Written Testimony of

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Dear Chairman Smith, Ranking Member Johnson, and distinguished Members of the Committee,

Thank you for offering me the opportunity to submit testimony to the Committee. It is an honor to be able to offer my perspective on a topic that is of great importance to the national interest.

My name is Venkatesh Narayanamurti. I am currently the Benjamin Peirce Research Professor of Technology and Public Policy at Harvard University. I was formerly the Dean of the Harvard John A. Paulson School of Engineering and Applied Sciences and Dean of Physical Sciences at Harvard. From 1992 to 1998 I served as Dean of the College of Engineering at the University of California at Santa Barbara.

From 1987 to 1992, I was Vice President of Research at Sandia National Laboratories. Much of my scientific research career was at the AT&T Bell Laboratories where I served first as Head of Semiconductor Electronics Research and then as Director of Solid State Electronics Research. It was in these roles that I came to understand the two key principles that underlie my testimony. Namely, that innovation is fostered when control over the research agenda resides as close as possible to the researchers in the lab; and that innovation is hindered by the traditional "linear model" that bifurcates research into categories of "basic" and "applied".

My testimony also stems from policy research I have conducted with fellow scholars at the Belfer Center for Science and International Affairs at the Harvard Kennedy School (HKS). Our group has led research on supporting decisions about the optimal levels of DOE R&D investments in various energy technologies considering technology uncertainty, the structure and management of research institutions, and the linkage between DOE and the private sector.

In addition, my recent service as Foreign Secretary (2011 to 2015) of the U.S. National Academy of Engineering, which involved many global interactions, has given me a broader view of R&D in an era of increased global competition. I currently serve on the Board of Directors of the American Academy of Arts and Sciences and co-chaired its 2013 report, "ARISE II: Unleashing America's Research & Innovation Enterprise." I was also a member of the American Academy's panel for its 2014 report, "Restoring the Foundation: The Vital Role of Research in Preserving the American Dream," co-chaired by Norm Augustine and Neal Lane.

This testimony was prepared in consultation with my colleagues with whom I have worked closely at the Harvard Kennedy School: Prof. Laura Diaz Anadon now at the University of Cambridge, Prof. Gabriel Chan now at the University of Minnesota, Dr. Amitai Bin-Nun now at Securing America's Future Energy, and Dr. Anna Goldstein. I also want to acknowledge the contributions of collaborators who have influenced my thinking over the years, including Dr. Jeff Tsao at Sandia National Laboratories and Prof. Tolu Odumosu now at University of Virginia.

Summary

The DOE is unique among federal R&D agencies in its multiple missions: "General" Science, National Security, and Energy. It is a major funder of research in physical sciences and engineering, and it oversees 17 National Laboratories. In this testimony, I will concentrate on R&D for the energy mission of DOE. Specifically, I will emphasize the need for support for transdisciplinary research and better integration of research efforts across academia, government, and industry in the energy space.

During my time as a researcher and research director at Bell Labs, Bell Labs produced major breakthroughs in semiconductor materials engineering that led to new scientific discoveries; these discoveries in turn enabled today's wireless and optical communication systems. The transformative impact of R&D at Bell Labs provides an important lesson for DOE research management: the creation of new technology requires the close integration of activities typically classified as "basic research" and "applied research." The boundary between "basic" and "applied" research is arbitrary and counterproductive. The processes of discovery and invention do not happen in isolation—the two must be holistically managed to maximize the societal benefit of research investments.

Strengthening federal energy R&D investments is especially important, given the low levels of private investment in energy R&D and the large potential for economic growth from new and improved energy technologies. DOE must continue to adopt a portfolio strategy that includes a diverse range of research management approaches, in addition to a diverse set of technologies. Reducing funding for so-called "applied" research through EERE and the other technology offices would severely undercut the ability of DOE-funded research to address energy goals and US competitiveness. DOE has taken several positive steps over the last 10 years to more tightly integrate science and engineering research activities across the "basic"/"applied" research divide, including the creation of ARPA-E. Continued efforts along these lines should be encouraged.

