E was given a unique management structure, with the flexibility to start and stop research projects based on performance. Program managers have expedited hiring and firing authority to make sure ARPA-E staff could adequately select and support projects.

Today, ARPA-E supports fundamental research over a wide range of cutting-edge energy technology areas, including bioenergy, battery technology development, and advanced nuclear.

But despite some fascinating areas of research, ARPA-E is not without controversy. For example, many of ARPA-E's programs have significant overlap with the program goals of DOE's applied energy research programs. We'll hear testimony today supporting big increases in spending for ARPA-E. But with $6 billion in annual spending already devoted to applied research elsewhere in DOE, ARPA-E – and any increased spending for it – is redundant if it's not refocused on more innovative research.

That brings us to the second problem. We've heard concerns over the years that ARPA-E isn't meeting its intended goal – to fund the kind of technologies that are so pioneering they would never attract private sector investment – but was instead providing funding to big companies with access to market capital, or funding research that was already succeeding in the private sector.

ARPA-E is a program that can and has had tremendous impact on the development of new energy technologies – but we must address these concerns and refocus the agency on funding the most innovative research. That's why last Congress I introduced a bill to reform ARPA-E, which passed the House with bipartisan support.

This legislation expanded the mission of ARPA-E to include the full DOE mission and empowered the agency to promote science and technology driven solutions to DOE's broader goals.

My bill also included important direction to prevent the duplication of research across DOE and ensure that limited taxpayer dollars are spent on the most transformative technologies, not in competition with the private sector.

I hope that we can work together to include these reforms in any reauthorization of ARPA-E this Congress.

It is our job to be good stewards of taxpayer resources. With the right mission goals and common-sense conservative management, I believe ARPA-E's innovative approach can build on the basic science and early-stage research at the Department. We can help fast track new technologies that will grow our economy, stabilize our environment, and maintain U.S. leadership in science and technology around the world.

I thank our witnesses for being here today, and I look forward to a productive discussion this morning.

Chairman LAMB. 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. First, Dr. Arun Majumdar is the Jay Precourt Provostial Chair Professor at Stanford University and a faculty member of the Department of Mechanical Engineering. Dr. Majumdar was the Founding Director of ARPA-E from 2009 to 2012. During his time at the Department of Energy, he also served as Undersecretary for Energy. His current research explores chemical processes and clean-energy technology, next-generation materials science, and efforts to improve the efficiency of the electrical grid.

Dr. Ellen D. Williams is a Distinguished University Professor in the Department of Physics at the University of Maryland (UMD). Dr. Williams was the Director of ARPA-E from 2014 through the end of the Obama Administration. Prior to joining DOE, she served as Chief Scientist to BP and founded the UMD Materials Research Science and Engineering Center. Her research currently focuses on surface physics and nanotechnology.

Dr. John Wall, now retired, served as the Chief Technology Officer for Cummins Inc. from 2000 to 2015 where he oversaw the company's worldwide commercial engine emissions-reduction activities. He does not, contrary to popular opinion, play point guard for the Washington Wizards. Dr. Wall served on the Committee on Evaluation for the 2017 National Academies' Review of ARPA-E. He currently serves as a Technical Advisor for DOE's Joint Bioenergy Institute and as an Advisor for Cyclotron Road, an energy technology incubator at the Lawrence Berkeley National Laboratory.

Dr. Saul Griffith is the Founder and CEO of Otherlab, a privately held research and development lab that develops clean energy, robotics and automation, and engineered textiles, among other technology areas. In its 10 years of existence, Otherlab's been the recipient of multiple ARPA-E awards. Over the course of his career, Dr. Griffith has founded several successful companies and named a MacArthur Fellow in 2007.

Mr. Mark Mills is a Senior Fellow at the Manhattan Institute and a Faculty Fellow at Northwestern University's McCormick School of Engineering and Applied Science where he codirects an Institute on Manufacturing Science and Innovation. He is also a strategic partner with Cottonwood Venture Partners, an energy tech venture fund, and an Advisory Board Member of Notre Dame University's Reilly Center for Science, Technology, and Values.

As our witnesses know, you will each have 5 minutes for your spoken testimony. Your written testimony will be included in the record for the hearing. When you have all completed your spoken testimony, we will begin with questions. Each Member will have 5 minutes to question the panelists. We will start with Dr. Arun Majumdar.

TESTIMONY OF DR. ARUN MAJUMDAR, JAY PRECOURT PROVOSTIAL CHAIR PROFESSOR, STANFORD UNIVERSITY

Dr. MAJUMDAR. I want to thank—extend my thanks to Mr. Chairman, the Ranking Member, and all the Members of this Committee.

Between 2009 and 2012, I had the honor of serving as the Founding Director of ARPA-E where I recruited the first team and helped create ARPA-E's DNA that involved multiple elements: A laser focus on the mission of ARPA-E that Congress laid out recruiting top talent in science and engineering; using the special hiring authority that Congress provided; creating a culture internally of an open debate and discussion to unleash this talent to fund research on the most profound breakthrough technologies; creating a model internally of operational efficiency, active program management, and financial integrity; and finally, an exemplar of engaging stakeholders via the ARPA-E Energy Innovation Summit, as well as creating a model of partnership with Congress.

Because of these elements, due to the remarkable breadth of new research that ARPA-E funded, it certainly caught the attention of many thought leaders in the United States. In 2012 at the summit, the Founder, Chairman, and CEO of FedEx, Mr. Fred Smith, said, quote, "Pound for pound, dollar for dollar, activity for activity, it is hard to find a thing the United States has done that is more effective than ARPA-E." Bill Gates and his colleagues had very similar comments as well.

Given all this, I'm going to address two questions in my opening remarks. No. 1, what is the key to ARPA-E's success that needs to be preserved? No. 2, what else can ARPA-E do to make the United States even more successful and globally competitive?

As you know, ARPA-E is modeled after DARPA that has an illustrious 60-year history. Like DARPA, ARPA-E defines the cutting edge of science and engineering research for breakthrough technologies that will form the foundation of entirely new industries that do not exist today and make the U.S. industries more competitive in the world. But to achieve this, it is critical to have the most talented people within ARPA-E at the cutting edge of research in science and engineering. It takes one to be at the cutting edge to recognize what is cutting edge, so in many ways ARPA-E is all about the people.

As the Director, I spend a large fraction of my time recruiting talent. None of these recruits needed a job. They joined ARPA-E to serve the Nation and be part of something special. After 3 to 4 years, they went back to the private sector or academia with an ARPA-E record as a badge of honor. During the time of ARPA-E, they conceived some of the most impactful and research programs that bridge two or three different fields of science and engineering to create something completely new that no one in the world had ever imagined.

So my message is the following: It is very important to preserve the special hiring authority that Congress has bestowed on ARPA-E to ensure that the leadership in ARPA-E uses this authority to recruit top talent. It is also important that ARPA-E maintain its

independence within the Department of Energy and the Director report directly to the Secretary of Energy.

Finally, one of the best things about the ARPA-E model is that the program directors stay for 3 to 4 years and then they are required to leave. This time constraint puts a level of urgency to make a difference, and this urgency is very important to create the internal efficiency within ARPA-E. This needs to be preserved as well.

Now, my second question. What else can ARPA-E do to make the United States more successful? I have two recommendations. In the last 10 years, a lot has changed in the global energy landscape. As was pointed out, there were three game-changers that have happened: Unconventional oil and gas revolution due to fracking, electrification of transportation via lithium-ion batteries, and carbon-free electricity generation from wind and solar.

While these are necessary, these are certainly not sufficient to help address the ARPA-E mission. Fossil fuels still comprise 80 percent of the global energy use. The scale is simply enormous. Reducing greenhouse gases—gas emissions, which is part of ARPA-E's mission, is a billion-ton-scale problem, and to go from a lab-scale concept, proof of concept that ARPA-E funds to the billion-ton-scale solution is a long and arduous process.

So the two important recommendations, it is important for Congress to be patient in its expectations of commercial impact from ARPA-E-funded research. Expectation of short-term success will produce increment thinking within ARPA-E, and that will defeat the whole purpose of ARPA-E, which should be going for the home runs.

Second, it is also very important to look at the gaps beyond ARPA-E funding and to see what has worked in the past to see if you could create private-public partnerships to enable some of these proof of concepts that has been proven in the labs and universities and national labs to go eventually make this journey to the private sector.

Thank you for your time, and I appreciate the opportunity.

[The prepared statement of Dr. Majumdar follows:]

Written Statement of Dr. Arun Majumdar
Hearing on The Future of ARPA-E
Subcommittee on Energy, House Committee on Science, Space and Technology
February 26, 2019

I would like to extend my thanks to the Chairman, the Ranking Member, and the esteemed members for inviting me to testify on the Future of ARPA-E.

I am currently the Jay Precourt Provostial Chair Professor in the Department of Mechanical Engineering at Stanford University and also the co-Director of the Stanford Precourt Institute for Energy. Before joining Stanford, I was the Vice President for Energy at Google. I remain deeply engaged with energy businesses across the world, either through work at Stanford or as a private citizen advising businesses.

Between 2009 and 2012, I had the honor of serving as the Founding Director of ARPA-E, during which I recruited the first team and helped create ARPA-E's DNA that involved multiple elements:

- recruiting top talent in science, engineering and business using the very important hiring authority that Congress provided.
- a laser focus on the mission of ARPA-E that Congress laid out in its authorization – reducing energy imports, energy efficiency across the economy, reducing greenhouse gas emissions and providing the US with a technological lead
- creating a culture of open debate and discussion within ARPA-E to unleash this talent to identify new opportunities and fund ideas with potential for breakthrough technologies;
- creating a model of operational efficiency, active program management and financial integrity, with the discipline and compassion to sunset futile projects;
- an exemplar of engaging stakeholders via the ARPA-E Energy Innovation Summit as well as a creating a model of partnership with Congress.

Because of these elements and due to the remarkable breadth of new research ideas that ARPA-E funded across the USA, ARPA-E certainly caught the attention of many thought leaders in the US. Here are a few examples of what they said.

At the 2012 ARPA-E Energy Innovation Summit, the Founder, Chairman and CEO of FedEx, Mr. Fred Smith, said "Pound for pound, dollar for dollar, activity for activity it is hard to find a thing the United States has done that is more effective than ARPA-E." In 2011, Senator Lamar Alexander noted "It is my belief that ARPA-E is one of the bright stars in innovation in the world today, and certainly for our country." And in the same year, Senator Dianne Feinstein suggested to the then Secretary of Energy, Steven Chu, in a Senate appropriation hearing: "Even though ARPA-E is a new agency, I'd like to ask that you apply ARPA-E program management to other DOE offices." Bill Gates and his colleagues at the American Energy Innovation Council had high praise for ARPA-E as well. I could go on and on, but I think you get the point.

ARPA-E has been viewed as one of the most valued organizations within the US government for research investments with the goal of making the US the most innovative and globally competitive nation in the world in the energy sector.

This year marks the 10th anniversary of ARPA-E. Therefore, this hearing is very timely indeed to reflect back and ask two key questions: (a) What is the key to ARPA-E's success that needs to be preserved? (b) What else can ARPA-E do to make the US even more successful and globally competitive?

What is the key to ARPA-E's success that needs to be preserved?
ARPA-E is modeled after DARPA that has a 60-year illustrious history during which it helped create the internet, stealth and many other technologies. Similar to DARPA, ARPA-E is an organization that funds research in science and engineering with the purpose that if the research ideas are successful, they will produce breakthrough technologies that will have large commercial impact in the future. These technologies will form the foundation for entirely new industries that do not exist today and make US industries much more competitive in the world.

To fulfill this important mission, it is critical to have the most talented people within ARPA-E, ones who are at the cutting edge of creative research in science and engineering with a deep understanding of how research could create value for society via the private sector. It takes one to be at the cutting edge to recognize what is cutting edge. So in many ways, ARPA-E is all about the people. As the Director, I used my own stature and network in the scientific community to recruit top talent as Program Directors from the best organizations within the US – MIT, Intel, NC State, PNNL, GE, etc. None of my recruits needed a job. They joined ARPA-E to serve the nation and be part of something special as one of the most intellectually stimulating and enriching environments. After 3-4 years they went back to the private sector or academia with their ARPA-E record as a badge of honor. During their time at ARPA-E, they conceived some of the most impactful programs that bridged two or three fields of science and engineering to create something completely new that no one in the world had ever imagined. These include batteries much more advanced than lithium-ion to provide multi-day support for the grid. Or entirely new routes to use biology and agriculture to convert carbon dioxide into fuels.

So my message is the following. It is very important to preserve the special hiring authority Congress has bestowed on ARPA-E and to ensure that the leadership in ARPA-E uses this authority to recruit top talent. One of the best things about the ARPA-E model is that the program directors stay for 3-4 years and then are required to leave. This time constraint puts a level of urgency to make a difference, and this urgency is very important. This needs to be preserved as well.

Finally, much of the research ARPA-E funds is often in the proof-of-concept stage. To go from a successful proof-of-concept to full-scale commercial impact is a long and arduous maturation process, which takes 15-20 years in the energy sector. After all, research on computer networks started in 1968 which eventually produced the internet, but the full commercial impact was felt 25+ years later. The point I am making is the following: It is very important for Congress to be patient in its expectations of commercial impact from ARPA-E funded research. Expectations of short-term success will produce incremental thinking from ARPA-E, and that will defeat the whole purpose of ARPA-E which should be going for the homeruns. What should be asked of ARPA-E is whether there are signs of potential future success, such as: intellectual property creation; follow-on private sector funding after ARPA-E's investment; creation of startup

companies; technologies going into demonstration projects and industrial testing; new manufacturing supply chains being created. We are indeed seeing this happen, but it will take another 5-10 years for large-scale commercial impact.

What else can ARPA-E do to make the US even more successful and globally competitive? In the last 10 years, a lot has changed in the global energy landscape. Today, three game-changing paradigm shifts are already shaking up this global energy landscape: unconventional oil and gas revolution due to fracking of shale formations; electrification of transportation via lithium-ion batteries; and carbon-free electricity generation from wind and solar. The rapid cost reduction in these technologies due to R&D have create these tectonic shifts in the energy industry.

Despite this remarkable progress, fossil fuels still comprise 80 percent of global energy use. And yet we now know that we have to reduce greenhouse gas emissions with fierce urgency to mitigate the ill effects of climate change. Reducing emissions is a billion-tonne-scale problem and it needs billion-tonne-scale affordable solutions. What are these potential solutions?

They include: grid-scale storage at one tenth the cost of lithium-ion batteries; small modular nuclear reactors at half the construction cost of today's reactors; refrigeration and air conditioning using refrigerants with no global warming potential; zero net energy buildings at zero net cost; using renewables to produce carbon-free hydrogen at the same cost as that from shale gas; decarbonizing industrial heat needed to make steel, concrete and chemicals and reimagining carbon-neutral construction materials; decarbonizing the food and agriculture sector, and leveraging agriculture to suck out carbon dioxide from the air and store it in the ground; and capturing carbon dioxide from power plant exhausts followed by sequestering it deep underground or using it make plastics or even fuels.

What I am describing is nothing short of a new industrial revolution. This is a remake of much of our economy – electricity, automobiles, steel, concrete, oil, gas, food, agriculture, etc. We stand at the doorstep of a colossal change of the energy sector worth $10 trillion per year, more than 10 percent of the global GDP. This change will impact every human being, and will shape the economy, environment, international security and geopolitics of the 21st century. In short, this global energy transition presents a historic opportunity for every country and region. And the race is on to seize this opportunity. We must ensure that the US remains globally competitive and maintains its technological lead, which is part of APRA-E's mission.

The seize this opportunity we need to create new solutions. These solutions often start from new ideas of breakthrough technologies that are initially too risky or disruptive for the private sector. ARPA-E's mission is to help our scientists and engineers try out a portfolio of new ideas in their laboratories. Many will fail, but if some of these succeed, they will form the foundation of this new industrial revolution.

But here is the key challenge in the US. is that the journey from ARPA-E funded laboratory-scale proof of concept to billion-tonne scale commercial solutions contains multiple valleys of death. We must address these gaps for the US to receive the full economic benefit of ARPA-E investments. Let me propose one option for your consideration.

When faced with global competition in the semiconductor industry in the mid-1980s, DARPA convened 14 US semiconductor companies who would otherwise compete with each other in the market, and created SEMATECH, a not-for-profit consortium that performs R&D to advance chip manufacturing. Some of the funds came from DARPA, but the industry chipped in. A GAO report noted that this government-industry R&D consortium helped improve US industry's technological position while protecting the government's interest that the consortium be managed well and public-funds spent appropriately.

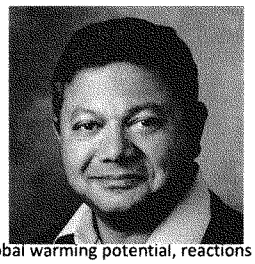
To address the first valley of death post-ARPA-E funding, Congress should seriously think about the lessons learnt from the past, adapt these lessons to the current energy landscape and allow ARPA-E to create such private-public consortia to enable the US energy industry become globally competitive. Such consortia could then nurture ARPA-E funded technologies beyond the proof-of-concept stage, and enable them to mature to pilot demonstration and beyond.

But let me also be very clear that such activity requires additional budget authority for ARPA-E. This should not come at the cost of ARPA-E research funding on new research ideas. When I was the Director of ARPA-E, I was often asked what should be ARPA-E's budget. My answer was very simple. Since ARPA-E was modeled after DARPA, one should look at DARPA's first budget. In 1962, the 87th Congress gave DARPA its first appropriated budget of $246M. In 2019 dollars, that is roughly $2B.

If we are serious about creating and leading in a new industrial revolution and compete with China, EU and other parts of the world, Congress should seriously consider ARPA-E's budget authority to be $1B at the very least. With the best scientific infrastructure and talent in the world, and with the entrepreneurial spirit that is in the American DNA, the US has a remarkable capacity to innovate and deliver on ARPA-E's investments. As Fred Smith implied, this is the best investment public dollars can make and best return on investment that our nation will receive.

I thank you for the opportunity to testify before you today, and I look forward to answering your questions.

Arun Majumdar Biosketch



Dr. Arun Majumdar is the Jay Precourt Provostial Chair Professor at Stanford University, a faculty member of the Departments of Mechanical Engineering and Materials Science and Engineering (by courtesy) and co-director of the Precourt Institute for Energy, which integrates and coordinates research and education activities across all seven Schools and the Hoover Institution at Stanford.

Dr. Majumdar's research in the past has involved the science and engineering of nanoscale materials and devices, especially in the areas of energy conversion, transport and storage as well as biomolecular analysis. His current research focuses on using refrigeration and cooling with zero global warming potential, reactions related to artificial photosynthesis, and a new effort to re-engineer the electricity grid.

