American Energy Innovation Council

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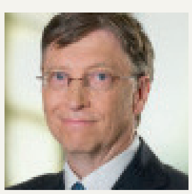

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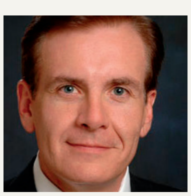

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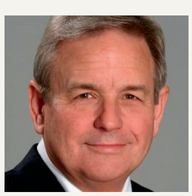

CHAD HOLLIDAY

Ret. Chairman and CEO, DuPont

American Energy Innovation Council

WHO WE ARE

The American Energy Innovation Council, originally formed in 2010, is a group of 10 corporate leaders who share a common concern over America's insufficient commitment to energy innovation.[a] We speak as executives with broad-based success in innovation, who, in the course of our careers, have been called upon to overcome obstacles, seize opportunities, and make difficult decisions, all in the pursuit of building great American companies.

MISSION STATEMENT

The mission of the American Energy Innovation Council is to foster strong economic growth, create jobs in new industries, and reestablish America's energy-technology leadership through robust, public and private investments in the development of world-changing energy technologies.

The American Energy Innovation Council is a project of the Bipartisan Policy Center.

BIPARTISAN POLICY CENTER

ABOUT THE BIPARTISAN POLICY CENTER

The Bipartisan Policy Center is a non-profit organization that combines the best ideas from both parties to promote health, security, and opportunity for all Americans. BPC drives principled and politically viable policy solutions through the power of rigorous analysis, painstaking negotiation, and aggressive advocacy.

[a] Ursula Burns, CEO of Xerox; Jeff Immelt, chairman and CEO of GE; and Tom Linebarger, chairman and CEO of Cummins Inc. were founding members of the AEIC and serve in emeritus status.

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LETTER FROM THE PRINCIPALS

In 2010, when the American Energy Innovation Council was formed, the premise was simple—as executives with experience leading and advising large companies in highly competitive industries, we understood the role that innovation plays in America's long-term competitiveness. We also recognized that access to clean, affordable, and reliable energy plays a foundational role in the nation's economic health—and that the path the United States was on raised serious questions about its ability to maintain the technological advantages that have been at the heart of America's success for as long as any of us could remember.

Much has changed in the intervening years—abundant natural gas has helped to transform the U.S. energy system, the costs of renewable energy systems have decreased dramatically, and improvements in end-use energy efficiency have saved consumers billions of dollars.[1] Global energy demand continues to rise while more than 20 leading nations have pledged to double their energy research and development budgets in partnership with private-sector commitments to spend billions pursuing the next generation of low-carbon energy technologies.[2]

Yet in many respects, much has not changed. The United States still relies on many of the same energy technologies it has used for decades, modernizing energy infrastructure to better integrate new technologies continues to be a challenge, and a tight federal budget continues to lead to underinvestment in the types of innovation needed to create jobs and revitalize the economy. This is especially problematic because public investments still fill persistent and vital gaps in the innovation cycle. Despite suggestions to the contrary, our experiences as CEOs and executives make clear that public and private investments both play necessary and complementary roles along the pathway to commercialization.

At times, it seems as though the nation has forgotten that a commitment to innovation helped America become the world's dominant technological and economic power. Federal support for energy innovation has waned—even as America's trading partners have increased their own commitments—despite clear evidence that targeted public investments have paid handsome dividends to taxpayers. As the United States focuses on ways to boost the economy, there is an increasing recognition among Americans that the power of innovation can unite us in the common pursuit of prosperity.

The good news is that the United States still enjoys substantial advantages in the pursuit of energy innovation, including a world-class group of national laboratories, research universities, and businesses. With the right mix of sophistication and vision, we can do more than capitalize on opportunities as they emerge—we can build on the best of American traditions and invent our own future.

We look forward to working with the administration and Congress to prioritize smart investments in the nation's energy future.

INTRODUCTION

Innovation has been the predominant driver of U.S. economic growth over the last century.[3] Scientific and technological innovations have produced new industries and the jobs that accompany them, helped maintain the competitiveness of a growing number of companies that rely on technology to succeed, and ultimately made American lives better. Throughout this history, the federal government has played a vital role in catalyzing innovation across a number of key, strategic sectors—such as defense, health, agriculture, energy, and information technology. In every instance, these sectors provide invaluable contributions to the United States while facing their own distinct sets of challenges. This is especially true in the energy sector.

Access to reliable, affordable energy has such a profoundly positive impact on people's lives as to nearly defy calculation. Yet unlike many other technology sectors, the energy sector in particular has suffered from underinvestment in research and development (R&D) for a number of reasons. As a generally low-cost commodity, it is often difficult for an energy supplier to differentiate itself and charge a premium the way products in other markets like communications hardware or biomedical technologies might. Energy infrastructure and technologies are also generally high-cost and long-lived, leading to large amounts of inertia and, in some cases, risk avoidance. Further complicating these challenges is the fact that energy markets are highly fragmented and often face a significant amount of regulatory fracturing and uncertainty.

These difficulties mean energy innovators are forced to cross not one, but two "valleys of death" before bringing a promising new technology to market. The first valley is technical: Innovators must leave the lab and create a viable product, which means confronting high technical and management risks that can compound the need for large amounts of patient capital. The second valley is commercial: Even once a technology has been demonstrated to be viable, developing manufacturing processes and supply chains can have prodigious costs, and projects are generally too far removed from commercialization to attract private investors. In both instances, targeted federal support can serve a critical role by reducing risks for promising technologies. In fact, such investments have a long and distinguished track record in providing important returns to the public in the form of job creation, economic growth, enhanced security, and environmental progress.

It is also important to note that the technology-development process is not always linear. The consensus that innovation follows a linear

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process from basic to applied research and then to deployment has persisted in the post-World War II era. While research can obviously be purely basic or purely applied in nature, what may be less obvious is that a significant amount of research is a blend between the two. What's more, the flow of information across the innovation process is often not one-directional. The development of new technologies can open up entirely new fields of research that seek to answer fundamental questions of science sparked by observations in applied settings. That is not to argue against the value of differentiating between various types of research, but rather to encourage policymakers to understand the importance of interactions across various stages of a technology's development, as well as the role that cross-disciplinary and interdisciplinary teams have to play in advancing the nation's scientific and technological interests.

A few decades ago, the United States found itself in the midst of an energy crisis. The response was a step change in U.S. investment in energy research that helped lay the foundation for an energy renaissance. Today, those investments have greatly increased U.S. energy security while creating good-paying jobs for Americans and bolstering the domestic manufacturing sector. Further, as global demand for energy continues to rise, these investments have helped to put the United States in a position to expand its global leadership in the energy sector, while reaping the economic benefits that come with doing so. The global energy market attracted $1.8 trillion worth of investments in 2015 alone[4] in what should be a clear signal to the nation's leaders that advanced energy technologies represent a multitrillion-dollar opportunity for American businesses and workers. Americans should embrace the nation's unique abilities to innovate as a way to create jobs, revitalize the economy, and enhance security while helping U.S. industry play a stronger role in providing clean, affordable, and reliable energy to the billions around the globe who currently lack it.

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The federal government can take a number of specific steps to spur innovation in the energy sector, including the following eight recommendations. These actions are critical to maximizing the potential of the nation's innovation capacity and realizing the economic, security, and environmental benefits advanced energy technologies can provide.

> **"Innovation is at the heart of America's ability to lead in a complex and uncertain world. America's capacity to innovate can provide an unassailable advantage in energy security, national security, and economic security, if we can demonstrate the vision and courage necessary to lead in rapidly evolving markets."**
>
> *- Thomas A. Fanning, Chairman, President, and CEO, Southern Company*

RECOMMENDATION 1: Build on efforts to develop comprehensive assessments and a strategic direction for the nation's energy sector.

The fundamental role that energy plays in the everyday lives of Americans means a coordinated national energy strategy continues to be pressing. In 2011, the Department of Energy (DOE) released the first Quadrennial Technology Review (QTR), which provided a framework for policymakers to better understand the variety of technical approaches available to solve the nation's energy challenges.[5]

Through a robust public and government-wide engagement process, the QTR established priorities for DOE and outlined the respective roles of the public and private sectors in executing various strategic approaches.

Complementing this effort, in 2015 DOE released the first Quadrennial Energy Review (QER), which outlined ways to modernize U.S. energy infrastructure.[6] As in the QTR, the QER sought out broad stakeholder input, and a 2015 update of the QTR highlighted the most promising research, development, demonstration, and deployment opportunities for meeting the nation's energy needs.[7] The QER, which is conducted in installments to provide an opportunity to review specific aspects of the expansive U.S. energy system in greater depth, released a 2017 installment that focused on the electricity system.[8]

These efforts are extremely important to the nation's ability to identify and measure progress toward national energy goals. Further, by identifying the nation's energy needs and opportunities, they provide a framework for developing priorities in public and private research. In essence, these efforts enable

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Americans to figure out where, as a country, they want to go and how to get there. With our vast executive experience, the American Energy Innovation Council (AEIC) has repeatedly found that success is much more difficult in the absence of such a plan.

> "During my career, I had the opportunity to see firsthand the impact that effective public-private partnerships can have on the development of new technologies, products, and jobs. By harnessing the unique strengths and ambitions of each partner, we can set the stage for a prosperous future—but only if we make smart investments in that future."
>
> *- Norman Augustine, Ret. Chairman and CEO, Lockheed Martin*

RECOMMENDATION 2: Invest $16 billion a year in advanced energy innovation.

In 2010, when the council initially made this recommendation, the federal commitment to energy research, development, and demonstration was roughly 0.044 percent of the nation's energy bill.[9] By 2016, that number had climbed to just over 0.06 percent,[10] or $6.4 billion. Put in historical context, since 1987 energy research has decreased from 14.4 percent of federal R&D outlays to 5.3 percent by 2017.[11] Over the same time frame, health research has tripled in constant dollars and increased from 36 percent of federal R&D outlays to more than 50 percent in 2017. The private sector continues to be a driving force in developing and commercializing new energy technologies, but without public investments at key stages of the innovation cycle, many of these technologies will never attract private-sector interest. Significant public underinvestment in energy innovation will have economic, security, and environmental consequences.

Recent rankings suggest that the U.S. innovation system may be in danger of losing ground to other nations that are simply making greater commitments to innovation than the United States. A 2016 Information Technology and Innovation Foundation study that ranked countries' contributions to global innovation found the United States to be the 10th most impactful nation.[12] The 2015 Global Innovation Index suggested that the United States has a supportive policy environment for innovation, ranking the nation fifth on this measure.[13] The U.S. system of national laboratories and university research centers is without peer, consistently attracting and producing world-

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class researchers. Yet, the United States has begun to consistently lag behind other nations in R&D spending relative to the size of its economy. America still spends more on research than any other nation—although China is expected to surpass the United States in the mid-2020s if current trends hold.[14] But America also has the world's largest economy to support, which is why R&D intensity—R&D spending as a percentage of GDP—is the preferred metric for measuring a country's commitment to innovation. The United States ranks only 12th in energy R&D intensity.[15] This is a drag on the energy innovation ecosystem and an under-utilization of a significant engine of economic growth and opportunity.

Thus, this AEIC funding recommendation would represent an increase in federal spending on energy research, development and demonstration (RD&D) to 1.6 percent of U.S. energy sales. This would bring spending on energy innovation closer to, although still well short of, other advanced technology sectors. It would also reestablish American leadership on energy research in the face of growing competitive pressures from trading partners, and it would more appropriately meet the scale of need for the capital-intensive energy sector.

RECOMMENDATION 3: Fund ARPA-E at $1 billion per year. At a minimum, ARPA-E should receive $300 million per year.

Originally authorized in the America COMPETES Act of 2007, the Advanced Research Projects Agency for Energy (ARPA-E) was modeled on the highly successful Defense Advanced Research Projects Agency (DARPA). ARPA-E focuses on high-risk, high-impact projects across an array of potentially transformative technologies.