Opportunities exist to reform DOE's approach to energy R&D investment so that new discoveries and new inventions can more rapidly be transferred to the private sector. DOE's ability to advance its mission is hindered by the "stovepiping" of research funding streams separately administered by the Office of Science and the "applied" energy offices and limitations to National Lab director discretion. Changes in management will decrease overhead costs and improve the effectiveness of R&D funds at DOE; any funding adjustments have to be made with a scalpel, not an axe.

Suggested Readings

1. National Research Council (2007), "Rising Above the Gathering Storm: Energizing and Employing America for a Brighter Economic Future."
2. American Academy of Arts & Sciences (2013), "ARISE II: Unleashing America's Research and Innovation Enterprise."
3. Narayanamurti, V., Odumosu, T. (2016), *Cycles of Invention and Discovery: Rethinking the Endless Frontier*, Harvard University Press, Cambridge, MA, and references cited therein.
4. Anadon, L. D., Bunn, M., & Narayanamurti, V. (Eds.). (2014). *Transforming US Energy Innovation.* Cambridge University Press.
5. Anadon, L. D., Chan, G., Bin-Nun, A. Y., & Narayanamurti, V. (2016). The pressing energy innovation challenge of the US National Laboratories. *Nature Energy, 1*, 16117.

1. There is harmony between public support for "basic" and "applied" energy research

Scholars and practitioners of science and technology have largely moved past the once dominant "linear model" of innovation, in which "basic" research is thought to precede "applied" research. Contemporary research describes the process of technological innovation with a "connected R&D" model, where innovation is not separated into "basic" and "applied" activities, but rather is one continuous activity-space; activities normally classified as "applied" and "basic" are mutually reinforcing and chronologically sequenced in a variety of ways. This connected model also emphasizes the knowledge feedback that develops when technologies are put into practical application. Under this new paradigm, which is considered a better description of how engineers and scientists actually operate, new inventions in the domain of engineering enable deeper understanding in the domain of science with a comparable frequency to the reverse direction of influence.[1,2]

History abounds with examples of the interdependence of science and engineering, especially in energy. The invention by James Watt of the steam engine led to the scientific theory of thermodynamics. The invention of the light bulb by Edison and the work of Tesla and Westinghouse on transformers for long distance electricity transmission led to the emergence of the field of electrical engineering for power generation. Einstein's seminal scientific work on relativity eventually led to the discovery of nuclear fission and the development of nuclear power. America's growth as an economic superpower is in many ways connected to its frontier spirit and superior ability to exploit the virtuous cycle of scientific discovery and engineering inventions to meet societal goals. This spirit is still alive and well in some places (e.g. the information technology sector), and yet the level of investment necessary to advance both science and technology in the energy space is prohibitively large for the self-funded "tinkerer."

The unity of "basic" and "applied" research activities was a major factor in the highly productive corporate R&D activities in the 20th century. Examples abound from AT&T Bell Labs, IBM, Xerox, DuPont and General Electric. My own experience at Bell Labs, alongside the history of the invention of the transistor and the discovery of the transistor effect, illustrates the importance of breaking down barriers between science and engineering. In the 1970's and 1980's, Bell Labs made enormous strides in artificially-tailored thin-film materials, which led to new scientific discoveries in semiconductor quantum physics. These advances led *simultaneously* to the creation of devices like high-mobility transistors, which are in every cell phone, and tiny communications lasers, which allow high speed fiber optic communications across the globe.

Since my time at Bell Labs, corporate R&D has shifted dramatically toward only those R&D activities that can produce immediate returns.[3] This leaves the public sector with the responsibility to support long-term, mission-focused R&D funding. And yet, mission-focused government R&D programs must not be limited to only funding science that is remote from applications. In order to achieve long-term technological progress, the processes of discovering new knowledge and inventing new technology must be coupled. The scientists and engineers, particularly those working on energy-related topics, in U.S. universities and national labs depend on public funding to be able to create the

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[1] Narayanamurti, V, Odumosu, T. (2016). *Cycles of Invention and Discovery: Rethinking the Endless Frontier*. Harvard University Press, Cambridge, MA.
[2] American Academy of Arts & Sciences (2013), "Arise II: Unleashing America's Research and Innovation Enterprise Transforming U.S. Energy Innovation."
[3] Arora A., Belenzon S., Patacconi A. (2015). "Killing the Golden Goose? The Decline of Science in Corporate R&D." NBER Working Paper Series, 20902.

new ideas that will support the nation's economic growth, security, and environmental well-being in the future.

