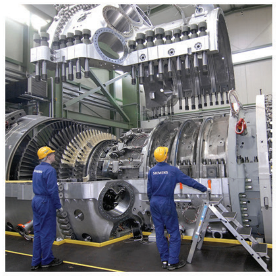
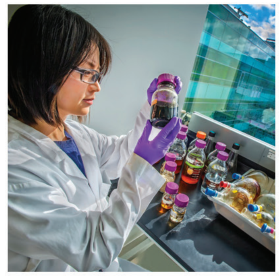
ENERGY INNOVATION PORTFOLIO PLAN FY2018 - FY2022

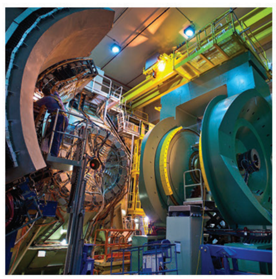
JANUARY 2017

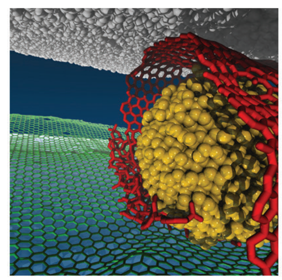
U.S. DEPARTMENT OF ENERGY







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Selected Acronyms and Abbreviations

AEO	Annual Energy Outlook
ARPA-E	Advanced Research Projects Agency-Energy
BEV	Breakthrough Energy Ventures
BRCs	Bioenergy Research Centers
CCS	carbon capture and storage
CCUS	Carbon Capture, Utilization, and Storage
CHP	combined heat and power
COMPETES	Creating Opportunities to Meaningfully Promote Excellence in Technology, Education, and Science
DARPA	Defense Advanced Research Projects Agency
DERs	distributed energy resources
DOE	Department of Energy
ECI	Exascale Computing Initiative
EERE	Energy Efficiency and Renewable Energy
EFRCs	Energy Frontier Research Centers
EGS	enhanced geothermal systems
EIA	U.S. Energy Information Administration
EVs	electric vehicles
FE	Fossil Energy
GDP	Gross Domestic Product
GHG	greenhouse gas
GPS	global positioning system
GRI	Gas Research Institute
HPC	high performance computing
kWh	kilowatt hour
LED	light emitting diodes
MW	megawatt
NE	Nuclear Energy
NGCC	natural gas combined cycle
NRC	National Research Council
OE	Office of Electricity Delivery and Energy Reliability

OPEC	Organization of the Petroleum Exporting Countries
OTT	Office of Technology Transitions
PCAST	President's Council of Advisors on Science and Technology
PPPs	public-private partnerships
PV	photovoltaic
QER	Quadrennial Energy Review
QTR	Quadrennial Technology Review
R&D	research and development
SC	Office of Science, DOE
SMRs	Small Modular Reactors
SST	solid state transformer
SubTER	Subsurface Science, Technology, Engineering & Research
U.S.	United States
USEER	U.S. Energy and Employment Report
VC	venture capital

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Executive Summary

Global energy markets are transforming. Technology improvements in production of oil and gas, deep reductions in the cost of technologies like solar and wind, increasing energy efficiency, and efforts to modernize the transmission and distribution of electric power, including deployment of energy storage, are reshaping the energy landscape for the United States and the world. Economies that are based on efficient, abundant, cost-effective, and clean energy supplies will lead international economic competition. Because of its long-standing technology innovation, the United States is well-positioned to lead energy innovation and capture large economic and environmental benefits, even as other countries step up their own investments in developing and deploying new energy technologies.

Failing to sustain this rapid pace of innovation would place American entrepreneurs, manufacturers, and workers at a competitive disadvantage in developing breakthrough technologies and creating jobs. Very large markets for energy technologies will develop—more than $60 trillion through 2040 according to the International Energy Agency. Accelerating investment in energy innovation will allow the United States to grow our economy, create new jobs across a wide range of energy supply and end-use technologies, and lead the transformation internationally to attain a significant share of the new energy market.

The Department of Energy (DOE) is the largest funder of clean energy innovation in the United States. DOE conducted a strategic review of its science and energy technology research and development (R&D) programs over the second half of 2016. The review assessed DOE's current investment portfolio and identified the future portfolio of investments necessary to ensure U.S. leadership in innovating for the global clean energy future.

This document describes DOE's approach to the development of this portfolio plan. Chapter 1 describes the role of energy technology innovation in meeting our national challenges. It shows that a diversified and clean energy system helps ensure our national security, contributes to our economic competitiveness, and makes our air and water cleaner, including by reducing carbon emissions. For example, today, the United States is closer to energy independence than it has been in decades because of three revolutions—in shale oil and gas, solar and wind energy, and energy efficiency—each of which is made possible by Federally-supported R&D.

The chapter also highlights other well-known technologies resulting from DOE's work including nuclear power, LED lighting, and electric vehicle batteries, and notes the substantial return on investment Americans have earned through publicly funded clean energy R&D. It notes that both major advances in existing technologies and fundamental breakthroughs that introduce entirely new options must continue to be pursued.

Chapter 2 reports how DOE, working together with the private sector, conducts R&D on energy innovation. This R&D is done by engaging a broad energy science and technology community to identify the most important opportunities, conducting fiercely competitive solicitations to select the best proposals, and rigorously monitoring the work to ensure it is done well.

The chapter notes that Federal funding of early-stage R&D is particularly important in the energy innovation area and documents how private investment alone is insufficient to meet these challenges. Long time frames and the risks of developing new technologies, high capital costs of energy technologies, low margins, and long payback times all pose serious challenges to private investment that mean that the Federal Government fills a key need where the market struggles, particularly for early stage R&D.

With annual U.S. consumer energy expenditures of roughly $1.3 trillion per year and security, health, environmental, and climate externalities totaling hundreds of billions more, R&D that reduces these costs by even a few percent can generate huge returns for ratepayers and taxpayers. Several recent reports have noted this fact and that current levels of public funding are insufficient, and they have called for a doubling or tripling of public clean energy R&D funding.

Chapter 3 details the future energy R&D portfolio required to ensure that the United States maintains its place as a global leader in energy technology innovation. This portfolio is designed to significantly expand and accelerate the pace of U.S. energy technology innovation and is consistent with the November 2015 pledge by the United States and over 20 other leading countries to double their government investments in clean energy innovation funding over five years.

Based on the 2016 strategic review, DOE's future energy R&D portfolio should include these key elements:

- The Advanced Research Projects Agency–Energy (ARPA-E) should be significantly expanded to the level of funding envisioned when it was initially proposed by the National Academy of Sciences.
- Regional energy innovation partnerships should be developed as a new element of the portfolio.
- Grid modernization R&D that is underway now should be continued and expanded significantly. That work, including energy storage, is essential to enable many of the options that will be created by energy innovation R&D.
- Well-diversified electric power generation (through advanced nuclear generation, advanced renewables, and advanced carbon capture and storage) is an essential component of an efficient, secure, and resilient electric power system. The significant current investments in this area should continue, with some targeted evolution, and funding for new efforts (e.g. advanced nuclear generation) should be expanded.
- Substantial growth for energy innovation R&D in the building, transportation, and industrial sectors is needed. These areas offer opportunities that are at an early stage and are ready for additional productive R&D effort.
- Even modest funding for R&D on innovative carbon management can diversify options for reductions in atmospheric concentration of greenhouse gases.
- Fuels R&D (on hydrogen production and uses, biomass conversion, and sunlight to fuels) should continue with targeted evolution of program activities. R&D to expand options and reduce costs of biofuels can lead the way to drop-in biofuels that have fewer barriers to deployment than other biofuel options.
- Support for use-inspired fundamental science, including the development of exascale computing, is an essential underpinning of future innovation in applied energy R&D, and should be expanded significantly.
- Continued use of crosscutting research teams and related coordinated budgets is an effective way to manage R&D in challenging areas that require expertise and have applications across multiple DOE program areas.

The United States does innovation better than anybody else, including linking technology advances to a private network of investors. Given the huge global clean energy market and the projection of more than $60 trillion for all energy technologies over the next 25 years, many countries will be competing for shares of this market using all the mechanisms they can bring to bear.

The issue is not whether these technologies and markets will develop; it is whether U.S. companies and U.S.-based manufacturing will succeed in capturing a significant share of these markets and the associated benefits for the American people.

Will the United States continue to be a global leader in energy technology innovation? Will the United States compete for these markets? With the investments outlined in this report, the answer to both questions will be a resounding "yes."

Introduction

"The capacity to innovate is fast becoming the most important determinant of economic growth and a nation's ability to compete and prosper in the 21st century global economy."

National Research Council, "Rising to the Challenge."[1]

Global energy markets are transforming. Technology improvements in production of oil and gas, deep reductions in the cost of solar and wind technologies, increasing energy efficiency, and efforts to modernize the transmission and distribution of electric power, including deployment of energy storage, are reshaping the energy landscape for the United States and the world. Economies that are based on efficient, abundant, cost-effective, and clean energy supplies will lead international economic competition. Because of the United States' longstanding commitment to technology innovation, it is well-positioned to lead energy innovation and capture the economic and environmental benefits, even as other countries step up their own investments in developing and deploying new energy technologies.

Failing to sustain this rapid pace of innovation would place American entrepreneurs, manufacturers, and workers at a competitive disadvantage in developing breakthrough technologies and creating jobs. The total global energy technology market is projected to be more than $60 trillion cumulatively to 2040.[2] Nations around the world want the jobs, energy security, and health and climate benefits that clean energy supply and efficient end-use systems can provide. By accelerating our investment in energy innovation, the United States will be better able to grow our economy, create new jobs across a wide range of energy supply and end-use technologies, and lead the transformation internationally to attain a significant share of the new energy technology market.

This report outlines a plan to significantly expand Federal investments in the portfolio of Department of Energy (DOE) science and energy technology research and development programs. The DOE has three major mission areas, one of which is the science and energy enterprise. The budget for science and energy research constitutes about $10 billion, or approximately one-third, of the $30 billion DOE budget (Figure 1). Almost half of the DOE science and energy mission, or $4.8 billion in FY 2016, is devoted to research and development (R&D) related to energy technology innovation. Within the science budget, use-inspired fundamental science research in areas like catalysis and materials science that have impacts across energy technologies is included in the wedge labeled "Energy Innovation" in Figure 1. In the energy R&D area, work on energy technologies includes power grid; electric power generation; energy efficiency; transportation; carbon capture, utilization, and storage; and others. The remainder of the programs within the science and energy mission is related to more fundamental science areas (e.g., exploration of neutrinos and the structure of quarks), nuclear waste R&D, deployment of energy technologies, as well as DOE activities like weatherization, operations of the Strategic Petroleum Reserve (SPR), and emergency response.

The portfolio plan described in this report is designed to significantly expand and accelerate the pace of energy technology innovation. The portfolio is consistent with a series of recommendations from various blue ribbon panels, including the National Academies of Sciences, Engineering, and Medicine, the American Energy Innovation Council, and the President's Council of Advisors on Science and Technology. This portfolio also reflects the U.S. pledge to Mission Innovation, a commitment by the United States and over 20 other leading countries to double their governments' investments in clean energy innovation funding over five years, providing more opportunities for transformative private sector investments.

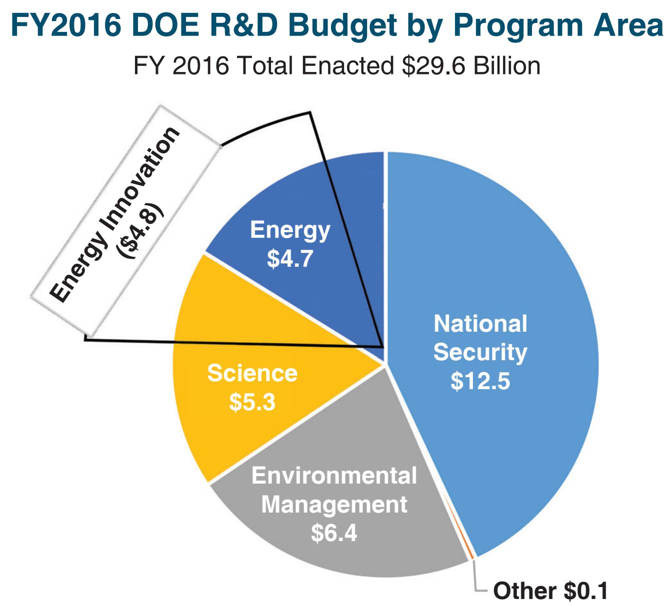


Figure 1: DOE FY 2016 budgets by program area. Numbers in figure are in billions of U.S. dollars

This document describes the U.S. analysis and approach to the development of this portfolio plan in three chapters:

1. The role of technology innovation in meeting the serious energy challenges we face;
2. The essential role for DOE, working together with the private sector, in the R&D of these innovations; and
3. The portfolio of priority R&D initiatives for increased DOE investment over the next five-year period (FY 2018–2022).

Together, these sections frame a plan for continued U.S. leadership in innovating for our global clean energy future.

Chapter 1: Energy Challenges and Opportunities

The U.S. energy system has served the country well, driving unprecedented economic growth and prosperity and supporting our national security. Yet we, and the world, face serious, large-scale energy-related challenges in this time of dramatic change (Box 1).

The overarching goal for the U.S. energy system is to provide an efficient, diversified, and clean energy system that is secure and resilient, economically competitive, efficient, and environmentally responsible. For simplicity, this will be referred to here as the advanced energy system.

Continued deployment of currently available technologies will foster significant progress toward this goal, but further innovation is needed if we are to be fully competitive with the rest of the world. A program of accelerated technology innovation, including major advances in existing technologies and fundamental breakthroughs that introduce entirely new options, will deliver the advances needed to achieve our security, competitiveness and job creation, and environmental goals in a rapidly evolving world energy system.