> "Access to affordable, reliable energy is critical for a healthy and growing economy. Innovation has the potential to transform some of the challenges we face in the energy sector into opportunities, and it is important that we work together toward solutions."
>
> *- Thomas F. Farrell, II, Chairman, President and CEO, Dominion Energy*

Initial funding for ARPA-E, as part of the 2009 American Recovery and Reinvestment Act, was $400 million. Yet, in annual appropriations since 2011, funding for this important program has reached the $300 million mark that the AEIC recommends as a minimum only once—$306 million in the most recent omnibus appropriations agreement for FY2017.

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> "An investment in a true energy transformation requires governments, research institutions, businesses, and private investors to work together. And it's hard to overstate how important this public commitment is."
>
> *- Bill Gates, Co-Chair, Bill and Melinda Gates Foundation*

The agency has received significant bipartisan support in recent legislative activity[16] that could further increase funding to $375 million by FY2019.

Since 2009, ARPA-E has invested in more than 580 breakthrough energy-technology projects. As the first few rounds of awardees have begun to reach the growth stage, where they would normally begin attracting private-sector support, 74 ARPA-E projects have already secured more than $1.8 billion in follow-on, private-sector funding across a portfolio of technologies, including energy efficiency, energy storage, liquid transportation fuels, nuclear energy, wind, solar, hydrogen, and carbon capture and sequestration.

ARPA-E's highly effective approach—a focus on game-changing technologies, strict performance metrics, and an ability to jettison projects that do not meet milestones—has been central to growing, bipartisan support for the agency. The size of ARPA-E's budget only allows it to fund a small percentage of proposals. A $1 billion annual budget would more closely align with the agency's potential impact.

RECOMMENDATION 4: Support and expand new and innovative institutional arrangements such as the Energy Innovation Hubs, Energy Frontier Research Centers, and the Manufacturing USA program.

DOE's Energy Innovation Hubs, first established in 2010, focus on combining basic scientific research and engineering to make progress solving a particular challenge. Integrated teams with a variety of technical expertise from universities, industry, and government labs focus on the most persistent research obstacles faced within the energy sector. The Energy Innovation Hubs invest in transformational, use-inspired research and play an invaluable role in the technology-development cycle. For example, when attempting to scale up a technology, scientists and entrepreneurs can run into engineering challenges that require them to retreat several steps back in the development process, which is both costly and time-consuming. Interdisciplinary teams at the Energy Innovation Hubs can identify these issues earlier in the process, saving money and time while increasing the likelihood that a technology will successfully navigate these challenges. There

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are currently four Energy Innovation Hubs: the Consortium for Advanced Simulation of Light Water Reactors, the Joint Center for Artificial Photosynthesis, the Joint Center for Energy Storage Research, and the Critical Materials Institute.[17] A fifth hub was recently proposed, focusing on Energy-Water Desalination, which would develop ways to decrease the cost and energy intensity of the desalination process.

> **"Collaboration between key industries will be critical to creating a sustainable energy future for America. Together, we can build coalitions to advance the right policies and maximize the benefits of energy innovation."**
>
> *- Anthony F. Earley, Jr., Executive Chair of the Board, Pacific Gas and Electric Corporation*

DOE also supports vital research efforts at 36 Energy Frontier Research Centers (EFRCs). Directed through the Office of Science's Basic Energy Sciences program, the EFRCs are awarded on a short-term (four to five years) and competitive basis. EFRCs also utilize an interdisciplinary approach that includes universities, national laboratories, industry, and non-profits, but that is focused on "grand challenges" in fundamental energy science. This is precisely the type of early stage, basic research that federal support is best suited to. At the start of the program, in 2009, there were 46 EFRCs, including 16 fully funded by the American Recovery and Reinvestment Act. Smart investments such as EFRCs are already having significant impact on America's understanding of fundamental energy science.[18]

The National Network of Manufacturing Institutes, collectively named the Manufacturing USA program, was launched in 2012; it is an interagency effort operated by the Advanced Manufacturing National Program Office. Headquartered in the National Institute of Standards and Technology in the Department of Commerce, this program operates a partnership with the Department of Defense, DOE, NASA, the National Science Foundation, the Department of Education, and the Department of Agriculture.[19]

Other innovative programs like Cyclotron Road, Chain Reaction, and Innovation Crossroads focus on human capital, providing access to national labs for the nation's brightest entrepreneurial researchers who work alongside government researchers. Awards are highly competitive and designed to support high-impact technologies that are not far enough along in the development cycle to attract private investment. An added benefit of this innovative institutional arrangement is the cross-pollination of scientific and business perspectives that allow each group to better understand the central challenges and needs that inform their work.

These programs represent a concerted effort to better utilize limited federal resources

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to fill critical gaps in the energy innovation ecosystem. Such efforts have already shown significant promise, and policymakers should maintain or even expand these programs as they enhance the nation's capacity for innovation in energy.

"Today, scientists and entrepreneurs all over the world are racing to develop the next generation of energy technologies. If America is going to maintain the competitive advantages that have driven our success for decades, we have to be willing to invest in the people who are working to invent the future."

- John Doerr, Partner, Kleiner Perkins Caufield & Byers

RECOMMENDATION 5: Make DOE work smarter—along the ARPA-E model where appropriate.

Many of the best practices at ARPA-E could be implemented to improve the performance of DOE's technology offices. These include reorganizing by sectors (e.g., transportation, electric power, buildings, etc.) instead of technologies—creating silos, instituting aggressive milestones for continued project funding, and focusing on transformative technologies instead of incremental advances or deployment activities that are more likely to receive support from the private sector.

Some research conducted at DOE, especially within the Office of Science, is not well suited to the ARPA-E model. Undirected, fundamental research plays a critical role in the nation's research portfolio, and approaches like aggressive stage-gating would be counterproductive in that setting. Importantly, research that aims to improve America's fundamental scientific understanding and does not have a commercial application produces a critical public good in the form of expanded knowledge.

DOE is charged with the significant task of overseeing and managing a sprawling research network and national security mission. A number of reforms have already been implemented that have made the department better at fulfilling its mission. For example, the Office of Energy Efficiency and Renewable Energy has already begun implementing many of these ARPA-E-style reforms. DOE's network of national labs is a world-class set of institutions that have made enormous contributions to the nation. Targeted and judicious reforms can make an already valuable public asset even more effective.

"The best use of limited federal funds is a smart approach that fosters accountability and fills gaps in the innovation cycle that the private sector cannot or will not invest in."

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RECOMMENDATION 6: Establish a New Energy Challenge Program for high-impact pilot projects.

Many important energy-technology options face great obstacles to development, particularly on cost and risk bases. Advanced nuclear power and carbon capture, utilization, and storage provide examples of essential technologies that face unique challenges, even within the energy sector. Without a significant commitment to pursuing these technology options, they will not thrive in the United States and unique export opportunities worldwide will be lost. This undesirable outcome would mean ceding American leadership in key technologies to trading partners and competitors who are actively pursuing them. This recognition is at the heart of the AEIC recommendation for a New Energy Challenge Program.[20]

> "Research and development has been the driving force behind cleaner, safer, more reliable, and affordable energy in the U.S. for decades. Constructive partnerships between the public and private sectors in energy innovation have been especially successful, leading to vast economic, environmental, and security benefits, creating jobs and boosting virtually every facet of our economy."
>
> *- Chad Holliday, Ret. Chairman and CEO, DuPont*

America's energy innovation ecosystem currently lacks a mechanism to enable the building, testing, and refining of large-scale technologies such as carbon capture, utilization, and storage. As noted, many of the energy technologies that require demonstration assistance are too big, expensive, or risky to secure necessary support from the private sector. The United States needs to address the structural challenges inhibiting the progress of important and potentially transformative projects through the second valley of death.

The New Energy Challenge Program, by accelerating advanced energy technologies to commercial or near-commercial scale, would explicitly deal with those obstacles. It would focus on high-impact energy projects, including those with large system sizes, and would concentrate on the transition from pre-commercial, scalable energy systems to integrated, full-size system tests. The New Energy Challenge Program would draw on a broad range of expert perspectives and a set of financial, technical, and management tools, with two main tasks: (1) to create detailed technology commercialization roadmaps for priority technologies as well as particular demonstration projects; and (2) to commission, finance, and build first-of-a-kind commercial-scale advanced energy facilities.

The AEIC recommends the New Energy Challenge Program be funded with a single

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appropriation of $20 billion over 10 years. This publicly owned, private corporation would employ a competitive selection process and cost-sharing to identify the strongest private partnerships. The program should have the ability to utilize a variety of financial tools but should prioritize direct equity investments. The New Energy Challenge Program is designed to unleash significant private capital in the development of high-impact technologies over the next half-century.

Importantly, this program will not pick winners and losers. Project selection would be designed to test multiple technology pathways, pursuing demonstrations of the most promising options. For example, a variety of competing designs for advanced nuclear projects—each using vastly different approaches, such as fuel cycles—would be able to apply for the program. Pursuing promising technologies in a non-prescriptive, highly competitive environment is key to effectively meeting national priorities.

RECOMMENDATION 7: Establish regionally centered innovation programs.

Regional differences in energy markets, natural resources, state and local policies, and research capabilities are important. Recognizing and leveraging the varying strengths across regions can encourage more efficient use of public resources, boost economic development, and accelerate innovation. DOE should lead an effort, involving private-sector partners, universities, non-profits, national labs, and relevant state and other federal agencies to develop regionally centered, energy innovation programs.

> **"Widespread public-sector investment in basic energy technology is critical to complement private investment and drive long-term economic growth in America and globally. With new energy markets only set to grow, technological breakthroughs can generate enormous economic dividends while providing the lower-cost, cleaner energy the world needs."**
>
> *- Mike Graff, Chairman and CEO, American Air Liquide Holdings, Inc.*

These programs should be designed to streamline and enhance engagement between the private and public sectors. Properly executed, such public-private partnerships have the potential to serve as engines of economic development in regions across the country by filling or augmenting critical gaps in the innovation cycle. Importantly, these partnerships will empower regions to make decisions that reflect and benefit from their understanding of local and regional economies. Geographic

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proximity among researchers, investors, and customers also facilitates the exchange of tacit knowledge that can be critical to removing obstacles to innovation.[21] Vibrant regional innovation ecosystems are key to maximizing the unique and specialized assets that vary across the nation in the pursuit of breakthrough energy technologies. Additionally, regionally focused energy innovation programs can also facilitate collaboration, maximizing the impact of state resources and better aligning state and regional policy towards localized, collaborative goals.

Importantly, these programs should be led at the regional level by private organizations or consortia, selected on a competitive basis and subject to fixed-terms and performance reviews. These consortia should work with DOE to identify the unique characteristics within regions; to foster collaboration among the region's stakeholders to address persistent gaps in the innovation cycle; to fund cost-shared research; and to identify potential synergies for aligning local, state, and federal policies that can accelerate innovation.

RECOMMENDATION 8: The federal government should support creative efforts to incentivize private-sector investment in energy research and development.

The high costs, long timelines, and technical and regulatory uncertainty involved in developing new energy technologies has consistently led to private-sector underinvestment in energy R&D.[22] While the federal role will always be critical to filling gaps in the innovation cycle, particularly in more basic research, it is imperative that the private sector play a leadership role in developing new technologies. In addition to the constraints of limited federal budgets, the private sector's expertise in commercializing new technologies is unique and critical to America's ability to successfully innovate. This is especially important as competition for expanding global energy-technology markets continues to intensify.

"American businesses, especially manufacturers, must innovate to realize their potential, revitalize our nation's economy, and spur an energy transformation. Public-private partnerships are the bedrock of innovation, creating a foundation for success in the worldwide economy."

- Mark Burns, President, Gulfstream Aerospace Corporation

The U.S. Energy Information Administration projects that global demand will increase by 48 percent by 2040, and the International Energy Agency estimates that by 2040,[23] $67

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trillion in investment will be needed to meet this demand.[24] For the United States to successfully engage in these trillion-dollar markets, a successful partnership between the public and private sectors is needed to leverage the strengths of each. The necessary investments far outstrip what the federal government can make, but with smart, targeted programs that leverage small amounts of federal investment to minimize some of the risks for private investors, the United States can address some of the chronic private-sector underinvestment in early and high-risk energy research.