In addition to the critical responsibility for funding research, government-sponsored programs must also support exploratory technology development. When new knowledge is derived from publicly-funded research, it must be shepherded across the "valley of death" before it finds an application suitable for transition to private sector development. The role of the government is to construct a bridge between scientists and engineers thereby creating both new ideas and new private companies focused on short-term product markets. Exactly how far this support should continue in the maturation of any given technology, from exploratory development toward manufacture and deployment, can be argued, but it is clear that government has an important role to play in supporting technologies across the "valley of death."

While the argument I have outlined above for public support throughout the innovation cycle is true for many areas of technology, it is especially urgent in the case of energy innovation. The markets for energy technologies are generally large, highly regulated, and based on long-lived hardware and infrastructure. Additionally, electricity and fuels—the main products of the energy sector—are sold as homogeneous commodities, making it hard to charge a premium for new ways of producing them. Partly as a result of these considerations, the incentive for private actors to invest in innovation is particularly low for energy technologies; the energy sector has one of the lowest rates of innovation per unit of revenue in any sector, both in the U.S.[4] and globally.[5] At the same time, the potential social benefits from energy innovation are particularly high, as explained in the following section.

2. DOE plays a critical role in U.S. energy innovation

The United States is facing both a set of challenges and opportunities related to its energy system. The challenges are global in nature and cut across issues of national security, economic growth, and environmental protection. Despite rapid increases in domestic crude oil production over the last six years, in 2016, the United States spent $7.3 trillion on oil imports from foreign countries.[6] In 2005, the most recent year a comprehensive assessment was conducted, the human health and environmental impacts of energy use in the United States (excluding any effect of climate change), was $120 billion.[7] Meanwhile, there are opportunities associated with our evolving energy system; the energy sector created 300,000 new jobs in 2016, representing 14% of all job creation in the United States.[8] This was led by 25% growth in employment in the solar sector and 32% growth in the wind sector.

The United States has entered an unprecedented era of globalization and economic competition. Achieving economic prosperity in this new era will require American companies to outcompete companies in an increasing number of countries around the world. Other countries are ramping up

[4] The Breakthrough Institute (2011). "Bridging the Clean Energy Valleys of Death."
[5] The Global Energy Assessment (2012). *Chapter 24: Policies for the Energy Technology Innovation System*
[6] U.S. Census Bureau, Economic Indicators Division. https://www.census.gov/foreign-trade/statistics/historical/petr.pdf
[7] U.S. National Research Council (2010). *Hidden Costs of Energy*.
[8] U.S. Department of Energy (2017). "U.S. Energy and Employment Report."

their public support for energy R&D.[9] If the United States withdraws support for energy R&D programs, China, Germany, Japan, and others will seize the opportunity to lead global markets in new technologies. Meanwhile, innovation is a fundamental driver of economic vitality in every Congressional district in the country.[10] Supporting innovation at the federal level will create economic opportunities nationwide and ensure that American companies have access to the most advanced inventions and discoveries.

To promote competitiveness of American companies, public sector R&D investments must be at least sustained. At a national level, there are increasing returns to innovation, meaning that the companies and countries that gain initial advantage in a technological area are much more likely to increase their advantage, while those who are behind tend to fall further behind. For example, a country with a technological advantage in new forms of energy production can use this advantage to capture market share and push out other countries, attracting further follow-on innovation by investors. Thus, early technological advantage, if sustained through strategic investments, begets further technological advantage in areas that build on the initial technology as catching up becomes harder and harder.