> **Box 1: Recent Changes in the U.S. Energy Sector**
>
> Several factors have contributed to a period of dramatic change in the U.S. energy sector:
>
> - a transition from analog systems to increasing use of digital electronics and information technology in every energy sector—electric power, transportation, buildings, and industry;
> - the introduction of new domestic energy supply technologies, dramatically increased oil and gas production, and renewables deployment;
> - more efficient end-use technologies, such as LED lighting, electric vehicles, additive manufacturing, and energy management technologies and systems; and
> - increased risk to energy infrastructure from extreme weather and sea level rise, regional water stresses, cybersecurity, and other factors.

Continuous vigorous innovation building on existing progress offers an important opportunity to improve our energy systems. The Department's 2015 Quadrennial Technology Review[3] (QTR) identified hundreds of clean energy research opportunities for our homes, businesses, transportation, and power sectors that can help contribute to the Nation's climate goals. From building taller towers to capture higher wind speeds for wind energy production to developing higher efficiency photovoltaic (PV) modules that use earth-abundant materials; from using advanced membranes to capture carbon emissions from fossil-energy resources (SMR) to advancing the development of small modular reactors (SMR) for nuclear energy generation; from improving energy storage technologies for the grid to doubling battery energy densities for electric vehicles, there are exciting technology challenges and opportunities in front of us that will revolutionize our energy sector, ensure

American Energy Innovation Council, "Restoring American Energy Innovation Leadership: Report Card, Challenges, and Opportunities," February 2015.

"America's competitive advantage is a tireless dedication to innovation, particularly in energy. U.S. companies are driving an energy boom today — … — largely because they have significantly benefited from federally funded technology innovation, research, and development over the last four decades. These investments, together with critical private-sector innovations and commercialization, have created dozens of technologies vital to America's economic growth, competiveness, and environment, …."

Norman Augustine, John Doerr, Bill Gates, Chad Holliday, Jeff Immelt, Tom Linebarger

our security, spare our environment from the worst climate outcomes, and promote continued American economic competitiveness in the 21st century.

Moreover, the first and second installments of the Quadrennial Energy Review (QER 2015 and 2017)[4] noted that past innovation investments have significantly contributed to energy technology cost reductions, and that innovation in generation, transmission, storage, distribution, efficiency, and demand response technologies is essential to a robust and resilient energy system. Many of the QER's recommendations also pointed to the need to support innovative generation technologies, grid modernization, and advanced distribution system technologies at the community scale, among other technologies.

Accelerating U.S. energy innovation has many benefits. Those directly related to the goal of developing an advanced energy system include energy security, economic competitiveness, and environmental quality. R&D in energy can also have significant impacts and benefits in other fields. These benefits are discussed below.

Energy Security

A strategic objective of the United States for a future advanced energy system is to be resilient against interrelated energy security threats:

- Improve the collective energy security of the United States and its allies, neighbors, and friends: Using more diverse energy sources and technologies as well as having a strong domestic market and manufacturing capabilities can increase the resiliency and flexibility of the domestic energy supply chain, protect markets from supply disruptions, including cyberattacks, and reduce energy price volatility.
- Enhance system reliability: Energy services are deeply embedded in all critical infrastructures and services—both commercial and those required for military operations—including the electric grid, transportation, and telecommunications. As a result, the economy requires energy system reliability.

Innovations, including both incremental improvements and new methods for energy supply and use, have led to substantial changes and improvements in our national and international energy systems. In the United States, nuclear power innovation progressed over a 20-year period from experimental technology to Federally owned and operated projects, and to Federally subsidized demonstration-scale power plants. Full-scale privately financed commercial deployment followed, eventually resulting in about 100 GW of generation capacity by 1990 (Figure 2).

U.S. Commercial Light Water Reactor (LWR) Generation Capacity and DOE LWR-Related Annual R&D Funding (1950 -2000)

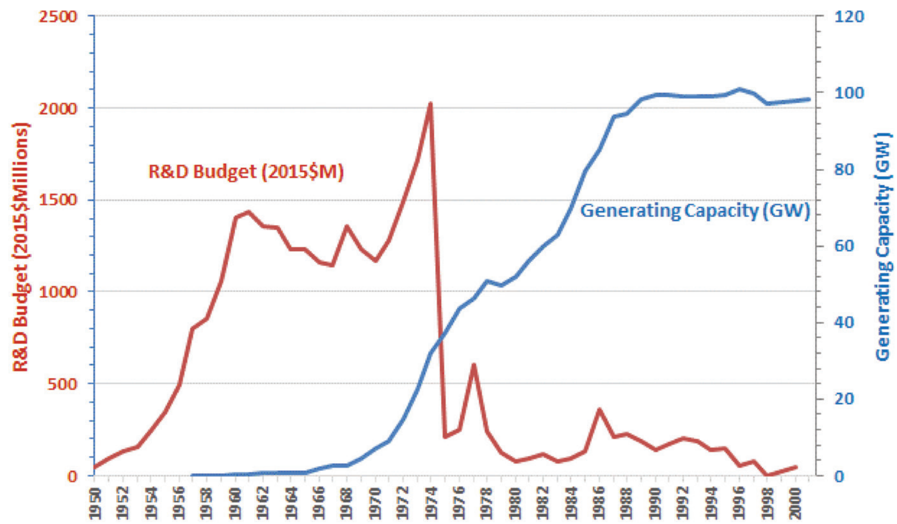


Figure 2: Innovation in nuclear power, supported by Federal R&D, enabled the subsequent development of U.S. commercial nuclear generation capacity (1950–2000). Source: DOE[5]

Early Federal shale gas R&D funding, primarily between 1976 and 1981, but continued to 1992, set the stage for the sharp increase in domestic shale gas production in the mid-2000s (Figure 3). The Federal funding (DOE R&D funding) was focused on reservoir characterization and basic science. A multipronged approach to public-private R&D and deployment, comprising Federal investment, Gas Research Institute (GRI) funding, and a time-limited tax credit, resulted in the emergence of shale gas as the most striking feature of domestic gas production since 2000, rising from less than 1 percent of overall production in 2000 to over 40 percent in 2015.

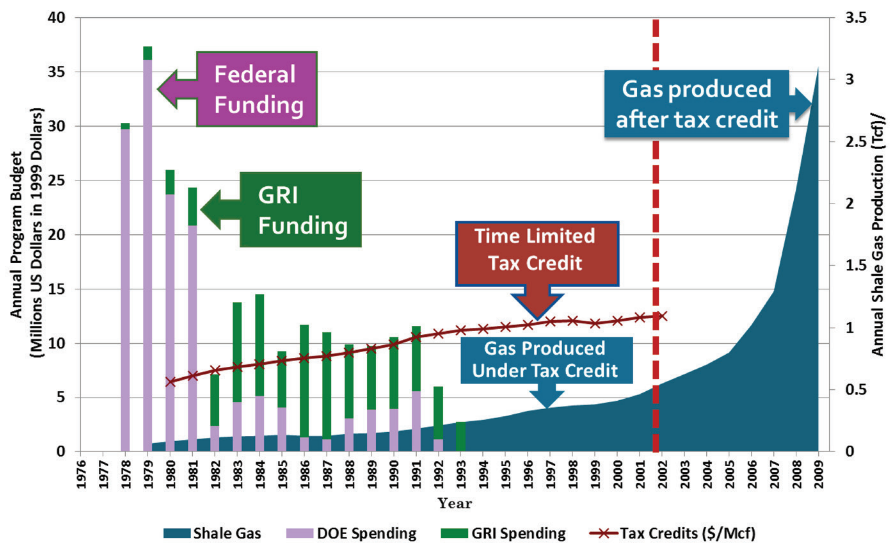


Figure 3: Steady R&D funding and a time-limited tax credit led to an increase in U.S. shale gas production (1976–2009). Source: MIT[6]

Finally, decades of Federal, state, and industry R&D investments have significantly contributed to recent cost reductions in renewable energy and energy efficiency technologies. Government and university R&D programs produced ten of the sixteen breakthroughs in solar PV cells, primarily during the 1970s and 1980s.[7] Intensive Federal R&D, followed by industrial R&D, together with economies of scale and learning in manufacturing and deployment led to the cost reductions shown in Figure 4 for wind, solar PVs, light emitting diodes (LEDs), and batteries from 2008 to 2015.

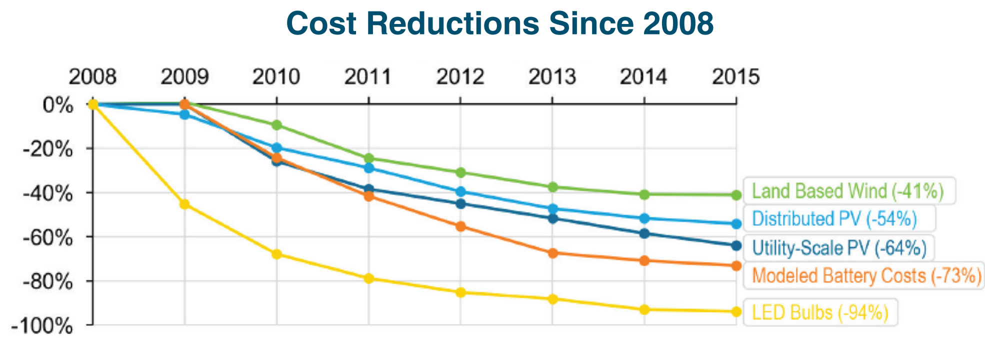


Figure 4: Indexed cost reductions for wind, solar PVs, LEDs, and batteries (2008–2015). Source: DOE[8]

In transportation, innovation in producing shale oil and gas (Figure 3), together with more efficient vehicles has reduced oil imports and is projected to further reduce them (Figure 5), making the U.S. energy supply (and economy) more resilient, although still vulnerable, to impacts from world oil market volatility.[9] The actual domestic supply will depend on oil prices over time (projected by the U.S. Energy Information Administration (EIA)[10] to reach roughly $130/barrel in 2015$), technology advancements, and other factors. Progress in hybrid and electric cars has been dramatic, substantially as a result of the reductions in battery costs shown in Figure 4. Innovations in electric or fuel cell vehicles that enable their large-scale market use could further strengthen U.S. energy security. As a result, the reduction in import levels, shown in Figure 5, is attributed to a combination of increased domestic supply and vehicle and other efficiency gains, and both are the result of technology advances.

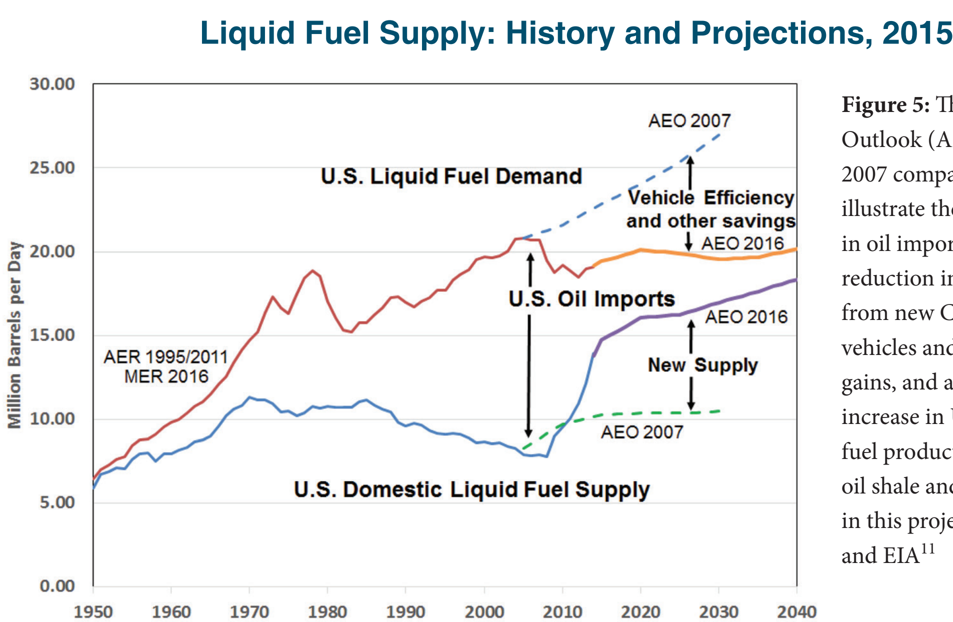


Figure 5: The EIA Annual Energy Outlook (AEO) projections for 2007 compared to those for 2016 illustrate the dramatic reduction in oil imports resulting from the reduction in demand growth from new CAFE standards for vehicles and other efficiency gains, and also because of the increase in U.S. domestic liquid fuel production, primarily from oil shale and natural gas liquids in this projection. Sources: DOE and EIA[11]

All of the examples shown in Figures 2–5 required concerted Federal R&D efforts to greatly reduce the risks of developing and introducing new technologies into the market.

Economic Competitiveness

Another strategic objective for the U.S. advanced energy system is global economic competitiveness. As energy underpins every aspect of the Nation's economy, the future advanced energy system would

- *Build economic opportunities:* Maintaining and expanding our technological edge will expand opportunities to export our clean technologies, products, and services to other countries while reducing those we import, leading to jobs creation and increased domestic manufacturing.
- *Drive down energy costs and use:* Low energy costs and reduced energy consumption will increase the competitiveness of U.S. businesses and provide greater spending power to American families.
- *Improve energy access and equity:* In many rural and remote locations in the United States, communities lack access to reliable and affordable energy services. Advanced energy technologies can enable greater energy access, helping boost the quality of life and economic development.

Ambitious and sustained action on energy innovation is also a pro-growth economic strategy. As energy use is so pervasive throughout the U.S. economy, the relationship between energy system improvements and the economy is complex. Based on an extensive survey of over 30,000 employers, the 2017 DOE U.S. Energy and Employment Report (USEER)[12] determined that

- 6.4 million Americans (of ~141 million total full-time workers) work in our traditional energy industries, including production, transmission, distribution, storage, and energy efficiency. Of these, about 800,000 employees contribute to the production of low carbon energy, including renewable energy, nuclear energy, and low emission natural gas.
- Of the 2.2 million Americans employed in the design, installation, and manufacture of Energy Star-rated products and services, there are about 1.4 million energy efficiency construction jobs and 290,000 manufacturing jobs.
- Of the 2.4 million workers in the motor vehicle and components industry (exclusive of auto dealerships), at least 710,000 employees work with alternative fuels vehicles, including natural gas, hybrids, plug-in hybrids, all electric, and hydrogen fuel cell vehicles, or with motor vehicle parts that contribute to fuel-efficient vehicles.
- Some of the fastest growing industries in 2016 were energy efficiency (+7%), solar (+25%), wind (+32%), and alternative fuels vehicles (+36%).