In October 2009, Dr. Majumdar was nominated by President Obama and confirmed by the Senate to become the Founding Director of the Advanced Research Projects Agency - Energy (ARPA-E), where he served till June 2012 and helped ARPA-E become a model of excellence for the government with bipartisan support from Congress and other stakeholders. Between March 2011 and June 2012, he also served as the Acting Under Secretary of Energy, enabling the portfolio that reported to him: Office of Energy Efficiency and Renewable Energy, Office of Electricity Delivery and Reliability, Office of Nuclear Energy and the Office of Fossil Energy, as well as multiple cross-cutting efforts such as Sunshot, Grid Tech Team and others that he had initiated. Furthermore, he was a Senior Advisor to the Secretary of Energy, Steven Chu, on a variety of matters related to management, personnel, budget, and policy. In 2010, he was of Secretary Chu's team that helped stopped the leak in the Deep Water Horizon (BP) oil spill.

After leaving Washington, DC and before joining Stanford, Dr. Majumdar was the Vice President for Energy at Google, where he created several energy technology initiatives, especially at the intersection of data, computing and electricity grid, and advised the company on its broader energy strategy.

Prior to joining the Department of Energy, Dr. Majumdar was the Almy & Agnes Maynard Chair Professor of Mechanical Engineering and Materials Science & Engineering at University of California–Berkeley and the Associate Laboratory Director for energy and environment at Lawrence Berkeley National Laboratory.

Dr. Majumdar is a member of the National Academy of Engineering and the American Academy of Arts and Sciences. He served as the Vice Chairman of the Advisory Board to US Secretary of Energy, Ernest Moniz, and was also a Science Envoy for the US Department of State with focus on energy and technology innovation in the Baltics and Poland. He served as a member of the Council of the National Academy of Engineering, the Advisory Council of the Electric Power Research Institute and currently serves on the Science Advisory Board of the Oak Ridge National Laboratory. He is a member of the International Advisory Panel for Energy of the Singapore Ministry of Trade and Industry and sits on the Advisory Board of Envision Energy, Breakthrough Energy Ventures and the New Energy Group of the Royal Dutch Shell.

Dr. Majumdar received his bachelor's degree in Mechanical Engineering at the Indian Institute of Technology, Bombay in 1985 and his Ph.D. from the University of California, Berkeley in 1989.

Chairman LAMB. Dr. Williams.

TESTIMONY OF DR. ELLEN WILLIAMS,
DISTINGUISHED UNIVERSITY PROFESSOR,
UNIVERSITY OF MARYLAND

Dr. WILLIAMS. Thank you, Chairman Lamb, Ranking Member Weber, and other Members of the Committee. I truly appreciate the opportunity to appear before you today to testify on the future of ARPA-E. I was the second Director of ARPA-E, and I benefited from the innovations and the activity that Professor Majumdar has just described to you.

I would like to say that ARPA-E is an innovation agency, and one set of words you never hear in ARPA-E is, "because that's the way we've always done it before." ARPA-E uses innovation in its thinking, in its development, and in its planning.

As Director of ARPA-E, I frequently consulted the agency's founding authorization, which I consider to be just brilliant. It recognizes the importance of technological innovation in the world's evolving energy systems and the implications for the United States of the international competition in advanced energy technologies. A goal called out in the authorization is for the U.S. to remain a leader in advanced energy technologies and, based on our capabilities, we should certainly be able to do so.

However, even though the United States has been a world leader in basic research for most of the last century, our country has been notably less successful in transferring the benefits of its basic research successes into domestic manufacturing and the economic benefits that follow. ARPA-E is tasked to address that problem by translating cutting-edge discoveries into technical innovations. To do this, ARPA-E has developed a transformative research management model in which brilliant innovators, like Saul, are supported and mentored to advance both the technical performance and the commercial potential of their innovations. This process is essential for drawing value from early cutting-edge technologies that the private sector will not support because they are considered too risky.

We've heard about ARPA-E's measures of successes, and we've heard that there have been many recommendations to increase the level of fundings for ARPA-E. I believe you'll hear some of the stories of actual technologies and the teams that make them successful from Dr. Griffith and Professor Majumdar, and I would also be happy to provide more examples. I would say that each year ARPA-E has far more opportunities flowing from the ingenuity of America's scientists, engineers than it has the ability to support. Many experienced observers such as the American Innovation Council have called for substantial increases in the agency's budget. I agree with that assessment, and I agree that it needs to be addressed in an innovative and creative fashion, not just more of the same but really addressing new challenges in new ways.

In creating strategies for growth at ARPA-E, as we thought about mechanisms for increasing the budget and using the budget effectively, we looked for opportunities to yield even greater impacts per dollar for the U.S. economy and identified three approaches. The first approach is to address the problem that at present even the most successful ARPA-E projects are still often

judged too high-risk by potential investors. As a result, they struggle to obtain early investments or may be undercapitalized compared with their international competitors.

ARPA-E could give such companies a faster start with expanded programs for innovative scaling and advanced manufacturing processes suitable for domestic manufacturing. These would not be incremental improvements. These would be looking for game-changing improvements in how we do manufacturing and how we bring technology to commercialization.

The programs would support the most competitive projects to move from the stage of successful prototype to pilot-scale demonstrations. The expanded effort would work collaboratively in terms of drawing funding and increased investment opportunities in the United States and prevent innovative U.S. companies from being stranded or frozen out of markets by international competitors who can move more quickly.

The second approach is to expand investment in the earliest stage, most innovation, and thus highest-risk technologies. These represent the pipeline of innovation for the future. ARPA-E's OPEN program funding opportunity announcements, which allow proposals at all areas of technologies, are an important discovery mechanism and have given rise to exciting new technologies such as slips, incredibly low-friction surfaces, sky cooling materials that spontaneously cool by sending heat into outer space, and Foro technology, which uses laser power for drilling in hard rock.

Finally, ARPA-E can expand its core focus programs to include more larger-scale technologies and integrate performance demonstrations and prototype the pilot funding to optimize handoff to commercial development. The vision of the future of ARPA-E requires changes, but that's important for—that's appropriate for an innovation agency, and it's already enabled by the flexibility built into its authorization. An expanded budget for ARPA-E will enable more early-stage cutting-edge technologies to be moved more quickly and more effectively to handoff for private-sector commercialization in the United States, boosting U.S. competitiveness and economic growth.

Thank you again for this opportunity to speak.

[The prepared statement of Dr. Williams follows:]

Testimony on 'The Future of ARPA-e' to the Subcommittee on Energy, House Committee on Science, Space and Technology

Ellen D. Williams
February 26, 2019

Chairman Lamb, Ranking Member Weber, members of the committee, I appreciate the opportunity to appear before you today to testify on the Future of ARPA-e. As you know, I was the second Senate-confirmed Director of ARPA-e and served from December of 2014 through January of 2017.

The founding authorization of ARPA-e recognizes the economic, environmental, and energy security importance to the United States of technological innovation in the face of the world's evolving energy systems. As energy systems are changing there is serious international competition in developing and deploying the advanced energy technologies of the modernized systems. I would like the US to remain a leader, and based our capabilities, we should. The United States has been a world leader in basic research for most of the last century. However, our country has been notably less successful in transferring the benefits of its basic research successes into domestic manufacturing and the economic benefits that follow.

ARPA-e was established specifically to support US competitiveness by speeding the translation of promising innovations into domestic advanced energy technologies. Since it started operations in 2009, ARPA-e has demonstrated a transformative research management model in which brilliant innovators are selected on the merit of their proposed work and supported to simultaneously advance the technical performance and commercial potential of their innovations. ARPA-e's model is designed to reduce the technical and financial uncertainty that deter industrial and venture investors.

ARPA-e's success with this model is quantified in part by the metric of private sector follow-on funding for the projects it has supported. As of February of 2018, 134 projects funded by ARPA-e had been able to attract private follow-on funding totalling at least $2.6 billion, significantly exceeding the cumulative support of $1.8 billion dollars provided to ARPA-e's more than 660 projects. The stories of the actual technologies and the teams that make them successful, are even more compelling, but less amenable to quick communication.

The project funding that ARPA-e is now able to provide falls far short of meeting the opportunities that flow from the ingenuity of America's scientists and engineers, and the resulting potential to advance US competitiveness. Many experienced observers, such as the American Energy Innovation Council, have called for a substantial increase in the agency's budget. I agree with

that assessment – as director I led strategic planning for how growth of ARPAE from roughly its present budget to a budget of one billion dollars per year over a period of 5 years could be implemented. In creating strategies for such growth, we recognized that, as successful as ARPA-e is, growth can be structured to yield even greater impact per dollar for the US economy.

The expanded impact can be realized with differential expansion in three areas. First, with an expanded budget ARPA-e should prioritize the problem that, at present, even the most successful ARPA-e projects are still judged to have high risk by potential investors. As a result, they struggle to obtain early investments, or may be undercapitalized. ARPA-E could decrease investment risk with significantly expanded research funding for innovative scaling and advanced manufacturing processes suitable for domestic manufacturing. With a larger base budget, this could be accomplished with funding levels well within ARPA-e's authorization limits on such investment to no more than 50% of the budget. The resulting programs would support the most competitive projects to move from the stage of successful prototypes to pilot scale demonstrations. This expanded effort will increase investment opportunities in the US and prevent prototype technologies from being stranded or frozen out of markets by international competitors who were able to move more quickly.

Second, under an expanded budget ARPA-e should moderately expand its investment in the earliest stage, most innovative, and thus highest risk energy technologies. These represent the pipeline of innovation for the future. ARPA-e's present "OPEN" funding opportunity announcements, which allow proposals in all areas of energy technology, now serve as an important discovery mechanism for new concepts and can readily be expanded. Those "OPEN" projects that prove most successful would then be able to compete for further development funding under the expanded prototypes-to-pilots program category described above.

Finally, ARPA-e should moderately expand its core Focused programs under an expanded budget to include more larger-scale technologies, and to integrate performance demonstrations and prototype-to-pilot funding to optimize hand-off to commercial development. For example, ARPA-e is now testing staged programming that supports a broad portfolio of moderate size projects in stage 1, and a smaller number of the most competitive projects at a higher level in stage 2.

This vision of the Future of ARPA-e is already enabled by the present authorization, and it builds on the successful operational approaches that ARPA-e has demonstrated. An expanded, budget for ARPA-e will enable faster and more effective hand-off of innovative energy technologies to private-sector commercialization in the U.S, boosting US competitiveness and economic growth.

Ellen D. Williams

Ellen Williams is a Distinguished University Professor at the University of Maryland, where she works at the interface of energy technology and policy. Before returning to the University in January of 2017, she was the Director of the Advanced Research Projects Agency, ARPA-E, which advances high-potential, high-impact energy technologies that are too early for private-sector investment.

Prior to Senate confirmation for her role in ARPA-E, Dr. Williams had been the Chief Scientist at BP (2010-2014), and a Distinguished University Professor in the Institute of Physical Science and Technology and the Department of Physics at the University of Maryland. At Maryland she established an internationally recognized research program in experimental surface science, exploring fundamental issues in statistical mechanics and nanotechnology. She founded and led the University's interdisciplinary Materials Research Science and Engineering Center from 1996 through 2009.

Dr. Williams has a distinguished history of professional service, including chairing the development of the NAS report on Technical Issues for the Comprehensive Test Ban Treaty, and extensive work in providing technical advice to the U.S. government, primarily through the Departments of Energy and Defence. She is a member of the National Academy of Sciences, a foreign member of the Royal Society (London), a fellow of the American Physical Society, American Vacuum Society and American Academy of Arts and Sciences, and has been recognized by awards from the American Physical Society and the Materials Research Society.

Chairman LAMB. Thank you, Dr. Williams. Dr. Wall.

TESTIMONY OF DR. JOHN WALL,
RETIRED CTO, CUMMINS,
MEMBER OF THE COMMITTEE ON EVALUATION FOR
THE 2017 NATIONAL ACADEMIES REVIEW OF ARPA-E

Dr. WALL. Chair Lamb, Ranking Member Weber, Chair Johnson, and Ranking Member Lucas, and other distinguished Members of the Subcommittee, thank you for the opportunity to testify about ARPA-E. My testimony today is guided by my career working on energy and environmental technologies at Chevron and Cummins, a Fortune 200 engine and power system manufacturer, and as a member of the National Academy of Engineering on a recent National Academies study to assess the first 6 years of ARPA-E.

I'd like to make three main points today. ARPA-E plays a vital role in U.S. energy innovation beyond what industry can do for itself. ARPA-E's unique use of experienced practitioners as program managers is important for its success, and ARPA-E is critical for U.S. global competitiveness.

First, ARPA-E plays a unique and vital role in U.S. energy innovation beyond what energy—what industry can do for itself. Innovation in the industry happens—in energy happens across a broad spectrum from novel, unproven hypotheses to integration into products that are then bought and used by customers. Innovation only has value if it makes it all the way into use. Required investments grow through this progression from thousands to millions to hundreds of millions of dollars. De-risking of novel concepts is a very important element of this development process to allow for rational business investment and product development and productionized manufacturing.

A manufacturing company is not equipped to do all the research required for breakthrough and disruptive innovation internally. In fact, they may not even recognize it when it's happening. But they can embrace it, scale it up, and bring it to market once it's validated. For example, this year, Cummins is celebrating its 100th year in the diesel engine business and also is introducing its first all-electric powertrain. While Cummins was innovating in the diesel engine space, those electric powertrain technologies were being developed and validated independently by innovators with unique skills that Cummins simply did not possess. But they've now been brought into the company for integration into a new product line. ARPA-E facilitates technology development and transfer like this with culture and talent specifically aimed at identifying promising concepts in critical energy areas and nurturing them to success.

The National Academies found that one of ARPA-E's strengths is its focus on funding high-risk potentially transformative technologies, and ARPA-E has funded research that no other funder was supporting at the time, technologies which are now beginning to enter the commercial market.

But it's not just about funding. ARPA-E attracts experienced practitioners into relatively short-term government service with the specialized skills to evaluate new technology concepts and to manage them forward. Empowered program managers are a unique and critical component of ARPA-E's success. They're accorded wide

latitude in identifying research themes, creating new programs, supervising projects, identifying commercial opportunities, and, when necessary, terminating projects through very active program management. So this is not casting our bread onto water. It's cultivating fish.

My final point is that ARPA-E is critical to U.S. global competitiveness. Energy is a multitrillion dollar industry. It provides jobs and security for our citizens. It is undergoing a global transformation from traditional energy sources to new generation, power, and storage technologies. And other governments get it.

Consider Cummins' experience in China. Cummins entered the Chinese engine market very successfully based on world-class emission technology that far exceeded indigenous capability and later moved on to a hybrid powertrain partnership with China government's support. That support was abruptly terminated as China realized that the rest of the world was ahead in that domain, too, and shifted to a focus on battery electric vehicle (EV) powertrains with a strategic intent to lead the world in EV production.

As I was reflecting on this, I looked up the current China 5-year plan. Here's some of what I found: Ensure innovation in science and technology takes a leading role; encourage public startups and innovations; develop strategic emerging industries; build a modern energy system. Make no mistake about it, we are in a race without a finish line, and it is a global race.

ARPA-E's unique mission, structure, active program management, and drive from innovation into commercialization are critical for American technology leadership, for American business leadership, and for American jobs, especially high-tech jobs. That's worth a billion-dollar investment in ARPA-E and secure year-over-year funding.

I ask that my full testimony and the executive summary of the National Academies' 2017 report and assessment of ARPA-E be submitted to the record, and I encourage the Committee and Subcommittee and staff to read the full report. Thank you very much. I look forward to your questions.

[The prepared statement of Dr. Wall follows:]

The Future of ARPA-E
Testimony before the House Science, Space, and Technology Committee,
Subcommittee on Energy
Dr. John Wall
February 26, 2019

Chairman Lamb, Ranking Member Weber, and other distinguished Members of the Energy Subcommittee of the House Science, Space, and Technology Committee, thank you for the opportunity to testify about ARPA-E.

My testimony today is guided by my career working on energy efficiency and environmental technologies at Chevron and Cummins, including 15 years as Cummins Chief Technical Officer. In addition, I served on a recent National Academies of Sciences, Engineering, and Medicine study committee tasked with assessing the first six years of ARPA-E.

The ARPA-E study committee

As this committee is well aware, the National Academies' assessment of ARPA-E was mandated in the authorizing legislation. The study committee was asked to conduct an assessment of the progress the agency made toward achieving its congressionally mandated mission and goals. The committee was composed of a diverse set of members, including academic and industry engineers (such as myself) and scientists, academic economists and statisticians, experts from private research organizations, and former government officials.

The committee concluded that there were clear indicators that ARPA-E is making progress toward its statutory mission and goals, while understanding it could not reasonably be expected to have completed fulfilled those goals given so few years of operation and the size of its budget.

I would also like to note that the idea of ARPA-E sprang from a recommendation in a 2007 National Academies' report, *Rising Above the Gathering Storm: Energizing and Employing America for a Bright Economic Future.* In the Gathering Storm report, the committee recommended that the federal government create a DARPA-like organization within the Department of Energy charged with sponsoring specific R&D programs to meet the Nation's long-term energy challenges and creating an opportunity for "out-of-the-box" transformational research.

Despite the fact that the genesis of the idea came from within the National Academies, the study committee that I served on conducted an independent and unbiased assessment of ARPA-E.

I would like to make three main points today.

First,

ARPA-E plays a unique and vital role in US energy innovation, beyond what industry can do for itself.

From my personal experience, I can tell you that innovation in energy happens across a broad spectrum – from novel, unproven hypotheses to concept validation to integration into products that are then bought and used by customers. Innovation only has value if it makes it all the way into use.

Required investments grow through this progression from thousands to millions to hundreds of millions of dollars from unproven concepts to productionized manufacturing. "Derisking" of novel concepts is a very important element of this development process to allow for rational business investment in product development and manufacture.

A manufacturing company is not equipped to do all the research required for breakthrough and disruptive innovation internally. In fact, they might not even recognize it when it's first happening. But they can embrace it, scale it up, and bring it to market once it's validated.

For example: In 2019, Cummins is celebrating its 100th year in the diesel engine business and also is introducing its first all-electric powertrain. While Cummins was innovating in the diesel engine space, those electric powertrain technologies were being developed and validated independently by innovators with unique skills that Cummins simply did not possess. But they have now been brought into the company for integration into a new product line.

My experience in industry was echoed in the findings of our National Academies report, where we found that

"One of ARPA-E's strengths is its focus on funding high-risk, potentially transformative technologies and overlooked, "off-roadmap" opportunities pursued by neither private firms nor other funding agencies, including other programs and offices within DoE." (NASEM report on ARPA-E, Finding 4-4).

and

"ARPA-E has funded research that no other funder was supporting at the time. The results of some of these projects have prompted follow-on funding for various technologies, which are now beginning to enter the commercial market." (NASEM report on ARPA-E, Finding 4-1)

ARPA-E has established an organization to facilitate technology development and transfer like this, with culture and talent specifically aimed at identifying promising concepts in critical energy areas and nurturing them to success.