Energy R&D funding has higher economic returns than many other forms of investment. There is considerable evidence that DOE energy R&D investment has stimulated additional private investment, serving as a catalyst for greater overall innovation.[11,12] Several prominent studies by experts,[13,14] bipartisan groups,[15] and business leaders[16] over the past couple of decades have called for significantly greater U.S. government spending on energy R&D. These studies have concluded that there would be significant benefits to the U.S. economy of increasing energy R&D. It has been estimated that the economic returns to increasing energy R&D by DOE are very significant and would still be positive if funding were increased by a factor of 10.[17]

Inconsistent support for DOE R&D programs has led to budget fluctuations that undermine the effectiveness of R&D investments and should be avoided. Implementing effective energy R&D programs requires a minimum of a 3-5 year planning horizon so that technical expertise can be directed toward an innovation mission, physical scientific equipment can be prepared and fully

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[9] Anadon, LD (2012). "Missions-oriented RD&D institutions in energy: a comparative analysis of China, the United Kingdom, and the United States." *Research Policy* 41(10), 1742-1756.
[10] Information Technology & Innovation Foundation (2016). *High-Tech Nation: How Technological Innovation Shapes America's 435 Congressional Districts.*
[11] Howell, S. (2017). "Financing Innovation: Evidence from R&D Grants." *The American Economic Review* 107 (4), 1136-1164.
[12] Chan, G. (2015). *Essays on Energy Technology Innovation Policy.* PhD thesis Ch. 2, Harvard University, Cambridge, MA.
[13] PCAST (2010). "Report to the President on Accelerating the Pace of Change in Energy Technologies through an integrated federal energy policy." Washington D.C. President's Council of Advisors on Science and Technology. Executive Office of the President.
[14] Anadon, LD, Chan, G, Lee, A. (2014). "Expanding, and improving targeting of, U.S. investment in energy innovation: an analytical approach." In *Transforming U.S. Energy Innovation*. Eds. LD Anadon, M Bunn, V Naranayanamurti. Cambridge University Press.
[15] NCEP (2004). "Ending the energy stalemate. A bipartisan strategy to meet America's energy challenges." Washington D.C. The National Commission on Energy Policy.
[16] American Energy Innovation Council. (2017). "The Power of Innovation: Inventing the Future."
[17] Chan, G, Anadon, LD. (2016). "Improving Decision Making for Public R&D Investment in Energy: Utilizing Expert Elicitation in Parametric Models." EPRG Working Paper 1631 and Cambridge Working Paper in Economics 1682. University of Cambridge. http://www.eprg.group.cam.ac.uk/wp-content/uploads/2017/01/1631-Text.pdf

exploited, and the right people recruited, trained, and supported. The highly volatile DOE R&D appropriations for specific programs have made this kind of long-term planning more difficult.[18] A more stable environment would increase the capability for program managers and scientists to pursue higher-risk, higher-reward research. Reducing volatility in funding could be achieved by following a multi-year high-level strategy, along the lines of those suggested by the first and second Quadrennial Technology Reviews.[19] Programs should be evaluated on a regular basis, and those that under-perform with regard to holistic measures of knowledge and technology advancement, as opposed to narrower metrics, should be cut.

3. EERE and ARPA-E are necessary to achieve strategic energy policy objectives

DOE energy R&D investments have advanced the scientific and technological frontier and are critical components of the U.S. national innovation system. These investments have made our economy more dynamic,have created new technological opportunities for American companies to deliver services here and to compete internationally, and have driven employment in every region of the country. In particular, I would like to highlight the impact of two R&D funding sources within DOE: EERE and ARPA-E.

EERE

The Office of Energy Efficiency and Renewable Energy (EERE) has existed under various names since the inception of the Department of Energy in 1978. Its strategic goals are to accelerate the development and increase the usage of sustainable transportation, renewable energy, and energy efficiency technologies. It also seeks to promote the domestic manufacture of clean energy technology and increase grid resiliency, reliability, and efficiency. EERE is organized on the principle of investing in high-impact activities that could not be realized without its participation. To this end, EERE works with academia, industry, and national labs on R&D, technology validation, and reducing market barriers for new technologies. Importantly, it also oversees the National Renewable Energy Laboratory in Golden, Colorado (NREL), which hosts state-of-the-art testing facilities and conducts research in renewable energy technologies.[20]

According to DOE, recent third-party evaluations found that "an EERE taxpayer investment of $12 billion has already yielded an estimated net economic benefit to the United States of more than $230 billion, with an overall annual return on investment of more than 20%."[21] A 2001 report of the independent National Research Council (NRC) found that DOE investments in energy efficiency research had yielded considerable net economic benefits, even apart from environmental benefits from reduced pollution and national security benefits from reduced petroleum consumption. The NRC