There are several programs policymakers should consider that are designed to achieve precisely these types of outcomes. The Tech-to-Market program at DOE's Office of Energy Efficiency and Renewable Energy, for example, recently issued funding opportunity announcements to develop testable, scalable models for financing as well as to foster partnerships between industry and start-ups. This program would not support any specific technologies, but rather would competitively award grants for stress-testing innovative models designed to incentivize private-sector investment. These funding opportunity announcements represent a modest amount of funding—$4.2 million over two years—that could potentially unlock exponentially greater private-sector resources in the pursuit of energy innovation and its myriad public benefits.

A second possibility for policymakers to consider is the development of a non-profit foundation for energy research that could work with DOE to foster collaboration between the national laboratories, academia, regulators, investors, and industry. Such foundations already exist for the National Institutes of Health[25] and the Department of Agriculture.[26] These programs leverage a small amount of federal funds to attract significant private capital and operate at the forefront of their respective research fields. For example, the Foundation for the National Institutes of Health receives $500,000 per year in appropriations, yet between 2014 and 2015, attracted more than $25 million in outside investment.[27]

> **"Ingenuity and innovation have always been the foundation of American prosperity. Now is the time to lay the long-term foundation for the next generation of energy technologies."**
>
> *- Neal Blue, Chairman and CEO, General Atomics*

A third approach could be to set aside a small amount of funding for industry, to be awarded on a competitive basis, to lead long-term R&D projects. This approach would require industry cost-sharing and would include partners from universities and the national labs. Such an approach would help involve companies in research while also strengthening the ties

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among them, the universities, and the national labs, leveraging the relative strengths of each in improving the nation's technology-transfer capabilities.

Identifying mechanisms that can foster improved public-private collaboration will maximize limited federal resources, leverage private-sector expertise, and promote synergies that will create jobs, enhance energy security, and provide the clean, affordable, and reliable energy the nation needs to thrive.

Public support for energy innovation is not only necessary, but creates benefits that far exceed the investments the AEIC recommends. In the end, this is a good business investment for the country.

If acted upon, these recommendations have the potential to significantly boost the nation's innovation capacity. Creating the next generation of advanced energy technologies in the United States will create jobs, enhance the security and resilience of the energy system, and pay geopolitical dividends. The AEIC recommendations are meant to address obstacles to innovation in the energy sector in ways that maximize limited federal resources. This report will outline these hurdles and the impact that smart federal investments have on the everyday lives of Americans.

THE INNOVATION PROCESS

Over the last half-century, scientific and technological advancement have been at the center of economic growth in the United States.[28] Disruptive new technologies like the automobile, airplane, computer, and internet have spawned new industries and created jobs that have fueled the U.S. economy. This economic growth was fostered by a unique combination of world-class entrepreneurs, supportive and sophisticated financial and legal systems, large technology companies with necessary skills and an understanding of the value of innovation, as well as a system of world-renowned research labs and academic institutions. But this innovation ecosystem did not materialize out of nowhere—it was cultivated by a commitment to supporting scientific and technological research. This commitment was built on the understanding of how crucial innovation was to U.S. economic prosperity, as well as the ways it improved peoples' everyday lives. Innovation will continue to be at the center of America's economic, military, and technological preeminence.

To fully leverage the impact that innovation can have in improving the U.S. economy, America needs to develop new technologies and create new ways to build and manufacture those innovations. This is true in virtually every sector, but especially in energy. By dramatically improving living standards, many of these 20th-century innovations have contributed significantly to growing global energy demand. One of the central questions for policymakers continues to be: What is the appropriate role of government in supporting these innovations? Some have argued that there is no role for government to play in energy innovation. The belief that profitability should be the primary arbiter of value for the development of new energy technologies leads these critics to conclude that the private sector will undertake all research worth pursuing. Ignoring the numerous pubic goods provided by secure access to clean, reliable, and affordable energy and the difficulty in monetizing these goods, opponents of federal support for energy innovation have called for the elimination of federally supported scientific discovery, innovation, and applied research—even going as far as calling for the elimination of federally funded basic research.[29]

Executive experience in the private sector leads the AEIC to disagree with this assessment. Of course, the private sector does and will continue to play a central role in driving innovation. However, the AEIC believes the federal government also plays a fundamental role in energy innovation. Synergistic partnerships between public and private sectors have been a source of tremendous innovation, with numerous examples in the energy sector, such as unconventional gas production,[30] advanced diesel engines,[31] and aeroderivative gas turbines.[32] Underpinning this debate is a lack of clarity in discussions surrounding the energy innovation

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FIGURE 1. THE INNOVATION PROCESS

Source: AEIC Generated

process and the ways in which targeted federal support plays a vital role in advancing new energy technologies.

The innovation process is by nature unpredictable, and would-be innovators face formidable challenges that vary across stages of development and technologies. Most conceptualizations of this process follow a linear progression from "blue-sky" science, which seeks only to advance humanity's fundamental understanding of scientific principles. The flow of that process looks something like (Figure 1).

This pipeline model of innovation is helpful in understanding the general flow of a technology from its beginnings in basic research to eventual commercialization. It does not, however, provide a three-dimensional view of the interactions among ideas, discoveries, and individuals working at various stages throughout the process.

FIGURE 2. PASTEUR'S QUADRANT: FOUR CATEGORIES OF RESEARCH

Quest for Fundamental Understanding?	Practical Use? No	Practical Use? Yes
Yes	Pure Basic Research BOHR	Use-Inspired Basic Research PASTEUR
No	Unnamed	Pure Applied Research EDISON

Source: Donald E. Stokes. "Pasteur's Quadrant: Basic Science and Technological" Brookings Institution Press. August 1997.

A MODEL EVOLVES

The pipeline model was first articulated in a 1945 report to the president by Vannevar Bush, "Science: The Endless Frontier." Bush directed virtually all U.S. military research during World War II, heading the U.S. Office of Scientific Research and Development. He functioned as President Franklin Roosevelt's primary science advisor. The Manhattan Project, Radar, and the Proximity Fuse all reported to the president through Bush. Five months before his death, Roosevelt requested a blueprint for the nation's postwar scientific efforts and "Science: The Endless Frontier" ushered in a golden era of U.S. science. It established basic research as the pacemaker of technological innovation, stressing the need for adequate federal support and relative insulation against the commercial pressures of applied research. Bush's already substantial credibility was further bolstered by the chilling effectiveness of the atomic weapons unleashed on Hiroshima and Nagasaki a couple of weeks later—effectively ending World War II with an acute demonstration of the importance of scientific supremacy.

Yet in 1997, Donald Stokes challenged Bush's theory of innovation by arguing for the recognition of use-inspired—yet still fundamental—research. Stokes used the example of Louis Pasteur to illustrate his case for a new model of scientific research. Pasteur's quadrant provided a new foundation for understanding not only how research was conducted, but how the relationship between the scientific community and the government should function. If the line between basic and applied research was not as discrete as once thought, the implications for policymakers were profound.

In his graphic representation of Pasteur's quadrant (Figure 2), Stokes provided examples of each type of research to help clarify his case, Nobel Prize-winning Danish physicist Niels Bohr, who helped establish a foundational understanding of atomic structure and quantum theory, exemplified pure basic research—or the pursuit of a fundamental understanding without concern for practical use. To illustrate practically inspired research with no regard for the underlying fundamental science, or pure applied research, Stokes turned to the work of Thomas Edison, including the first successful commercial light bulb and an early electricity-generation and -distribution system. The addition of use-inspired basic research as a bridge between pure basic and pure applied research was exemplified by Pasteur's work in microbiology, which sought to both expand a fundamental understanding of disease and to serve a practical purpose—eliminate spoilage in milk and other beverages—demonstrates the importance of research that is both practical and seeks to understand the underlying physical science behind useful applications.

DYNAMICS OF ENERGY INNOVATION

At the heart of the political debate surrounding the appropriate role for government support in innovation is the sometimes-arbitrary division between basic and applied research. This distinction has fostered an ideological disagreement: Advocates of limited government argue that the federal government has little to no role to play in supporting applied research, and advocates for a broader role for government stress the critical need to fill gaps across the innovation process that the private sector will not. It is important to differentiate between investments that are expected to create significant public benefits as well as whether the private sector will not make these investments for economic reasons—for example, the returns will take too long to materialize. This is an example of what economists call a "market failure." Yet by incentivizing innovators to define their research as either basic or applied, policymakers have created and reinforced silos across federal research efforts.[33] Meanwhile, science and technology do not reflect these types of distinctions, and silos can limit the potential of research, leading to duplicative and inefficient uses of resources.

In 1932, Irving Langmuir earned a Nobel Prize for his work on surface chemistry while employed by General Electric in Schenectady, New York.[34] Langmuir's work stretched the world's fundamental scientific understanding, but it was sparked by his observation of a single layer of hydrogen atoms on the surface of an incandescent light bulb. More recently, physicists have been working to develop increasingly small semiconductors, which will have broad commercial applications but will also require new breakthroughs in fundamental science.[35] As these and numerous other examples demonstrate, the free flow of ideas and interactions among various stages in the innovation process are crucial to the success of the nation's innovation enterprise.

In fact, while basic research generally informs and leads to breakthroughs in applied research and eventually to new technologies, those new technologies also drive many of the questions asked by those engaged in basic research—like Langmuir's work with the incandescent light bulb. As such, innovation should also be considered a cyclical process of continual interaction and progress. Importantly, any of these types of research could produce an idea for a new commercial product.

Through the lens of this new model, one can gain a more nuanced perspective on the process of innovation. The evolution of America's understanding of the innovation process does not fundamentally alter key truisms in science and technology policy, namely the importance of undirected, basic research. However, it does illustrate the important role that government plays at various stages in the innovation process.

DYNAMICS OF ENERGY INNOVATION

Beyond basic research, there is great value in smart and targeted government support for research that the private sector is unlikely to undertake yet would provide spillover benefits for the public. Of course, the process for making such determinations, as well as limiting duplication of research or other inefficient uses of taxpayer resources is dependent on the institutional arrangements innovators rely on to execute the nation's R&D agenda.

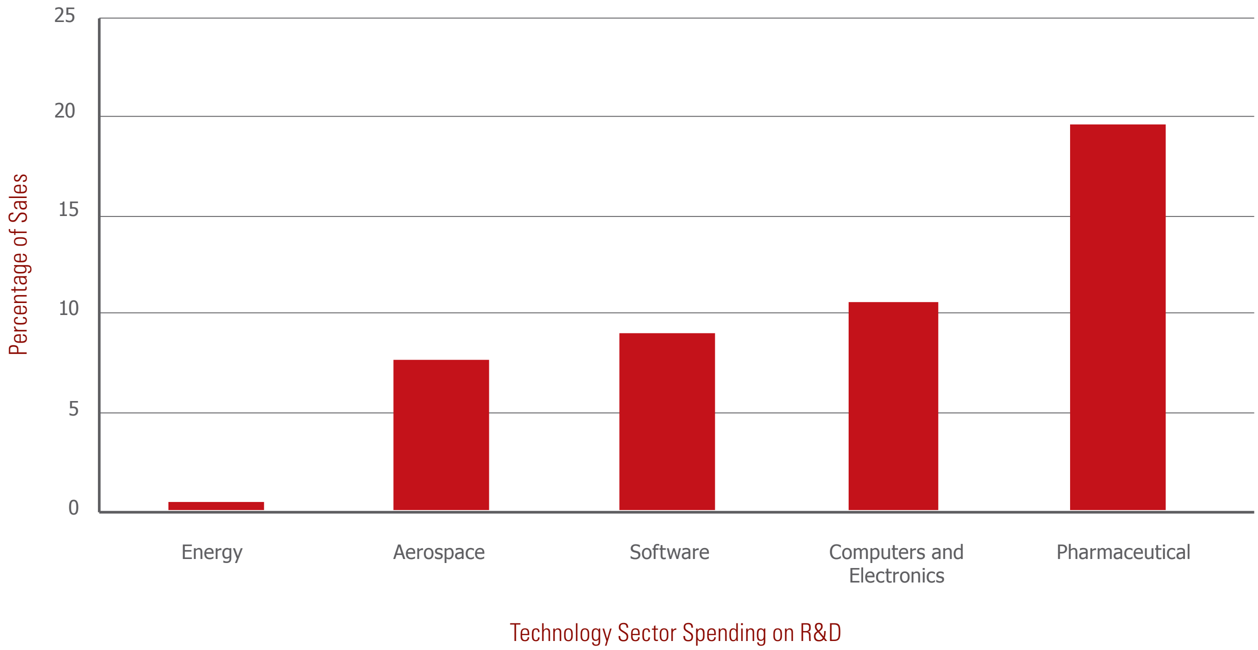
The dynamics that lead to systematic underinvestment by the private sector in energy innovation shape the role that the federal government should play. There are two key reasons that government support is vital to energy innovation. First, innovations in energy can create significant public benefits that are not necessarily captured in market prices, such as enhanced resiliency in energy delivery systems, decreased reliance on foreign energy supplies, decreased pollution, and general spillover effects of R&D. Since no company can fully monetize or predict these benefits, their incentives for investing in energy R&D will naturally lead them to spend less on energy research than the potential benefits to the public suggest they should.