The National Academies report documented the work done by ARPA-E to look for perceived gaps or opportunities in the energy technology landscape. ARPA-E searches for technological approaches that are truly novel or greatly underexplored, and searches to fill gaps left in other research or funding programs. One example of this in the report is the Full-spectrum Optimized Conversion and Utilization of Sunlight (FOCUS) program which merged concentrating solar power and photovoltaic technologies to create a combined technology with lower cost per kilowatt hour than either technology alone. The report's case study appendix (Appendix D) highlights other effective programs as well.

But it's not just about funding.

This leads to my second main point.

ARPA-E attracts individuals into relatively short-term government service as program managers with the specialized skills to evaluate hypotheses that can be quite arcane and to manage them forward.

The National Academies committee also concentrated on ARPA-E's internal operations to appraise the effectiveness of its structure at achieving its mission and goals.

The committee found that the ARPA-E benefits from three defining organizational features:
1. The director exercises technical and leadership skills that enable a culture of empowerment to be sustained.
2. ARPA-E's program directors are empowered with the authority, responsibility, and ability to make program-and project-related decisions.
3. Active project management is important to ARPA-E.

The National Academies report found that

"ARPA-E program directors have wide authority to develop new focused technology programs that are potentially transformative." (NASEM report on ARPA-E, Finding 3-8)

and

"ARPA-E program directors actively manage projects through technical research guidance and feedback, regular and frequent assessments of progress made toward stated technical milestones, and revision of milestones in response to new findings and research discoveries." (NASEM report on ARPA-E, Finding 3-9)

Program directors are accorded wide latitude in identifying research themes; creating new programs; supervising projects; identifying commercial opportunities; and, when necessary, terminating projects.

And the program directors are specifically recruited for their technical domain knowledge.

Interviews with current and former ARPA-E program managers led the study committee to conclude that program managers found that working at ARPA-E allowed them to "work on truly revolutionary ideas or technologies" in contrast to private industry "where research is focused on supporting existing product lines and over short time spans." (NASEM report on ARPA-E, p. 57)

The National Academies also recommended that ARPA-E retain its practice of keeping program managers for short terms. "ARPA-E should continue its practice of hiring program directors for 3-year terms, allowing one, term-limited extension when necessary to complete implementation of a new program or for other reasons determined by the ARPA-E director." (NASEM report on ARPA-E, Recommendation 3-4).

So this is not "casting our bread on the water", it's "cultivating fish"!

Many of ARPA-E's internal processes were patterned after DARPA. The committee highlighted many of the similarities – and some differences – between ARPA-E and DARPA (NASEM report on ARPA-E, pp. 74-79). Both of the agencies have low levels of hierarchy, an organizational culture of risk taking, a focus on hiring highly qualified technical staff with academic and industrial backgrounds, and providing broad autonomy for program managers to identify and support relevant technologies.

There are a number of differences between the agencies, the largest and most important of which is the size of each agency's budget and the uncertainty surrounding whether it will be funded. As discussed in the National Academies' report, DARPA's annual budget is roughly 10 times that of ARPA-E, nor has DARPA experienced threats of having its budget reduced to 0 each year. This scale and certainty of funding allows DARPA to take a broader and longer-range view to supporting technology development.

Despite its smaller budget, my third point is that

ARPA-E supports US global competitiveness.

Consider Cummins experience in China. Cummins entered the Chinese engine market very successfully based on world-class emission technology that far exceeded indigenous capability, and later moved on to a hybrid powertrain partnership with China government support. That support was abruptly terminated as China realized that the rest of the world was ahead in that domain, too, and shifted to a focus on battery electric vehicle powertrains with the strategic intent to lead the world in E.V. production.

As I was reflecting on this, I looked up the current China Five-Year Plan. Here's some of what I found:
(http://en.ndrc.gov.cn/newsrelease/201612/P020161207645765233498.pdf)

PART II INNOVATION-DRIVEN DEVELOPMENT

With innovation as the basis from which to pursue development, we will give a central role to innovation in science and technology and a supporting role to the development of talent, closely integrating scientific and technological innovation with business startups and innovation by the general public in order to achieve leading-edge development that relies more on innovation as its driver and offers greater incentives for first innovators.

Chapter 6 Ensure Innovation in Science and Technology Takes a Leading Role

We will see that scientific and technological innovation leads the way in all areas of innovation. We will strengthen basic research, bolster primary innovation, innovation based on the integration of existing technologies, and innovation based on import and assimilation, and improve China's own capacity for innovation, so as to provide an inexhaustible driving force for economic and social development.

Section 1 Breakthroughs in Strategic and Frontier Fields

Chapter 6 Ensure Innovation in Science and Technology Takes a Leading Role
Chapter 7 Encourage Public Startups and Innovations
Chapter 8 Establish Innovation Promoting Institutions and Mechanisms

Chapter 23 Develop Strategic Emerging Industries

Chapter 30 Build a Modern Energy System

Chapter 48 Develop Green and Environmentally Friendly Industries

This isn't their energy policy – it's the blueprint for all dimensions of their national policy – and it is heavily focused on innovation in energy.

Make no mistake about it -- we are in a race without a finish line. And it's a global race.

ARPA-E plays a critical role here

for American technology leadership,

for American business leadership,

for American jobs, especially high-tech jobs.

That's worth a billion-dollar investment in ARPA-E.

I would also like to highlight a few recommendations for improvement of ARPA-E from the National Academies report, which were offered very much in the spirit of "you don't have to be bad to get better".

ARPA-E should reconceptualize its "technology-to-market" (T2M) program to account for the wide variation in support needed across programs and performers with respect to prospective funding, commercialization, and deployment pathways. (NASEM report on ARPA-E, Recommendation 3-3)

The director of ARPA-E should continue to promote and maintain a high-risk culture within the agency. Means to this end include periodic reassessment to ensure that the principles that drive support for high-risk projects are being maintained. (NASEM report on ARPA-E, Recommendation 4-2)

The National Academies found that through its projects and programs, ARPA-E is accumulating not only technical knowledge of what is working and has promise, but also potentially very useful information on what does *not* work that can be an important addition to ARPA-E documentation (NASEM report on ARPA-E, Finding 4-7), and recommended that program managers compile a repository of lessons learned on all projects, included both positive and negative outcomes. (NASEM report on ARPA-E, Recommendation 4-6)

The National Academies also recommended that ARPA-E increase and improve its communication for non-technical audiences, which would help demonstrate how the projects and programs are working toward its stated mission and goals to a more general audience. (NASEM report on ARPA-E, Recommendation 4-7)

And finally, the National Academies' report recommended that ARPA-E should consider streamlining some its reporting requirements to ease the burden on performers. (NASEM report on ARPA-E, Recommendation 4-5).

I ask that my full testimony and the Executive Summary of the National Academies 2017 report **An Assessment of ARPA-E** be submitted into the record. And I encourage the Committee and Subcommittee members and staff to read the full report.

Dr. John C. Wall

Dr. John C. Wall has more than 40 years of industry experience in internal combustion engine technology, fuels and emissions, and in global engineering organization development. Most recently, John served as Chief Technical Officer of Cummins Inc., the world's largest independent manufacturer of diesel engines and related technologies, retiring in 2015. As he progressed from research and product engineering into engineering leadership, John remained directly involved in the most critical technology programs for low emissions, powertrain efficiency and alternative fuels. He also led the growth of Cummins technical organization from 1000 engineers, mostly centered in the U.S., to more than 6000 engineers globally, establishing new technical centers in India and China. Prior to joining Cummins in 1986, John led Diesel and Aviation Fuels Research for Chevron, where his team was first to discover the important contribution of fuel sulfur to diesel particulate emissions. He is currently an advisor to the DOE Joint BioEnergy Institute and Co-Optima Program, the Cyclotron Road energy incubator at Lawrence Berkeley Laboratory, to the International Council of Clean Transportation and to the Institute of Transportation Studies at the University of California – Davis. He is active in a number of roles with the National Academies, including the Board on Energy and Environmental Systems, and is a member of the Board of Directors of Achates Power. He has been recognized for his technical contributions by election to the National Academy of Engineering and as a Fellow of the Society of Automotive Engineers. He has received the SAE Horning Memorial Award and Arch T. Colwell Merit Award for research in the area of diesel fuel effects on emissions, the SAE Franz F. Pischinger Powertrain Innovation Award, the ASME Soichiro Honda Medal for significant engineering contributions in the field of personal transportation, and the California Air Resources Board Haagen-Smit Clean Air Award and US EPA Thomas W. Zosel Individual Achievement Award for career accomplishments in diesel emission control. John studied mechanical engineering at the Massachusetts Institute of Technology, where he received his SB and SM degrees from the Mechanical Engineering Honors Program in 1975 and ScD in 1978.

Chairman LAMB. Thank you, Dr. Wall. And I can assure you we will. Dr. Griffith, please.

TESTIMONY OF DR. SAUL GRIFFITH,
FOUNDER AND CEO, OTHERLAB

Dr. GRIFFITH. Good morning, and thanks, everyone, for giving me the opportunity to talk about my favorite topic: Energy innovation.

I moved to the United States in 1998 to do my Ph.D. at MIT, and, after completing that, I moved to Silicon Valley in 2004 to be at the heart of the technology industry in this country.

We created Otherlab. It's a small independent research lab created to make technologies that are commercialize-able, and we commercialize them by spinning companies out of Otherlab that grow themselves into stand-alone, viable entities.

I guess I'm here to give case studies of successful ARPA-E projects. I just founded a company, a wind energy company called Makani Power in 2006. The idea was to build wings the size of 747s and fly them on a string about a mile above the ground and flying in circles at 200 miles per hour and generating electricity from them.

In 2009, we got ARPA-E funding, $3 million, and I can say with certainty that Makani Power would not have existed were it not for that investment. Makani Power then got acquired by Google, and under Google X, about $100 million more was invested in the company. They are now generating net positive power and just this year have announced a partnership with Shell, one of the world's largest energy companies, to do offshore deployments of what is fundamentally a transformational new energy technology.

In 2012, we started another company called Sunfolding. The sun moves across the sky. Sunfolding is a very simple idea. How do you track the solar panels as they—as the sun moves across the sky? You get about 25 percent more energy by doing so. Traditionally, this is done with complicated machines and expensive little electric motors, gearboxes, and mechanical components. We had a radical idea to move those with plastic bags. That turns out is a crazy idea but it works. We got three different rounds of funding from ARPA-E to make that technology work. There was no—we tried to get investment in that technology prior to ARPA-E funding. Nobody would believe that it was going to work. That is so successful that we are now producing 10 or 20 megawatts a week of these trackers. We are manufacturing in six States across the United States. We are employing 25 people. We'll be doing a C round of funding for that company this year, and it looks like it may be the next success story in the solar industry.

Other examples, we started—there was a MOVE program, Methane Opportunities for Vehicular Energy. In 2012 ARPA-E wanted——

Chairman LAMB. Don't worry about that.

Dr. GRIFFITH. I'm in Washington. I worry about those things.

ARPA-E wanted to support the natural gas industry with technologies to run vehicles on natural gas that would make them lower carbon per mile. One of the problems, however, with natural gas vehicles is the big spherical tank that doesn't fit very well in the back of the truck or in the trunk of the vehicle, so they wanted

to make what's called a conformable gas tank, make a gas tank that can fit in the nooks and the crannies of the vehicle so that you can get more natural gas in there and make the cars go faster. We used some arcane mathematics to come up with a new idea and basically imagined that instead of one big tank we made a giant intestine of a tank. This reduced the cost of making tanks by about 20 percent, the weight by about 20 percent, increased the range of those tanks by 30 to 40 percent.

That technology has been licensed into the natural gas industry and is being commercialized with—in partnership with Westport. That technology was then further developed with funding from many different automotives, so we got about $10 million in development revenue from the major automotives to also develop the same technology for hydrogen vehicles, and that hydrogen technology has now been licensed to Linamar, a major OEM (original equipment manufacturer), and is going to market in that industry.

Another radical idea we had was to make clothing that could change its shape in response to temperature, the idea being if it gets cooler, the clothing gets warmer. If it gets warmer, the clothing gets cooler. I did that in partnership with a colleague from MIT who had originally come to work on Sunfolding as our material science, but the one point to emphasize here is that ARPA-E is funding a community of people. When they get funded on one project, then they often go on to work on other energy technologies. And the community is fundamental to the value of ARPA-E.

We have been able to use that ARPA-E funding to develop entirely new manufacturing processes, knitting and weaving processes to create this textile. We've secured so far about $2.5 million in venture funding. That company will probably be deploying that technology in real products, bedding and clothing, next year and will be doing another fundraise this year.

We did another program called the Super Sankey. This was not focused so much on making an energy technology but rather how do we understand the U.S. energy economy in the greatest possible detail? So we pored over all existing government sources of data and some nongovernment sources of data to build the most comprehensive flow diagram of all the nuanced relationships in the U.S. energy economy, and this tool is now online. And in fact in their last—ARPA-E's last OPEN FOA (funding opportunity announcement), they suggested that teams use this tool to understand the potential impact of their technologies on the U.S. energy economy. It also highlighted that there are great opportunities for re-examining how we gather data about the U.S. energy economy and how we report it in order to support how we transition to a new energy economy.

[The prepared statement of Dr. Griffith follows:]

Saul Griffith, PhD, CEO Otherlab.

Testimony to the Energy Subcommittee,
Committee on Science, Space, and Technology
U.S. House of Representatives

Scheduled for Tuesday February 26.

Big Ideas, Small Companies, and ARPA-E innovation.

Otherlab and associated companies have been very successful leveraging ARPA-E funding to commercialize new energy technologies that are starting to have a major impact on the energy economy.

ARPA-E has a critical role in technology development in the US not only in the earliest stages of technology development (the first valley of death) but in assisting through pilot programs and manufacturing scale-up to get the most promising technologies over the second valley of death and into the market.

About Otherlab:

Otherlab is a small independent research lab whose business model is to invent and develop new technologies, find product-market fit, and spin out financeable start-up companies. Much of the reason to use this model is that it allows us to leverage early government investment and transition to other sources of capital such as angel investment and venture capital to grow successful companies.

This is a powerful model for commercializing technology, and reflects the recent analysis that small teams are more effective at early-stage technology disruption[1], while large teams are good at later-stage technology development, cost reduction, and improvement. At any one time Otherlab has 4-8 projects running with anything from 1-20 people on the teams. We have a focus on new energy technologies because of the importance of building a robust 21st-century energy infrastructure that will help us deal with climate change.

Otherlab is not a university, nor is it a federally funded or national lab, which puts it in a unique position. We have, however, partnered with both universities and national labs. We are known for being both inventive and effective, as evidenced by three companies growing out of ARPA-E funding and ARPA-E seeing the value in that research to the point of awarding follow-on funding for each. As well as being pioneers in new energy technologies, we are well known for our pioneering work in soft robotics, soft exoskeletons, and advanced manufacturing. Otherlab typically has 25-50

[1] https://www.nature.com/articles/s41586-019-0941-9

people on its payroll, and at any one time may have as many as 200-500 people employed by the various companies that have spun out.

However, because of our status as a for-profit independent research and development lab, we cannot apply for all categories of federal funding. I believe making more federal R&D money available to groups like ours will lead to a more innovative America.

Fortunately, ARPA-E and DARPA are agencies that will work with all categories of institutions. We have had a great deal of success working with both DARPA and ARPA-E, and we have also done research contract work for EERE, SOCOM, ONR, NASA, NSF, and NIH. We have had partnerships with universities including MIT, Stanford, Berkeley, Tulane, Purdue, and more. We have similarly partnered with major industrial concerns including Ford, Toyota, Facebook, Google, Adidas, Specialized, Nike, GE, Autodesk, OReilly Media, and more.

Otherlab and ARPA-E (Case Studies in Chronological order)

Makani Power, funded under ARPA-E Open 2009.

I founded the company Otherlab on April 22, 2009 (Earth day). I had previously been working as the CEO of Makani Power, which I founded in 2006. One of the last things I did at Makani was helping with their ARPA-E proposal for the inaugural funding round "Arpa Open 2009." Makani was successful in obtaining an ARPA-E contract which was critical in the survival of the company in the depths of the global financial crisis of that period. I think it is reasonable to assume that the airborne wind energy technology Makani has pioneered would not have survived until today without the assistance of ARPA-E. Makani was later acquired by Google and absorbed into Google X. It has since partnered with Shell for its initial pilot commercial deployments. Makani has employed hundreds if not close to 1000 of the country's best young engineers over the 10-plus years it has taken for the technology to move from equations on a sheet of paper and sketches in our imaginations to a powerful contender as a platform technology for high utility offshore wind energy. I estimate upwards of $200M has been invested in making this technology commercial, a successful example of the leverage of a relatively small ARPA-E investment (around $3M).

Sunfolding. Funded under ARPA-E Open 2012 with two "plus-up" awards

Sunfolding is on the cusp of becoming the next solar success story. We are redesigning solar trackers from the ground up -- these are the machines that move solar panels to follow the sun and are being installed in almost every utility-scale system today. Powered by air, Sunfolding's tracker uses just three components while others use over twenty, making our solar plants easier, faster and cheaper to build and operate. Over the last 7 years, Sunfolding has gone from revolutionary concept with funding from ARPA-E to a 60MW portfolio being installed this quarter, including projects with one of the biggest solar developers and one of the largest utilities in the U.S.

Sunfolding started with questions: What would a machine look like if it were specifically designed for solar? What problems could we solve by redesigning the fundamental building blocks of machines?What if we could use high volume manufacturing methods and advanced materials to create reliable, scalable solar trackers right here in the United States, rather than manually assembling these machines overseas, like nearly all existing tracker technologies today.

Back in 2011, we tried to get investors and corporate partners interested. Were it not for ARPA-E funding Sunfolding would not exist today. With ARPA-E funding we were able to do the fundamental R&D to determine whether or not the technology could work. Our progress was such that we received two "plus-up" awards from ARPA-E to continue the work. Both were critical to get the technology to the stage that it was investable by the private sector. There are still many hurdles to getting a new hardware out of the R&D lab and into the energy market. One challenge is proving that the the technology will survive in the field for 20-plus years before you have put them in the field for 20 years. A crucial part of this process are real world deployments and pilot projects. It is hard to find funds for this stage of development; often the developing entity of the technology has to finance these deployments and tests themselves, yet another difficult hurdle in bringing these projects to market.

Sunfolding was extremely fortunate at a critical moment to secure California Energy Commission funding for a pilot project. Without it, this promising technology may have withered in the lab without ever being tested in the real world. I cannot emphasize enough the importance of funds to do test deployments and pilot projects in de-risking new energy technologies. Without that de-risking, banks aren't willing to finance projects with that energy technology, which is one of the final and biggest hurdles to entering the mainstream energy market.

Sunfolding has been able to leverage the investments of ARPA-E to raise investor funding, including Y-combinator. Sunfolding now employs 25 people and has manufacturing partnerships across the country, including Dupont. Our US-based supply chain partners are behind some of the most dependable material applications in the world typically employed in automotive, rail, marine, and industrial lift applications. We are partnering with them to bring their manufacturing methods, materials and quality standards to the solar industry. Sunfolding's tracker technology is poised to install 100's of MW of plants all over the US and internationally over the next 2 years. By all measures the company is succeeding greatly in lowering the cost of zero carbon renewable energy and keeping the US at the forefront of Solar.