The world's largest economies recognize that scaling up low-carbon technologies is an economic opportunity. For example, global clean energy investment in 2015 was estimated to be roughly $350 billion.[13] The International Energy Agency estimates that the pledges made by the countries in the Paris Agreement require a cumulative total of more than $60 trillion of global investment in the energy sector through 2040.[14] As the demand for these technologies grows, this will lead to investments in manufacturing capabilities and jobs.

Given the jobs and economic impacts cited above, the United States can achieve a cleaner energy system while maintaining robust economic growth. Over recent decades, the United States has successfully decoupled economic growth from emissions. Per EIA data from 2008 to 2015, energy CO_2 emissions fell 9 percent while the U.S. economy grew by 10 percent, and since 2000, the U.S. GDP went up by 30 percent while carbon emissions decreased by 10 percent.[15] Over the last two years, the global economy grew by over 6 percent while energy emissions stayed flat. As other nations invest in energy innovation, America's challenge will be to maintain our leadership, accelerate the pace of economic growth, and reduce emissions at the same time.

Because energy is treated in the markets as a commodity, direct industry R&D investment has been relatively low, and the R&D investment that has taken place has often been focused on incremental improvements of technologies. Further, because of the long times to market and capital intensive nature of energy systems, venture capital in this space has declined to low levels (see Chapter 2). As a result, Government R&D has been critical in supporting R&D advances for the U.S. energy system. Numerous studies have found large public returns on Government-funded R&D in energy. A retrospective analysis by the National Academies of Sciences, Engineering, and Medicine found a 20 to 1 return (in direct economic benefits) on public investment in energy efficiency R&D for the portfolio they examined from 1978 to 2000.[16] U.S. consumers currently spend roughly $1.375 trillion per year on energy, and the external (nonmarket) costs of pollution add hundreds of billions more;[17] additional advances in clean energy technologies could provide substantial savings in these direct and indirect costs.

DOE's energy innovation investments have paid off directly for individual consumers. Some 40 years ago, a typical refrigerator used roughly 1900 kWh per year of electricity and was increasing. Today, with Federal and State supported R&D and standards, a new refrigerator uses roughly 400 kWh per year of electricity, and it costs less in constant dollars even with more features. Compared to the typical refrigerator 40 years ago, this saves the average family about $150/year in electricity use;[18] for the 115 million U.S. households, total savings are then about $17 billion per year, more than the cost of all the DOE appliance R&D work over its nearly 40-year history and roughly 4 times all of the energy efficiency, nuclear, fossil, renewable, and grid modernization R&D supported annually by DOE.

A standard 60-watt incandescent lightbulb costs roughly $1 and lasts about 1,000 hours; in comparison, while an LED light now costs about $2 (and continues to drop), it uses just 8 watts of power and lasts 20 times longer. Compared to incandescents, the 200 million LED lights already sold in the United States[19] will save roughly $24 billion in net costs over their lifetimes.[20]

Going forward, successful development of advanced batteries with high energy densities, fast recharge rates, and low costs to make electric vehicles broadly competitive with conventional vehicles could provide substantial savings to consumers. A vehicle using $3/gallon gasoline that gets 30 mpg costs about $0.10/mile in fuel costs. An electric vehicle using $0.10/kWh electricity at 0.34 kWh/mile costs $0.034/mile, or one-third the cost for gasoline. This would provide large operating cost savings to consumers; it could also save the United States roughly $90–$100 billion/year[21] if these vehicles were able to displace the oil imports shown in Figure 5.

Opportunities for consumers and businesses to move beyond the commodity paradigm are now emerging. This is especially true as the integration of electricity and information infrastructures proceeds rapidly, as described in QER installment 2.

Environmental Quality

The third strategic objective of the U.S. energy system is to be environmentally responsible. The future advanced energy system would have a minimal environmental footprint, including reductions of pollutants that impact human health and the environment. A shift to a clean energy system can lead to deep reductions in greenhouse gas (GHG) emissions ("deep decarbonization") and other harmful pollutants associated with energy use across all aspects of energy production, transformation, and use.

Energy innovation will also provide substantial benefits related to clean air, clean water, and reduced CO_2 and other GHG emissions. In the near-term, reduced air pollution can lead to a range of health benefits as air pollutants have been linked to health impacts, such as respiratory and cardiovascular problems. In the United States, for example, an analysis attributed the number of particulate matter and ozone-related premature deaths due to energy sector emissions at 36,000 per year.[22] An analysis published in 2011 estimated economic damages at about $60 billion per year in 2002 from the utility sector, attributable to SO_2, NO_x, VOCs, NH_3, $PM_{2.5}$, and $PM_{10-2.5}$, mostly from coal-fired power plants.[23] The National Academies of Sciences, Engineering, and Medicine's National Research Council (NRC) found similar costs of about $60 billion for 2005 due to SO_2, NO_x, and PM.[24] Lower energy-related pollution generates better health outcomes and lowers health care costs. Some other studies incorporated a wider range of emissions and damages and found higher values.[25] Increasing the pace of energy innovation can further aid in reducing the cost of compliance with existing emission standards and in reducing the time required to achieve compliance.

Energy innovation can also reduce impacts of climate change, which are expected to increase as atmospheric concentrations of GHGs increase. The impacts include the following:

- Increasing temperatures above a certain range reduce the human ability to work outdoors[26] and are expected to impose significant costs on national GDPs.[27]
- Precipitation patterns are expected to shift and evaporation to increase, with increased drought in many subtropical and mid-latitude regions, with severe drought expected in the U.S. Southwest,[28] and increased wet conditions in some mid-latitude and many high latitude areas.[29]
- Higher temperatures and more extreme weather will generally lower agricultural yields, and projected increases in drought will also challenge agriculture in many areas.[30]
- Increased temperatures are expected to lead to more extremes in weather patterns.[31]
- Sea levels are projected to rise by roughly 0.5 to 1 meter by 2100 because of rising temperatures causing ocean water to expand[32] and land-based ice to melt. Large-scale loss of ice from Greenland or Antarctica would further increase these levels.[33]
- About a quarter of the CO_2 that is released into the atmosphere by burning fossil fuels is absorbed by the oceans on an annual basis[34] and over time is perhaps 70–80 percent of total emissions.[35] This increase in CO_2 in the oceans has made surface levels about 30 percent more acidic[36] since the industrial revolution began and will increasingly impact ocean ecosystems.[37]

Thus, the pollution of air, water, and land and the release of GHGs due to energy-related activities pose substantial costs to human health and the environment. These are examined in more detail in the QTR 2015.[38]

Path Forward

The pursuit of an advanced energy system for the United States is rich with opportunity and challenges. The United States can and has made great strides toward improvement with existing technologies, but it is clear that innovation, including major advances in existing technologies and fundamental breakthroughs that introduce entirely new options, must continue to be pursued. Numerous opportunities were identified in the Department's 2015 QTR and the first and second installments of the QER (2015, 2017). The following chapters describe how to pursue these opportunities.

Chapter 2: Public and Private Roles in Energy Technology Innovation

A substantial public role has developed over many decades to address the energy challenges that face the United States. Long experience has led to the use of cost-shared competitive awards of publicly funded R&D, and such R&D is demonstrating a significant record of performance. The following sections examine the basis for these R&D activities, how they are structured, and what their results are.

Need for Federally Funded R&D

American Energy Innovation Council, "Restoring American Energy Innovation Leadership: Report Card, Challenges, and Opportunities", February 2015.

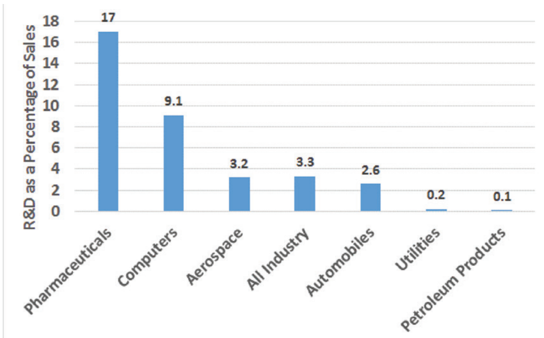
"Federal funding remains the only viable avenue of support for energy technology research and large-scale demonstration projects."

Norman Augustine, John Doerr, Bill Gates, Chad Holliday, Jeff Immelt, Tom Linebarger

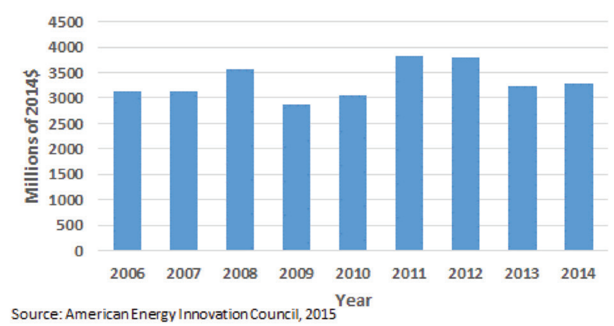
Federal funding of early-stage R&D is particularly important in the energy innovation area. Corporate investments in energy R&D as a share of sales are generally smaller than those in other key technology industries, as shown in Figure 6a for selected sectors. For clean energy, the American Energy Innovation Council (AEIC) estimated that corporate R&D investments were roughly \$3.0–\$3.8 billion per year during the period 2006–2014 (Figure 6b), and U.S. venture capital (VC) investments dropped sharply from their level of roughly \$4 billion per year in 2007–2012 to roughly \$1 billion in 2014 (Figure 6c). VC support for early-stage opportunities dropped even more in the United States from 2007 to 2014, but rose a bit in 2015 and 2016, as shown in Figure 6d.

Chinese early stage investment started sharply in 2015 and dwarfed that of the United States through the third quarter of 2016.[39] Total global investment in clean energy technologies is estimated by Bloomberg New Energy Finance at \$348 billion in 2015, with China's investment through private and state-owned enterprises nearly double that of the United States. Further, China announced a plan in January 2017 to invest \$360 billion in renewable energy by 2020.[40]

6a. R&D Intensity of Industry, 2013

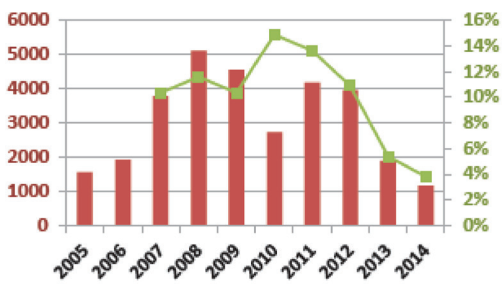


6b. Estimated U.S. Corporate Clean Energy R&D



6c. U.S. Clean Energy Venture Capital Investment

$M; % Total U.S. VC Investment



6d. Early Stage Investment in Clean Energy Technology

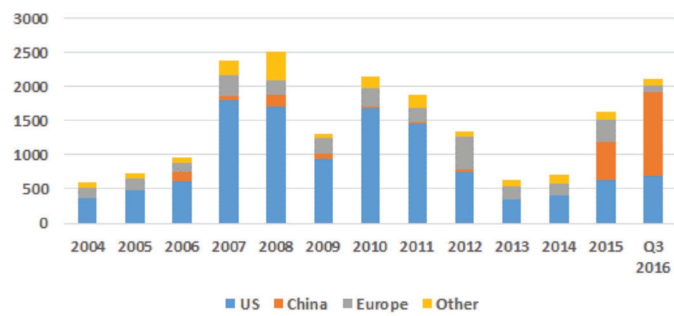


Figure 6: Private R&D investment. (a) Private R&D investment as a percentage of sales for key technology sectors (source NSF[41]); (b) U.S. corporate clean energy R&D investment (Source: AEIC)[42]; (c) U.S. Clean energy venture capital investments (Source AEIC[43]); (d) Global early-stage clean energy technology investments (Source: BNEF[44]). It is useful to note the low level of private energy R&D investment in the United States (Figure 6a) and the sharp decline in U.S. VC investment in Figure 6c with a small uptick in Figure 6d, compared to heavy Chinese early stage investment in Figure 6d. These investments can be compared to U.S. DOE applied energy R&D, as indicated in Figure 7 below.

Some analysts have examined this record and concluded that the standard VC finance model is not well suited to the challenges of the energy sector.[45] Further, they found that the limited continuing VC investments shifted away from hardware and more towards software in the clean energy space.

Corporate and VC investment in energy technology R&D is low because of factors such as the long time frames and risks of developing new technologies; the high capital costs of energy technologies; the low margins for producing commodity fuels and power, resulting in long payback times; and requirements for new capital intensive infrastructure (see text box). Further, the full costs of energy, such as energy security or impacts on public health or the environment, are not included in the market price of energy, undercutting the market viability of advanced energy technologies that could help address these challenges. These and other factors that discourage private investment are detailed in the appendix.

Federal R&D investment in the early stages of science and technology innovation will be essential to stocking the pipeline of ideas, materials, devices, and processes that contribute to energy innovation.The public role is particularly important in early stage R&D and early maturation of the technology, followed by a transition to a primarily private sector activity.

Venture Capital: The Wrong Model

"Cleantech companies commercializing innovative science and engineering were especially unsuited to the VC investment model for four reasons. First, they were illiquid, tying up capital for longer than the 3–5 year time horizon preferred by VCs, because working out the kinks in new science is time consuming. Second, they were expensive to scale, often raising hundreds of millions of dollars to build factories, even while the fundamental technology was still being developed. Third, there was little room for error because these companies competed in commodity markets with razor-thin margins—against cheap silicon solar panels or abundant oil and gas—making it difficult to invest in R&D while also operating a lean manufacturing operation. Finally, the likely acquirers—utilities and industrial giants—were unlikely to acquire risky start-ups and averse to paying a premium for future growth prospects when they did invest. For most cleantech start-ups, this meant that the sale price couldn't offer the outsize returns investors needed. These factors conspired to cost VC investors hundreds of millions of dollars before learning whether their cleantech bets had a chance of success—an order of magnitude greater than the equivalent software experiment."