Second, key features in energy markets also depress private-sector investment in disruptive new energy technologies. Because energy is generally a low-cost commodity—a light switch works the same way whether the electricity comes from a coal-fired power plant or a wind farm—it is often harder to add a cost premium for a new energy technology in the same way one could for a phone or computer with new features. Many energy technologies and the systems they are a part of often have high initial development and capital costs, but are economically viable over their long lives. This is true on both the supply and demand sides, from power plants to the homes that use the electricity they generate. For example, a new utility-scale power-generation technology could easily cost hundreds of millions of dollars, even a few billion dollars,[36] and last 30 to 80 years.[37] Combined with high degrees of technical risk, long commercialization timelines, and an uncertain regulatory environment, these costs can create inertia in the energy sector that often discourages private-sector companies from investing in breakthrough energy technologies. It's one thing to prototype a new tablet computer; it's another thing entirely to prototype a new nuclear plant—the required investment is orders of magnitude larger, the potential returns much later, and the technical, regulatory, and economic risks much larger.

> ***"It's one thing to prototype a new tablet computer; it's another thing entirely to prototype a new nuclear plant."***

KEY TRENDS IN R&D SPENDING

FIGURE 3. TECHNOLOGY SECTOR SPENDING ON R&D AS A PERCENTAGE OF SALES



Source: BPC Generated.

Data Source: NSF. "Science & Engineering Indicators 2016." Chapter 4: Research and Development: National trends and international comparisons. Page 54. January 2016. https://www.nsf.gov/statistics/2016/nsb20161/uploads/1/nsb20161.pdf
Pharmaceutical Research and Manufacturers of America (PhRMA). "2015 profile: biopharmaceutical research industry." April 2015. http://phrma-docs.phrma.org/sites/default/files/pdf/2014_PhRMA_PROFILE.pdf
Industrial Research Institute. "2016 Global R&D Funding Forecast." 2016. Available at: https://www.iriweb.org/sites/default/files/2016GlobalR%26DFundingForecast_2.pdf

That's at least partly why, as a percentage of sales, the energy sector invests significantly less in R&D than other key technology sectors (Figure 3).

This places an even greater importance on federal support for energy R&D, yet federal energy research funding continues to lag far behind government support for other fields—comprising just 2.8 percent of R&D funding in FY2016 (Figure 4). In addition, the United States places less emphasis on energy research than other nations, with energy's share of the total U.S. research budget ranking 22nd globally for 2015 (Figure 5).

KEY TRENDS IN R&D SPENDING

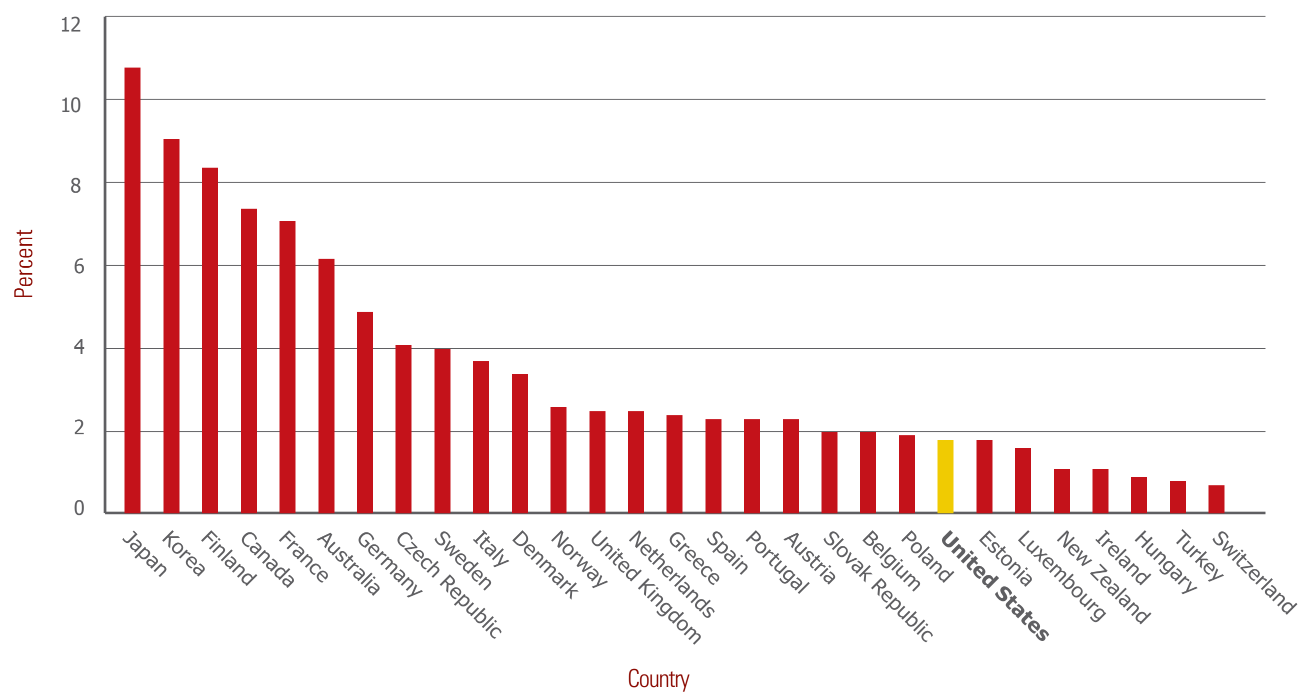
FIGURE 4. MAJOR FUNCTIONAL CATEGORIES OF R&D

Budget authority in millions of dollars, base budgets only

	FY 2015 Actual	FY 2016 Estimate	FY 2017 Budget	Change FY 16-17 Amount	Change FY 16-17 Percent	Percent of Total ('16)
Defense	72,721	77,963	80,825	2,862	3.7%	53.8%
Nondefense	65,607	70,343	69,297	-1,045	-1.5%	46.2%
Space	10,897	12,773	11,645	-1,128	-8.8%	7.8%
Health	31,717	33,571	32,680	-891	-2.7%	21.8%
Energy	3,170	3,452	4,136	684	19.8%	2.8%
General Science	11,088	11,422	11,683	261	2.3%	7.8%
Environment	2,389	2,619	2,703	84	3.2%	1.8%
Agriculture	2,152	2,359	2,306	-54	-2.3%	1.5%
Transportation	1,420	1,442	1,414	-28	-1.9%	0.9%
Commerce	863	1,118	1,088	-30	-2.7%	0.7%
International	290	315	327	12	3.8%	0.2%
Justice	962	628	621	-7	-1.1%	0.4%
All Other	659	643	694	51	7.9%	0.5%
Total R&D	138,328	148,305	150,122	1,816	1.2%	100.0%

Source: Matt Hourihan and David Parkes, Guide to the President's Budget, Research & Development FY 2017, American Association for the Advancement of Science. September 2016. Available at: http://www.aaas.org/sites/default/files/AAAS%20R&D%20Report%20FY17%20web.pdf

FIGURE 5. SHARE OF ENERGY IN TOTAL R&D | 2015



Source: International Energy Agency. "Key Trends in IEA Public Energy Technology RD&D Budgets." October 2016. Available at: http://www.iea.org/media/statistics/topics/IEA_RDD_Factsheet_2016.pdf

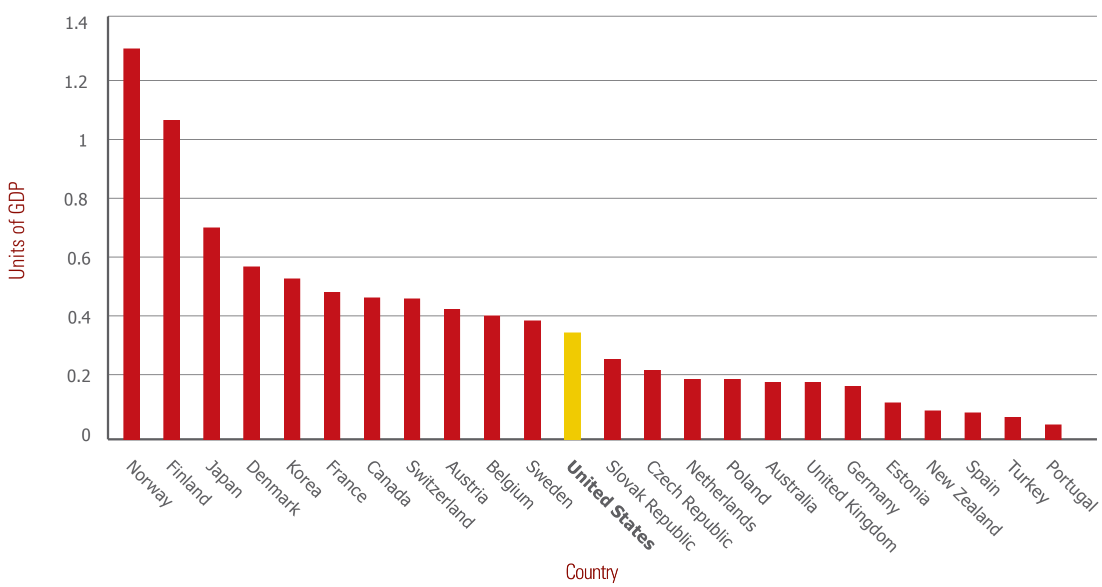
KEY TRENDS IN R&D SPENDING

When these indicators are placed in the broader context of U.S. and global R&D funding trends, it's difficult to see this underinvestment as anything other than a missed opportunity. The United States spent decades building the world's preeminent innovation ecosystem, but for years has consistently failed to invest enough to maximize its potential.

Recent rankings suggest that the U.S. innovation system may be in danger of losing ground to other nations, which are simply making greater commitments to innovation than the United States. A 2016 Information Technology and Innovation Foundation study that ranked countries' contributions to global innovation found the United States to be the 10th most impactful nation.[38] The 2015 Global Innovation Index suggested that the United States has a supportive policy environment for innovation, ranking the nation fifth on this measure.[39]

The U.S. system of national laboratories and university research centers is without peer, consistently attracting and producing world-class researchers. Yet, the United States has begun to consistently lag behind other nations in R&D spending relative to the size of its economy. America still spends more on research than any other nation—although China is expected to surpass the United States in the mid-2020s if current trends hold.[40] But America also has the world's largest economy to support, which is why R&D intensity—R&D spending as a percentage of GDP—is the preferred metric for measuring a country's commitment to innovation. The United States ranks only 12th in energy R&D intensity, as shown in Figure 6. This is a drag on the energy innovation ecosystem and an under-utilization of a significant engine of economic growth and opportunity.