FOCUS "Full-Spectrum Optimized Conversion and Utilization of Sunlight" 2014-2017.

Otherlab and Sunfolding became involved in another ARPA-E program in collaboration with Tulane University and Boeing's Spectra lab. The program "FOCUS" targeted increasing the total system efficiency and even adding storage to solar energy through hybrid systems that captured more light and more heat and utilized both. Ultimately the technologies developed

under this program were not core to either Otherlab's or Sunfolding's mission, and we novated that award to the Sub Awardees to continue the good work in the University research setting which is now itself spinning up into a company.

Volute Inc. Funded under ARPA-E MOVE program. "Methane Opportunities for Vehicular Energy," 2012 and 2013-2015.

The MOVE program was designed to create technologies that supported Natural Gas Vehicles which can have lower operating costs and lower emissions than gasoline vehicles. Under that program, we developed a conformable tank technology exploiting some cunning mathematics and geometry. This technology improves the range, safety, and cost of natural gas vehicles. The program was initially funded with $250,000 to prove the concept, and upon successful proof we were granted a second contract of ~$4.1M of which we had to meet ~$870,000 in cost share.

Volute was able to leverage the $3.5M (federal share of the funding) to find another $10M in development revenue from major automakers in co-development programs.

The technology was licensed to Westport Fuel Systems (a natural gas vehicle company) for compressed natural gas vehicles.

Technology has been licensed to Linamar (a large supplier to major automotive OEMs) for hydrogen fuel cell vehicles. Linamar is continuing development and has hired several members of the core team that worked on the initial ARPA-E project.

Approximately 15 full-time jobs were created in the US; roughly 10 on the Volute team now at Linamar with a further 5 at contract manufacturers in the US.

Kestrel Materials, Funded under DELTA program. "Delivering Efficient Local Thermal Amenities." 2015-Ongoing.

Kestrel Materials was an idea that we developed at Otherlab to create textiles that use ambient temperature changes to change the loft (thickness) and hence the insulation (warmth) of fabrics. These can be used to make clothes that increase the comfortable temperature range of people within buildings and also outside. The idea was developed principally with Brent Ridley (PhD, MIT) who was originally hired to help with the materials science components of Sunfolding. It is important to recognize the importance of the role of ARPA-E in developing communities of experts and professionals not only across institutional boundaries but across disciplinary boundaries. Many of these people work together on multiple projects at different times. They are the institutional memory and skilled workforce of America's energy innovation ecosystem.

Otherlab secured a phase 1 award of $1.84M with a follow-on award of $3.6M after we proved the technology was on a successful pathway. Once again we have met the cost share of almost $1.5M with a combination of internal funds, angels, and professional venture capital. Kestrel

has secured more than $2.2M in venture funding and has advanced the technology to functional prototype articles of clothing and a scalable manufacturing process for producing bulk active textiles at affordable rates for inclusion in commodity clothing articles.

Kestrel employs 9 full time people and a number of contractors and has moved to Portland, Oregon to be closer to the epicenter of the apparel industry in the US. Kestrel will be releasing its first products in 2020 and anticipates raising a larger round of venture funding in mid 2019.

Super-Sankey, IDEAS program, "Innovative Development in Energy-Related Applied Science" 2017-2018.

In 2017 Otherlab secured close to $500K in funding from ARPA-E to build analysis tools and data visualizations to create the highest resolution mapping of US energy flows yet produced. The notion behind this project is that if we understand the flows and interactions of various energy sources in the US economy we can more effectively allocate federal research dollars and create greater professional and public understanding of the options for innovation and change in our energy economy.

This small project successfully highlighted problems with how we view energy flows born of historical legacies in how we defined and represented the data. This project has also enabled us to draw up scenarios for the US energy economy that enable us to think more clearly about the various pathways to decarbonization, or to american energy independence as examples of scenarios that can be looked at.

The Super Sankey project never had a commercial outcome in mind, but is a clear success in helping experts and the general public in understanding the energy flows of the American economy. ARPA-E's latest OPEN FOA even suggested that applicants cite this tool in their proposals to quantify their impact.

Near-Isothermal-Compression, OPEN 2018. 2019-ongoing.

Otherlab received a new award that started under contract only a few days ago, on February 20th, 2019. The award is to develop a near-isothermal compressor technology that will have profound implications for many applications where a gas needs to be compressed. It could be an enabling technology for the hydrogen economy, have huge implications for industrial efficiency in compression of air and other gases, potentially lower the huge energy cost of pumping natural gas, and enable new classes of refrigerators, air conditioners, and heat pumps. The award is only $500K and Otherlab has already been able to find a cost share partner (an angel investor) for the project. This project will employ 4 people in 2019 and will hopefully succeed and expand as we prove the viability of the design.

Closing Summary.

ARPA-E has been an excellent source of early stage funding for audacious and ambitious new energy technologies. The majority of the successful companies and projects discussed here would simply not exist if it were not for the early stage funding of ARPA-E.

ARPA-E has demonstrated an unbiased approach to funding non-traditional research entities. I think this is fantastic. In my experience (and backed up by recent research results) small teams, small companies and small start-ups are a vital national resource for high-risk transformative technologies.

Without exception, the challenge with bringing any of these technologies to market is the transition from a proof of concept—something that works—into a tested, validated, bankable, finance-able, product. ARPA-E currently does not provide funding for this stage of technology development. Again, in my experience, this phase of development always represents a cost of $1-10M (and sometimes much more) after the initial costs of technology development. This is due to the nature and expense of hardware development, and the timelines of development and proof of energy technologies. It would be in the national interest to increase ARPA-E funding in a manner that would enable it to help finance the very risky second valley of death: the proof by pilot or field testing of energy technologies.

I would further suggest that like DARPA, the agency that ARPA-E is loosely modelled on, ARPA-E is one of the most effective and transformative technology development agencies in the country. DARPA's budget is around $3bN. It wouldn't be crazy were the US to similarly prioritize its energy infrastructure and technology development program to a similar level, something like 10X what it is today.

ARPA-E isn't perfect. The cost-share concept which I initially was in support of, I have found through experience to force the developers of technology to make poor partnerships or take ill-matched investments to meet, and it generally leads to bad outcomes of one kind or another, including the death of otherwise high-potential technology development projects.

ARPA-E could also improve on its billing cycle; small government contractors the nation over suffer enormous cash-flow problems in financing the receivables of government research contracts. On many occasions I had to take out extreme or egregious loans including home mortgages to cover the receivables on ARPA-E grants. On occasion, the federal government would pay more than 90 days after the work was completed. This may be absorbable by universities or National Labs, but it is fatal to small companies—the most innovative engine in the economy in bringing transformative technologies to market. I was on the brink of closing down on numerous occasions with more than half a million dollars in receivables to the government.

ARPA-E also has some egregious clauses in their contracts that do not ultimately benefit the US economy downstream despite the intention of those clauses. The worst perhaps is the "made in

the USA" clause which wants most of the technologies to be made in America. While a good goal, this is impractical in the global marketplace of energy technologies that have complicated supply chains. These clauses become issues when raising venture to commercialize the technology as Venture Capitalists appropriately don't want any unnecessary constraints on how they build successful US-based, globally operating companies.

There is absolutely no doubt in my mind that the American taxpayer and the American economy is benefiting greatly from investments that ARPA-E is making. In addition to the economic impact of the companies mentioned above themselves, the employees, Interns and contractors working on these projects have gone on to run dozens of related projects and have used skills learned on these projects to improve their careers, move to the top grad schools in the country, and launch new technology companies in every domain from electric aircraft to autonomous cars to advanced robotics to ag-tech.

We should find every possible way to help government research agencies fund and support the best work in the country, by the best people, no matter which lab or organization they work in. There are transformative technologies in garages that are finding it hard to escape because of biases in the federal funding system.

We should expand the funding and scope of ARPA-E in this moment of the international energy economy transition. The dominant energy technology players of the next century are being started and funded today.

The challenge of most hardware technologies, particularly in the energy industry, is proving that they will survive in the field for 20-plus years before you have put them in the field for 20 years. A lot of resources are spent testing this as it forms a critical component of the "bankability" of the technology—meaning the willingness of a bank to finance the projects that include the technology. A crucial part of this process are real-world deployments and pilot projects. Often the developing entity of the technology has to finance these deployments and tests themselves, yet another difficult hurdle in bringing these projects to market.

Government could choose to fill the different funding gaps for energy technologies. As we see it, there are 4.

The 1st is fundamental and exploratory research finding out what is possible and exploring new opportunities. This is obviously the traditional domain of government funding of the NSF variety.

The 2nd is development. This is applied research taking fundamental ideas and shaping it into a technology with the potential to have an impact. DARPA, ARPA-e and agencies like the California Energy Commission (CEC) have been fundamental in our experience in this phase.

Bankability (the 3rd) is using the proven elements of research and development and building a tested and piloted project or product sufficient to get first customers (the ones that will take risk)

and private investment (that wants to see that a customer will buy it). This is definitively the energy technology's most difficult valley of death and a giant opportunity for ARPA-e to help accelerate energy technology transition to market. This stage may also include assistance in funding the manufacturing innovations required to bring the technology to market.

The 4th category is commercialization and deployment. This is where government should not be involved, this is financeable by banks and late stage venture. This is where the market can pick the winners.

Thank you for your time and your interest in this topic that I have devoted my career to.

Saul Griffith,
Otherlab.

Dr. Saul Thomas Griffith

Short Bio:

Saul Griffith is the Chief Scientist at Other Lab where he focuses his work on engineering solutions for energy production and energy efficiency in light of climate change science. He has multiple degrees in materials science and mechanical engineering and completed his PhD in Programmable Assembly and Self Replicating machines at MIT. He is founder or co-founder of numerous companies, including Optiopia, Squid Labs, Potenco, Instructables.com, Howtoons and Makani Power. Saul has been awarded numerous awards for invention and was recently named a MacArthur Fellow. Saul holds multiple patents and patents pending in textiles, optics, nanotechnology, and energy production. He also co-authors childrens comic books called Howtoons, about building your own science and engineering gadgets, and is a technical advisor to Make magazine and Popular Mechanics. He rarely wears shoes, is typically found knee deep in machinery with fists full of tools, and has holes in most of his pockets.

Chairman LAMB. All right. Thank you, Dr. Griffith. We'll stop you there at the end of the 5 minutes and move on to Mr. Mills.

TESTIMONY OF MARK MILLS,
SENIOR FELLOW, MANHATTAN INSTITUTE

Mr. MILLS. Good morning. Thank you, Mr. Chairman and Members of the Committee, for the opportunity to testify here. I'm honored and in fact humbled to join such an esteemed team of witnesses and join in enthusiasms for ARPA-E. It's one of the rare opportunities for true bipartisan enthusiasm.

In that context, I'd like to use my minute—5 minutes to frame the ARPA-E transformational mission by talking about the energy scale challenge. Traditional metrics are really inadequate for visualizing the magnitude of the global oil, coal, and natural gas production. Other witnesses have pointed out that 85 percent of the world's energy comes from hydrocarbons, but if they were all in the form of oil and laid out in physical barrels that would form a row stretching from Washington D.C. to Los Angeles, and that row would grow in height by a Washington Monument every single week.

Then as the world's poorest 4 billion increase their energy use of just 15 percent of the per capita level that we enjoy in the West, the world's demand for energy will increase by the equivalent of adding the United States' worth of demand. And in the developed countries, we can consider the applications in the future of just two fast-growing sectors. Every billion dollars spent in commercial aircraft or billion dollars spent on data centers each leads to about $2 billion in energy purchases over a decade. And the world currently spends over $100 billion a year building and supplying the market's new airplanes and data centers.

Meanwhile, we do know something about the cost of policies to impact this enormous market. Over the past 2 decades the world has spent more than $2 trillion on non-hydrocarbon energy, but hydrocarbon use rose nearly 150 percent over that time. And hydrocarbon's share of global energy supply decreased by barely a few percentage points.

This scale challenge of course commonly elicits the aspirational proposition that we should embrace the spirit of the Apollo program. The problem with this analogy is that it's a category error. Transforming the energy economy is not like putting a dozen people on the moon a handful of times. It's like putting all of humanity on the moon permanently. But in the decades since the Apollo program, we've seen another and bigger tech revolution that's inspired a similar trope. This is of course the computing and communications revolution, often short-formed as Moore's law. The International Monetary Fund, to just pick on one example, has asserted that, and I quote, "Smartphone substitutions seemed no more imminent in the early 2000's than large-scale energy substitution seems today," end quote.

But the Moore's law in transformation of how energy is produced or stored isn't just unlikely. It can't happen with the physics that we know today. If photovoltaics (PVs) scaled like computing, a postage-stamp-sized solar array could power the Empire State Building. Similarly, if batteries scaled like computing, a book-sized bat-

tery that costs 3 cents would fly an A380 to Asia. Only in comic books does the physics of energy production work like that.

Of course, wind turbines, solar cells, batteries, all those will improve. So, too, will drilling rigs and combustion turbines and of course software will bring very important and even dramatic efficiency gains. But there's no possibility that more Federal funding will lead to digital-like disruptive tenfold gains in these old technologies. All are approaching their physics limits.

The relevance of ARPA-E is that its out-of-the-box mission can only come from new phenomenologies and that leads eventually then to radically new technologies, all of which can only come from basic research.

Now, to state the obvious, internet didn't emerge from improving the rotary phone; the transistor didn't come from subsidizing vacuum tubes; and the car didn't come from studying railroads. Policies in pursuit of an energy revolution require a focus on basic science. One example in an area which is seeing a deficit of research support where I think magic can yet happen is in the basic materials sciences.

Let me conclude by summarizing three things Congress could do in order to fulfill the mission originally envisioned for ARPA-E. All three are found in fact in the original Gathering Storm report. First, ARPA-E should ensure a very clear focus on basic science. A vital role for ARPA-E is in filling the often ignored gap between the foundational science discovery, invalidating whether that radical discovery is in fact useful. This is quite different from the oftencited gap between innovation and commercialization.

Second, the Congress should I think put ARPA-E's role under the Undersecretary of Science, as originally envisioned, to both signal a commitment to basic research and insulate it from the—what I would call contamination of near-term outcomes.

Finally, ARPA-E's budget, I agree, should increase, but I would also stipulate as a caveat that we should adhere to the Academies' original recommendation, finding those funds but reallocating from those Federal programs that are already doing what I would call de facto private-sector development.

Finally, I think Congress should follow the Academies' proposal to continue to review the performance of ARPA-E but in particular this time with an independent committee that is not dominated but includes Federal representatives so that the private markets that understand basic science transitions participate. I have no doubt that scientists will yet unveil what Bill Gates calls an energy miracle. That's the word Bill Gates used, but that won't come from spending more money on yesterday's technologies.

Thank you.

[The prepared statement of Mr. Mills follows:]

Testimony of
Mark P. Mills, Senior Fellow, Manhattan Institute
Before
Subcommittee on Energy
Committee on Science, Space, and Technology
U.S. House of Representatives
On
The Future of ARPA-E

February 26, 2019
Rayburn House Office Building, Washington D.C.

Good morning. Thank you for the opportunity to testify before this Committee. I'm a Senior Fellow at the Manhattan Institute where I focus on the policy implications at the intersection of technology and energy,

I am also a Faculty Fellow at the McCormick School of Engineering at Northwestern University where my focus is on the technology and the future of manufacturing. And I note for the record that I'm as well a strategic partner in a boutique venture fund dedicated to startup companies developing software and artificial intelligence for oil & gas technologies.

Permit me to begin with a brief observation about the report "Rising Above the Gathering Storm" in which the National Academy of Sciences originally proposed the creation of ARPA-E. That report specifically focused on the "long-term energy challenges" and the "need for creative 'out-of-the-box' transformational" research. So, as a predicate for thinking about the future of ARPA-E, it is worth framing the scale of this energy challenge.

As is well known by this Committee, roughly 85% of global energy comes from oil, coal and natural gas. Traditional metrics are inadequate to visualize the magnitude of hydrocarbons our digitally infused industrial society requires. But, for context on the scale challenge, consider that if global hydrocarbons were all produced as oil and stacked up in a row of barrels, that row would stretch from Washington D.C. to Los Angeles, and would grow in height by a Washington monument every single week.

That's today's state of affairs, and that challenge is expanding. When, not if, the world's poorest four billion people increase their energy use to a mere 15% of the per capita level of developed economies, global energy use will rise by an amount equal to adding an entire U.S.A.'s worth of demand. Meanwhile, in the developed nations, we can illuminate the scale challenge looking at just two fast-growing sectors: every $1 billion of commercial airlines put into service leads to some $2 billion in aviation fuel consumed over one decade. Similarly, every $1 billion spent building datacenters leads to $2 billion in electricity use over a decade. The world is buying both at a rate north of $50 billion a year.

We already know how challenging it is to find any means, never mind practical ones, for making "transformational" changes at these scales. Over the past two decades, the world has spent more than $2 trillion on non-hydrocarbon energy alternatives; meanwhile hydrocarbon use has *risen* nearly 1.5-fold and hydrocarbon's share of global energy supply has decreased by only a few percentage points. These realities are what likely motivated Bill Gates – who has given serious thought and significant capital to energy innovation -- to recently state that "there is no [energy] substitute for how the industrial economy runs today."

The scale challenge commonly elicits the proposition that a solution can be found by embracing the spirit of the Apollo program: "If we can put a man on the moon, surely we can [and we can fill in the blank with any aspirational goal]." This popular rhetorical analogy is in fact a profound category error. Transforming the energy economy is not like putting a dozen people on the moon a handful of

times. It is like putting *all of humanity* on the moon —permanently. To do the latter would require science and engineering that doesn't exist today.

But in the decades since Apollo, we've seen another, far bigger engineering revolution that has also inspired a similar trope. This is of course the computing-communications revolution – often short-formed as simply, Moore's Law.

it has become a cliché to observe that smartphones are not just far cheaper but also far more powerful than a room-sized IBM mainframe from 30 years ago. Invoking the Moore's Law analogy, the International Monetary Fund, to name only one example, asserts in it's "Riding the Energy Transition" manifesto: "Smartphone substitution seemed no more imminent in the early 2000s than large-scale energy substitution seems today."

But this analogy is also based on a category error. A similar transformation in how energy is *produced* or *stored* isn't just unlikely, it can't happen with the physics we know today.

In the world of people, cars, planes, and large-scale industrial systems, increasing speed or carrying capacity causes hardware to expand, not shrink. The energy needed to move a ton of people, heat a ton of steel or silicon, or grow a ton of food is determined by properties of nature whose boundaries are set by laws of gravity, inertia, friction, mass, and thermodynamics.