Benjamin Gaddy, Varun Sivaram, Francis O'Sullivan, "Venture Capital and Cleantech: The Wrong Model for Clean Energy Innovation," An MIT Energy Initiative Working Paper, July 2016[45].

Enabling Energy Science and Technology Innovation

The Federal government provides the support of the basic science that opens options for future energy systems as well as trains the next generation of scientists and engineers needed in high technology industries. DOE, through its applied energy offices (Energy Efficiency and Renewable Energy [EERE], Fossil Energy [FE], Office of Electricity Delivery and Energy Reliability [OE], Nuclear Energy [NE]) and ARPA-E, has been the largest U.S. Federal supporter of applied energy R&D, generating new inventions, conducting early stage R&D, and working with industry to provide leverage and reduce risks. The DOE (from the Office of Science) supports the majority of the physical sciences (physics, chemistry, etc.) research in the United States, including fusion research as well as materials science, computational science, and biological sciences relevant to energy and environment. The Office of Science also supports major scientific user facilities for all U.S. scientists, time on which is awarded competitively.[46] About a third of the supported research is inspired by the needs of truly transformative energy technologies (e.g., developing new materials that could better withstand extreme environments, developing new lower temperature catalysts that could lower the energy usage of industrial processes, developing new computational techniques for modeling combustion in new efficient and smaller engine designs, to name a few).

DOE supports energy innovation through a variety of mechanisms.[47] The work generally begins by engaging the entire energy science and technology community—industry, universities, National Laboratories, nonprofits, stakeholders, and others—to identify the best R&D opportunities. Much of the R&D is then conducted through competitive solicitations with rigorous ongoing peer review. The R&D process includes a number of key elements:

- **Engaging the community.** DOE conducts many dozens of workshops annually with thousands of scientists and engineers from the energy community to identify key R&D opportunities, challenges, and other issues.[48]
- **Technology Roadmaps.** Building on this community engagement, detailed technology roadmaps identifying the most important R&D opportunities are developed involving leading experts from industry, universities, National Labs, and others in the respective R&D fields. Over 100 DOE roadmaps, multiyear program plans, and basic research needs reports for key areas of R&D are currently available online.
- **Competitive Solicitations.** Drawing from the technology roadmaps and other sources, detailed funding opportunities are developed and run by DOE. The competition is intense. Internal and external experts serve as peer reviewers to score the proposals and enable selection of the most promising R&D activities. Award rates reflect this intense competition. For EERE in 2015, on average one award was granted per 12 proposals received. The first ARPA-E solicitation, attracted over 3,700 concept papers, of

which some 312 were invited to develop full proposals, for which there were only 37 awards. The high rate of applications and low award rates (given available funding) underscores that there are many good ideas and strong interest in energy R&D that private investors are not funding.[49]

- **Project Monitoring.** After an award is under contract, there is ongoing tracking of financials and performance, and there are rigorous independent expert peer reviews during the course of the project to determine if the awardee is making appropriate progress. Of the 46 Energy Frontier Research Centers (EFRCs) that won 5-year competitive awards in 2009, 22 of them were able to win new 4-year awards in the open competition in 2014, a success rate of 48 percent, and 10 awards were made to new entrants.[50]
- **Modalities.** Different types of R&D missions benefit from different funding modalities, and DOE works to match them well.[51] Much work is funded through principal investigators; these are generally smaller, more focused R&D efforts. Larger teams of researchers are funded through modalities such as the Energy Frontier Research Centers, which are focused on basic research by assembling a critical mass of dedicated researchers in closely related disciplines. Energy Innovation Hubs and Bioenergy Research Centers (BRCs) are large, comprehensive, multidisciplinary research centers, with Hubs focused on bridging the gap between basic and applied research to address a single critical national energy need and BRCs focused on developing the basic science for realizing commercially viable cellulosic biofuels and related work. Manufacturing USA centers are public-private partnerships that each have a distinct technology focus but a common goal of advancing U.S. interests through manufacturing innovation, education, and collaboration. Regional partnerships offer a new approach for key areas of innovation.[52] Each of these approaches has particular strengths suited for its particular R&D mission.
- **Technology Transition.** To better coordinate, measure the effectiveness of, and optimize the transition of early-stage R&D to applied energy technologies through technology transfer, commercialization, and deployment activities, the Office of Technology Transitions (OTT) measures and coordinates this work across DOE. OTT builds on technology transfer and commercialization activities for specific areas of R&D within programs and National Laboratories, administers the statutorily created Technology Commercialization Fund, and facilitates the exchange of information on innovative technology and commercialization practices among DOE Program Offices and National Labs.[53]

Thus, DOE's R&D programs largely focus on earlier stage R&D and the best technical concepts before transitioning and handing off to industry as technology options mature. DOE's Loan Programs Office also contributes to that transition to the marketplace. DOE engages the broad energy science and technology community to identify and roadmap key R&D opportunities; DOE's competitive, cost-shared, limited-term awards force a high level of performance; and DOE's rigorous review processes work to ensure performance throughout the contract period. These and other activities develop a strong portfolio of R&D projects, drawing from the knowledge base of the broad community and using competitive processes to guide selections. These performance-based processes have generated a high level of R&D performance.

R&D Performance

All R&D is risky, and some projects will fail. Indeed, if there aren't failures, then it isn't really research. The goal of R&D investments is to have enough successful projects, and some that "hit the ball out of the park," so that these more than compensate for the failures. For DOE, the goal of R&D is to provide net benefits for the American public, considering national energy security, economic competitiveness, and environmental quality.

One indicator of performance is the R&D 100 Awards. These "Oscars of Innovation" have been given annually to innovations around the world for the past 50+ years.[54] Judges for this competition are independent experts. DOE-supported R&D at National Labs, industry, and universities won 33[55] of these awards in 2016 and has typically won about one-third of these awards each year in recent years. No other institution comes close. A study in 2008 found that Federally funded R&D with private partners took an increasing share of R&D 100 Awards over time, increasing from the 10–20 percent range in the 1970s to the 50–70 percent range since the late 1980s.[56]

Invention disclosures and patents are another important measure. DOE and its National Labs have generated more patents per R&D dollar, by far, than other Federal agencies conducting R&D that are tracked in the annual Federal Laboratory Technology Transfer report to Congress, as shown in Figure 7 for the six largest R&D funding agencies.

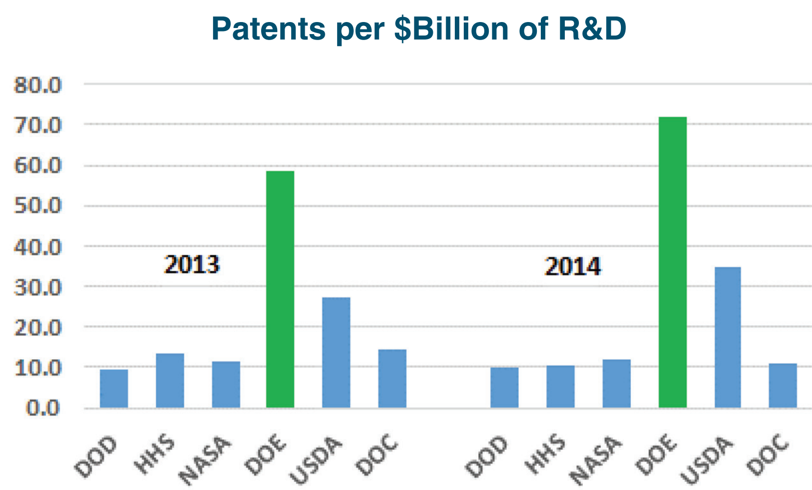


Figure 7. Patents per billion dollars of R&D investment for the six agencies that are the largest funders of R&D. DOD=Department of Defense, HHS=Department of Health and Human Services, NASA=National Aeronautics and Space Administration, USDA= U.S. Department of Agriculture, and DOC=Department of Commerce. Source: National Institute of Standards and Technology.[57]

Mission Innovation

Givin the importance of public sector innovation, in November 2015, the United States and 19 other nations launched a new initiative called Mission Innovation seeking to double their public investment in clean energy R&D over five years.[58] Such a doubling would result in nearly $30 billion of global public R&D investment in 2021. The partner countries, including the countries that have joined since 2015, represent 75 percent of the world's CO_2 emissions from energy, and more than 80 percent of the world's clean energy R&D investment.

The U.S. commitment is to double annual public clean energy R&D funding from $6.4 billion to $12.8 billion over five years.[59] Currently, DOE accounts for about three-fourths of the U.S. energy innovation portfolio or $4.8 billion.

In parallel, far-sighted private sector investors (the Breakthrough Energy Coalition) pledged at the Paris climate talks in 2015 to develop large new investment vehicles to help move outcomes from the Government-funded efforts into commercial applications. This is intended to complement a doubling of public investment in clean energy R&D by the 20+ Mission Innovation countries. In December 2016, the Coalition announced their first fund, called Breakthrough Energy Ventures (BEV), which will invest more than $1 billion across early stage R&D to commercialization of clean energy opportunities. BEV intends to differ from normal VC practice by providing long-term patient capital (for example, the fund has a life of 20 years—double the normal VC fund lifetime) that will make larger investments across a spectrum of early-stage to commercialization opportunities.[60]

Together, these two initiatives establish clean energy innovation as a foundation for energy security, economic prosperity, and environmental stewardship.

Energy Innovation R&D Funding

In its 2010 report on energy R&D, the President's Council of Advisors on Science and Technology (PCAST) noted that "[a] standard benchmark for overall Federal R&D funding in industrialized countries is 1 percent of GDP … If energy expenditures represent 8 percent of GDP, a fairly typical level for industrialized countries …, then 0.08 percent would be the benchmark for Federal energy R&D." [61] U.S. GDP was about $18.7 trillion at the end of the third quarter of 2016. Applying the benchmark estimate to that GDP gives Federal R&D funding of about $15 billion/year, more than double the current energy innovation R&D funding of $6.4 billion/year. The American Energy Innovation Council, a group of technology company CEOs, made a similar recommendation of $11 billion to $16 billion per year for energy innovation R&D.[62]

This report recommends growth of the budget to double its current level over a five-year period of FY 2018–2022. That level of funding would allow for significant new programs as well as reorientation of current research to high priority areas. This funding level is also consistent with the DOE portion of the Mission Innovation effort described above.

As described in this chapter, Federally funded R&D serves a critical role in meeting U.S. energy security, economic competitiveness, and environmental challenges. This R&D is done by engaging the broad energy science and technology community to identify the most important opportunities, conducting fiercely competitive solicitations to select the best proposals, and rigorously monitoring the work to ensure it is done well. These efforts have generated high returns for the American public. Further, the level of investment is low relative to the need by a factor of two or more. The sections that follow describe strategic directions for the US R&D clean energy portfolio as the existing funding is reallocated and as the additional Mission Innovation funding is deployed.

Chapter 3: Opportunities for Innovation

Given pressing energy challenges described above, the R&D mechanisms to address them through public-private partnerships, which have a demonstrated record of performance, and the general scale of funding needed for energy innovation R&D, this chapter focuses on the key question of priority. Specifically, what are the high-priority technology opportunities that could build a strong foundation for the Nation's continued leadership in global energy innovation?

Figure 8 presents a funding profile for a doubling of the energy innovation R&D budget from FY 2018 to FY 2022. The profile envisions growth of the ARPA-E annual budget to $1 billion, the creation of regional energy innovation partnerships funded at $500 million per year by FY 2022, and significant growth in the Science and Applied Energy R&D programs.

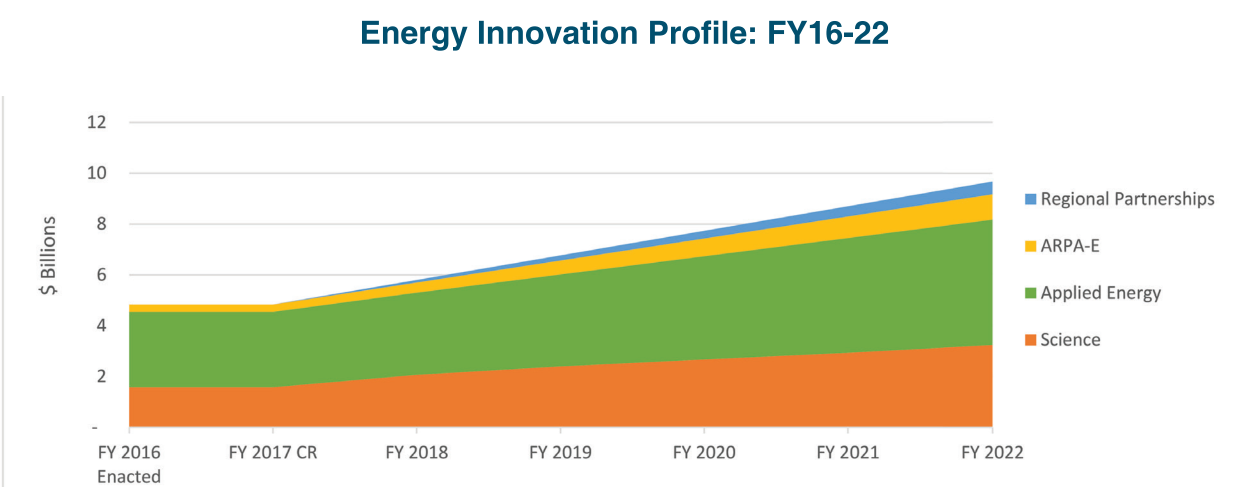


Figure 8. Potential funding profile over the five-year period FY 2018–2022 for Science, Applied Energy, ARPA-E, and Regional R&D. CR=continuing resolution

Framework for Review

In 2016, DOE conducted a strategic review of its entire energy science and technology R&D portfolio. This review engaged the Department's senior leaders and technical staff and National Laboratory experts, and drew from the work of the 2015 QTR and the broad research literature.