[18] Anadon, LD, Chan, G, Lee, A. (2014). *Ibid*.
[19] U.S. Department of Energy. "The Quadrennial Technology Review." https://energy.gov/under-secretary-science-and-energy/quadrennial-technology-review
[20] U.S. Department of Energy. "About us." https://energy.gov/eere/about-office-energy-efficiency-and-renewable-energy
[21] U.S. Department of Energy. "About the Office of Energy Efficiency and Renewable Energy" https://energy.gov/eere/about-office-energy-efficiency-and-renewable-energy

found that from 1978 to 2000, EERE invested $7 billion (1999 dollars), which yielded a total economic benefit of $30 billion by 2000.[22]

One example of EERE's important role in the American energy innovation system is its SunShot Initiative. Since 2011, SunShot has funded R&D and demonstration projects with public and private partners; EERE's budget for solar technologies was $233 million in 2015. Meanwhile, the U.S. solar power industry has grown enormously due to continuous cost reductions for residential, commercial, and utility-scale photovoltaic systems. The total power generated by solar photovoltaics in the U.S. increased by a factor of 2,000 during the decade from 2007-2016.[23] According to a 2017 DOE report, there were 374,000 solar industry jobs in the United States in 2016, slightly higher than the number of jobs in the natural gas sector (362,000 jobs) and more than twice that of coal sector jobs (160,000 jobs).[24] In terms of growth rates, the number of jobs created in 2016 by the U.S. solar power industry was nearly 5 times greater than the number of jobs created by the oil, natural gas, and coal sectors combined.

As another example of EERE's impact, their Solid-State Lighting (SSL) program was instrumental in developing and promoting the adoption of solid-state lighting. The National Research Council performed an assessment of these investments and concluded, "DOE has done an impressive job in leveraging a relatively small level of funding to play a leading role nationally and internationally in stimulating the development of SSL."[25] The progress in SSL development and deployment resulted from a combination of R&D and DOE efficiency standards established in the bipartisan Energy Independence and Security Act of 2007. According to the Department, the introduction of SSL could save Americans $50 billion annually in lighting costs by 2035.[26]

ARPA-E

Modelled after DARPA to fund transformative research, the Advanced Research Projects Agency for Energy (ARPA-E) was established by the America COMPETES Act of 2007 and funded by the Recovery Act (ARRA) of 2009. Its goal was to support technology ideas that were not being funded by the private sector or other DOE programs. ARPA-E has received broad bipartisan support. In the FY 2017 budget proceedings, 44 Democrats and 26 Republicans supported an amendment by Sen. Schatz to increase funding for ARPA-E; the House passed a similar amendment by Rep. Schiff by a voice vote[27]. ARPA-E's funding has been relatively stable over the past 3 years (2014-2016) at $280-290 million/year, which constitutes about 7-8% of all DOE funding for energy research development and demonstration (RD&D).[28]

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[22] National Research Council (2001). *Energy Research at DOE: Was It Worth It? Energy Efficiency and Fossil Energy Research 1978 to 2000.*
[23] Energy Information Administration (December 2016). "Electric Power Monthly: Table 1.1.A. Net Generation from Renewable Sources: Total (All Sectors), 2006-December 2016."
[24] Department of Energy (2017). *U.S. Energy and Employment Report.*
[25] National Research Council (2013). *Assessment of Advanced Solid State Lighting.*
[26] U.S. Department of Energy (2017). "DOE Solid-State Lighting Program: Modest Investments, Extraordinary Impacts." https://energy.gov/sites/prod/files/2017/01/f34/ssl-overview_jan2017.pdf
[27] S.Amdt. 3802 to S.Amdt. 3801 to H.R. 2028 (Energy and Water Development and Related Agencies Appropriations Act, 2016)
[28] Gallagher, KS and Anadon, LD. (2016). "DOE Budget Authority for Energy Research, Development, & Demonstration Database." Harvard Kennedy School, Belfer Center. Available at: https://www.belfercenter.org/publication/doe-budget-authority-energy-research-development-demonstration-database

One characteristic that differentiates ARPA-E from other DOE programs is the recruitment and empowerment of program managers on short-term contracts.[29] Another is its direct reporting to the Secretary of Energy, rather than being embedded in the existing structure of DOE. These features allow the agency to pursue priorities of long-term importance, in consultation with academics and industry professionals, without being subject to political interference on spending priorities.