In order to illustrate how far from reality this kind of thinking is, consider that if combustion engines, for example, could achieve Moore's Law scaling, a car engine would generate a thousand-fold *more* horsepower and shrink to the size of an *ant*. With such an engine, a car could actually fly, very fast. Or, if photovoltaics scaled that way, a single ant-sized solar array would power an entire office building. Similarly, if batteries scaled like computing, a battery the size of a book, costing less than a dime, could power an A380 to Asia.

But only in comic books does the physics of energy production work like that. In our universe, power scales the other way. The challenge in storing and processing information using the smallest possible amount of energy is distinct from the challenge of producing energy, or moving or reshaping physical objects. The two domains entail different laws of physics.

Of course wind turbines, solar cells, and batteries will yet see useful improvements in cost and performance; so too will drilling rigs and combustion engines. And of course Silicon Valley information technology will bring important, even dramatic efficiency gains in the production and management of energy and physical goods. But the outcomes won't be as miraculous as the invention of the integrated circuit, nor the discovery of petroleum or nuclear fission.

The point of all this is precisely relevant to ARPA-E. An "out-of-the-box" energy revolution can only come from discovering new "transformational" science, new phenomenologies that then lead, eventually, to radically new technologies. That can only come from basic research. It won't come from deploying R&D funds to improve – or subsidize -- yesterdays' technologies. The Internet didn't emerge from improving the rotary phone, nor the transistor from subsidizing vacuum tubes, nor the automobile from subsidizing railroads. Policies in pursuit of an energy revolution require a focus entirely on *basic* scientific research.

To be blunt: there is simply no possibility that more federal funding for wind turbines, silicon solar cells or lithium batteries will lead to a "disruptive" 10-fold gain. All those technologies are approaching physics limits, just as aviation engines have. And while one cannot, by definition, predict what kind of entirely new phenomenologies have yet to be discovered, we do know from history that such discoveries do happen. But history also shows that they rarely if ever emerge from directed goal-specific funding.

I can offer one example of an area where there is a serious deficit in support for research where 'magic' can yet happen, and that is in the basic materials sciences. We already know that metamaterials and quantum-

engineered catalysts or alloys – areas that will yet benefit from the emerging capabilities of artificial intelligence and exascale computing – hold the potential for "big bang" energy impacts. Radically new materials can profoundly change how energy is produced, transported, stored and used, from the still chimerical pursuit of batteries as effective as fuel tanks to doubling combustion engine efficiencies, to engineered bacteria that excrete diesel fuel.

Returning then to the Academy's *Gathering Storm* report: its recommendations provide a clear roadmap for three things Congress should do in order to fulfill the mission envisioned for ARPA-E.

First, APRA-E should have a clear focus on basic science. While it is often tempting and perhaps more politically comfortable to fund projects with directed and near-term utility, that focus fails the science challenge set out for ARPA-E.

The role of ARPA-E should not be in duplicating private sector R&D, which in any case vastly outspends the government in this area. Nor should it try to bridge the oft-noted "valley" between innovation and commercialization, which again is not only a private sector activity but is already engaged (for better or worse) by many other DOE and federal programs. A vital role for ARPA-E is in the far more challenging gap between foundational science discovery and validating whether a radical new discovery, while clever, is useful.

My second recommendation is that Congress follow the Academy's original plan and place ARPA-E's function within the office of DOE's undersecretary of science. This should be done both as a signal of the commitment to basic research – again, with a focus away from commercial goals like speed-to-market, or incremental cost-reductions -- and as a practical operational insulation from the inevitable 'contamination' by policies oriented towards near-term outcomes.

Third, I support those who propose increasing ARPA-E's budget, but with two caveats. The first, to restate, is that spending must be focused on long-term basic science. I believe the evidence is clear that ARPA-E has significantly drifted towards near-term goals to improve yesterday's technologies. This is not just duplicative but a drift away from critical "transformational" possibilities. My other caveat regards the source of funding. Rather than new appropriations, the funding should follow, again, the Academy's original recommendation to expand ARPA-E "through reallocation of existing funds." The reallocation should come from federal programs at both DOE and other federal agencies where the spending is duplicative of what private markets do.

In order to support these recommendations, Congress should also follow the Academy's original proposals to undertake a review of ARPA-E's performance. Such an audit should focus on how well ARPA-E has fulfilled its primary "basic science" mission as originally envisioned. And, critically, such an audit should be undertaken by an independent panel that is neither run by nor dominated by federal agencies, drawing mainly on private sector and university experts in basic science domains.

I have no doubt that scientists will yet unveil, and engineers will yet commercialize an energy "miracle" – the specific word Bill Gates has used for this goal. But, to repeat and close on my central theme, that will not come from helping private markets make yesterday's tools better.
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Mark Mills is a senior fellow at the Manhattan Institute, a faculty fellow at Northwestern University's engineering school, and a partner in Cottonwood Venture Partners. He writes a column for *Forbes.com* on the intersections of technologies and is published widely including frequently in *The Wall Street Journal.* He earlier served as chairman and CTO of ICx Technologies, helping take it public in a 2007 IPO. He is author of *Work In The Age Of Robots* (Encounter Books, 2018), and earlier co-authored the book, *The Bottomless Well*, which rose to #1 in Amazon science. He served in the White House Science Office under President Reagan, and previously was an experimental physicist and engineer in semiconductors and fiber optics, working at Canada's Bell Labs and RCA's Sarnoff Research Center.

Chairman LAMB. Thank you, Mr. Mills. At this point we will begin our first round of questions, and I will recognize myself for 5 minutes.

First, I want to talk about how we track the success of ARPA-E over time. And I think, Dr. Majumdar and Dr. Williams, you both kind of addressed this in your testimony. I'll start with Dr. Majumdar. What do you think about the idea of this metric of the amount spent by the Federal Government on ARPA-E versus the follow-on private funding that has resulted from it? Recognizing those two don't match up exactly because the private funding only attracted to a small percentage of what was funded in the first place, but do you consider that to be a decent measure of progress for ARPA-E?

Dr. MAJUMDAR. Well, thank you, Mr. Chairman. I think this is a really important question. I was asked this question, believe it or not, in my confirmation hearing for being the ARPA-E Director by Senator Murkowski, and we spent a lot of time thinking about it. The question is how do you define success? And one can think of success as a full commercial scale like the internet today. And just taking the example of internet, the research and computer networks started in 1968. It took 25-plus years to really get full commercial impact of the internet. And during that time, it was funded by DARPA to really improve and finetune that.

So looking at ARPA-E's technology, ARPA-E's funding mostly proof-of-concept ideas. To take proof of concept and go—to go all the way to commercial scale is, as I've mentioned, is a long process. It takes 15 to 20 years. So the only thing we can really say post-ARPA-E right now is, what are the signs or metrics of future success that we should be looking for? And I think there are many of them. There's not one single—there's no silver bullet in this one. I think one should be looking at is there intellectual property creation that has happened? Is there follow-on private-sector investments in—on ARPA-E-related projects that are showing some signs of success?

Chairman LAMB. And I agree with you there, not to cut you off, but time is limited, so thank you.

And, Dr. Williams, you specifically cited that figure of the follow-on private investment, so I know it's tough because of the timescale that you all are talking about. Something could take 15, 20 years to commercialize. But do you still think us tracking that comparison over time is a useful measure of success even if it's not the only one?

Dr. WILLIAMS. I absolutely believe it is a useful measure of success. It's an early-stage measure, as Professor Majumdar says. It's something we can measure, and it is indicative of future success. As time goes on, you will see our ability to measure more metrics such as jobs creation and manufacturing, but that's a longer-term process. And the scale problem that we heard about is acute. This will not happen overnight. And the cumulative impact of these types of investments and these early metrics are very, very useful for predicting that.

Chairman LAMB. Great. Thank you very much.

Dr. Wall, go ahead.

Dr. WALL. Just a quick comment and a watch-out. I think as we discovered as we were doing our Academies study, that there's an inherent tension between the 3-year funding cycle in ARPA-E, people wanting to see success, and the longer-term nature of the investment. So the watch-out here is that, as we want ARPA-E to be really focusing on long-term benefits, that we don't put so much pressure on showing early success that we wind up shortening the cycle and then turning it into some of the issues that have been raised about the—starting to look like short-term—more short-term research.

Chairman LAMB. Absolutely. Thank you.

Mr. Mills, I just wanted to ask one question of you before I close. I take your point about the tension between the basic science research and some of the other proposed ideas for ARPA-E. I guess one concern that I have is that this isn't happening in the vacuum of the United States. We have foreign competitors, especially China, who will really stop at nothing to dominate certain industries. They're very open about that actually. And there was the great example from Dr. Wall about what happened with electric vehicles. So they have no hesitation about putting a lot of money into the commercialization of existing technologies. Given that competition that we face, do you think there's still a role for the commercialization funding as a way of accelerating what might otherwise happen through the private market to keep us competitive?

Mr. MILLS. The short answer is yes, there is a role, but this is always a challenge that you have in Congress is the—where you lie on the spectrum of the nature of that role. I'll give as one example when I—as you know, I worked in the Science Office in the Reagan White House, which dates me as not being young anymore. The—Congress and the White House was lobbied heavily then to mount a program that countered the Japanese program mounted by MIDI for next-generation computing. We were told then that the Japanese were going to take over the computing business and leapfrog IBM, which dominated world markets then.

The approach of the Science Office then was that we didn't—we liked to support the commercialization of next-generation technologies, but the President did not believe that anyone in government actually knew specifically what to commercialize. And that was the same year, by the way, that Steve Jobs took Apple public, and it was not one of the companies that was on the radar of changing the computing world.

So I think this is the tension but also the temptation is to fund what we think will be the revolution against the huge funding by our competitors, then Japan, today China.

Chairman LAMB. Thank you very much. That's a helpful example.

And I now recognize Mr. Weber for 5 minutes.

Mr. WEBER. So actually I'm going to yield to Mr. Norman for 5 minutes.

Mr. NORMAN. Thank you, Congressman Weber. I appreciate you yielding.

And, Mr. Mills, this will be directed to you. I'm from the private sector. We look at results, not intentions. We look at results. And let me just read some of the numbers. As of February 2018, the

program has invested approximately $1.8 billion in R&D, which funded over 660 projects through more than 44 programs. And in your testimony you mentioned the need for audits. Do you think these audits would be useful in highlighting duplicative programs overlapping so that we can track where the dollars are yielding results?

Mr. MILLS. Well, thank you for that question. I—I'm deeply conflicted in this area because I have written about and in an early life I was a research scientist. I'm extremely enthusiastic about the prospect for government giving more money to scientists. At the same time, I work in the private sector, and I'm very sensitive to results outcomes.

My proposal for an audit is really focused on two things, not just looking for duplication, which I—there's some merit in duplication. I mean, as—you know, we do this in the private sector, as you know. You might have two teams trying to solve problems orthogonally. But there can be too much duplication. What I would like ARPA-E to focus on is avoiding doing work that doesn't adhere to its mission. There are missions for basic development, but the underlying transformational science mission I think there's a potential looking at some of the programs as adrift toward doing things that are in fact the missions of other agencies in the Department of Energy but that are really not transformational.

So the other part I would like to add just briefly is that the—holding ARPA-E to a utility function that can be specifically measured like dollars and patents is a natural tendency, but I think it's a mistake. I think it's useful, but it will not measure transformations, and that's the—I think it's not trivial. There's no easy measurement. I think the witnesses have pointed this out. And I think if you were in a confirmation hearing, you would be forced to say what's my measure? I understand that.

I think there would be merit to forming a committee as part of ARPA-E's future look to come up with an additional creative answer to that question. What else could we use that would help us understand that what ARPA-E's funding has the potential to be transformational, not simply evolutionary to making a PV cell better? That's important, but that would be a private-sector mission in my view.

Mr. NORMAN. Do you think it would be beneficial to put it under the Department of Energy?

Mr. MILLS. The—ARPA-E or the——

Mr. NORMAN. Correct.

Mr. MILLS. Well, I think it's got a good home. I think the challenge is a version of being insulated from the near-term. If you report to the Secretary, it's better status, I understand that, but the Secretary is driven by the budget and near-term mission. One would hope that you create an entity that has some of the insulation that an SEC (U.S. Securities and Exchange Commission) might have. Some of the agencies that can operate on 5-year cycles or the chairman or the head of it isn't turfed out for failing on a budget metric but rather they have a different mission. The SEC doesn't have a budget mission, for example. It has a broader social and regulatory mission. In my view, ARPA-E is more in that category than it is in the traditional research category.

Mr. NORMAN. Dr. Griffith, did you want to say something?

Dr. GRIFFITH. Absolutely. Your concern I believe was that ARPA-E's funding may be duplicative of other agencies.

Mr. NORMAN. Not—I don't know that. I'm saying why not put a measure in place that could see for the benefit of the program to see if——

Dr. GRIFFITH. I might respectfully suggest that it's not terribly relevant. We applied for—I have now created and commercialized technologies that would not have existed without ARPA-E. We tried to have those things funded through the other agencies of the Department of Energy, and they were non-receptive because in general those agencies are more prescriptive about what they're looking for. So ARPA-E's beauty is that it is—has very wide view, purview on what is transformational, and so it can pick and choose. And I think it is doing a very good job.

So I think it almost by necessity needs to be duplicative in the sense that there's solar here and there's solar there because the transformative is in the details and in the—in how ARPA-E is—has a wider mandate to fund a broader array of entities. For example, ARPA-E can fund a small startup company like mine that doesn't look like a national lab, doesn't look like MIT or Stanford, and don't believe that they are the only places that ideas in this country come from. In fact, in nature they just showed that small teams operating independently are the biggest force for transformational R&D in the world. That looks like small companies like mine that quite frankly aren't allowed to access a lot of the underfunding within the DOE. So ARPA-E is really the only option.

Mr. NORMAN. Thank you for your testimony.

Chairman LAMB. The Chair now recognizes Mr. Lipinski for 5 minutes.

Mr. LIPINSKI. Thank you, Mr. Chairman. Thank you for holding this really important hearing. It's great that Chairman Gordon is here. I remember working—I think I'm the only one up here who was here when we established ARPA-E. I wish that there were more chairs that were filled here because there's a lot of talk right now about climate change and what should be done. There's a lot of talk in politics, social media about some other vague, big, broad ideas, but this right here, ARPA-E may be—this may be the most important thing we do on climate change this year if we put more funding into ARPA-E.

I was just talking to Bob Inglis, who used to sit on this Committee. He's been dedicated over the last 10 years to getting a carbon fee put in place. It's something I support. But here is something I think we should all be able definitely to support is more funding for ARPA-E. It was envisioned to be funded at $1 billion annually, not $1 trillion, $1 billion annually. Fiscal year 2019 it's at $366 million.

So I wanted to ask, what do you think would be the difference if we could get that funding for Fiscal Year 2020 up to $1 billion? What difference would that make in really advancing these green energy technologies? So, Dr. Majumdar, do you want to begin?

Dr. MAJUMDAR. Thank you, Mr. Congressman. I think—first of all, I appreciate your support of ARPA-E right from the beginning. I think the billion-dollar budget, there's a lot of discussion on that

going on. And if you look at internally within ARPA-E what fraction of these amazing ideas that come in as proposals to programs, what fraction gets funded? In a regular program that is announced in a funding option announcement and if you go through the whole screening process, it's only about 10 percent or 15 percent of the actual proposals get funded. The next 10 to 20 percent are equally good ideas; we just run out of funding.

If you look at OPEN funding option announcement, and there's a lot of, you know, discussion on the rest of the Department of Energy. There's no one in the Department of Energy that actually has an OPEN funding option announcement, open for any ideas. And in those OPEN FOAs, the rate of success for proposals is less than 5 percent. And so there's a tremendous appetite for innovation in the United States that is not being funded. In fact, at the Energy Innovation Summit, on the recommendation of former Chairman Gordon and others, we actually invited the people we could not fund because we wanted them to get funded as well from other sources because these were really, really good ideas.

So there's a tremendous opportunity to raise and build the ecosystem and the community, the energy innovation community to be much larger, as is needed to address the major challenges that we have. I also——

Mr. LIPINSKI. Let me move on to Dr. Griffith. I'm sorry; I have a limited amount of time here. I know Dr. Griffith had his hand up.

Dr. GRIFFITH. I existed the coalface or maybe I should say I existed the solar cell of this issue. I haven't had to really place a job ad to hire people for the last decade. I have volumes, probably 10 of the best and brightest young Americans who've been trained by the best universities in the world volunteer themselves to me every week. We want to work on energy technologies. We want to work on climate change. We want to come and work for you. We have our own ideas.

Without a doubt there is at least tenfold the good ideas that are currently being funded under ARPA-E existing in the minds of your young people. And you want to get the money as directly as possible to the 25-year-olds, not their professors. Their professors are working on last year's technology. You got to get it to the grad students who are imagining next year. ARPA-E can do that.

I would argue that it should have funding that looks more like DARPA, $3 billion a year as a budget.

Mr. LIPINSKI. I don't have much time, but Mr. Mills raised an interesting argument there that we need transformational not evolutionary. I think Dr. Williams wanted to respond on that. I just want to see what your thoughts were on that.

Dr. WILLIAMS. Yes, so very much the case that ARPA-E does not want to do evolutionary research and does not fund evolutionary research. Every project is selected for its potential to be a game-changer, to move outside of the normal boundaries of industry roadmaps or long-term planning and things are already mapped out and being done by the Department of Energy.

So, as an example of something that is transformational that ARPA-E is working on right now, even though it is a project within the broad sphere of wind, it is a project to transform how we think

about designing and developing wind technologies, using machine learning and engineering technology to develop better methods of designing and deploying and manufacturing wind turbines. So that—if that succeeds, it will be a completely transformational approach in an old technology. And that's the type of projects that ARPA-E can do more of and should do more of.

Mr. LIPINSKI. I see my time is up, so I yield back.

Chairman LAMB. And I now recognize Mr. Weber for 5 minutes.

Mr. WEBER. Thank you, Mr. Chairman. Excuse me. Very interesting.

Mr. Mills, in your prepared testimony—well, you said a couple things about patents, for example. And I like that because not all patents yield results. I'm reminded, Thomas Davenport had a patent on the electric motor in 1837 and it went absolutely nowhere, and so while it was transformative, it wasn't practical.

You also say that transforming the energy economy is not like putting a dozen people on the moon a handful of times. It's like putting all of humanity on the moon permanently. And, quite frankly, I've got some friends that I wouldn't mind doing that with. And let me just say that, get that out of the way. But to do the latter would require science and engineering that doesn't exist today is what you said in your statement. And we're talking about raising the funding to $3 billion, which would necessitate that we cut from somewhere else. We have to find that money. So I don't know that it is practical. Could you expand on this comment and detail the science and engineering capabilities that would be required for success in a non-carbon energy economy moonshot today? I'm—I like to hear you elaborate on that.

Mr. MILLS. Well I—you know, I—first, if I might, as I—it's part of the elaboration, I—I'm in agreement with probably 99 percent of what's said in this hearing by other witnesses. It's one of these areas that's a challenge because the debates that are important are in the 1 percent of disagreements, which where—it's where the transformations happen. And my concern is in the implementation and as it relates to vision to your point that it won't be a single magical thing.