As part of this review, DOE conducted an analysis of the impact of meeting or exceeding Departmental energy technology program goals on energy-related CO_2 emissions in the United States. DOE analyzed the impacts of such successful innovation both alone and in combination with additional policies that incentivize reductions in energy-related CO_2 emissions.[63] The analysis estimated the potential aggregate impact of these goals on CO_2 emissions from the U.S. electric power and end-use (i.e., buildings, industry, and transportation) sectors.

Successful R&D activities that drive innovation in clean energy technologies can result in significant reductions in energy-related CO_2 emissions through a cleaner electricity generation mix and improved efficiency of end-use energy consumption. However, the projected emissions reductions from end-use sectors—particularly the industrial and transportation sectors—in this analysis fall short of the levels needed to mitigate the worst impacts of climate change.

Also as part of this review, a map of the Department's current energy innovation portfolio was developed (Figure 9), which set a baseline for this analysis and was also used to identify critical gaps.

The portfolio map is structured around the energy sectors—grid, electric power supply, transportation, industry, buildings, and fuels—rather than the DOE program structure to enable an informed discussion of key technology opportunity areas. This also illuminated gaps in the current portfolio, especially the need for a new program in innovative carbon management, which is described further below. Boxes within the columns indicate some of the most important technologies or energy services provided. The numbers in each box represent the FY 2016 funding Congress has provided for each of these activities.

Color coding indicates the relative level of investment of the programs collaborating in a particular sector. The six Departmental R&D crosscutting budget initiatives are included at the bottom of the map for reference: advanced materials, energy-water technologies, exascale computing, grid modernization, subsurface science and technology, and supercritical CO_2 technology. Funding shown for each of these priority areas is included for transparency but is already embedded in the sector totals in the portfolio map.

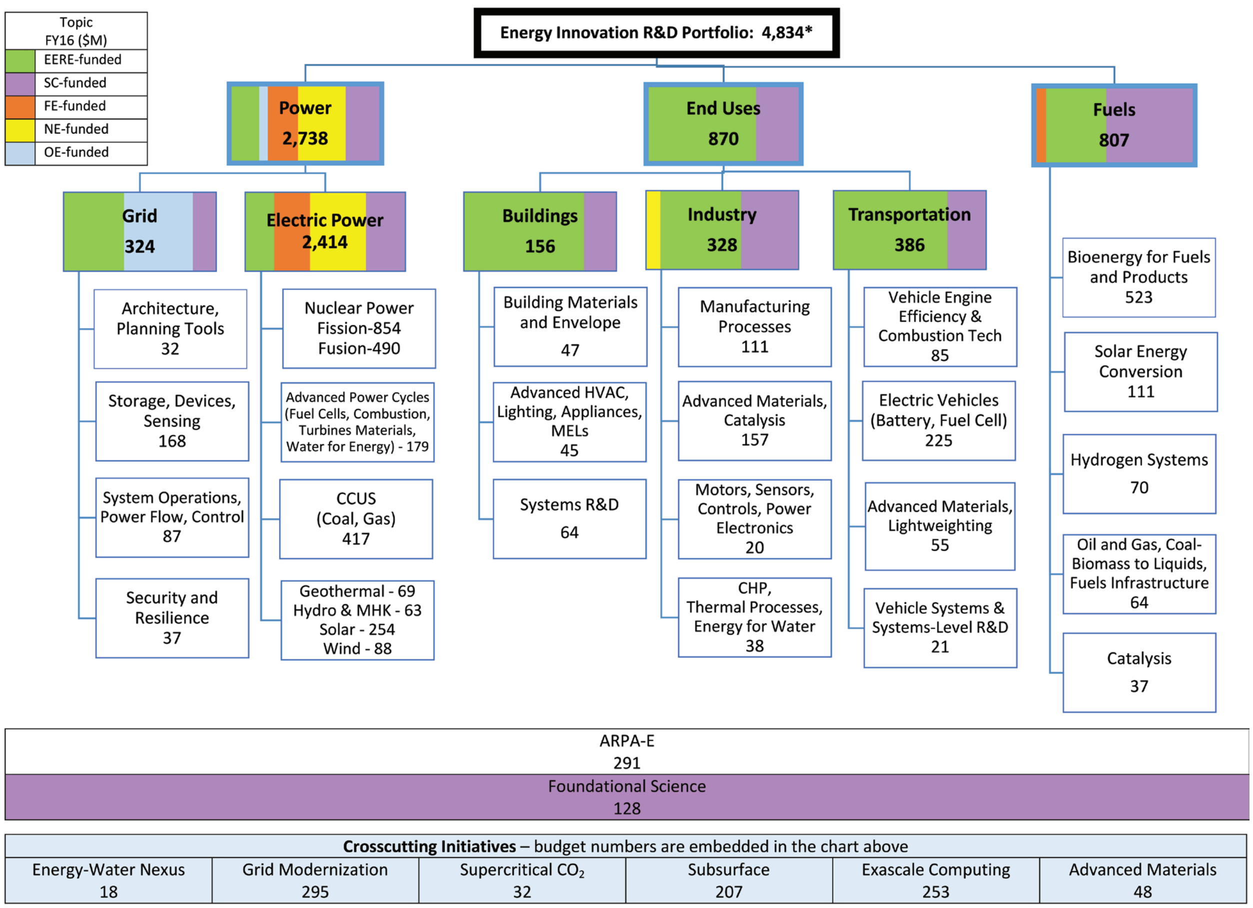
Where appropriate, Office of Science basic research programs (e.g., solar energy conversion, cataylsis R&D, materials R&D) are mapped to applied technology sectors, but the inherent application-agnostic nature of basic research resulted in some of this funding being placed in a separate box unattached to a particular energy sector column. Basic science activities have the potential to benefit numerous other applications, including non-energy applications.

Key takeaways from the strategic review included the following:

- ARPA-E should be significantly expanded to the level of funding envisioned when it was initially proposed by the National Academy of Sciences;
- Regional energy innovation partnerships should be developed as a new element of the portfolio;
- Grid modernization R&D that is underway now should be continued and expanded significantly. That work, including energy storage, is essential to enable many of the options that will be created by energy innovation R&D.
- Well-diversified electric power generation (through advanced nuclear generation, advanced renewables, and advanced carbon capture and storage) is an essential component of an efficient, secure, and resilient electric power system. The significant current investments in this area should continue, with some targeted evolution, and funding for new efforts (e.g. advanced nuclear generation) should be expanded.
- Substantial growth for energy innovation R&D in the building, transportation, and industrial sectors is needed. These areas offer opportunities that are at an early stage and are ready for additional productive R&D effort.
- Modest funding for R&D on innovative carbon management can diversify options for reductions in atmospheric concentration of greenhouse gases.

- Fuels R&D (on hydrogen production and uses, biomass conversion, and sunlight to fuels) should continue with targeted evolution of program activities. R&D to expand options and reduce costs of biofuels can lead the way to drop-in biofuels that have fewer barriers to deployment than other biofuel options.
- Support for use-inspired fundamental science, including the development of exascale computing, is an essential underpinning of future innovation in applied energy R&D, and should be expanded significantly.
- Continued use of crosscutting research teams and related coordinated budgets is an effective way to manage R&D in challenging areas that require expertise and have applications across multiple DOE program areas.

While this should not be viewed as a full budget plan, the sections that follow describe in detail how DOE's portfolio could evolve and expand productively over the five-year FY 2018–2022 period over which the planned doubling of energy innovation funding would occur. The scale of the planned doubling opens important new opportunities, highlighted in Chapter 3, that cannot be explored at current budget levels. The purpose here is to show how doubling might manifest and the dramatic gains to the nation that doubling would represent.



*Numbers are approximations and have been rounded

Figure 9. Portfolio map for DOE energy science and technology R&D.

ARPA-E

($291 million in FY 2016)

In 2005, leaders from both parties in Congress commissioned a report on U.S. competitiveness, which recommended that Congress establish an Advanced Research Projects Agency within the U.S. DOE modeled after the successful Defense Advanced Research Projects Agency (DARPA), the agency credited with such innovations as GPS, the stealth fighter, and computer networking.[64]

In 2007, Congress passed, and President George W. Bush signed into law, The America COMPETES Act, which officially authorized ARPA-E's creation. In 2009, Congress appropriated $400 million to the new Agency, which funded ARPA-E's first projects.

ARPA-E was established with the mission to overcome long-term high-risk technological barriers in the development of energy technologies by promoting revolutionary technical advances and accelerating their development in areas that industry by itself is not likely to undertake because of technical and financial uncertainty.

In its first eight years of funding, the Agency has developed a unique and effective operational model to address its mission and goals and has demonstrated significant early impact. As of February 2016, about 200 project teams had graduated from ARPA-E support. At that time, 36 projects had formed new companies, 45 current and former ARPA-E project teams had already raised over $1.25 billion in private-sector investment to commercialize their new technologies, and many of these had begun sales of products.

ARPA-E plays a unique role in DOE that is complementary to the Department's other R&D programs. In its first eight years of operation, the agency has demonstrated the ability to deliver value from early stage innovations and to identify and act quickly to address urgent needs and opportunities in advanced energy technology. The size of the young Agency is now disproportionately small given its role in advancing innovative technologies to the scale and readiness-level needed for hand-off to the commercial sector. In addition, ARPA-E's program solicitations are heavily oversubscribed – the average success rate from proposal concept to project is approximately 10% for focused technology programs and only about 1% for open solicitations. A significant number of innovative new ideas for advanced energy technologies are being left on the table.

It is clear that more funding could be deployed effectively in this area. To better fill the demonstrated demand and breakthrough opportunities, ARPA-E warrants an increase in funding to $1 billion, a 244 percent increase over current levels of $291 million. This funding level is what was recommended by the National Academies report, *"Rising Above the Gathering Storm."*

Regional Innovation Models

(No funding in FY 2016)

The United States has significant regional variation in its energy resource base, end-use energy markets, and innovation capabilities and interests. Exploring the linkage of these characteristics through regional partnerships offers the opportunity to leverage the needs and strengths of specific regions through the coordination of RD&D efforts among academia, industry, and government, including complementary DOE programs and capabilities at the National Laboratories.

As was shown in a series of university-hosted workshops in 2016[65], a regionally focused and directed approach to innovation could attract energy stakeholders and R&D performers not typically engaged through other government-funded research and draw upon the strengths of a geographic region's innovation ecosystem, linking the needs of industry and energy decision-makers with the unique capabilities in the region.
The workshops highlighted the value of regional partnerships, envisioned as cost-shared, public-private

partnerships (PPPs) that will develop regional R&D portfolios tailored to the characteristics of the regions that they serve. Partnerships that leverage public support with private-sector support to encourage industry investment and connect small businesses to resource networks, were highlighted as effective tools for building capacity and sustainable ecosystems. It was recognized that different types of investors are needed at various stages in the innovation cycle and that pathways to commercialization tend to require a range of partners throughout the technology life cycle. In nearly all of the forums, participants recognized that harnessing the opportunity to partner can strengthen the vital connections between innovation, manufacturing, a diverse workforce, and economic competitiveness. The value of a regional focus on innovation is widely recognized.

A decade ago, the Council on Competitiveness reported that "although national and state policies create a platform for innovation, the locus of innovative activities is at the regional level, where workers, companies, universities, research institutions and government interface most directly....Regions are the building blocks of national innovation capacity because they offer proximity and can provide specialized assets that foster firm-level differentiation."[66] In addition, recent studies concerning the growth of U.S. manufacturing reinforce the importance of applied research institutions, such as the DOE National Laboratories and land grant universities. These institutions can be anchors for regional innovation and growth.

Similarly, the National Academies' recent report, "The Power of Change: Innovation for Development and Deployment of Increasingly Clean Electric Power Technologies," highlights the value of regional partnerships to accelerate innovation and discusses the establishment of Regional Energy Innovation Development Institutes to complement Federal agency programs. The report envisions growth in funding for such Institutes "…over a 5- to 10-year period…" and emphasizes that such "…federal funding support would be critical to incentivize states, regions, state regulators, and private companies to come together to provide matching regional funds for these institutes."[66]

The regional partnership effort would require an initial investment of $100 million, increasing by $100 million per year to $500 million in FY 2022. The PPPs could maximize the synergies among capabilities and activities that are well underway to collectively accelerate the pace of innovation in the United States and positively impact economic and workforce development.

The Electricity Grid
($324 million in FY 2016)

Virtually every aspect of American commerce and industry depends on the continuous availability of affordable power from the electric grid. But today, the Nation's grid is facing increasing stress as a result of fundamental changes in supply and demand technologies, customer needs and expectations, and evolving policies and regulations. In short, the system is being asked to perform in ways for which it was not designed. As businesses, homes, and communities increasingly integrate digital technologies and automated systems into nearly all aspects of modern life, these stresses will continue to grow. Our dependence on the grid is highlighted when widespread power interruptions affect whole communities and regions after catastrophic natural disasters and other hazards.

The development of new technologies to modernize the electric power system would require investments from the private sector and the Federal Government. Utilities, power providers, consumers, and technology developers make investment decisions in an increasingly complex and changing regulatory and market environment. Through collaborative R&D, DOE can help to catalyze, accelerate, and facilitate the adoption of advanced technologies, tools, and techniques that will benefit the overall system and investment decision-making process. To address the challenges such as a changing generation mix; low load growth; increasing vulnerability to severe weather because of climate change; and growing interactions at the Federal, state, and local levels, the 2015 QER recommended that a Grid Modernization Initiative be funded at $3.5 billion over

10 years. The initiative was aimed at coordinating early and strategic investments by DOE in foundational technology development, enhanced security capabilities, and development of a set of tools that balances electric industry and consumer interests.