The goal of ARPA-E is to fund projects that may lead to long-term transformation in our energy system, to increase efficiency, national security, and environmental protection. This year, a study from the National Academies found "clear indicators that ARPA-E is making progress toward achieving its statutory mission and goals."[30] ARPA-E has funded over 400 projects across 39 states, including 42% from universities, 32% from small businesses, 14% from large businesses, 8% from Federally Funded Research and Development Centers, and 4% from non-profits. As of this year, the $1.5 billion in public funds that have been awarded through ARPA-E has attracted $1.8 billion in follow-on private investment.[31]

Because it is impossible to predict the long-term impact of R&D in advance, and given the long timescales involved in demonstrating and deploying energy technology,[32] the full impact of ARPA-E investments will only be fully realized in a decade or two. However, the international push to find cost-effective ways to accelerate energy innovation has provided impetus for researchers to start documenting what we know about the short-term success of ARPA-E projects.

Non-partisan evaluation and research, including the National Academies study, has begun to shed light on the results of ARPA-E's first several years. It appears that ARPA-E has funded a distinct portfolio of technology areas when compared to other DOE programs and the bulk of U.S. cleantech startups. In particular, ARPA-E has invested a larger fraction of its startup-led projects in energy storage.[33] Interestingly, previous work has identified energy storage as a particularly high social-return opportunity for public energy R&D.[34] Other results show that ARPA-E-funded projects are more likely to produce a patent when compared to projects funded at a similar level elsewhere in DOE.[35] This advantage may relate to the fact that ARPA-E program directors are empowered to select risky projects for funding, and yet these projects perform as well as those with higher ratings from external reviewers on metrics of publications, patents, and market engagement.[36]

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[29] Bonvillian, W.B., Van Atta, R. (2011). "ARPA-E and DARPA: applying the DARPA model to energy innovation." *Journal of Technology Transfer* 36, 469–513.

[30] National Academies of Sciences, Engineering and Medicine (2017). *An Assessment of ARPA-E*. The National Academies Press, Washington, D.C.

[31] Advanced Research Projects Agency – Energy (2017). "ARPA-E Projects Receive more than $1.8 Billion in Private Follow-on Funding for Transformational Energy Technologies."

[32] Grubler, A, Wilson, C, Nemet, GF. (2016). "Apples, oranges, and consistent comparisons of the temporal dynamics of energy transitions." *Energy Research & Social Science* 22: 18-25.

[33] Goldstein, AP, Doblinger, C, Anadon, LD. (2017). Unpublished research. Please contact Anna P. Goldstein anna_goldstein@hks.harvard.edu for more information.

[34] Chan, G, Anadon, LD. (2016). *Ibid*.

[35] Goldstein, AP, Narayanamurti, V. (2017). "Simultaneous Pursuit of Discovery and Invention in the U.S. Department of Energy." Ongoing research.

[36] Goldstein, AP, Kearney, MJ. (2017). "Uncertainty and Individual Discretion in Allocating Research Funds." Ongoing research.

These early indicators suggest that the institutional model of ARPA-E complements efforts elsewhere in the innovation system and should be preserved. Public investment in risky, uncertain, paradigm-transforming research is necessary in order to create new technologies which can grow into entirely new industries. The benefits to this type of research cannot be captured by any single company, so private investment is severely limited.

4. Opportunities for improved performance

To be most effective, DOE investments in energy R&D should be targeted at all stages of the innovation process. Unfortunately, the current DOE structure consists of siloes between artificially determined budget categories based on outdated and counterproductive characterizations of "basic" and "applied" research. In reality, the distinction between so-called "basic" and "applied" research is impossible to determine, and the most transformative R&D occurs with seamless interactions across disciplines of science and engineering. Therefore, making R&D budget decisions along this artificial line necessarily limits creativity and out-of-the-box thinking required for the creation of new technologies.