I mean, the magical thing we need to change the world's energy economy would be the equivalent of the discovery of fission or, to use a materials science example, if one were able to engineer a meta-material that could—that was strong enough and functioned—and it was lightweight that was a shield against x-rays and gamma rays, you could make what engineers thought you could do in 1950, a nuclear-powered car. I mean, you'd make a little pellet-sized reactor, and this is—this would be magical.

It's not crazy to think of those things. It's certainly not possible with anything we know today. That kind of transformation would certainly be the equivalent of the discovery of petroleum or the photovoltaic effect. Some things can't be done, and my point really was that you can't make a photovoltaic cell more efficient than the photons that arrive at Earth and converting them at some—you can't convert 100 percent efficiency, so we know what the boundaries are.

So when one looks at a proposal, one can know without knowing anything about its merits first whether it can be transformational.

If you change the cost of something by 20 percent or 30 percent, in business that's meaningful. It's not necessarily transformational to the world because you're chasing other things that are changing by 20 or 30 percent.

The market that solar, wind, and biofuels and batteries compete against is the hydrocarbon market. It gets better all the time, too, to the benefit of everybody on the planet.

So I think your point of patents is a particularly important one. Patents are a metric, and they're important. I have a few patents for my early career. They were fairly foundational ideas. One wasn't. Some are pretty sloppy patents. The patent office can be overwhelmed, as we all know if we've been applicants. But they're an important measure. They're useful. But they don't necessarily measure foundational change unless you look at—as you know, not to get into the weeds—prior art. If there's no prior art, it might be foundational. That'd be one mechanism, for example, to sort of fine-tune the ARPA-E mission is if we get a patent, is it a derivative, an incremental patent or is it actually foundational with no prior art?

Mr. WEBER. Well, thank you for that. I do need to move on to a second question for all the witnesses. I'm running a little bit out of time here. We've heard a lot today about the need to significantly increase ARPA-E's budget as quickly as possible, but in Congress, as I mentioned, we're going to have to find that money somewhere. We're called to be good stewards. And I'm not sure than any of our constituents—my constituents would be on board with an increase of close to $700 million. That's hard to justify back home in spending at the Department of Energy. So providing this kind of funding increase for ARPA-E is almost, as I said earlier, going to require cutting somewhere.

So let me put you all in the driver's seat for a minute. Where would you cut, Dr. Majumdar? I'll start with you.

Dr. MAJUMDAR. Well, that's a really difficult question to answer, Mr. Congressman.

Mr. WEBER. Tell me about it.

Dr. MAJUMDAR. I think this is a discussion between you and Secretary Perry and the current team out there, the Under Secretaries and others——

Mr. WEBER. So you've not—I'm sorry to cut you off but I'm really short on time. You've not thought through this, don't have an exact—example? Dr. Williams, I'll give you the same question.

Dr. WILLIAMS. Well, of course one thing that can be done and is being done increasingly at the States' level is more leveraging. And there are a variety of interesting new financial mechanisms for increasing leveraging and the output benefits of what we get from ARPA-E and from other programs and government. So I would strongly encourage that as one mechanism for getting more bang for bucks out of the Federal funds that we do supply.

Mr. WEBER. Dr. Wall?

Dr. WALL. Yes, I think I'd go down the same path. First of all, I'm not sure that I would close the budget debate just within energy considering the importance of energy for our future but to look at the entire budget, which gives you a little more flexibility.

But I think as we look at growing the ARPA-E budget, we ought to be also looking at other things that they could be doing, models—other models that could be added. Dr. Majumdar raised a parallel to SEMATECH (semiconductor manufacturing technology), which involves—brings in more industrial partners who can participate in a way that's a little bit different than the model that we have now. So I'd also look at changing the operating model with this incremental funding at the same time.

Mr. WEBER. OK. Well, I appreciate that. I got to go on. Dr. Griffith, finally, be brief, please.

Dr. GRIFFITH. To tie it to your moonshot question of the previous—what does a moonshot look like, if America plays its card right and completely electrifies its economy, it will only need half of the primary energy it needs today to supply the economy as it is. If it does that, it will be the leader of the world economy, and it will more than pay for itself. If you had to just very callously look at—I would look at other poorly spent budgets within the Department of Energy and the Department of Defense, their research budgets.

Mr. WEBER. OK. Let me stop there because I'm way over my time, and I appreciate you all's indulgence. Thank you, Mr. Chairman.

Chairman LAMB. I now recognize Ms. Stevens for 5 minutes.

Ms. STEVENS. Thank you, Mr. Chairman, for this important and necessary hearing, and thank you to our expert witnesses for joining us today.

As a former Obama Administration official who worked in the advanced manufacturing space, I couldn't think of a more timely hearing in part because just the other week, as my colleagues and I pondered on the House floor what should be our moonshot vision for innovation for the quarter-21st century, for the mid-21st century—we find ourselves in the room with the sign that says where there is no vision, the people will perish.

So the burden of American greatness and our industrial might must be how we define these moonshot visions, not debating the merits of funding them, but seizing hold of the opportunities to invest and win the future. We are still in the race for our innovation and what we saw in the mid-20th century as we were racing to get to the moon. We are competing against the likes of China and Western Europe, and so we know we need to continue to invest.

I now today represent Michigan's 11th District, the suburbs of Detroit, the most robust automotive supply chain in the country. We are the recipients of $35 million from ARPA-E projects largely going into electrification, electric vehicle battery development. And we've heard other questions from this great panel. We've heard other questions on exercising what the ARPA-E funding does for this work.

I'd like to just take it a layer deeper because the headline that I find quite alarming among many alarming headlines is that China is leading the charge for lithium-ion mega factories, China is leading the charge for battery electrification, that China now has over 70 OEMs in the battery efficiency space. Where are we? So what does it mean if we fail to invest or don't increase our budget?

Dr. Williams, I'd like to start with you particularly on the automotive industry, please.

Dr. WILLIAMS. Yes. Well, it's a pleasure to hear from you. I grew up in the suburbs of Detroit, and I also experienced the health and the dynamism of the automotive industry there.

In terms of electric vehicles, we do face very stiff international competition. I would say that much of the growth that we are seeing now on lithium-ion battery and battery development is using old technologies and driving down cost by better manufacturing techniques. ARPA-E has invested lightly in electric vehicle batteries only in areas where we think we can make a transformative change in the actual battery chemistry and the future—and allow us to have future batteries that will be better than the ones that we are seeing developed in China.

Coming out of that research we're seeing many innovative exciting new battery chemistries, and I can't emphasize to this Committee too much the peril that we face. We do phenomenal basic research in the United States. We train great graduate students. We send them out to do great research. ARPA-E tries hard to take some of those exciting new ideas and move them forward to prototypes. If those prototypes reach a certain stage of development and readiness and that next stage of investment is not there, they fall dead. We lose that investment. Other companies, countries will know about what we've done, and they will take it forward. We have to make sure that we are able to support our young innovators to not just do the innovation but to actually deliver the benefits that come from it. And EV batteries is one area where we absolutely need to maintain that primacy.

Ms. STEVENS. Yes, thank you so much. Dr. Majumdar, this reminds me of your testimony and where you talked about the return on the investment and the lifecycle of the investment, and I was wondering if you could just shed a little bit more light on where Dr. Williams left off, around the continuity of funding and ensuring that we don't allow new technologies to fall into the valley of death, what this means for industries like our great automotive industry, which, by the way, has said they want to see zero emissions. They want to embrace electrification. They are looking and waiting for us to continue these partnerships, to continue to invest if not but for the government to lay the foundation, to set the table. That's the conversation we're having here. So if you don't mind.

Dr. MAJUMDAR. Sure. Thank you, Congresswoman. I think the automotive industry, as you pointed out, is trying to pivot. This is a time of extreme importance because this is a once-in-a-century colossal change that is happening to an industry that has grown in a certain way and they're trying to pivot. We are very proud of course in the United States of the Gigafactory that is going to make batteries. In China there are two and now I'm hearing the third Gigafactory being built.

So the question that comes at—the fundamental question that Dr. Williams raised is that how do you go from a proof of concept to a proof of system to a proof of—in a pilot demonstration so that it gets into the Gigafactory? And I think this is where in my written testimony I propose that look back at what DARPA did. When there was a challenge to the semiconductor manufacturing indus-

try, DARPA said, OK, you have your competitors, Texas Instruments, Intel, and others. Let's just come together to create something called a SEMATECH to nurture some of the DARPA-funded fundamental research in breakthrough technologies that led them—then they were nurtured by the industry and then they took those technologies and they competed in the marketplace with products and services. So I think that's a model——

Ms. STEVENS. Yes.

Dr. MAJUMDAR [continuing]. That's—the semiconductor industry is not the same as the energy industry. So we should look at these opportunities, the things that have been done in the past and see what are the lessons learned that could be adapted to the energy field and see what we can do in the private and public sector together.

Ms. STEVENS. Thank you so much. I cede back.

Chairman LAMB. Thank you. And the Chair now recognizes Mr. Foster for 5 minutes.

Mr. FOSTER. Thank you. And I guess I'd like to start off by just seconding all the praise that's been showered on ARPA-E for its achievements to date and my gratitude to Bart Gordon for his role in initiating this.

And I'd also like to emphasize that this is complementary to the role that national labs play. An example of that would be, since we're talking about batteries, the JCESR (Joint Center for Energy Storage Research) program where one of the main deliverables is computer models of battery chemistries that will be developed and maintained by a large team of people that has to stay around more than 3 years. So it's not a one-shot thing. This will be a national resource, and I think the labs are appropriate stewards for this.

But there's a real need for something like ARPA-E to fill gaps in the private-sector research and development. You know, you can sort of analyze this as why, if this is such a great idea, isn't the private sector doing it? And the reasons that occur when you ask venture capitalists, they said, well, this is too long-term, that the payoff will be outside the patent window, and it's a real reason for ARPA-E to exist.

The second is the low probability of success. Now, you're placing some bets that are unlikely to pay off. They'll be transformative if they do, and that's not an attractive investment to a VC (venture capital) firm that has to show the fund is making money after some small span of years.

The third reason that I'd like to look into a little bit is the lack of patentable intellectual property. Very often you have a great idea, and this is wonderful, it will be transformative if it works, but it's not really patentable. And so very often venture capitalists won't invest in that. And I was wondering how you handle the issue of patentable IP (intellectual property) both in the selection of projects to decide to get behind and also when you contemplate follow-on funding and the probability of handing off to the private sector where patentable IP will be important. You know, either Dr. Williams or Dr. Griffith.

Dr. WILLIAMS. So I'll start. I would say that ARPA-E's commercialization activities strongly encourage its teams to develop patentable IP. We don't initially select on the basis of whether or not

they're—they have patents or patentable IP. As they move forward, there are certainly different models for companies. Many—there are many types of technologies which, if they can't be patented, are kept as company and proprietary secrets. ARPA-E supports our project teams in developing such technologies and respects when they need to develop that proprietary technologies and move it forward without risk of exposure. I hope that's helpful.

Mr. FOSTER. Yes. Dr. Griffith?

Dr. GRIFFITH. Writing and obtaining patents is really easy, and you can do it all day. It's expensive, so you want to do it as little as possible when you're starting new technology companies. I think it's a very bad predictor of success, but it's one of the—it's easily measurable, so we use it, but it's not at all good. In the global marketplace today and because of the dysfunctionalities of the whole patent process, your really only advantage now is to speak to market. And inasmuch—what do patents exist for? Maybe to help you get financing, but apart from that, it's all about speed of execution, so it's the wrong thing to measure.

Mr. FOSTER. So how much of this has to do with what I view frankly as a sort of assault on the patent system that's happened in the last several years, led actually by Congress. The sort of systematic weakening of patentholder rights and various forms that have been passed?

Dr. GRIFFITH. I think it's more fundamental and structural than that. The patent system has existed long enough that it easily gamed.

Mr. FOSTER. In what sense?

Dr. GRIFFITH. The large corporations can play it very easily. They can afford to. Small companies that are doing the really innovative thing can't. And you can have large corporations basically outmaneuver you. And so I think that is one example of a structural problem. We evolved through lobbying the patent system toward advantaging large companies because they could afford to, and small companies who do the innovation are disadvantaged in the patent-playing field.

Mr. FOSTER. Well, also, when they try to enforce those patents, they're characterized as trolls and so on.

Dr. GRIFFITH. Yes.

Mr. FOSTER. Yes, Dr. Mills? Or Mr. Mills.

Mr. MILLS. Mr. Mills. Yes, I was one of the ones that quit graduate school, but I wasn't as successful as Bill Gates when he quit graduate school. It's a very good point——

Mr. FOSTER. He quit undergrad if I remember properly but——

Mr. MILLS. That's right. The patent issue is interesting, and I agree with Dr. Griffith that it can be gained and often is. And I'm worried about the attack on the patents because it's not just the Constitution; it has real merit. But I would point out, as an active venture capitalist, that patents are only one measure of what you would make in investment. Frequently, such speed to market is critical, but there are many things one does in the technology business. And I know I—I know you know this is truth, that are what you call process knowledge and domain knowledge that you deliberately don't patent because once you patent them, you've told people how to do it. And it's remarkable how much of innovation lies

in that area and how little relies on the patents. So I just—just for the record, I think—and that's a hard one to measure. That's measuring the team, which is a challenge for ARPA-E, and it's a challenge for venture capitalists.

Mr. FOSTER. OK. And let's—we've had a lot of sort of discussion of transformative high-payoff research. But, you know, Dr. Griffith's examples he gave, many of them seemed incremental, a 20 percent decrease in the tank for compressed air or a change in the actuator mechanism for solar tracking, which it's a potentially good idea that will take over that segment of the market, but will not really transform the economics of solar power. And I was just wondering what is the payoff that you're shooting for something that will transform a very small sector and make an incremental improvement? Yes, Dr. Williams?

Dr. WILLIAMS. So I would say that I wouldn't measure incremental in the sense of 20-percent or 10-percent impact on the energy. It's—incremental I consider to be a fundamental—the idea of how the technology transforms the approach. So something like the pointing mechanism based on a completely different technical approach, that's a technical innovation, and it is far from incremental. It really transforms the mechanism.

And what we see in an innovation system is that small—what are initially small projects like that combined together to create a whole learning curve, which ultimately grows and blossoms and creates much bigger impacts overall.

And so this comes down to some of Dr. Majumdar's comments about the need for patience. The innovation——

Chairman LAMB. And that's helpful. We'll probably have to stop you there, Dr. Williams, because we're past time, and we'll go to Mr. Casten for 5 minutes.

Mr. CASTEN. Thank you very much. Thank you all for coming.

I have to frame this by saying that this is a bit of an unfair question for Dr. Majumdar and Dr. Williams, but bear with me. I think a lot of this conversation is about metrics, and I think we really need metrics. I'm a chemical engineer and a biochemist by training. I'm an entrepreneur by career, and a couple months ago I decided to get a new job. I mentioned that because early on in my career we did work on biofuels and fuel cells, and it was before ARPA-E existed. I actually had colleagues who were able to get money from DARPA, and I'm thankful that my colleagues here created ARPA-E to follow that example because you guys really have done a lot of neat stuff, and I thank you for that. And it was urgent and necessary.

In the private sector, if you're any good on the entrepreneurial side you look at the total cost, the total benefit, and then you figure out how to structure your business to get as much of the benefit and as little of the cost. In this new job I have, we tend to think about offloading cost to the private sector as being fiscally irresponsible, and I don't think that's always the case.

If I'm doing the math right, ARPA-E has invested $1.8 billion, $2.6 billion of follow-on. That's pretty successful. Relative to the challenge we face in the climate, respectfully, it's a fart in the whirlwind. And so if we're going to get to a point where you have the resources to take on the challenge that we have as a society,

we need to somehow get people thinking about what you do as being closer to the way that the venture capital world works, where they celebrate the unicorns, they maybe focus on the portfolio returns and do their best not to talk about the failures. Witness Solyndra. We've kind of done the opposite on the political side where we talk about the failures, we don't talk about the portfolio, and the unicorns go on to be privatized, and we don't talk about them too much.

How do we get metrics that you all can manage to, and be rewarded for, that can build the political will so the people can recognize the value that we are creating here and not have it come out buried in the last freshman commenter in a science hearing about the net gain? And what are your thoughts on what those metrics might be?

Dr. MAJUMDAR. Thank you, Mr. Congressman. I think this is a very fundamental question and it has come up many times before. I think you have to look at metrics over time scale. I have been funded by DARPA in my research career several times. I was not involved in the internet, but what we talk about for DARPA is internet, GPS, and things like that, right? It is the unicorns. So I think long-term you will get to see some of the ARPA-E technologies—you know, you have talked about the return—you know, the follow-on funding. Well, this is just the start of the follow-on funding. There will be many more later on as these technologies mature and come—become products and services.

So I think it's important, as I mentioned in my written comments, it's important to be patient with these. But in terms of the metrics, I would look at a portfolio of metrics, not just one because I think if you fix—if someone gets fixated on one metric, you could be misled as to the true impact on the future.

Mr. CASTEN. OK. One follow-on with the bit of time I got left. Last Congress, my colleague Congressman Luján introduced the *Impact for Energy Act*, which would have established a nonprofit foundation at DOE with the private sector to raise funds to support the commercialization and development of innovative energy technologies. I'm working with Congressman Luján to—on a similar bill that would bring it forward.

Dr. Majumdar and others who can comment, if I'm following, the NIH (National Institutes of Health) has raised about $1 billion in total funds and supported 550 projects alongside NIH to do this on the biomedical side. Do you believe that such a nonprofit foundation at DOE, similar to NIH, could help further facilitate private follow-on dollars to leverage what we're talking about here, and give you whether or not we can improve the kind of funding that's necessary to make sure that there's other sources that can?

Dr. MAJUMDAR. Mr. Congressman, I think we should look at all the great examples of the past and the lessons learned from that. I think the NIH foundation is one of them. I think SEMATECH is another, and there are several other private–public partnerships that have nurtured technologies through research from the government-funded stage, which is early stage, the proof of concept to the later stages.

The medical—the healthcare industry is quite different from the energy industry. The semiconductor industry is different from the

energy industry as well. So I think we should take a look at all of these and really figure out what applies, how can they be adapted to the energy industry and see if you could create public-private partnerships like the SEMATECH, like the NIH foundation, but may be adapted to the energy sector. So I think that's what I would suggest Congress consider.

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

Chairman LAMB. Thank you. And I recognize Mr. McNerney for 5 minutes.

Mr. MCNERNEY. Well, I thank the Chair, and I thank the witnesses. And I apologize for missing your testimony this morning, but ARPA-E is a great program, and I'm a big supporter. I want to see it continue.

Dr. Williams, could you say if there exists a gap between the cutting-edge technology that ARPA-E helps foster and the DOE loan program that commercializes technology? Is there a gap there?