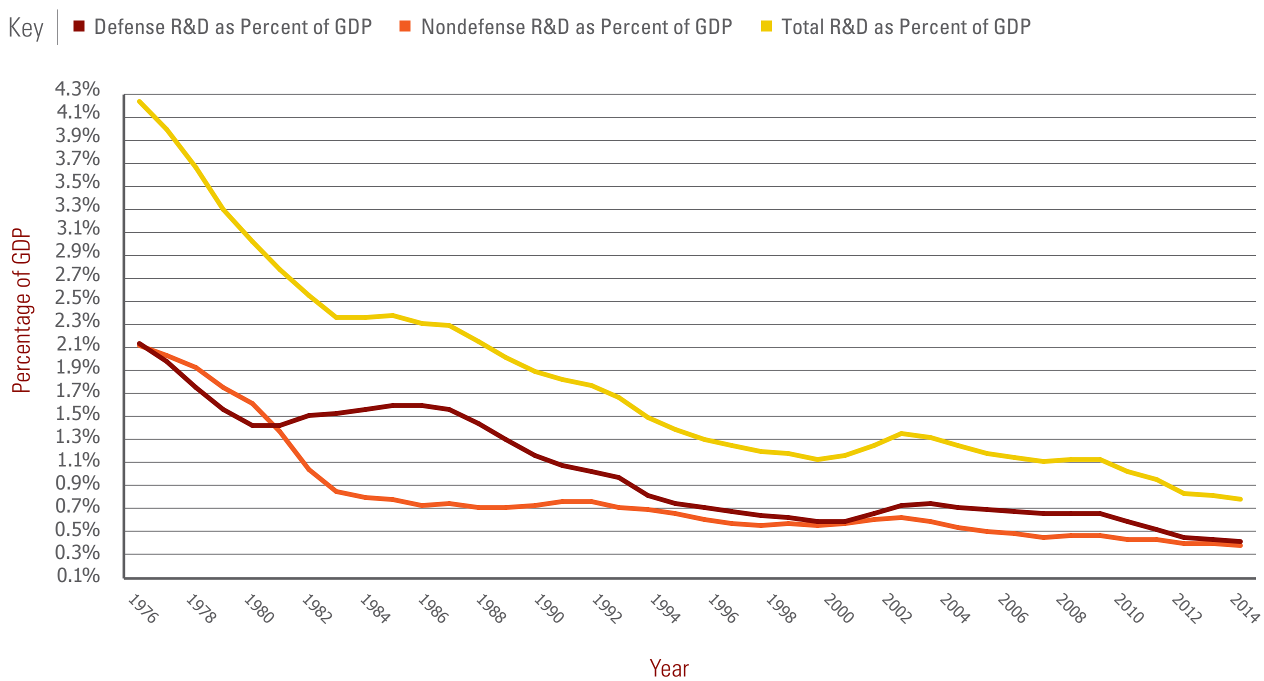
FIGURE 6. ENERGY R&D PER THOUSAND UNITS OF GDP | 2014



Source: International Energy Agency. "Key Trends in IEA Public Energy Technology RD&D Budgets." October 2016. Available at: http://www.iea.org/media/statistics/topics/IEA_RDD_Factsheet_2016.pdf

KEY TRENDS IN R&D SPENDING

FIGURE 7. TRENDS IN FEDERAL R&D AS A PERCENT OF GDP



Source: AEIC Generated.

Data Source: American Association for the Advancement of Science. Historical Trends in Federal R&D.

The underfunding of energy R&D is also part of a larger, problematic decrease in federal support for innovation that has been slowly eroding the foundation of the nation's prosperity for decades.

Across all sectors, the federal contribution to R&D spending as a percentage of the U.S. economy has fallen considerably from what it was in 1976 (Figure 7).

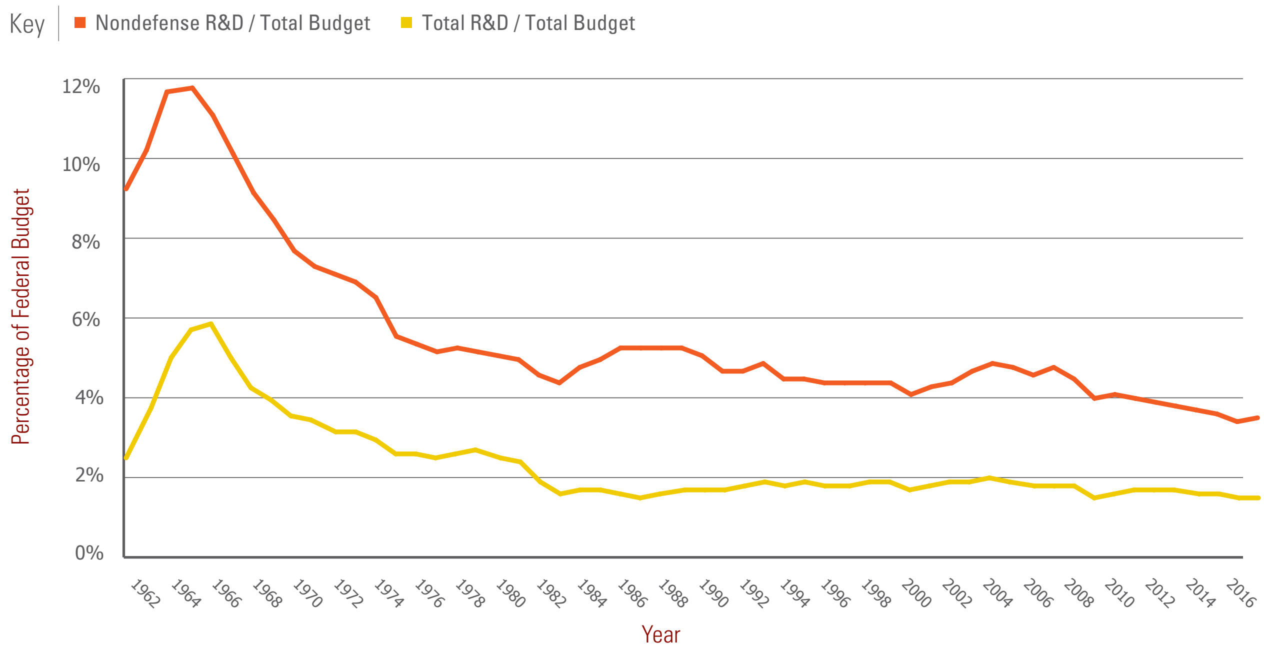
Meanwhile the percentage of the federal budget dedicated to non-defense R&D has been flat since the early 1980s (Figure 8). As growth and contractions of the federal budget do not always correlate with GDP, reviewing the emphasis that policymakers place on R&D is also instructive. Trends clearly and troublingly point to a diminished focus on R&D investments over the last few decades.

Once again, when placed in a global context, over the last 20 years, the United States has allowed several other nations to close the gap or surpass the U.S. commitment to research (Figure 9). As success in the global economy becomes increasingly dependent on scientific and technological supremacy, this trend should be concerning to every American.

KEY TRENDS IN R&D SPENDING

FIGURE 8. R&D AS PERCENT OF THE FEDERAL BUDGET

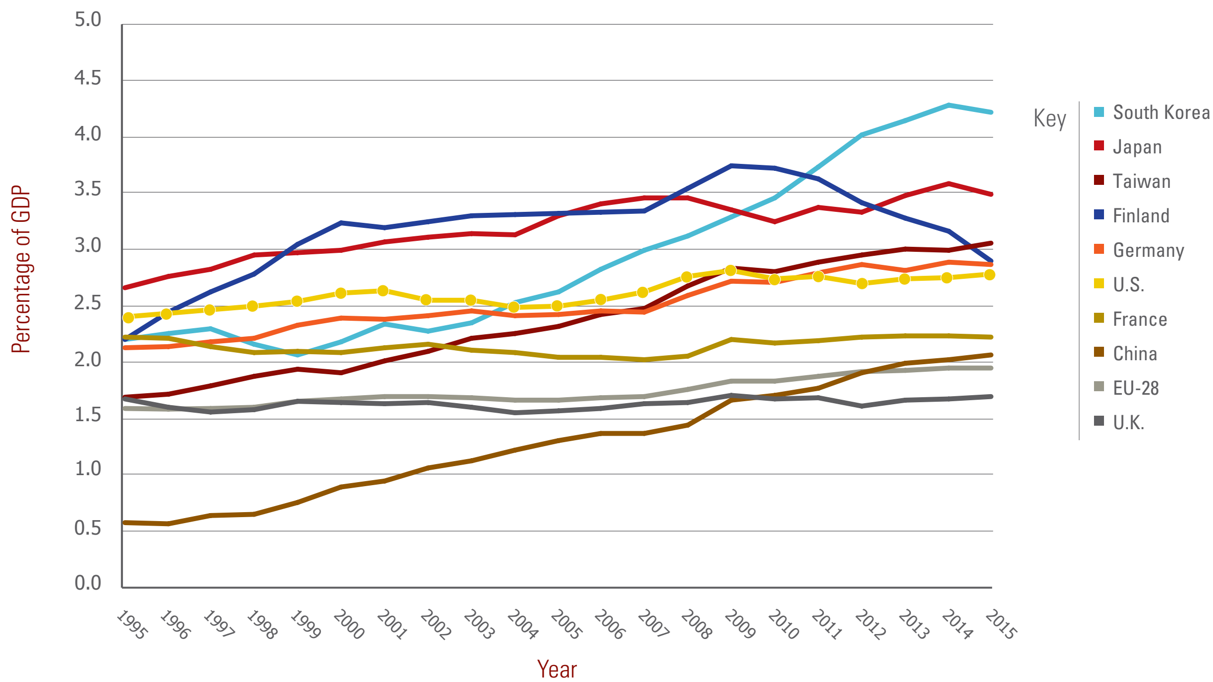
FY 1962-2017, in outlays



Source: American Association for the Advancement of Science. Historical Trends in Federal R&D. "R&D as a Percent of the Total Federal Budget, 1962-2017." Updated June 2016. Accessed May 1, 2017. Available at: https://www.aaas.org/sites/default/files/Budget;.jpg

FIGURE 9. NATIONAL R&D INTENSITY

Gross R&D investment as a percent of GDP



Source: OECD, Main Science and Technology Indicators, February 2017, available at http://www.oecd.org/sti/msti.htm.

KEY TRENDS IN R&D SPENDING

PROFILES IN INNOVATION: SOUTHERN COMPANY

Southern Company is developing the full portfolio of energy resources, and its leadership recognizes that new advanced nuclear technologies must be available for a low-carbon energy future. Through its progressive R&D strategy and strategic partnerships with DOE and companies worldwide, Southern Company is exploring potential opportunities with next-generation advanced reactors.

In 2016, Southern Company was awarded up to $40 million from DOE to explore, develop, and demonstrate aspects of TerraPower's molten chloride fast reactor (MCFR) technology—an advanced concept for nuclear generation—through a new public-private partnership with DOE, TerraPower, Oak Ridge National Laboratory, the Electric Power Research Institute, and Vanderbilt University. With non-federal cost-share contributions of $30 million, this project represents up to $70 million in new advanced reactor research.

These new reactors will have more advanced safety systems, fewer byproduct materials, and greater cost efficiencies than the existing reactor fleet. These reactors could also serve as a source of process heat for various industrial applications.

The MCFR technology has its roots in work done by the Atomic Energy Commission at Oak Ridge National Laboratory under the Aircraft Reactor Experiment and later via the Molten Salt Reactor Experiment. TerraPower has advanced this technology over the past several years. With a very high energy density, flexibility in operation, and high-efficiency electricity generation, Southern Company and its partners believe the MCFR has the potential to be a revolutionary, low-cost supply technology.

Innovative policies, licensing frameworks, and regulatory structures will be needed to encourage private investment and facilitate the efficient and predictable commercialization and deployment of these new technologies.