DOE's grid investments are paying off. For example, in 2009, DOE, along with the utility industry, invested more than $9.5 billion to help modernize the electric power grid by deploying more than 16 million smart meters, more than 9,000 automated switches, and more than 1,300 phasor measurement units to increase the amount of energy that can be reliably transmitted over the high-voltage transmission system. This helped to launch a period of extensive private investment, and electric companies have installed about 70 million smart meters through 2016, covering more than 50 percent of U.S. households. The phasors are helping avoid major outages on the transmission system, and the smart meters are providing consumers more information to better manage their electricity consumption and helping utilities restore power after outages more quickly.

This is just one example of how DOE investments in grid-related projects can create large societal and system-wide benefits, yet are too risky for the private sector to develop on its own. Building a reliable and resilient system as the transformation of the electric grid continues, rather than adopting a piecemeal approach, would help ensure that we effectively address the national challenges.

While much progress has been made, much more work is needed. Research opportunities to advance the capabilities of today's electricity delivery system include grid design and interoperability, control systems, transmission and distribution components, distributed energy resources, electric energy storage, planning tools, and physical and cybersecurity.

Reliability is a key attribute of the modernized grid. Current costs of power system disruptions have been estimated at roughly $20 billion to $50 billion per year, not including damage due to extreme weather.[67] Costs will rise as climate change drives increased severity of extreme weather events. Innovation in new grid architectures and associated monitoring, control, visualization, and prediction software and hardware could address these challenges.

Cybersecurity is a serious and growing security, safety, and economic challenge for the electricity sector and therefore establishes a need to develop innovative technologies to assess system trust, identify and eradicate embedded malware, and ensure resilient and adaptive control systems that can survive an incident while sustaining critical functions. Building on DOE's ongoing Cybersecurity program, an expanded, robust effort to support efforts focusing on securing all forms of communication systems and component devices (including fiber optic, wired, wireless, and microwave) would cost about $330 million over FY 2018–2022.

To date, the transformation of the power grid has focused on applying advanced digital information and communication technologies, but advances in hardware are also needed. Transformers are one of the fundamental building blocks of today's electric grid; essentially all energy delivered flows through at least one. An advanced solid state transformer (SST) could be utilized in strategic locations because of its enhanced functionality and flexibility. An expanded investment in support of a Transformers and Advanced Components R&D program would cost an estimated $200 million over FY 2018–2022.

The future grid will likely require substantial deployment of energy storage to enable electricity to be generated now and used later, especially as increased deployment of distributed generation is anticipated. In support of this objective, expanded investment for an applied Grid Storage R&D program would cost an estimated $250 million over FY 2018–2022 to focus on the development and system integration issues to enable the performance target of $125/kWh (system cost) for flow batteries through the development of innovative aqueous soluble organics. A complementary early science program focusing on new and emerging storage chemistries is estimated at $235 million over FY 2018–2022.

Demand-side management (including demand response, storage, and energy efficiency) can enable flexible demand, and time-varying electricity pricing can encourage consumers to use electricity at times when it can be supplied most affordably. This will be especially important as the integration of electricity and information infrastructures combine to form "the internet of things," where billions of smart devices hooked together can provide new services and business opportunities.

With a more flexible electricity system, variable renewable generation could supply the majority of our electricity generation. QER's second installment finds that in some regions system planners, taking into account technological advancements and the increased use of electricity storage, already operate periodically with up to 40 percent renewables and are planning for medium-term scenarios with 60 percent or more energy from variable energy resources (VERs).[68] Electricity markets on the modernized grid should provide accurate price signals and recognize the full value of flexible resources as well as externality costs, thereby encouraging efficient investment in and deployment of the most cost-effective resources. A substantial public-private investment is necessary to enable effective integration of emerging technologies into the grid system, and a regional grid demonstration program would cost an estimated $1 billion, to be cost-shared 50-50 with the private sector (DOE portion $500 million) over FY 2018–2022. These demonstrations would validate the ability to have a reliable system operating with lean reserve margins, an integrated planning, operations, and analytic platform, and a distribution system operating with high percentages of low-carbon resources. The QER's second installment also recommends significant expansion of existing programs to demonstrate the integration and optimization of distribution-system technologies. Demonstrations under this expanded program would be specifically designed to inform standards and regulations and increase regulatory and utility confidence in key technologies or technology systems.

This list is not exhaustive, but it highlights some of the major opportunities for R&D to meet the technical challenges of a grid in transition. Taken together, the estimated cost of Federal investments in grid technologies would potentially increase from $324 million in FY 2016 to $650 million in FY 2022 (+100%).

Electric Power Supply
($2.4 billion in FY 2016)

Substantial R&D and sustained investments in advanced supply technologies would provide essential elements of a modernized U.S. electricity grid, including clean fossil, nuclear, and renewable generation sources, in order to further reduce their costs (Figure 4), improve their performance, and better integrate them into the grid.

Carbon Capture, Utilization, and Storage (CCUS): Numerous studies show that a transition to clean, low-carbon energy systems is much less expensive in the long run if carbon capture with subsequent utilization or subsurface storage is available to support a diversified electric power generation system.[69]

First-generation CCUS technologies are currently being demonstrated. Two large-scale projects are operational and two more are nearly complete in the United States. To date, DOE-funded projects have captured and successfully stored over 13 million metric tons of CO_2. This is the equivalent of taking more than 2 million cars off the road for one year.

Globally, there are 16 large-scale CCUS projects in operation, many with DOE involvement, providing a wealth of data on CO_2 capture systems and CO_2 storage. As a result of continued DOE investment, the cost of CO_2 capture has dropped over 40 percent from 2000 to 2015. But new major investments are needed in coal and gas power systems to further reduce the cost of CCUS.

R&D to develop advanced combustion systems can improve the efficiency of CO_2 capture (e.g., pressurized oxy-combustion, chemical looping, and others) is a key element of reducing the cost of CCUS. Improving the performance of chemical separations of CO_2 from power plant emissions is another key element of cost reduction. Important lines of R&D in this area include advanced liquid solvents with lower energy requirements for CO_2 removal. Other solvents that create an easily separated solid precipitate containing the CO_2 offer potential energy benefits. Solid sorbents (e.g. metal organic frameworks) with high affinity for CO_2 and rapid reaction but still require less energy for CO_2 removal also offer opportunities. Still other third generation separations include advanced membranes with improved selectivity and easy passage of CO_2. All of these areas require R&D on system design and integration. This ambitious research program would cost an estimated $950 million over FY 2018–2022.

For CO_2 storage, R&D would further develop the capability for safe, permanent, cost-effective storage systems; improve understanding of reservoir geology and geochemistry; develop tools and computational models for the injection of the CO_2 underground and how it subsequently moves; identify and control risks of induced seismicity (earthquakes); and conduct field validation of the technologies, among others. A robust storage program would be funded at $440 million over FY 2018–2022.

There is also an opportunity to use the CO_2 in the production of low carbon products which, in the process, offsets CCUS costs. This would be a new initiative, with an estimated cost on the order of $80–$100 million over FY 2018–2022.[70]

During the review, DOE identified an emerging research area, bio-energy combined with CCUS systems, as offering the potential to draw down atmospheric CO_2 levels. A new research effort would focus on opportunities to facilitate the use of biomass residuals in modular gasification systems and existing power plants that will enable the economic capture, purification, and utilization of CO_2. This new initiative would have an estimated cost on the order of $60 million over FY 2018–2022.

Transition to a low carbon electricity sector would involve the need for CCS technology for natural gas combined cycle (NGCC) power systems. With the number of natural gas-fired plants increasing rapidly, the DOE proposes a first-of-a-kind carbon capture pilot project optimized for a natural gas energy system. Demonstration of natural gas-specific carbon capture technologies at 50 MWe scale or larger would pave the way for industrial stakeholders to address the key issues associated with optimizing carbon capture systems for natural gas power plants. The results of the demonstration would validate technologies to reduce the cost of energy from a NGCC unit by at least 20 percent and reduce the cost of captured CO_2 by at least 33 percent. Implementing this new initiative would have an estimated cost of $75 million over FY 2018–2022.

Nuclear Power: The 99 U.S. nuclear power reactors in operation are the Nation's most reliable source of electricity with a capacity factor routinely over 90 percent, and they represent America's largest share of clean, emission-free electricity generation. These reactors provide about 20 percent of our electricity and approximately 60 percent of our zero-carbon electric generation.

The first new U.S. reactor in about 20 years recently came online, and four more units are under construction. However, further nuclear capacity additions may be limited unless cost and schedule performance issues are addressed. Recently, six existing units have retired earlier than their licensed time frame, and a significant portion of the fleet may be at risk of early retirement[71] because of competitive pressures from low-cost natural gas and new capacity additions of wind and solar power, driven in part by favorable tax incentives and state government mandates.

A continued strong domestic nuclear industry is essential for the Nation's energy security, national security, and economic prosperity. However, sustaining and expanding nuclear energy's contribution to the energy mix would only be possible with technical and policy solutions that improve the economic competitiveness of nuclear energy. Given the complex, expensive, and national security aspects of the technology, there is a clear Federal role in technology development and demonstration.

The second installment of the QER recommends increased funding for nuclear life-extension R&D to accommodate the expected increase in renewal applications and to enable the continued operation of existing plants through technology development. R&D could enable reduction in the capital costs of new nuclear units to improve their market competitiveness, could improve safety, could address waste disposal, and could minimize proliferation risks when deployed abroad.

Small Modular Reactors (SMRs) have been a key focus of DOE's R&D and are currently in the licensing process with a goal of deployment in 2023. In January 2017, a company submitted the first SMR design certification application to the Nuclear Regulatory Commission - a step that portends a bright future for the industry. SMRs have been designed for greater simplicity while providing passive safety systems, and as smaller units to capture economies of scale and learning in factory production rather than being primarily built on-site in the field; these and other factors can reduce costs. Building on the successes of its SMR Licensing & Technical Support program, the DOE proposes an SMR Enterprise Innovation program that improves the base of capabilities supporting SMRs by accelerating factory fabrication of innovative SMR designs, expanding the potential customer base, and conducting focused R&D to demonstrate advanced manufacturing capability and alternate SMR applications. The goal of the program is to create a new U.S. nuclear reactor design that provides clean domestic energy, maintains U.S. leadership in nuclear technology, and serves as a valuable export to support domestic manufacturing jobs. The estimated cost for this new initiative would be $750 million over FY 2018–2022.

A recent report of the Secretary of Energy Advisory Board[72] outlined how R&D on advanced reactor concepts could offer opportunities to make broader use of nuclear energy. In addition, nuclear power plants could be designed to more rapidly ramp their output up or down, providing valuable flexibility to the grid. These and other advances will be pursued as part of a new Advanced Reactor Technologies 2030 Program for the design and licensing of two non-light-water advanced reactor concepts in support of commercial deployment in the early 2030s. The program would require funding of about $1.5 billion over FY 2018–2022. Finally, additional R&D on waste management together with continued work on a phased, consent-based siting program could substantially address disposal issues.

Fusion Energy: Fusion has been pursued for decades because it holds the promise of a power source, with abundant fuel, effectively zero emissions, manageable waste, and minimal proliferation risk. However, researchers have yet to achieve a self-sustaining, controlled fusion reaction that consistently produces more power than it consumes. Fusion is a nuclear reaction where two small atoms like hydrogen combine to form a larger atom and produce an enormous amount of energy as a byproduct. In controlled thermonuclear fusion, these reactions are facilitated by heating and confining fusion fuel in the form of a plasma, which is created when a gas absorbs enough energy to separate the electrons from the nuclei, making it susceptible to electric and magnetic fields. It requires a great deal of energy to attain the temperatures and pressures required for fusion, and confining plasmas to sustain these conditions is a monumental technical challenge.

Most mainstream fusion research currently focuses on one of two approaches to confining plasmas: magnetic confinement, which uses magnetic fields and lower-than-air ion densities, and inertial confinement, which uses heating and compression and typically involves greater-than-solid densities although intermediate density options may enable transformative routes to fusion power. The Department supports research in both magnetic fusion energy (MFE) and inertial fusion energy (IFE) as well as fundamental studies of plasmas. The Department conducts its research in both MFE and IFE using medium and large-scale domestic and international facilities, including the world-effort involved in constructing ITER, which aims to demonstrate net fusion power from MFE. These efforts are pursued with collaborators from around the world. The Department also explores novel approaches to both MFE and IFE with university researchers and small companies. Continued progress on domestic and international fusion research would require an investment of approximately $3.0 billion over FY 2018–2022.

Renewable Power: Over the past decade, U.S. policy and R&D investments have led to dramatic cost and performance improvements in wind and solar technologies. These efforts have increased renewable power generation in recent years, from 8 percent of all utility-scale generation in 2008 to 13 percent of all utility-scale generation in 2015.[73] Projections show that this trend is likely to continue.[74] In 2015, solar and wind power made up two-thirds of new U.S. electricity generation capacity, driven by the combination of declining costs and complementary policies.[75]

Since 2008, the cost of land-based wind energy has fallen by 41 percent, spurring a tripling of wind capacity. In 2015, land-based wind generated enough electricity to power more than 17 million households and, in 2016, the Nation's first offshore wind farm began operations. Land-based utility-scale wind energy costs continue to drop, and today wind energy is one of the most cost-competitive sources of new generation, reliably delivering over 5 percent of our Nation's electricity. With nearly 1GW of installed capacity domestically throughout every state and territory, distributed wind installations provide a great opportunity for consumers, communities, retailers, and off-grid applications to benefit.

One million rooftops now have installed solar panels, inspired in part by a 54 percent reduction in overall costs for rooftop solar since 2008. The cost of utility-scale solar PV has dropped by 64 percent since 2008 and now generates enough electricity to power more than two million homes. In 2008, there were no photovoltaic solar plants greater than 100 MW operating in America; now, catalyzed by the DOE Loan Program's initial funding of the first five plants, there are 50, nearly all financed by the private sector and driven largely by rapidly falling costs.

Further R&D would continue cost reductions and performance improvements in renewable power technologies and their integration into the grid, enabling additional private sector options for clean power generation in the future. Improved forecasting for wind and solar generation and better communications between grid operators can facilitate the integration of more solar and wind energy.