Several programs created within DOE in recent years, including ARPA-E, have fostered transdisciplinary research and supported activities across the "basic-applied" divide. These new programs serve an important function, while also functioning in combination to create a portfolio of different approaches. The Energy Innovation Hubs are a set of 5-year awards made to a partnership between universities, national labs, and private companies formed around a specific technological mission. First funded in 2009, the Hubs were modeled after the Manhattan Project and the AT&T Bell Laboratories.[37] Each of the current Hubs is based at a National Lab; extending this model outside of the labs may bring additional benefits. Also created in 2009, the Energy Frontier Research Centers (EFRC) are smaller competitive awards, organized around "grand challenges" in energy-related research. In addition to a portfolio of management approaches, DOE must also support a diverse portfolio of programs spanning multiple primary energy resources, multiple technology readiness levels, and multiple timescales for application of those technologies.

To enhance the public benefits of DOE's energy R&D, a closer integration is needed between activities typically managed by the Office of Science and the technology offices. The appointment in 2014 of a single Undersecretary for Science and Energy is a step in the right direction for DOE R&D management; this organizational structure should be maintained. This move enabled the creation of crosscutting initiatives, wherein multi-office teams coordinate funding for a set of specific technical challenges, such as grid modernization. Further steps to improve the structure at the Assistant Secretary level may be needed. One possible improvement is to create a new "Office of Energy Research" that would combine activities across the full spectrum of energy-related research. This office could coordinate initiatives that fill existing departmental functions, including core research programs in science and engineering that span the range from distant commercial relevance (e.g. condensed matter and atomic physics) to a strong technology focus (e.g. energy storage). An example of such initiatives can be found at the National Science Foundation, which has since the 1980's successfully fostered interdisciplinary research through Physics Frontier Centers, Science and

[37] Anadon, LD. (2012). *Ibid.*

Technology Centers, and Engineering Research Centers; these efforts have been evaluated very positively in their impact over multiple decades.[38]

The DOE's 17 National Laboratories are major investments in long-term R&D in the physical sciences and engineering. The lab system contributes significantly towards energy innovation, but could extract better outcomes with improved management structures.[39] As discussed in our recent work,[40] this would require increasing the funding for lab-directed research and development (LDRD) at the margin to give more control over funds to those closer to the research. We also recommend changes in the contracting procedures to provide incentives for collaboration between the labs and the private sector, including more support for technology transfer through the Lab-Embedded Entrepreneurship Program (e.g. Cyclotron Road), Sandia's efforts to promote entrepreneurship, and other initiatives. These issues require attention in parallel with other needed changes, in order to enhance the benefits of publicly-funded DOE research for the U.S. energy innovation system.

5. Concluding remarks

Congressional support for energy R&D investments from the DOE has a long bipartisan history that should continue. These public investments in energy R&D have been critical in addressing the energy security challenges faced by the country since the oil crisis of the 1970s. More recently, DOE R&D investments in all forms of energy have paved the way for some of the most vibrant economic sectors in terms of employment (in both fossil and renewable sectors). Sustaining strong public support for DOE's energy R&D mission is more important now than ever, as our security, economic, and environmental challenges are becoming more pressing for Americans everywhere and as other nations are working to position themselves as global leaders. After nearly 40 years of experience, independent studies of DOE R&D investments have shown that, in total, DOE R&D investments have strongly advanced American interests. Reducing these investments now would be a critical strategic failure. Instead, DOE R&D investment should be strengthened and managed more strategically through tighter integration of "basic" and "applied" research, with concurrent organizational changes and greater engagement with the private sector.

[38] Currall, SC, Frauenheim, E, Perry, SJ, Hunter, EM. (2014). *Organized Innovation: A Blueprint for Renewing America's Prosperity.* Oxford University Press.
[39] Glauthier, T. J. et al. (2015). "Securing America's Future: Realizing the Potential of the DOE National Laboratories. Final Report of the Commission to Review the Effectiveness of the National Energy Laboratories Vol. 1."
[40] Anadón LD, Chan G, Bin-nun AY, Narayanamurti V. (2016). "The Pressing Energy Innovation Challenge of the US National Laboratories." *Nature Energy*, 16117.