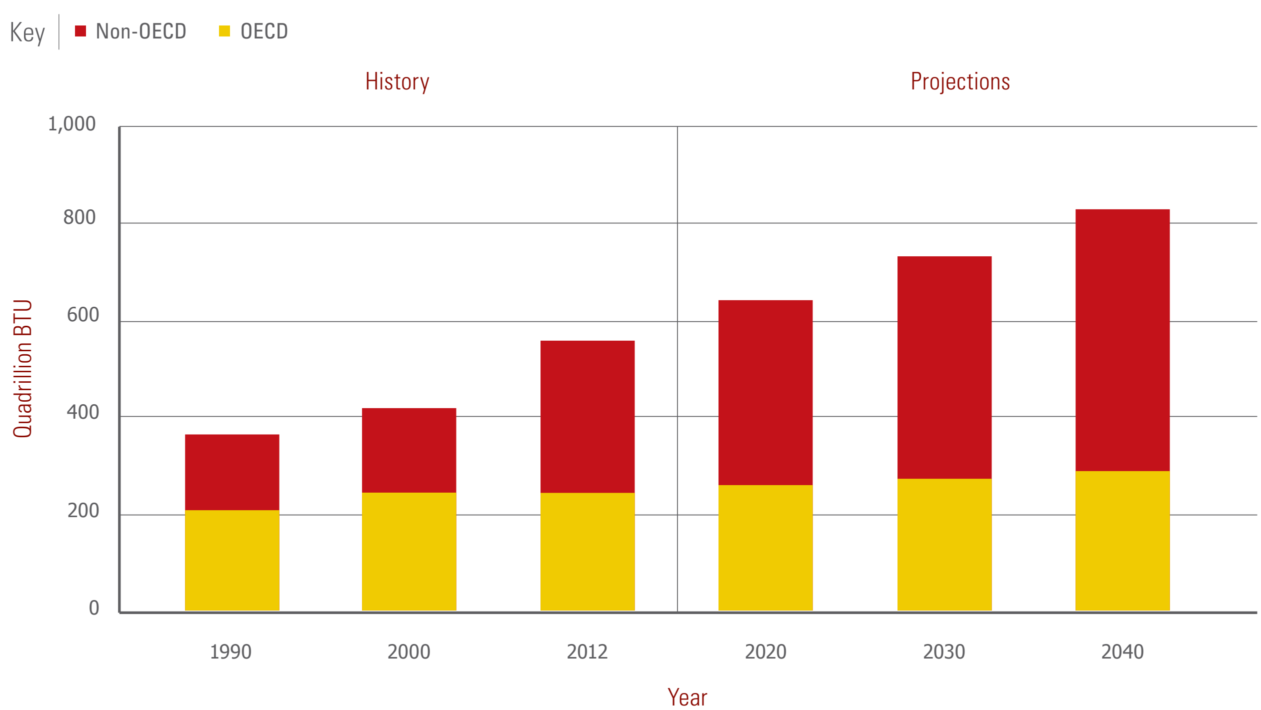
As the industry continues changing, it is important to maintain support for research, development, and deployment of innovative energy technologies. Since the 1960s, Southern Company has managed approximately $2.3 billion in R&D investments, often partnering with government to expand the scope of its research initiatives. Over the past decade, Southern Company has leveraged R&D investments of $436 million to return benefits exceeding $3.4 billion. Many of these investments were bolstered by strong public-private partnerships, and Southern Company's relationship with DOE is key to many of its R&D efforts. For example, Southern Company manages and operates DOE's National Carbon Capture Center and the 25-MW carbon capture capture demonstration at Alabama Power's Plant Barry. DOE support has also been crucial in Southern Company's research initiatives at the Southeastern Solar Research Center, connected microgrid community demonstrations, and smart-grid development.

ECONOMICS OF ENERGY INNOVATION

There are fiscal challenges that require policymakers to balance numerous competing and important priorities. Yet as policymakers look for ways to improve the nation's financial situation, there are several key economic reasons to prioritize energy innovation. For example, power outages cost the United States at least $150 billion a year, or about $500 for every man, woman, and child,[41] yet funding for DOE's Office of Electricity Delivery and Energy Reliability was only $206 million for FY2016.[42] Short-changing support for researchers working on the nation's energy challenges doesn't save taxpayers money; it costs them billions of dollars every year in lost efficiencies that could lower residential energy costs and make U.S. businesses—especially energy-intensive industries like manufacturing—more competitive. It also prevents the nation from capturing the economic benefits of developing new, exportable energy technologies that can help meet the world's growing appetite for cleaner, affordable, and reliable energy.

Numerous estimates point to tremendous growth in demand coming from the developing world. As shown in Figure 10, the U.S. Energy Information Administration projects that global demand will increase 48 percent by 2040,[43] and the International Energy Agency estimates that by 2040, $67 trillion in investment will be needed to meet this demand.[44] Make no mistake—global energy markets, which are increasingly focused on low-carbon technologies, are a multitrillion-dollar economic opportunity and will continue to be for decades to come.

FIGURE 10. WORLD ENERGY CONSUMPTION | 1990-2040



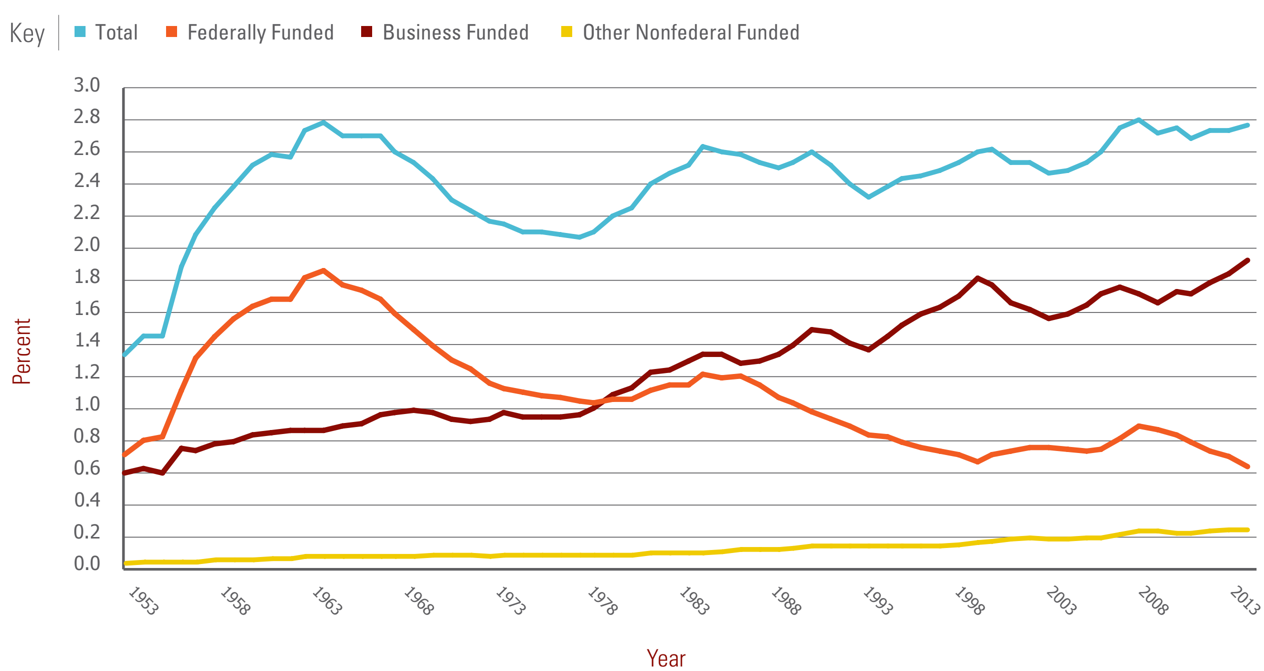
Source: Energy Information Administration. "EIA Projects 48% Increase in World Energy Consumption by 2040." May 2016. Available at: http://www.eia.gov/todayinenergy/detail.php?id=26212

ECONOMICS OF ENERGY INNOVATION

Critics argue that if such a market opportunity exists, the private sector will happily step in and make the necessary investments to capture a share of the multitrillion-dollar opportunity that future energy markets represent. They might even point to the fact that business-funded research has largely offset decreases in federal investment, as evidenced in Figure 11. Yet once again, a closer examination of the data reveals a more accurate view of these trends. Basic research comprises only 18 percent of all U.S. R&D, and applied research fares only slightly better at 20 percent.[45] Roughly 62 percent of total U.S. R&D spending is devoted to development activities,[46] and the private sector provides more than 80 percent of this funding. While the private sector is generally doing what they do best—conducting late-stage, commercialization-related development activities—there are clear gaps in both basic and applied research that the private sector is not filling.

Of course, this makes sense from an economic perspective, as the private sector excels at commercialization. Yet as the percentage of corporate funding for long-term growth investments such as basic R&D hit all-time lows,[47] concerns about short-termism highlight the need for a strong federal role supporting key stages in the energy innovation process.[48]

FIGURE 11. RATIO OF U.S. R&D TO GDP, BY SOURCE OF FUNDING FOR R&D | 1953-2015



Source: National Center for Science and Engineering Statistics. "U.S. R&D Increased by More Than $20 Billion in Both 2013 and 2014, with Similar Increase Estimated for 2015". Sept 2016. Available at: https://www.nsf.gov/statistics/2016/nsf16316/nsf16316.pdf

ECONOMICS OF ENERGY INNOVATION

PROFILES IN INNOVATION: AIR LIQUIDE

Amid dramatic changes across the energy sector, Air Liquide is working to harness the potential of a revolutionary resource that has already begun to change the energy landscape: hydrogen. Through its own R&D program and strategic partnerships with public- and private-sector partners, Air Liquide continues to explore new uses for this domestically produced, sustainable, and versatile form of energy. Meanwhile, these partnerships have also been critical to expanding the 21st-century energy infrastructures capable of utilizing hydrogen across its many potential applications.

Much of today's work across the range of hydrogen applications has its origins in federal research. The hydrogen fuel cell, originally developed as part of the space program, has emerged as a cornerstone of numerous end-user applications. Pioneering research conducted at Los Alamos National Lab led to the development of a thin-film, low-platinum electrode for the polymer electrolyte membrane fuel cell, which is currently used by manufacturers around the world. DOE has also been critical to demonstrating fuel-cell applications for forklifts, and its work with the Defense Logistics Agency has facilitated pilot programs that engendered a burgeoning forklift market, which today supplies major retailers with commercial fuel-cell-powered fleets.

Air Liquide has built on these efforts to lead the industry in providing the modern transportation fueling infrastructure necessary to deploy commercial and consumer fuel-cell vehicles. Air Liquide is currently constructing hydrogen-fueling stations in California and across the northeastern United States. Air Liquide has also recently commissioned the largest hydrogen storage facility in the world, an underground cavern in America's Gulf Coast region. This unique hydrogen storage cavern complements Air Liquide's robust supply capabilities along the Gulf Coast, offering greater flexibility and reliable hydrogen supply solutions to customers via Air Liquide's more than 2,000-mile pipeline system. Looking forward, Air Liquide is confident that hydrogen, due to its exceptionally versatile capability as a storage medium for energy, will be the answer to resiliency, power, and demand-management challenges in modernizing the 21st-century electric-power grid.

As Air Liquide has engaged communities in the expansion of this infrastructure, DOE and the national labs have played a critical support role, providing technical expertise to local communities considering hydrogen-infrastructure deployments and validating technical capabilities, potential, and most important, safety. This successful partnership has helped to reinforce Air Liquide's U.S. manufacturing operations, which employ more than 20,000 people across all 50 states.

Ongoing, robust collaboration also has the potential to leverage the nation's vast and varied domestic energy resources, including natural gas, to spur additional hydrogen applications. DOE will continue to be critical in realizing the full potential of hydrogen as a versatile domestic energy resource.

VALLEYS OF DEATH AND THE ENERGY INNOVATION PROCESS

In practice, the technical and financial obstacles to developing new energy technologies identified here are best represented by what is commonly known as the "valley of death." What is less known is that in the case of capital-intensive, hard-technology projects such as those in the energy sector, there are two valleys of death. These valleys occur at stages during the development cycle where technical risk is high, and the capital to solve those challenges may be extraordinarily difficult to come by as a result.