For wind systems, substantial further advances are possible, including the use of advanced materials and manufacturing to develop taller towers to tap higher wind speeds, longer blades to generate more power from these winds, advanced generator technologies that minimize the use of rare earth materials, and power electronics technologies. R&D will also improve computational modeling of the flow of the wind into and through a wind farm in order to optimize power output and the development of advanced offshore systems. Pursuing these technology pathways and advancing U.S. leadership in wind technology would require an investment of $690 million over FY 2018–2022.

Another opportunity for wind power is offshore wind. The United States has more than 2,000 GW of wind resource potential off our coasts that could provide affordable and reliable power for the large, critical, coastal load centers. Given the complexities of offshore wind in the United States (e.g., water depth, hurricanes, soil conditions), technology and deployment solutions that address these issues are critical to enabling offshore wind to become a more scalable option for our Nation.

In November 2016, DOE announced new SunShot Initiative goals to reduce the average cost, by 2030, to 3¢/kWh for utility-scale solar. Achieving these new targets could more than double the projected electricity demand that could be met by solar in 2030. R&D opportunities include much higher efficiency and lower cost systems, and systems that use earth-abundant materials.

Residential, commercial, and community solar installations of megawatt scale are growing steadily as the prices continue to drop. Solar is one of multiple growing distributed energy resources (DERs), which include on-site energy storage, distributed wind, electric vehicles, and home energy management systems that can optimize utility capabilities supporting consumer choice while maximizing grid reliability, electricity affordability, and cybersecurity.

For concentrating solar thermal power, research on high temperature systems, potentially using supercritical CO_2 power cycles, and systems combined with high efficiency hydrogen production could expand the opportunity space for this technology. In addition to increased funding for grid integration and demonstration activities described in the previous section, further investment of $870 million over FY 2018–2022 would be required to enable the continued transformational success of solar energy.

For geothermal energy, a major R&D challenge is to prove the enhanced geothermal systems (EGS) concept, which has the potential to provide a geographically diverse, baseload energy resource of 100GW.[76] EGS systems fracture a subsurface reservoir of hot rock to enable the circulation of fluids through it to extract heat for use. EGS R&D challenges include advanced drilling technologies, ensuring the integrity of wells and boreholes, and developing tools for the remote characterization of subsurface conditions. Subsurface energy resources, including geothermal, constitute 80% of our national energy supply, which is why DOE has established a crosscut to address shared subsurface energy R&D challenges. Further information on these crosscutting initiatives is included later in this chapter.

For hydropower, needs include R&D in new stream reach development that addresses sustainability issues, powering non-powered dams, and the development of advanced technologies for pumped hydro storage. For marine power, this includes robust systems for wave, current, and tidal energy.

Taken together, the estimated cost of new Federal investments in electric power supply technologies would potentially increase from $2.4 billion in FY 2016 to $3.8 billion in FY 2022 (+53%).

Buildings
($156 million in FY 2016)

Energy efficiency is a low cost way to save money, support job growth, reduce pollution, and improve the competitiveness of our businesses. Homes, offices, schools, hospitals, restaurants, and stores consume a lot of energy and money. Americans spend more than $430 billion each year to power our homes and commercial buildings, consuming more than 70 percent of all electricity used in the United States,[77] accounting for about 40 percent of our Nation's total energy bill, and contributing to almost 40 percent of the Nation's CO_2 emissions. On average, families spend about $2,000 per year on energy for their homes, particularly for heating and cooling, lighting, water heating, and refrigeration. If U.S. buildings cut energy use by 20 percent, we could save approximately $80 billion annually on energy bills, reduce greenhouse gas emissions, and create jobs.[78]

Changes in the marketplace make it clear that R&D by DOE and the National Labs in energy efficiency is working. As a result of significant DOE R&D, the cost of highly efficient LED lighting has dropped in cost by more than 90 percent, leading to 200 million bulbs installed in the United States through 2015. Today, some stores carry these bulbs for under $2 per unit. And the best performing 60-watt equivalent LED bulbs available now consume 85 percent less energy than incandescent bulbs. DOE’s R&D investments in a whole host of technologies like air conditioners, refrigerators, water heaters, and windows, to name a few, are cutting energy bills for Americans.

Across the buildings sector, Chapter 5 of the DOE QTR[79] identified significant additional opportunities for innovation that would reduce costs for home owners, building owners, and renters, including in areas such as advanced cooling, improved building envelopes, improvements in miscellaneous electric loads, and building systems and controls.

Challenges in this sector include building stock turnover. Building lifetimes are 50–100 years or more, and the existing stock is large and generally less efficient than new buildings. Therefore, retrofitting existing buildings with minimal disruption would be important for capturing significant near- to mid-term energy savings and emissions benefits.[80]

Equally important, deployment of highly efficient energy technologies in new construction would ensure that new buildings are built for optimal efficiency from the start and provide long lifetimes of savings.

Efficiency improvements begin with R&D to improve the cost and performance of the building envelope (roofs, walls, floors, and windows) to reduce thermal loads and also to develop membranes that can control the flow of moisture in and out of a building. R&D is also very important to improve key technologies such as advanced HVAC systems, lighting, sensors and controls, and building design tools, among others.

Building systems integration within buildings as well as with external energy systems, such as the grid and fuels, and with systems for water supply, waste management, and more offers many more opportunities for productive R&D. Communications and control systems and strong cybersecurity capabilities are important for this.

In addition, with additional investments, DOE's historical expertise in high performance computing, big data, and modeling could help cities and surrounding communities, which are projected to account for 87 percent of total U.S. energy use by 2030, become smart and energy-efficient.

Finally, advanced facilities at the National Laboratories, could also be deployed in support of substantially expanded investment into advanced materials research within the science portfolio with a huge potential impact for future building stock.

Taken together, the estimated cost of new Federal investments in this area would potentially increase from $156 million in FY 2016 to $530 million in FY 2022 (+240%).

Industry
($328 million in FY 2016)

Manufacturing has the greatest economic multiplier of any sector, creating 4 additional jobs for every manufacturing job. Further technological innovation would improve processes and systems, energy and materials use, waste management, system integration, and more, while at the same time developing the technology and infrastructure to manufacture clean and efficient technology here in the United States rather than having to rely on imports.

As part of these efforts, DOE has been a leader in developing Manufacturing USA,[81] and has established five of the 15 Manufacturing USA Innovation Institutes across the country. Each institute has mandated clear goals to drive U.S. manufacturing competitiveness through new technologies and innovation; reduce GHG emissions and improve energy productivity; stimulate regional economic growth; and develop an advanced workforce in each of the focus areas. Today, nearly 60 percent of the Fortune 50 manufacturers are members, and the institutes have attracted $1.3 billion in private sector funding for breakthrough technologies. Some 250 projects are already underway or completed, delivering results like core truck parts that are 40 percent lighter, increasing fuel efficiency and saving consumers money.

In-depth analyses of multiple industrial subsectors show significant technical potential for cost-effective reductions in energy use. Other areas of innovation include continuing development of "smart manufacturing" (i.e., manufacturing processes driven by information technology); improving the efficiency of manufacturing processes; developing advanced materials; intensifying processes; furthering new processes such as additive or roll-to-roll manufacturing; reducing the use of critical materials or developing advanced material substitutes for them; improving the purification of used materials to enable their use in remanufactured products with no performance loss; recovering waste heat; improving controls and sensors, including high performance metrology for real-time in situ process control; accelerating the use of high performance computing for modeling and simulation of manufacturing processes and systems; and many more, as described in the QTR 2015, Chapter 6.[82]

Industrial combined heat and power (CHP) also offers opportunities for near-term solutions to cost-effectively reduce industrial energy use.[83] Electricity and process heat generated from CHP can use 25–35 percent less primary energy than electricity from the grid together with separate production of process heat. The Process Heat R&D program has two technical targets: (1) develop low-thermal-budget manufacturing technologies that reduce energy intensity by at least 50 percent compared to 2015 typical technology, and (2) develop advanced process heating unit operations that provide improved properties, quality, and/or product value at cost parity to conventional techniques. The estimated cost for this effort would be $150 million over FY 2018–2022.

There are also opportunities for capturing nearly pure-stream CO_2 for use in such applications as enhanced oil recovery, while also improving CCUS technologies.[84] The pace of innovation in industrial CCUS applications could be accelerated through a new program of public-private partnerships focused on application of CCS technologies for specific industrial sectors and assessment of regional opportunities. The Federal cost of this public-private partnership would be an estimated $125 million over FY 2018–2022.

Taken together, the estimated cost of new Federal investments in this area would potentially increase from $328 million in FY 2016 to $840 million in FY 2022 (+155%).

Fuels

($807 million in FY 2016)

Fuels play a critical role throughout our economy and provide nearly all the energy used by our national transportation system. Fuel resources include oil, natural gas, biomass and hydrogen, each of which possesses its own security, economic, and environmental challenges and benefits. For example, hydrogen fuel burns clean, with water being essentially the only by-product, but the limitations of the current conversion technology and distribution infrastructure mean it is not yet price competitive for broad application in the transportation sector. Oil and gas, on the other hand, have a larger carbon footprint and pose other environmental challenges, and can be subject to significant price swings and other energy security impacts, but are readily available domestically and at relatively low cost today.

DOE is well positioned—as it was with the shale boom—to catalyze the fuel revolution of the future and continue to boost our Nation's competitiveness and national security. Given the commercial and technological maturity of oil and coal development, early-stage R&D on fuels at the Department focuses on emerging gas production sources and efficient delivery infrastructure, as well as advances in biomass and hydrogen technology. In addition, the Department is undertaking basic research into efficient pathways for conversion of sunlight to fuels.

Natural gas is a key fuel for the power industry and buildings sectors, and shale gas has dramatically reduced its cost and increased its resource base (Figure 3). Further R&D is needed to ensure wellbore integrity, treat and use produced water, and control methane emissions—both recovering methane for commercial sales and minimizing atmospheric impacts. The cost of this R&D would be an estimated $170 million over FY 2018–2022.

In addition, further research on the currently untapped potential of methane hydrates is warranted. The Department's methane hydrates program is the only entity actively supporting fundamental science to assess gas hydrates' stability and their role in the global carbon cycle, which must be better understood before development of gas hydrate reserves is viable. Further reseach would be an estimated $80–$100 million over FY 2018–2022.

Biomass-based fuels can be used with current widely available vehicle technology, but additional R&D is needed to reduce biomass production costs, improve the efficiency of conversion plants, and reduce the cost of fuel conversion in either biochemical or thermochemical systems. Using biomass to produce "drop-in fuels" that can be direct replacements for conventional fuels is an important approach. Though technically very challenging to produce at competitive costs, these could potentially be directly used in existing infrastructure and vehicles, avoiding the infrastructure challenge faced by other fuels. Given the diversity of applications, higher priority should be given to low-carbon biofuel and bioproducts with the highest value or where good alternatives do not exist, such as jet fuel or industrial applications. An expanded R&D effort targeted to produce drop-in biofuels at $2/gasoline gallon equivalent would cost an estimated $1 billion over FY 2018–2022.

Hydrogen is another important commodity. It can be produced from fossil fuels, nuclear energy, or renewables, essentially any resource available domestically. It is extensively used today in the petroleum refining, fertilizer production, and other industries; and with the commercial availability of hydrogen fuel cell electric vehicles in today's market, demand is expected to increase over time. R&D opportunities include innovative approaches for cogenerating hydrogen, heat, and electricity from natural gas, technologies for cost-effectively extracting hydrogen from biomass and waste streams, and advanced water-splitting technologies utilizing solar and/or nuclear energy. A broad portfolio of hydrogen production and delivery approaches is needed to leverage diverse domestic resources and reduce hydrogen fuel costs for use in fuel cell electric vehicles and other important industrial applications. An expanded program of hydrogen fuel R&D would cost an estimated $385 million over FY 2018–2022.[85]

More energy from the sun strikes the earth in one hour than is consumed by all humans on the planet in a year. Through the process of photosynthesis, plants can effectively convert energy from the sun into energy-rich chemical fuels using the abundant feedstocks of water and CO_2. However, there are no commercially generated fuels via artificial photosynthesis. Office of Science-supported research focuses on the molecular and atomic mechanisms responsible for the capture and conversion of light energy into chemical fuels for both natural and man-made systems. The Fuels from Sunlight Energy Innovation Hub's objective is to conduct foundational research aimed at harnessing solar energy for the production of transportation fuels, using only sunlight, water, and CO_2 as inputs. Building on the Hub, funding for a robust solar energy conversion research program would be about $685 million over FY 2018–2022.

Taken together, the estimated cost of new Federal investments in this area would potentially increase from $807 million in FY 2016 to $1.2 billion in FY 2022 (+50%).

Transportation
($386 million in FY 2016)

Improving vehicle efficiency and electrifying our vehicle fleet is essential to reducing America's fuel costs, supporting domestic industry, minimizing pollution, and increasing energy security. Americans spend more than quarter a billion dollars a day to import oil, mostly for transportation.

In part due to DOE's R&D, remarkable progress has been made on vehicle technologies in recent years. For example, the cost of battery storage has decreased 70 percent since 2008, making it easier and cheaper to develop affordable electric vehicles (EVs). Nearly 30 EV models are available, up from only one in 2008, from more than a dozen manufacturers, giving vehicle buyers more choices of manufacturer, size, capabilities, and appearance. Total sales of EVs now exceeds 500,000 EVs on the road as of September 2016. There are now more than 16,000 publicly accessible charging stations, up from 500 in 2008, giving electric car owners more confidence in the range of their vehicles.

DOE's SuperTruck initiative is working to develop and demonstrate cost-effective technologies that more than double the freight efficiency of Class 8 trucks, commonly known as 18-wheelers. With the first phase complete, more than twenty fuel saving technologies have reached the commercial market and another two dozen are expected to do so in the next 2–4 years.