Dr. WILLIAMS. Yes, there certainly is a gap. The projects coming out of ARPA-E are generally at the earlier stage, prototypes, just getting ready to put up their first manufacturing. At the loan program level, basically the projects that will be supported under loans have to be fully established with manufacturing and have customers already in line. So there is a big gap between those two programs.

Mr. MCNERNEY. So there's room for public-private consortia to help fill that valley of death?

Dr. WILLIAMS. Absolutely.

Mr. MCNERNEY. OK. Well, thank you. I'm not sure which one of you would want to answer this next question, but while ARPA-E does a lot with carbon capture and sequestration, I'm also interested in carbon renewal and solar reflection technology development because I feel it's pretty clear to me we're going to blow past the 2-degree milestone even if we were to eliminate carbon emissions today, so we need to develop that technology. Can you discuss what opportunities and challenges might exist with ARPA-E in developing that kind of technology?

Dr. WILLIAMS. Yes. So ARPA-E has investigated a lot of different areas for carbon removal. I think in addition to what one might normally think of as standard approaches such as taking CO_2 from a fossil generation plant, putting it through some other chemical process to turn it into a different useful product, that's one typical approach.

There are other very different and more creative approaches as well. One is learning to breed—use plant breeding to create plants that actually capture CO_2 and store it permanently in the soil. That's a completely different form of carbon capture with tremendous benefits to the agricultural community, to the rangeland community, and to forestry. If we can select and breed plants that actually take CO_2 out of the air, put it in the soil, it improves the soil——

Mr. MCNERNEY. So ARPA-E is a good—OK. What about the albedo modification technology? Is ARPA-E a place to do that kind of research?

Dr. WILLIAMS. ARPA-E is not specifically invested in that, although we've had some interesting projects, as I mentioned earlier,

in technologies that are able to take waste heat and transform it into light that gets sent out into outer space, and that's a little different than albedo modification, though.

Mr. MCNERNEY. Yes, Dr. Griffith?

Dr. GRIFFITH. I think when you're talking about carbon removal, you have to think about what material flows humanity has that are as big as our carbon emissions problem in tonnage and basically the only materials that we move in the same quantities are cement and food. So the big opportunities are in putting the carbon into cement or putting it back into the soil or putting it into wood products. And I think there is enormous opportunity for fundamental materials science and applied materials science in those domains, and it would be a very high value.

Mr. MCNERNEY. Thank you. So what types of programs would ARPA-E expand into if the appropriations were expanded, whoever cares to answer that? What areas are ripe for ARPA-E to move into?

Dr. MAJUMDAR. Well, I think there are plenty of them. If you're really looking at the carbon emissions challenge, how about, you know, really looking at very low cost—at 1/10 the cost of lithium-ion batteries to store electricity for the grid, new ways of fission and fusion reactors that will enable carbon-free electricity, producing hydrogen lower than the cost that you can produce from shale gas. If you could do that, that'll be transformative for the oil and gas and the agricultural industry. Reimagining how to make concrete and steel with very low-carbon emissions, so you—I can go on and on. Decarbonizing the food industry and the agriculture sector and helping and using agriculture, as Dr. Williams pointed out, to store carbon in the soil. And there are several others you can go on.

What we're really talking about is a remake of a large fraction of our economy that is tens of trillions of dollars, and that's the global competition. This is the electricity, the automobiles, the steel, concrete, oil, gas, food, agriculture, et cetera. This is why other countries like China, as Dr. Wall and others are pointing out, are looking at this opportunity of the world transitioning to a new energy economy, and this is why it is so important to invest in ARPA-E right now because this time of the pivot is where the transitions happen, and we need to be at this game right now.

Mr. MCNERNEY. Thank you. I'm glad I asked that question. I yield back.

Chairman LAMB. Thank you. And I recognize now Mr. Beyer for 5 minutes.

Mr. BEYER. Mr. Chairman, thank you very much. I'm sure this has already been done because I'm a late arrival, but I'd like to recognize the presence of my friend, the former Chairman of the Science, Space, and Technology Committee, Mr. Gordon, and just say that he's better looking in person than his portrait here on the wall.

Dr. Williams, you know, the President requested $3.5 billion for DARPA, and Congress appropriated roughly $2.5 billion for DARPA. And the President requested $0 for ARPA-E. Congress did $336 million. And I noticed that in your leadership, it got to $1 billion over that 5-year period. Do you have a sense of where it should

be right now in terms of its return on investment and is good for our society? Is $1 billion the right target number for us in Congress looking to appropriate?

Dr. WILLIAMS. I think $1 billion is a good target. I would say that rationally one could grow that—grow to that $1 billion over a period of several years, probably 5 or a little bit more years to grow to that level of $1 billion. In that growth I expect ARPA-E would innovate, develop new approaches, demonstrate new ways of leveraging, and overall provide a whole new set of metrics and understanding about what can be delivered. So I'd say that going to $1 billion and then assessing and evaluating the success of that project would be a really excellent target for the House.

Mr. BEYER. Dr. Griffith?

Dr. GRIFFITH. You have a really strong bench in this company—country in terms of the talent, and they're sitting on the bench unfortunately and not playing the energy game. They're running software to sell ads.

Mr. BEYER. Yes.

Dr. GRIFFITH. You know, to use DARPA as an example, it funded robotics for many, many, many years. Every single robotics company out there right now has DARPA talent funded by DARPA in the DNA of all these companies that are doing all of the big radical transformations in robotics. I think you can easily justify a DARPA-sized budget for ARPA-E to do the same for energy. So I think $1 billion is low. It's not nearly aligned with the scale of the energy transformation challenge, and I think you have enough people and there are enough ideas and things worth working on that it would be money well spent.

Mr. BEYER. Yes, one of the things that we heard in this Committee in years past was that the percentage of excellent-rated projects submitted to the National Science Foundation (NSF) and to NIH continues to decline. We're down in the 10 percent ratio, which would argue that we could allocate much more money there that would still be very well spent. Dr. Majumdar?

Dr. MAJUMDAR. So given the discussion on the budget, I mean, I just want to point out—and the comparison to DARPA. So one can ask what was DARPA's budget when it started off? So 1962 was the first appropriated budget for DARPA. It was started in 1958, but the first appropriated was 1962. And that was $246 million in 1962 dollars. And today, if you do the prorating for that, in today's dollars it's about $2 billion. So if you are to take this energy transition seriously as DARPA took in response to the Sputnik threat, I think that this is the level.

And so what we're asking is the budget to be in the order of $1 billion, to grow, as Dr. Williams pointed out, to—you know, within a few years, not to put it suddenly, $1 billion from $300 million in 1 year would be difficult for it to handle. But if you could do that, I think that the agency can then grow, bring in the talent, create new programs, create these public-private partnerships, and then be at the level of the DARPA impact that it ought to have.

Mr. BEYER. And, Doctor, you were head of ARPA-E when you invented the internet, too, right? I'm just kidding.

But Dr. Majumdar, in your testimony you talked about the transformation that's happening. There have been a number of inter-

esting articles in the last couple of days about the need to go to negative net carbon. Is there a better player in the U.S. economy to help us move to net negative than ARPA-E? Dr. Griffith?

Dr. GRIFFITH. If DARPA wants to get involved, that would be good. But both, yes.

Mr. BEYER. And carbon capture, how plausible is removing carbon for the air or from the ocean?

Dr. GRIFFITH. I think you need to place realistic expectations on it. It's very, very difficult. When you remove carbon from the ground and you combine it with oxygen, that's what happens when you burn it. It expands in volume a lot. So we can't stuff the carbon dioxide back into the hole it came from because it's bigger than what came out. And a freespace floating molecule of carbon dioxide is very hard to capture. And thermodynamically, it's highly uncertain that's possible. I think what you should really focus the mind on is a complete commitment to electrification by nuclear, wind, solar, and renewables, and the electrification of heat that has to be done. Otherwise, we're going to be natural gassing our way through heat forever. And then focus on the materials side of the economy where there are opportunities to do limited carbon sinking, which is concrete and cement, wooden, paper, and pulp industry, agriculture.

Mr. BEYER. Great. Thank you. Mr. Chair, I yield back.

Chairman LAMB. Thank you. That ends our round of questioning. I did want to—and the Members that have to leave don't need to stay for this, but I did want to just give the—first of all, thank the witnesses again for coming all this way and for the information. There were a number of you throughout the hearing that I could tell really wanted to jump in on a certain topic, and we appreciate that. So we could start in reverse order with Mr. Mills and just ask you to keep it short, but if there was sort of one small thing that you wanted to mention that you didn't get out—and don't feel obliged to take me up on this, but if there's one short thought, we'll just go down the row. Thank you.

Mr. MILLS. Well, I do feel obliged. I'm sure all of the—my colleagues do. I'd like to just point out that you heard a common theme, which would be the materials science domains that are extraordinarily important here, and they're very difficult to justify on a venture-capital basis. And they're—but they do hold the potential for magic, but they will require much more basic science, support for chemists and mechanical engineers, Saul said physicists, doing things that are very, very challenging. The NIH may not—it's not NIH but the NSF may not do, a good role. I'd love to see the budget to go up. I'd like the DARPA-level budget, but my caveat, I'd like to take it away, the hard task that you all have from programs that are short-term focused in other areas of DOE.

Dr. GRIFFITH. Contradicting my colleague, Mr. Mills, and even contradicting Mr. Gates, you don't need a miracle technology to go—to decarbonize the U.S. economy. Everything we know today, everything that's on the table, we just need a huge commitment to it. I think you should look at—ARPA-E isn't perfect, but it's better than all the other agencies. I think the fact that, like DARPA, it can look all over the U.S. economy for the best ideas is—speaks to its benefit. We need more research money, R&D money that looks

like that. And I think you really need to understand that at the end of the day you—that this type of funding is about building your team, building your bench. DARPA's investment, investing in communities of people to become the intellectual communities that form the foundation of AI, the foundation of computing, the foundation of the internet, the foundation of robotics. And you need consistent, long-term funding at much, much higher levels than you have today if you want to have the world-class bench in energy technology.

Dr. WALL. So being the big industry guy, I will take a little different approach to my remarks here because I feel like—you know, I may have a cleaner—a clearer picture of the global competition and business once the technologies are developed, who manufactures it, who sells it, who has the jobs, who makes the money. And I worry a little bit when we get into this discussion about taking money from one part of the energy—our energy investment and putting it into another or being focused internally on the United States, we lose the fact that China is not the least bit confused about this.

I've spent time over the last 20 or 30 years in Japan, in Western Europe, in India, in China, and so I'm keenly aware of what it's like to compete in those markets. And also, as I mentioned in my testimony, a specific example of what happened in China where they've decided they want to dominate in EV. They're not having a debate about whether or not they should be working on basic research.

I do think that one of the things that we could be doing with ARPA-E is looking at the enabling technologies that might be required to make some—to bring some of these into production. So advanced manufacturing, advanced materials hand-in-hand with new concepts for new energy. But if the United States starts focusing on do we put a dollar here or a dollar there and taking it away from other energy investments, then I think we could be making a big mistake in setting ourselves back behind the competition who's not the least bit confused about this.

Dr. WILLIAMS. And I'll just add a last comment, which is that energy is a very big problem, it's a very old field, but we have at our command is advances in understanding that allow us to approach these old problems in completely new ways. And we really need to be open to out-of-the-box thinking, thinking very hard about the fact that each new innovation that comes to us in the past 20 years, vast improvements in our ability to design and create materials are now making a huge impact in what we can do with energy systems.

Moving forward, we're seeing advances in biology, the ability to understand and manipulate organisms. Those will be important in energy as well. We're seeing advances in information technology, in artificial intelligence, in machine learning. All of those things are going to be applied to energy and create new opportunities, and we need to have the ability and the flexibility to look at those in new ways about how they applied energy, and we will continue to expand and find new opportunities to make a big difference.

Dr. MAJUMDAR. I just want to double down on what Dr. Wall just said. Since I was not only the Director of ARPA-E, I was also the

Under Secretary for Energy with all the applied programs reporting to me, and I looked at the budgets as well. One thing I would say is that it's—one has to think about it the right way. Any technology, whether it's lithium-ion batteries or semiconductor chips, there's a learning curve. That means the more you do, the cheaper it gets, the more—the better it performs.

And ARPA-E's role, as opposed to the applied energy's role, are two different roles. The applied energy takes today's lithium-ion batteries and makes it better and better and better and better and better, and that's very important. And that's going down an existing learning curve that's extremely important. ARPA-E's role is to create entirely new learning curves that do not exist today, but if they're successful, they'll be disruptive to the—today's lithium-ion batteries so that the competition comes from within the United States as opposed to coming from outside the United States. And this is the hedging that has been created through the applied programs and ARPA-E.

And I think one has to look at the whole discretionary budget and not just the budget of the Department of Energy to see how do we want to compete in this time of pivoting of a colossal change in the whole energy industry globally? And I think you need to do both, because if you don't do, I think it'll be a mistake for the United States.

Chairman LAMB. Excellent. Thank you again to all the witnesses, especially for keeping it brief here at the end. We really appreciate it.

The record will remain open for 2 weeks for additional statements from the Members and for any additional quick questions the Committee may ask of the witnesses.

The witnesses are now excused and the hearing is now adjourned. Thank you.

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

Appendix I

Additional Material for the Record

REPORT SUBMITTED BY DR. JOHN WALL, RETIRED CTO, CUMMINS, INC.

An Assessment of ARPA-E

Committee on Evaluation of the Advanced Research Projects Agency-Energy
(ARPA-E)

Board on Science, Technology, and Economic Policy
Policy and Global Affairs

Board on Energy and Environmental Systems
Division on Engineering and Physical Sciences

Pradeep K. Khosla and Paul T. Beaton, Editors

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Summary

Under a mandate from the U.S. Congress, the Advanced Research Projects Agency-Energy (ARPA-E) asked the National Academy of Sciences to conduct an assessment of the progress the agency has made toward achieving its congressionally mandated mission and goals. This report includes both an operational assessment of the agency's funding programs and a technical assessment of its awards, to the extent possible. The ad hoc committee convened to conduct this assessment relied on quantitative and qualitative analyses of data on ARPA-E's creation of technology-focused funding programs, its decision-making processes for granting awards, its management of projects and awardees, the patenting and publishing activities of awardees, and further investments made in awardee projects following ARPA-E funding.

There are clear indicators that ARPA-E is making progress toward achieving its statutory mission and goals, and it cannot reasonably be expected to have completely fulfilled those goals given so few years of operation and the size of its budget. Importantly, especially at this early stage, the committee found no signs that ARPA-E is failing, or on a path to failing, to deliver on its mission and goals. From its complete set of 18 findings, the committee developed 14 recommendations, which are listed in full at the end of this summary. This summary presents an overview of the study and highlights the 5 findings and 5 recommendations the committee believes are most important. The complete list of the committee's findings and recommendations is presented in Boxes S-1 and S-2, respectively, at the end of this summary.

SCOPE OF THE ASSESSMENT

The first part of the committee's task was to assess the progress ARPA-E has made toward achieving its statutory mission and goals during the first 6 years of its operation and whether it is on a trajectory to achieve them. Congress established the agency with a mission "to overcome the long-term and high-risk technological barriers in the development of energy technologies," and specific goals to

> "(A) enhance the economic and energy security of the United States through the development of energy technologies that result in—
> (i) reductions of imports of energy from foreign sources;
> (ii) reductions of energy-related emissions, including greenhouse gases; and
> (iii) improvement in the energy efficiency of all economic sectors; and
> (B) ensure that the United States maintains a technological lead in developing and deploying advanced energy technologies."[1]

The second part of the committee's task was to conduct both an operational assessment and a retrospective and prospective technical assessment in the context of the agency's statutorily defined means of achieving its goals "through energy technology projects by—

> (A) identifying and promoting revolutionary advances in fundamental and applied sciences;
> (B) translating scientific discoveries and cutting-edge inventions into technological innovations; and
> (C) accelerating transformational technological advances in areas that industry by itself is not likely to undertake because of technical and financial uncertainty."[2]

The committee's operational assessment considers how ARPA-E is organized, how it selects projects to support, how it partners with performers to manage those projects, how it actively manages projects, and what nontechnical support it provides to projects. The technical assessment outlines how ARPA-E, through its project selection and management, has made progress toward producing commercial products with the potential to transform the energy sector. The committee also considered the value to ARPA-E of developing a framework, processes, and specific systems for the collection of data that will be valuable for continuous improvement of operational processes and can serve as the basis for future self- or external technical and impact assessments.

The scope of this study did not include providing a comprehensive benefit-cost analysis or other review of ARPA-E's value, such as a comparison with other possible uses of federal funding. Such an analysis is infeasible with currently available data. The study scope did include consideration of what

[1] 42 U.S.C. 149 § 16538(c)(1).
[2] 42 U.S.C. 149 § 16538(c)(2).

lessons learned from the operation of ARPA-E may apply to other DOE programs, as well as factors that Congress should take into account in determining the agency's future.

STUDY METHODOLOGY AND LIMITATIONS

The committee's findings and recommendations are based on both quantitative and qualitative data, including agency data, publicly available data, observations at agency events, presentations by personnel from ARPA-E, DOE, and the Defense Advanced Research Projects Agency (DARPA), case studies of completed awards, consultations with current and former ARPA-E personnel, and consultations with individuals from other programs and offices at DOE. The development of new or transformative energy technologies from initial discovery to broad market deployment typically takes several decades. ARPA-E provides support for projects very early in this process, typically around first translation from scientific discovery to engineering—focusing on ideas at technical readiness levels 2 to 4—with the possibility of leading to a marketable product. Most ARPA-E awards last for about 3 years, much shorter than the decades required to commercialize energy technologies. Unsurprisingly, few data were available for this study regarding ARPA-E's impact on energy technologies or the sector as a whole. Still, 6 years of operation provides data demonstrating the intermediate impacts of ARPA-E's activities. The committee developed its findings and recommendations by analyzing these available data.

DEFINING ORGANIZATIONAL FEATURES OF ARPA-E

Within the Department of Energy (DOE), ARPA-E can be distinguished by its culture, methods, and focused mission and goals. Through the course of its deliberations and analyses of the evidence gathered for this assessment, the committee found that ARPA-E benefits from three defining organizational features:

- The director provides technical and leadership skills that enable and sustain a culture of empowerment.
- ARPA-E's program directors are empowered with the authority, responsibility, and ability to make program- and project-related decisions.
- Active project management is important to ARPA-E.

Collectively, these three features have the potential to contribute to ARPA-E's ability to achieve its intended mission and goals. The absence of these features would not guarantee failure, and their presence does not ensure success.

However, these features are important to creating a culture that can enable success.

KEY FINDINGS

Closely linked to the defining organizational features set forth above, the committee developed 18 findings based on the available data and evidence. While all of these findings are necessary for understanding the progress ARPA-E has made toward fulfilling its mission and goals, five stood out to the committee as especially important.