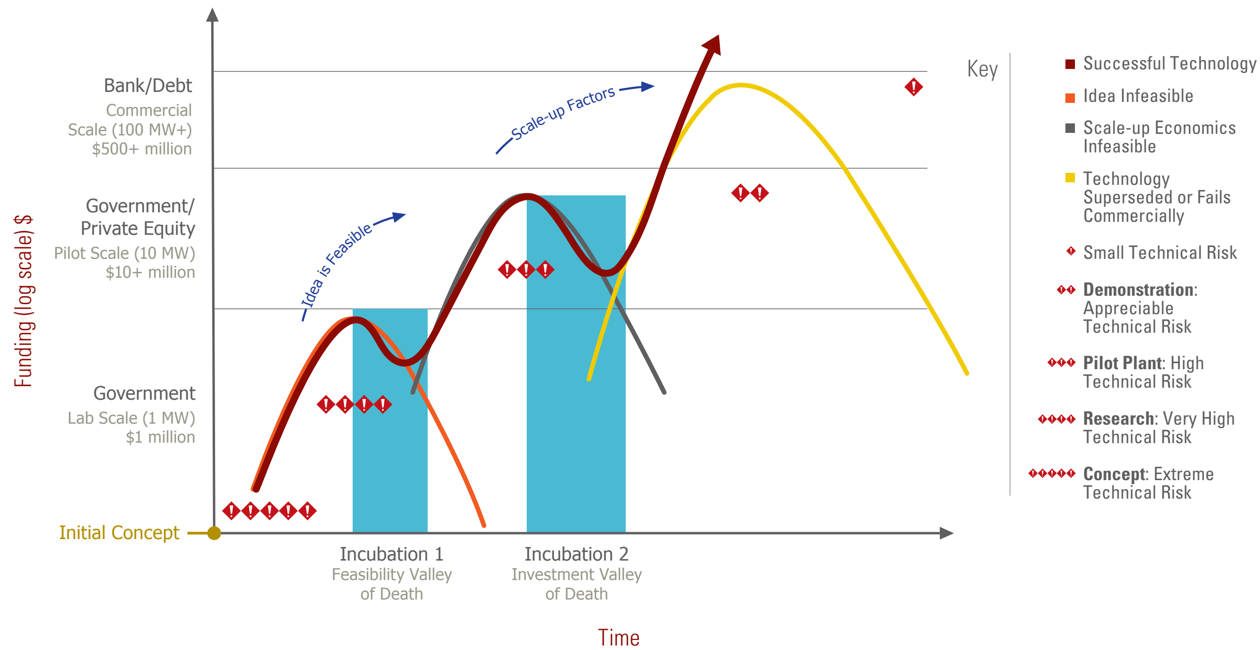
Early in the technology-development cycle, when a research or technical concept is taken out of the lab and used to create a viable technology, the technical risks are incredibly high. Additionally, technologies at this stage are a long way from commercialization and often the scientists or entrepreneurs developing these technologies may not have a substantial enough track record to reassure investors. This leads to the first valley of death, where many promising ideas are unable to secure the funding necessary to test out whether their idea for adapting research into a technology are even viable. Government support generally drives the initial validation of the science behind an idea across this phase of development. Once the idea has proved technically feasible, venture capital and private equity are generally relied upon to help build a pilot-scale project.

While financing a pilot project for a new technology is not without risk, and only the most promising of these projects receive funding, the private sector will sometimes support technologies through this part of the development cycle. Yet after a successful pilot-scale project, the challenge becomes one of being able to scale it up. In addition to the technical challenges of bringing a technology to scale, often entirely new production or manufacturing processes must be developed and innovators must establish the reliable supply chain necessary to build a full-scale demonstration project. Scale is of course the operative word as often this part of the development cycle for energy technologies can require tens or hundreds of millions of dollars. As a result, debt equity and other institutional investors such as banks are often the only investors capable of making investments at the necessary scale, and their appetite for risk is much lower than most projects present. Of course, this challenge also points to a constructive role for government in mitigating some of the risks for investors, thus enabling promising technologies to advance along the energy innovation process.

It can often take 10 to 15 years for a new energy technology to successfully navigate this process, requiring significant financial support along the way that isn't always well matched to the interests and risk appetites of private investors. To ensure that the investments the United States makes in basic and early stage research do not wither on the vine requires a significant

VALLEYS OF DEATH AND THE ENERGY INNOVATION PROCESS

FIGURE 12. CARBON CAPTURE TECHNOLOGY DEVELOPMENT PATHWAY



Source: John Burgess, Lewis Jeffrey, Allen Lowe, Stephen Schuck, Warren Flentje. "Novel CO2 Capture Task Force Report" December 2011. Global CCS Institute. Available at: http://hub.globalccsinstitute.com/sites/default/files/publications/44151/novelco2capturetaskforcereportfinal.pdf

commitment to filling those gaps in the innovation cycle that the private sector simply will not. Using the example of a carbon-capture project, Figure 12 demonstrates where these valleys of death arise in the course of the project's development.

Government should focus its efforts specifically on those areas where the private sector is unable to support the progress of promising technologies. An approach that does so while allowing the private sector to bring new innovations to market is the best way to create synergies that maximize limited public and private funding.

Federal investments can and do play a complimentary role in energy innovation and in securing the economic, security, and environmental benefits of cleaner, more affordable, and reliable energy products and services. By actively working with the private sector, the federal government can ensure that these investments are targeted and make good technical and financial sense. Indeed, there are numerous examples of the potential of this process to achieve these objectives.

VALLEYS OF DEATH AND THE ENERGY INNOVATION PROCESS

PROFILES IN INNOVATION: GULFSTREAM

The development of alternative jet fuels has been one of the more difficult innovation challenges for the aviation industry. Fuel comprises a significant portion of operating expenses and the cost of alternative fuels has long been a limiting factor, and many producers have struggled to operate at the scales necessary to produce a cost-competitive product. Yet effective public-private partnerships have helped to make significant progress toward solving this challenge.

Gulfstream has been making significant investments in renewable-fuel options as part of its innovation and sustainability strategy. A recent agreement with World Fuel Services, its fuel supplier, will provide a 30/70 blend of low-carbon, drop-in renewable fuel and conventional jet fuel to support daily flight operations in Savannah, Georgia. This fuel provides the same performance as conventional, petroleum-based jet fuel and requires no changes to factory-standard engines or aircraft. Each gallon of renewable fuel burned is expected to achieve a more than 50 percent reduction in greenhouse gas emissions, relative to petroleum-based jet fuel, on a lifecycle basis.

The fuel supplied by World Fuel Services is produced by AltAir Fuels, which received a $2 million grant through the American Recovery and Reinvestment Act in 2010 to build a first-of-its-kind renewable jet-fuel refinery. AltAir Fuels has subsequently expanded its portfolio to include fuels derived from agricultural waste, and it now produces more than 45 million gallons of low-carbon, drop-in replacement jet fuel per year. The agricultural-waste-derived fuel used by Gulfstream meets the same industry specifications as the U.S. petroleum benchmark, Jet-A.

Aviation is a highly competitive global industry, and success depends on the ability to innovate consistently. Since 2011, when a Gulfstream G450 became the first business jet to cross the Atlantic using biofuels, renewable fuels have played a growing role in Gulfstream's innovation and sustainability strategy. In the last year, Gulfstream's Field and Airborne Support Teams have completed more than 300 missions, many using the renewable fuels provided through the supplier agreement with World Fuel Services. In fact, all of Gulfstream's Savannah-based demonstration aircraft and the G500 flight-test fleet have flown on the renewable-fuel blend produced by AltAir Fuels. Innovation continues to be central to Gulfstream's long-term strategy, and effective partnerships are critical to its success in those efforts.

REAPING THE REWARDS OF FEDERAL INVESTMENTS

To appreciate the impact that such successful public-private collaborations can have on the nation's future, it is instructive to review the ways in which it has already benefited America. A good example of this is the development of horizontal drilling and hydraulic fracturing, which have unlocked vast amounts of unconventional natural gas across the United States. In the late 1970s, DOE launched the Unconventional Gas Research Program,[49] researching the potential for shale gas development in the United States in collaboration with academia and industry. Through the Eastern Gas Shales Project,[50] DOE funded early, experimental shale wells when those companies working on unconventional gas development had little or no capital to fund this type of R&D. Over the next several decades, DOE partnered with industry to complement private-sector research and conducted applied research into micro-seismic mapping and advanced drill bits that had implications beyond hydraulic fracturing. Working with businesses, DOE helped revolutionize the energy sector with a technological breakthrough.

A 2015 Harvard Business School analysis determined that in 2014 alone, hydraulic fracturing contributed $430 billion to U.S. GDP, supported 2.7 million jobs, and saved the average American household $800 in energy costs—all while decreasing America's dependence on foreign oil.[51] The Harvard analysis projects that by 2030, these figures could rise to almost $600 billion in additional GDP, 3.8 million jobs, and roughly $1,100 in savings for American households.[52]

DOE research into renewable energy technologies like wind and solar have also had tremendous impacts on the U.S. economy. Driven by federally funded research and programs like the SunShot Initiative,[53] the costs of solar power have decreased by 62 percent[54] over the last five years, and roughly 260,000 Americans now work in the solar industry.[55] Similarly, federally funded research into wind energy, including advanced wind turbines, reliable and lower-cost supply chains, and grid integration[56] has helped the wind energy industry to grow. By 2014, the wind energy industry was supporting more than 500 manufacturing facilities across the United States,[57] and 2016 saw a record 88,000 jobs in the wind industry as it led the nation in new electricity-generation capacity.[58] Time and again, publicly funded energy research has provided high-impact returns for taxpayers. From 1976 to 1983, DOE invested roughly $2 million into researching low-emissivity windows that better insulate buildings, and by the mid-1980s, industry investment into these windows had grown to $150 million. By 2000, these windows had already saved Americans more than $8 billion.[59] Research into high-efficiency diesel engines that began in the 1970s has likewise paid an enormous return on investment to the American taxpayer. From 1986 to 2007, investments totaling

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less than $931 million (adjusted for inflation) created more than $70 billion in economic benefits for the United States—a seemingly impossible return of roughly $70 for every dollar of taxpayer investment.[60]

But these programs are not isolated success stories. A 2016 DOE study found that a portfolio of R&D investments at the Office of Energy Efficiency and Renewable Energy totaling $12 billion from 1976 to 2012 yielded net economic benefits to the United States of $230 billion (in inflation-adjusted dollars) with an annual return on investment of 20 percent.[61] This study confirms research conducted by the National Academies of Science, Engineering and Medicine in 2001, which evaluated a portfolio of 17 energy-efficiency R&D programs at DOE representing roughly 20 percent of total energy-efficiency R&D expenditures from 1978 to 2000.[62] These programs received $1.6 billion in funding over 22 years but yielded direct economic benefits of $30 billion, a return of roughly $20 for every dollar invested.[63]

The Office of Energy Efficiency and Renewable Energy isn't the only DOE office with this type of success. The same National Academies of Science, Engineering and Medicine study [64] reviewed 22 fossil energy R&D programs at DOE, representing 73 percent of total appropriations to the Office of Fossil Energy from 1978 to 2000. From 1986 to 2000, these programs received $4.5 billion, generating $7.4 billion in economic benefits. In fact, 75 percent of domestic coal-fired power plants include technology with roots in Office of Fossil Energy's Clean Coal Technology Demonstration program.[65] More recently, a 2013 study found that the $8.5 billion Clean Coal Technology program at DOE will create more than 1.2 million jobs and deliver $111 billion in economic benefits to the country—returning $13 for every taxpayer dollar invested by 2020.[66]

For comparison's sake, in 2010, the pharmaceutical industry generated a return on investment of 10.1 percent on R&D activities—a number that is expected to slide to 3.6 percent for 2016.[67] The private sector is simply unable to capture the vast array of public benefits of energy R&D, such as increased energy security, enhanced energy system reliability, decreased pollution, as well as knowledge and workforce-development spillovers. This means the federal government fills a unique and critical role in supporting this research, but also in securing those public benefits for the American people.

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As previously noted, the expected growth in energy markets presents a multitrillion-dollar opportunity. To seize this opportunity, countries around the world are increasing their commitments to R&D. At the United Nations Framework Convention on Climate Change, held in Paris in late 2015, 197 nations made commitments to reduce their carbon emissions.[68] In addition to the framework of policies around the globe that will stimulate demand for clean-energy technologies, 22 nations representing more than 80 percent of global clean-energy investment have agreed to double their R&D spending on clean-energy research over the next five years as part of Mission Innovation, a global initiative committed to significantly accelerating clean-energy innovation.[69] The Breakthrough Energy Coalition,[70] a group of private investors who have committed billions in patient, private capital to help advance the next generation of low-carbon technologies, will focus their efforts on those nations participating in Mission Innovation. This global partnership reinforces the complementary roles that public and private sectors will play in developing advanced energy technologies. It also signals broad recognition of the long-term economic opportunities presented by energy innovation and will serve to intensify competition in the years to come.

Broadly, global investment in all research areas increased in 2016 by 3.5 percent to $1.948 trillion with more than 110 nations investing more than $100 million.[71] Asian nations continue to comprise larger and larger shares of global R&D spending—led by China. Chinese investments in research have grown consistently by 10 percent or more, year over year, since the 1990s before slowing down to 7 percent in 2016.[72] By comparison, growth rates in the United States have struggled to keep pace with inflation, ranging from 2 to 3 percent over the same time span.[73] Global R&D in the energy sector is estimated to have risen nearly a billion dollars to $23 billion in 2016.[74] Whether through incremental improvements or the development of new, breakthrough technologies, global competition for advanced, low-carbon energy technologies is clearly accelerating.

The fact that energy is a basic input for virtually every American business means that success or failure in the development of advanced energy technologies has a profound effect on America's overall competitiveness. For example, because of the early collaboration between DOE and the private sector to develop unconventional gas resources, the United States had a 10- to 15-year head start in commercializing these technologies. As a result, wholesale natural gas prices in the United States are about one-third of those in other industrialized nations.[75] As Figure 13 shows, increased availability of low-cost, domestic natural gas has had an immense impact on employment in the U.S. manufacturing sector. Lower natural gas prices have also helped keep electricity prices low. This has meant that industrial electricity prices—so critical to the competitiveness of U.S. manufacturing—are 30 to 50 percent lower than in other major export nations.

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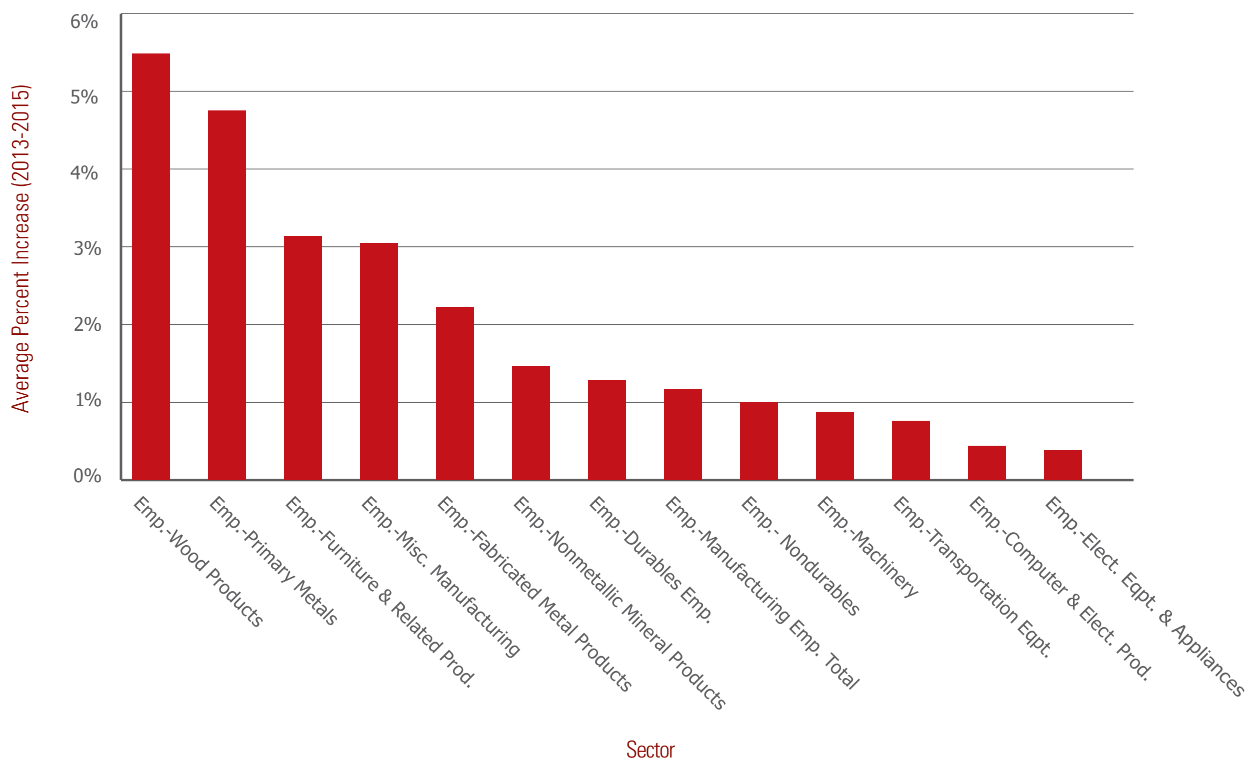
FIGURE 13. PERCENT INCREASE IN MANUFACTURING SECTOR EMPLOYMENT FROM HIGHER NG SUPPLY



Source: Brendan O'Neil, Phil Hopkins, Julie Gressley. "The Economic Benefits of Natural Gas Pipeline Development on the Manufacturing Sector". IHS Economics May 2016. Available at: http://www.nam.org/Data-and-Reports/Reports/Natural-Gas-Study/Energizing-Manufacturing-Full-Report/

Beyond its impact as an input for the broader U.S. economy, markets for exporting advanced energy technologies also present important economic opportunities for American businesses. Lithium-ion batteries present one such example. Much of the early research into lithium-ion batteries was conducted in the United States and funded by taxpayers. The global market for these batteries is poised to grow from $29.68 billion in 2015 to $77.42 billion by 2024 with even greater potential in the long-term.[76] Given the time it takes to translate research into a commercial product, the investments being made today will have an enormous impact on establishing long-term supremacy in this important market. An abdication of American leadership in developing advanced energy technologies will not only cost direct jobs, it would deprive domestic businesses of the competitive advantages of lower-cost and more reliable energy while imperiling national energy security. What's more, doing so would create structural disadvantages that would have

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profound long-term implications for America's innovative capacity and competitiveness. Together, China, Japan, and South Korea represent 85 percent of global lithium-ion battery production capacity.[77] Tesla's $5 billion gigafactory [78] aims to reduce the cost of a battery pack by 30 percent through the advantages of large-scale manufacturing, and, importantly, Tesla is working to try and source raw materials in the United States where possible.[79] Well-developed Asian supply chains are key to the competitive success of lithium-ion battery producers in those nations; Asian producers have also paired this advantage with highly automated, advanced manufacturing techniques to secure the early lead in this burgeoning industry.

A second example—advanced nuclear technologies—similarly provides a significant potential export market for new energy technologies. The domestic nuclear industry has struggled in recent years for several reasons, including low natural gas prices, high capital costs, and regulatory uncertainty. Long-term concerns about nuclear waste, safety, and proliferation will continue to be concerns that the industry must address, but innovators across the United States and the globe are racing to meet these challenges.[80] Because nuclear is a low-carbon power source that can provide baseload electricity at an impactful scale as the world moves to decarbonize, many see the potential of advanced nuclear technologies to meet demand for low-carbon energy as a boon to the technology. In fact, the U.S. Department of Commerce projects that nuclear could generate more than $100 billion in U.S. exports over the next decade.[81] The International Energy Agency estimates that by 2040, new nuclear will account for as much new global electric-power generation as natural gas.[82] China and Russia are both aggressively pursuing advanced nuclear technologies, which raises concerns not only about economic competitiveness but also the national security imperative.[83]

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PROFILES IN INNOVATION: GENERAL ATOMICS

The Achilles' heel of light-water reactors (LWRs) has always been the need to continue core cooling after shutdown, because the radioactive material in the fuel rods continue to generate heat long afterward. Loss of cooling can cause the fuel rods to overheat to the point that the metal fuel-rod casing, or cladding, reacts with steam in the core to produce hydrogen. In addition to the hydrogen-explosion risks, this reaction generates substantial additional heat, further increasing the risk of a core meltdown—exactly what occurred in the Fukushima Daiichi Nuclear Power Plant accident. The challenge is to find new, far more durable materials for fuel-rod cladding that do not carry these risks. This would enhance the safe operation of the existing U.S. nuclear fleet and reduce construction, operational, and maintenance costs.

There are now three vendor groups working to develop these materials. For the past seven years, General Atomics has been working on an engineered ceramic that does not react with steam, takes temperatures more than two times higher than current metal cladding, and is structurally extremely strong. General Atomics has made significant advances in fabricating LWR cladding from these materials, thanks in part to cost-sharing with DOE and collaboration with industry and government partners, including Oak Ridge and Idaho National Labs, which have provided both specialized expertise and facilities that have been critical along the development pathway for these materials. Because of the potential benefits for nuclear safety and economics, Congress has directed DOE to test the first lead rods and assemblies using these materials in a commercial reactor by 2022. However, there has been insufficient funding from DOE to support meeting this objective. Besides effective collaboration, additional federal and private investment will be required.

General Atomics is confident that productive partnerships like these will lead to successful deployment of ceramic test rods for LWRs by the 2022 deadline. The cost benefits of these new ultra-safe fuel rods could be key to the long-term future of the existing U.S. nuclear fleet, while also creating substantial opportunities in export markets. However, this window of opportunity will not stay open forever. The urgency to develop these materials is countered by their considerable financial risk, stemming from the long lead time and regulatory uncertainties that make it difficult for private industry, by itself, to justify the substantial investments. Federal R&D support to enhance the private effort is key to reducing these risks.

Though existing LWRs are safe, these new fuel rods would be a game-changing innovation that would make Fukushima-like incidents nearly impossible while substantially reducing the costs for LWR operation by decreasing down time, increasing energy production, and reducing operations and maintenance costs. General Atomics is eager to continue its productive partnership with DOE and make this dream a reality.

CONCLUSION

Energy underpins virtually every facet of Americans' lives. The best way to ensure America's future is to make the investments necessary to thrive in a 21st-century global economy. A strong, bipartisan group of lawmakers have recognized the power of innovation and are actively working to leverage it to unify the country in pursuit of shared prosperity. New institutional arrangements within DOE that focus on improving the efficiency and effectiveness of federally funded research—such as ARPA-E, Energy Frontier Research Centers, Innovation Hubs, Cyclotron Road, and the Manufacturing USA network—are already having a tremendous impact as the nation innovates the process of innovation itself.[84]

In determining the best, most appropriate role for the federal government in supporting innovation, a continued focus on early stage, basic research is warranted. Breakthroughs in fundamental science hold the potential to transform the planet. America's leadership in these disciplines is as critical to the nation's future as it is to the world's.

The federal government has a role to play in those stages of the innovation cycle where private-sector support is systemically lacking. It is wasteful and irresponsible to allow promising technologies to go undeveloped because of a mismatch between the interests of the private sector and advancements that could greatly benefit the public's economic, security, and environmental interests. Numerous studies have pointed out the significant ways that federal support at these key moments in a technology's development has benefited the nation. America's leaders would be wise to heed these lessons well.

As the United States confronts a slew of economic, security, and environmental challenges, the AEIC is optimistic about the nation's ability to meet them. Science and technology will continue to have an outsized influence on the world, creating economic opportunities that play directly to America's strengths as a nation. A robust innovation ecosystem, created to help the United States reach its potential, can serve as the engine of a prosperous future if leaders remember to cultivate the scientific and technological advantages that have long been at the heart of America's success.

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