> ***Finding 3-7:[3] ARPA-E selects projects to fund through a multifaceted process that entails evaluating each project's potential to contribute to the achievement of the agency's goals should it be successful.***

Quantitative evidence demonstrates that ARPA-E has instituted a system focused on finding and funding ideas with a high potential for impact on achievement of the agency's goals. The evidence also shows that this system involves a numbers of stages, and that at each stage ARPA-E uses a multifactor process to make decisions regarding applications. This process emphasizes technical comments from internal and external reviewers; applicants' responses to those comments; and a holistic assessment of funding recommendations that considers the technical content of the applications, the potential for impact on achieving agency goals should projects be successful, and nontechnical factors. The process addresses such important issues as portfolio balance, both across technical categories and within the funded program, with an eye to ensuring sufficiently varied approaches. This process is distinguishable from those of some other agencies that make funding decisions based principally or solely on numerical reviewer scores, often utilizing a strict cutoff that does not allow for discretion on the part of the agency or program directors. Strong and consistent evidence indicates that projects selected through ARPA-E's process have the potential to yield measurable outcomes at least as good as, if not better than, those of projects that would have been selected had less discretion been allowed.

> ***Finding 3-8: ARPA-E program directors have wide authority to develop new focused technology programs that are potentially transformative.***

[3]The committee's findings and recommendations are numbered according to the chapter and ordering where they appear.

The committee consistently found both qualitative and quantitative evidence that ARPA-E's program directors are empowered with wide authority to carry out their responsibilities, including those outlined in the agency's authorizing statute. Program directors create new technologically focused programs through a process that encourages novel ideas with the potential to identify and promote revolutionary advances or translate discoveries into technological innovations. This process involves collaboration and critical review with the agency director, other program directors, and the wider research community. It also encourages the pursuit of ideas overlooked or ignored by other funders, as well as truly novel ideas.

> ***Finding 3-9: ARPA-E program directors actively manage projects through technical research guidance and feedback, regular and frequent assessments of progress made toward stated technical milestones, and revision of milestones in response to new findings and research discoveries.***

Throughout a program's life cycle—from review of applications, through award negotiations, to completion of individual projects—program directors engage in active project management. They work closely with performers to create milestones, which can be modified in accordance with what the team learns through the course of its research. Program directors regularly engage with performers to discuss a project's technical approach and collaborate to revise it based on results to date. They work with performers to modify their research approaches, when appropriate, in response to data obtained through the course of research. Such changes can range from minor modifications of protocols, techniques, or project milestones to more significant project restructuring or changes in direction. Program directors even can, and do, recommend personnel changes and work with performers to identify and recruit qualified personnel or subcontractors. They also recommend that the agency terminate funding early when projects repeatedly fail to meet their milestones and appear unlikely to do so in the future.

Collectively, findings 3-7, 3-8, and 3-9 suggest that ARPA-E has thus far maintained its independence from such constituencies as groups seeking funding. Implementation of several of the recommendations presented below, particularly Recommendations 3-1, 4-3, and 4-8, would help ensure that ARPA-E maintains its independence.

> ***Finding 4-2: The projects ARPA-E has funded support its statutory mission and goals.***

> ***Finding 4-3: While 6 years is not long enough to produce observable evidence of widespread deployment of funded technologies, there are clear indications that ARPA-E is making progress toward its statutory mission and goals.***

While the full market impacts of the technologies that ARPA-E has funded undoubtedly will not be seen for years, some intermediate outcomes are evident now. Roughly half have published results of their research in peer-reviewed journals, and about 13 percent have obtained patents. One quarter of the supported project teams or technologies have received follow-on funding for continued work. All of these are positive indicators for technologies on a trajectory toward commercialized products. In fact, several are either already commercially available or poised to enter the commercial market.

Two important observations can be derived from these facts. First, there is an inherent tension to be managed by ARPA-E between having a short-term impact on a technology within the 3-year funding timeframe while producing transformational technologies. Second, after 6 years of operation, there exist only about 3 years of completed projects to serve as evidence of progress toward ARPA-E's mission and goals. These two observations speak simultaneously to the need to consider ARPA-E's impact in context and over a duration that is well aligned with the agency's mission and the reality of the market dynamics of energy technologies, and to the need to gather, systematically, more and better data that can be used to discern and monitor mechanisms that may lead to a better understanding of how a technology's full impact is achieved over time.

Reviewing the findings presented above, together with all the findings and evidence gathered and presented for this report, it is evident that assessing ARPA-E at this time is a difficult task. ARPA-E's was expressly created to achieve long-term environmental, security, and competitiveness goals. It was structured to fund and manage research and development (R&D) undertaken by entities other than the agency rather than undertaking its own R&D activities. Because the agency is tasked with seeking out transformational technological advances, it has necessarily utilized novel operational benchmarks to try to accomplish its goals.

Any assessment of the agency at this time will encounter a well-known problem in R&D management: since sufficient time has not passed for outcomes to have become evident, an assessment cannot draw strong conclusions unless the enterprise is in an extreme situation, such as doing very badly. The findings make clear that ARPA-E is not in an extreme situation. The agency is not failing and is not in need of reform. In fact, attempts to reform the agency—such as applying pressure for ARPA-E to show short-term successes rather than focusing on its long-term mission and goals—would pose a significant risk of harming its efforts and chances of achieving its mission and goals.

Nonetheless, the committee is confident that the data obtained and analyzed for this assessment indicate that ARPA-E has grown from a concept into a functioning organization and has made demonstrable progress toward achieving its statutory mandates. Moreover, the committee hopes that this report will provide useful guidance to ARPA-E as it continually assesses its data collection procedures with an eye toward improving operations and supporting future self- and independent evaluations of the agency.

KEY RECOMMENDATIONS

On the basis of its findings, the committee formulated 14 recommendations intended to help ARPA-E continue to strengthen and build upon its early success. Five of these 14 recommendations stand out as key to positioning the agency for success to fulfill its mission and goals, and are presented here with their supporting findings.

> **Recommendation 3-1: ARPA-E should preserve its distinctive and flexible management approach that empowers program directors and stresses active project management.**

Findings 3-1, 3-2, and 3-3 show how ARPA-E has internalized the principles of an innovative culture, dynamic leadership, and program director autonomy in its organizational structure. Specifically, it is evident that ARPA-E's program directors have been empowered to take risks in project selection in line with the agency's mission; have been given discretion that enables ARPA-E to fund relatively risky projects, with no clear indication that average project performance in the short term is reduced; and continuously engage in active management of ongoing projects, as reflected in the altering of project milestones, budgets, and timelines. These findings highlight the important role of the program directors in supporting ARPA-E's vitality and in enabling the agency to execute its mission and goals.

The committee recommends that ARPA-E strive to preserve this management approach that gives its program directors wide authority to develop new focused technology programs with potential to be transformative and enables them to manage projects actively through technical research guidance and feedback, regular and frequent assessments of progress toward stated milestones, and revision of milestones in response to new findings and research discoveries. This management approach is a defining organizational feature that can contribute to the agency's ability to achieve its statutory mission and goals, and helps to distinguish ARPA-E from other public funding initiatives for energy R&D.

> **Recommendation 4-8: The ARPA-E director and program directors should develop and implement a framework for measuring and assessing the agency's impact in achieving its mission and goals.**

As described in Finding 4-9, ARPA-E is not yet able to assess the full extent to which it has achieved its statutory mission and goals. The agency has in place an extensive data gathering and recordkeeping system at the project level with which to track and monitor internal metrics and facilitate active

program management. It has a less extensive system for collecting, tracking, and reporting publicly available high-level innovation metrics such as publications; funding from other sources; and intellectual property information, including disclosures and patents over time. Even if these traditional innovation metrics were available through a more systematic approach to their collection, they could not enable a robust, quantifiable assessment of whether and how ARPA-E's activities have contributed to achieving its statutory mission and goals. Consequently, neither the agency nor any other assessor can at present perform such an assessment. ARPA-E is, however, in a good position to develop a framework for prospectively mapping project-level data from program creation, through project selection and management, to mission success and achievement of goals.

The development and implementation of such a framework would be very valuable and important for ARPA-E to undertake as soon as practicable, providing the agency with greater ability to demonstrate its value and impact. It is critical that ARPA-E not delay implementation. The longer the agency waits, the more difficult it will be to implement such a framework and the less valuable it will be, and it will become more difficult if not impossible to assess program impacts in a way that allows for meaningful reform in response. The agency could link data from its robust internal database of project-level metrics to program-level goals, including indicators of commercial and noncommercial outcomes over the short and long terms; connect those goals to standard, observable innovation metrics; and then translate those metrics into progress toward achieving the agency-level mission and goals. Such a framework would need to include a system for tracking performers postfunding for at least 10 years, and very likely longer, to capture technologies that are transferred in arms-length transactions along with other ways of observing technology deployment.

At the agency level, ARPA-E already is known for a willingness to assess its structure and operations and experiment with changes aimed at improving both operations and outcomes. Designing and implementing such a framework could place the agency at the forefront of self-evaluation, with the ultimate aim of improving the outcomes of its work. To develop and implement this framework in a way that would best serve the agency, ARPA-E's director and staff would need to be empowered with the autonomy to do so based on their direct experience with running the agency and managing projects.

> **Recommendation 3-3: ARPA-E should reconceptualize its "tech-to-market" program to account for the wide variation in support needed across programs and performers with respect to prospective funding, commercialization, and deployment pathways.**

Finding 3-4 describes how ARPA-E views its "tech-to-market" (T2M) activities as an ongoing experiment, and the challenge of developing such a

program may be greater than originally thought. Incumbent energy technologies have long usable life spans. Adequately verifying and validating new energy technologies usually takes decades, and large amounts of capital are required relative to what is necessary in other technology sectors. Still more time is required to develop technologies into commercial products. The roughly 3-year timeframe of an ARPA-E project is too short to expect a technology to move from concept to market.

The value added by ARPA-E's T2M activities varies by project and performer. Some performers consulted during this study, in particular those with established product development and marketing capacity, have not found ARPA-E's current approach for T2M helpful. Other performers, such as academic teams, have found value in the agency's T2M guidance. Given that the agency continually strives to evolve and improve its approach to T2M, the committee encourages further evolution of that approach while cautioning against overexpansion. For example, ARPA-E should consider making full T2M plans optional—encouraging development of these plans by performers most likely to benefit, such as academics—but requiring performers to describe potential product applications if they can prove technological feasibility. It also could provide information or research to performers on critical nontechnical factors that could impact market adoption of future products, such as regulatory risk and other, common risks other than business-market risks.

Recommendation 4-3: ARPA-E should continue to use processes designed to identify and support unexplored opportunities that hold promise for resulting in transformational technological advances.

Finding 4-4 describes the importance for ARPA-E of seeking high-risk, potentially transformative technologies and overlooked, "off-roadmap" opportunities pursued by neither private firms nor other funding agencies, including other programs and offices within DOE, as a way to position itself to accomplish its mission. ARPA-E's underlying organizational features include encouraging its program directors to seek potentially high-impact projects and recognizing that many of its projects will produce only valuable knowledge, including knowledge of research pathways that should not be pursued further, instead of commercialized products.

Maintaining this focus will be one of the greatest challenges for ARPA-E in the future. It is not guaranteed that ARPA-E will be able to maintain a culture of pursuing high-risk but potentially transformative technologies and research pathways characterized as novel or significantly underexplored as the energy technology landscape evolves. ARPA-E leadership and the secretary of energy should actively work to sustain this culture. ARPA-E should continue to balance its overall portfolio between technologies that appear to have the potential to be transformative and other valuable opportunities that are being ignored.

Recommendation 3-5: The secretary of energy should ensure that other offices and programs within DOE continue to explore and adopt elements of ARPA-E's practices that can improve the department's operations.

Findings 3-1, 3-2, and 3-3 provide details on ARPA-E's program creation and project management. Finding 3-6 supports the positive influence those practices have had on other offices within DOE. To cite a direct example, the Office of Energy Efficiency and Renewable Energy has incorporated several elements of ARPA-E's approach into the management of its programs, including use of a workshop to define a program, use of concept papers to screen funding applicants, and early termination of underperforming projects. While some elements of ARPA-E's approach may be difficult to scale or translate to other programs and offices, there is great benefit in exploring their adaptability and suitability. Of particularly high value would be finding suitable ways to incorporate such key features as term-limited program managers, use of constructive engagement among program directors to sharpen the focus of programs, the degree of operational freedom accorded to program managers, and the risk-taking orientation of programs. Other DOE offices have expressed interest in adopting a number of these features. The secretary of energy should encourage and empower those offices to explore and adopt appropriate practices.

FINAL THOUGHTS

ARPA-E has the ability to make significant contributions to energy R&D that likely would not take place absent the agency's activities. The committee believes that implementation of its recommendations would benefit ARPA-E, and the nation, as the agency continues to evolve and improve its operations in service of its mission and goals. The committee also believes that these recommendations should be helpful to Congress as it considers ARPA-E's future.

BOX S-1
COMPLETE LIST OF ALL FINDINGS

Findings regarding ARPA-E's Internal Operations: Culture, People, and Processes (Chapter 3)

Finding 3-1: ARPA-E program directors have been empowered to take risks in project selection in line with the agency's mission.

Finding 3-2: Program director discretion enables ARPA-E to fund relatively risky projects, with no indication that average project performance in the short term is reduced.

Finding 3-3: Program directors are continuously engaged in ongoing projects, as reflected by the altering of project milestones, budgets, and timelines, to help ensure that projects support ARPA-E's mission and goals.

Finding 3-4: ARPA-E considers its "technology-to-market" (T2M) activities to be an ongoing experiment, and the challenge of developing such a program may be greater than originally thought.

Finding 3-5: The program director hiring policies at ARPA-E appear to complement the agency's programmatic timelines. Many projects experience a program director transition, but on average, this transition is not detrimental to project performance.

Finding 3-6: ARPA-E is a positive agent of change in DOE and the federal government, and its best practices are being adopted in some DOE offices. ARPA-E's role as a positive change agent has been facilitated by its outreach and bridge-building efforts with respect to other federal organizations since its formation.

Finding 3-7: ARPA-E selects projects to fund through a multifaceted process that entails evaluating each project's potential to contribute to the achievement of the agency's goals should it be successful.

Finding 3-8: ARPA-E program directors have wide authority to develop new focused technology programs that are potentially transformative.

Finding 3-9: ARPA-E program directors actively manage projects through technical research guidance and feedback, regular and frequent assessments of progress made toward stated technical milestones, and revision of milestones in response to new findings and research discoveries.

(Continued)

BOX S-1
Continued

Findings regarding Technical Assessment (Chapter 4)

Finding 4-1: ARPA-E has funded research that no other funder was supporting at the time. The results of some of these projects have prompted follow-on funding for various technologies, which are now beginning to enter the commercial market.

Finding 4-2: The projects ARPA-E has funded support its statutory mission and goals.

Finding 4-3: While 6 years is not long enough to produce observable evidence of widespread deployment of funded technologies, there are clear indications that ARPA-E is making progress toward its statutory mission and goals.

Finding 4-4: One of ARPA-E's strengths is its focus on funding high-risk, potentially transformative technologies and overlooked, "off-roadmap" opportunities pursued by neither private firms nor other funding agencies, including other programs and offices within DOE.

Finding 4-5: Some of the language used by ARPA-E creates an impractical expectation and mission that are not necessarily in the agency's original authorizing statute.

Finding 4-6: The high-touch nature of project management at ARPA-E is a hallmark of the agency and has been praised by performers. That said, quarterly reporting in terms of required written documentation is currently challenging, depending on the technical context. Given that quarterly written reports are offset in time with site visits from program directors and their teams, a project performer may end up having 8–10 direct interactions with ARPA-E per year.

Finding 4-7: Through its projects and programs, ARPA-E is accumulating not only technical knowledge of what is working and has promise, but also potentially very useful information on what does not work that can be an important addition to ARPA-E documentation.

Finding 4-8: ARPA-E is in many cases successfully enhancing the economic and energy security of the United States by funding transformational activities, white space, and feasibility studies to open up new technological directions and evaluate the technical merit of potential directions. However, ARPA-E is doing a poor job of creating awareness of

BOX S-1
Continued

these very real successes while at the same time holding itself to a metric of success that is not aligned with its authorizing statute or fundamentally essential to the energy and economic security of the United States (see Finding 4-5).

Finding 4-9: ARPA-E is not yet able to assess the full extent to which it has achieved its statutory mission and goals. However, it is in a good position to develop a framework for prospectively mapping data on project selection and management to mission success and goal achievement.

BOX S-2
COMPLETE LIST OF ALL RECOMMENDATIONS

Recommendations regarding ARPA-E's Internal Operations: Culture, People, and Processes (Chapter 3)

Recommendation 3-1: ARPA-E should preserve its distinctive and flexible management approach that empowers program directors and stresses active project management.

Recommendation 3-2: ARPA-E should continue to hire exceptional program directors and empower them to create programs and manage projects.

Recommendation 3-3: ARPA-E should reconceptualize its "technology-to-market" program to account for the wide variation in support needed across programs and performers with respect to prospective funding, commercialization, and deployment pathways.

Recommendation 3-4: ARPA-E should continue its practice of hiring program directors for 3-year terms, allowing for one, term-limited extension when necessary to complete implementation of a new program or for other reasons determined by the ARPA-E director.

Recommendation 3-5: The secretary of energy should ensure that other offices and programs within DOE continue to explore and adopt elements of ARPA-E's practices that can improve the department's operations.

Recommendation 3-6: ARPA-E and DOE should provide incentives to encourage more interaction between other DOE program offices and ARPA-E, which could potentially help reduce DOE's bureaucratic culture.

(Continued)

BOX S-2
Continued

Recommendations regarding Technical Assessment (Chapter 4)

Recommendation 4-1: Policy makers should recognize that there is limited evidence to date on transformational impacts emerging from ARPA-E, given the short time since ARPA-E began.

Recommendation 4-2: The director of ARPA-E should continue to promote and maintain a high-risk culture within the agency. Means to this end include periodic reassessment to ensure that the principles that drive support for high-risk projects are being maintained.

Recommendation 4-3: ARPA-E should continue to use processes designed to identify and support unexplored opportunities that hold promise for resulting in transformational technological advances.

Recommendation 4-4: ARPA-E should be careful not to misinterpret or extend its interpretation of its original authorizing statute, whose careful language is appropriate to the agency's mission and goals.

Recommendation 4-5: ARPA-E should consider streamlining the quarterly reporting process so it consists of presentations to the program directors and their teams, with only the fourth-quarter/annual report providing full written details. Doing so would allow the agency to maintain close contact with performers while relieving some of the burdens on them.

Recommendation 4-6: ARPA-E program directors should compile a document or other repository of lessons learned on all projects, including both positive and negative outcomes.

Recommendation 4-7: ARPA-E should increase and improve its communication for non-technical audiences, including the impact of its activities, the diversity of appropriate metrics to judge the success of individual projects and programs, and the fact that no single metric is appropriate for this purpose.

Recommendation 4-8: The ARPA-E director and program directors should develop and implement a framework for measuring and assessing the agency's impact in achieving its mission and goals.