Even with these significant advances, additional innovation is needed for widespread market penetration. This includes cleaner and more efficient vehicles, as well as smart urban design, traffic management, and other approaches that can reduce vehicle miles traveled while supporting improved mobility. Advances in vehicle automation and connectivity could contribute to making efficient vehicles more cost-effective and freeing up urban space now used for parking. For certain transportation modes, particularly those that are difficult to electrify like long-haul trucks and aircraft, far more R&D would be required to uncover the most cost-effective ways to improve transportation energy use.

For battery electric vehicles, R&D could advance battery energy densities, decrease the time needed to recharge, and reduce costs to roughly $80 per kWh. For hydrogen fuel cell vehicles, R&D is needed to reduce the costs of fuel cells, and to improve the performance of hydrogen storage systems. For heavy duty vehicles, opportunities include R&D to advance diesel engine efficiency, increase waste heat recovery, improve transmission systems, improve aerodynamics, reduce tire rolling resistance, and reduce parasitic loads.

Across the range of vehicle types, further research could reduce the cost, improve the performance, and reduce the energy-intensity of producing lightweight materials such as advanced high strength steels, magnesium alloys, aluminum alloys, carbon fiber composites, and others. More efficient heating and cooling systems for passenger compartments also offer energy savings opportunities. Engine efficiency research opportunities include better fuel injection, advanced combustion, air handling, and after treatment. Finally, connected vehicle and vehicle automation technologies are advancing rapidly and have potentially profound implications for energy use. R&D would be required to develop these technologies and help guide implementation along pathways that can help solve pressing problems such as energy security, and transportation system efficiency and avoiding gridlock.

Significant changes are occurring to how people and institutions use mobility technologies and services, and there is an opportunity to examine how these changes may help Americans spend less on transportation while increasing their mobility and enabling deep gains in energy efficiency in the transportation sector. These changes are technological (vehicle connectivity and automation, expansive electrification) and also socioeconomic (shared use/mobility on demand, big data analytics, behavioral decision-making). The Energy Efficient Mobility Systems program, which includes complementary efforts in the Buildings sector, aims to understand these new mobility patterns and assess resulting energy and emissions changes. The estimated cost of this new initiative would be on the order of $500 million over FY 2018–2022.

Taken together, the cost of new Federal investments in this area would potentially increase from $386 million in FY 2016 to $930 million in FY 2022 (+140%).

Innovative Carbon Management
($19 million in FY 2016)

U.S. soil quality has declined in many areas over time. Drivers of soil quality loss include land use and land-use change, ecological disturbance (e.g., forest fires), and climate change and extreme weather, among others.

Rebuilding U.S. soils will provide multiple benefits to agriculture and forestry, will allow reclamation of degraded land, and also—because this is how soils are built—will capture carbon from the atmosphere to grow roots and other plant matter, thus serving as an important carbon sink. To develop the capabilities for such a soil rebuilding effort, fundamental science is needed to understand the soil microbiome: what soil microbes are present under different conditions for both healthy and depleted soils, what specific roles these microbes serve, how these microbes interact with each other and with plants, what their metabolisms are, and so on.

DOE led the Human Genome Project—which has had profound impacts throughout our economy—and is a pioneer in genomics and biological sciences. DOE is also the U.S. leader in computational science, which is important in supporting genomic and biological research generally, and especially for analyzing the very complex microbiomes of soils. DOE and its National Labs therefore provide key capabilities to conduct this R&D in partnership with other agencies, universities, and industry.

The research would generate new data and understanding of soils and how they could be restored under different conditions, enable the development of advanced computational models of land/soil/plant/atmosphere interactions to confidently evaluate changes in these systems, quantify potential feedback effects, and predict potential system performance and improvements.

In addition, while climate intervention cannot substitute for reducing greenhouse gas emissions and adapting to the changes in climate that occur, some types of deliberative climate intervention may someday be one of a portfolio of tools used in managing climate change. As recommended by a 2015 National Academies report,[86] there is a need to understand the possibilities, limitations, and potential side effects of climate intervention. DOE should use its historical capabilities in modeling to contribute to the U.S. Global Change Research Program's work in this area.

The estimated cost of these new initiatives would potentially increase from $19 million in FY 2016 to $44 million in Fy 2022 (+134%) and be on the order of $200 million over the five-year period FY 2018–2022. This funding addresses an identified gap in the Department's innovation portfolio that does not show up in the sector map (Figure 9). Funding for this area is included in the Foundational Science box in that mapping.

Foundational Science

($110 million in FY 2016)

Improving energy technologies often requires and always benefits from advances in the performance of materials, catalysts, energy conversion, energy storage, and other areas. Basic science underpins technology development in these areas—advanced computing, materials science, electrochemistry, catalysis, biological processes, and every other aspect—and is a crucial enabler for addressing the full range (security, economic, and environmental) of national energy challenges.

As the leader for physical science research in the United States and as the custodian and operator of critical scientific research user facilities, DOE serves a foundational role in advancing the basic science required for fossil, nuclear, renewable, grid, and end-use energy technologies. Such advances can require large upfront investments. For example, scientific research user facilities provide critical capabilities for understanding fundamental phenomena, but can cost hundreds of millions of dollars to build and operate.

The Department's FY 2016 basic science innovation portfolio includes nearly $1.6 billion that is mostly spread across the energy sectors discussed above; this spread is also mapped in Figure 9. In addition to a few specific examples listed previously (e.g. solar energy conversion), there are a number of other foundational research areas and modalities that will feature prominently in the Department's FY18-22 innovation funding profile. Most of this funding is captured within the various sector totals, but some high-priority activities are described in this section to avoid duplication elsewhere. Within the totals, the Department proposes a robust high-performance computing (HPC) program that is application-agnostic. This HPC program is captured in the Foundational Science box within Figure 9.

Some basic science is specifically motivated by particular technology needs (use-inspired), but it is also important to conduct curiosity-driven basic science to make discoveries in new areas. Basic science research is linked to applied R&D through a variety of mechanisms, including EFRCs, various energy innovation hubs, research centers, and others described above, as well as key crosscutting technology team efforts described below.

The EFRC program accelerates transformative discovery, combining the talents and creativity of our national scientific workforce with a powerful new generation of tools for penetrating, understanding, and manipulating matter on the atomic and molecular scales. In 2009, five-year awards were made to 46 EFRCs. As of 2016, the EFRCs have produced more than 7,500 peer-reviewed publications, 490 invention disclosures, 50 issued patents, 380 U.S. Patent applications, and 100 licenses. The opportunities and capability for expanded EFRCs suggest that the current number of EFRCs could be doubled, at a total estimated cost of $675–$700 million over the five-year period FY 2018–2022.

Basic science work on catalysis is another critical area. Catalytic transformations impact virtually all of DOE's missions. For example, catalysts are needed for all of the processes required to convert crude petroleum into a clean burning fuel. The production of chemical-based consumer products such as plastics requires catalysts. Catalysts are crucial to energy conservation in creating new, less-energy-demanding routes for the production of basic chemical feedstocks and value-added chemicals. Environmental impacts from catalytic science can include minimizing unwanted products from production streams and transforming toxic chemicals into benign ones. Office of Science-supported activities concentrate on establishing the fundamental understanding to control the conversion process at the level of single electrons to enable (1) the design of high catalytic specificity (selectivity) towards pathways that make only the desired products, and convert or prevent the undesired subproducts; (2) enhanced versatility and adaptability for multiple reactions and environments; and (3) multifunctional catalysts inspired by nature's catalysts, enzymes, or devised de novo that can be be synthesized to operate at ambient conditions. The estimated cost for this new program would be in the range of $175–$200 million over the five year period FY 2018–2022.

Many enabling science R&D activities have implications across many sectors. In addition to advanced materials, biological, catalysis, and computing research noted above, subsurface science is important for oil and gas production, carbon capture and storage, geothermal energy, nuclear waste disposal, and other issues. These only scratch the surface of the myriad critical ways the enabling science broadly serves U.S. advanced energy technology needs.

Advanced computational capabilities are beginning to enable the first principles computational design of materials, which can be combined with high throughput experimental validation.[87] This has the potential to dramatically reduce the time to develop advanced materials. Advanced computational capabilities are also becoming increasingly capable for technology design and system integration.[88] Together, with further development, these have the potential to substantially accelerate the R&D process. Although extremely promising, these capabilities are in their infancy, and a combination of fundamental and applied R&D would be needed to fully develop and broadly implement them in industry and elsewhere.

Other nations recognize these and other critical roles for high performance super computing and are aggressively pursuing domestic development of HPC, and some, including China, are making rapid progress and increasingly threaten U.S. leadership. A critical initiative for the Department is to develop the next generation of HPC (Exascale) with approximately 50 times the performance of America's current fastest supercomputer across a range of applications, including data-intensive science. The U.S. Exascale Computing Initiative (ECI) is jointly led by DOE's Office of Science and the National Nuclear Security Administration. The ECI is a high priority within the innovation portfolio, and further analysis of the opportunities supports acceleration of the ECI, originally targeted to achieve exascale systems by 2025, to significantly advance the staged development of at least two capable exascale computing systems with novel and diverse architectures no later than 2021 and 2023. This will meet the competitive challenge from abroad, with China having announced its intention to develop an advanced-architecture exascale system by 2020. To address the threat Chinese investments in HPC pose to U.S. national and economic security will require acceleration of both hardware and software development, and significant increases in mathematics, computer science, networking and related research. Competition for HPC skilled labor is fierce and investments in workforce development are vital to the Nation's future HPC capabilities.

Taken together, the cost of critical HPC innovation investments in this area would potentially increase from $110 million in FY 2016 to $295 million in FY 2022 (+170%). Overall, the total basic science innovation would potentially increase from $1.6 billion in FY 2016 to $3.2 billion in FY 2022 (+105%).

Crosscutting Energy Science and Technology

DOE has significantly advanced its ability to integrate R&D across its many different research areas through the use of crosscutting R&D teams formed under a new Departmental structure, implemented in 2013, that placed all of the science and applied energy programs together under a single Under Secretary for Science and Energy.

This structure enabled the development of multi-office, integrated budget recommendations. Beginning with the FY 2015 budget request, the Department has developed and put forward crosscutting R&D program proposals that advance science and technology objectives shared by programs that may not be closely linked organizationally. All appropriated funds and program decisions ultimately reside with the separate offices involved in each budget crosscut, but the Department has found that programs are better able to identify and tackle common challenges when formulating budgets as an interdisciplinary team. In addition, these teams have worked to streamline hand-offs from earlier stage and foundational research (e.g., in the Office of Science) to more application-oriented technology development (in the Applied Energy programs). Just as important, programs are better able to avoid unintended overlap of investment across the science and energy portfolio, thus ensuring efficient stewardship of taxpayer dollars. The Department currently has funding in six crosscutting R&D programs, which account for $860 million, or 8 percent of the Department's current science and energy portfolio:

- Advanced Materials: supports coordinated R&D for advanced materials in multiple applications, including lightweighting and materials under extreme environments.
- Energy-Water Nexus: supports the Nation's transition to more resilient energy-water systems.
- Exascale Computing Initiative (ECI): described above and crosscuts the Office of Science and the National Nuclear Security Agency.
- Grid Modernization: provides the tools to develop a resilient, secure, sustainable, reliable, flexible, and affordable grid of the future.
- Subsurface Science, Technology, Engineering & Research (SubTER): enables mastery of the subsurface by advancing characterization, engineering, and monitoring across a range of energy and environmental applications.
- Supercritical CO_2: develops a higher efficiency, lower cost, lower water consumption, alternative power system for fossil, solar, and nuclear fueled electric power generation.

Expanded funding for these efforts is fully accounted for in the budgets referenced in previous sections. Crosscut budgets are integrated not only across programs but also within existing budget and organizational structures.

Opportunities Ahead

As described on these pages, the United States faces substantial energy challenges: security, economic, and environmental. Early stage, publicly funded R&D, guided by engagement of the entire energy science and technology community and competitively awarded for the most innovative and important R&D, has demonstrated remarkable success. Development of shale gas and oil, wind and solar energy, and LEDs, to name only a few, have deep roots in DOE-sponsored R&D.

These and other advances have already had a remarkable pay-off for the American people. Energy technology innovation is the key to this success, and the United States does innovation better than anybody else.

The roughly $350 billion global clean energy market in 2015 and the IEA projection of more than $60 trillion for all energy technologies over the next 25 years guarantee that many countries will be competing for shares of this market using all the mechanisms they can bring to bear. The energy technology innovation portfolio described in this document will not only serve our domestic needs, but will also enable U.S. companies and U.S.-based manufacturing to compete for a significant share of the global market opportunities for the benefit of the American people.

Will the United States continue to be a global leader in energy technology innovation? Will the United States compete for these markets? With the investments outlined in this report, the answer to both questions will be a resounding “yes.”

Appendix: Barriers to Private Investment in Early-Stage Energy Innovation

Corporate and VC investment in energy technology is low for good reasons—from the perspective of investors. In brief, returns to private investors are often low because investments in energy R&D require long periods to generate a return; there are high risks; energy technologies typically produce or save low margin commodity fuels or power; and new capital intensive infrastructure may be required. That private returns are low does not mean this is a bad investment for the public; quite the contrary. Energy and energy R&D are critical for national security, the economy, and the environment. The public role is particularly important in early stage R&D and early maturation of the technology, followed by a transition to a primarily private sector activity. It is useful to examine these issues in more detail, beginning with factors impacting private returns, such as the following:

- **Long Time Frames for R&D.** Directed basic research and early applied R&D can require as much as a decade or more of iteration and gestation before demonstration of a new technology even begins (Table A1). This is too long for most private companies or investors to support without a return on investment, especially smaller innovative companies. These long R&D gestation times motivate public attention to early and accelerated R&D efforts, especially for basic and early applied R&D, if U.S. energy challenges are to be met.
- **Appropriability.** Once a technology is demonstrated to be viable, it is much easier for a competitor to copy it or find alternative approaches to achieve the same thing. This can sharply reduce the financial return for the innovator. Intellectual property protections may not be sufficient to protect the innovator, particularly in international markets.
- **Risk.** Energy R&D activities face many risks, including technical, managerial, financial, market, regulatory, and policy risks; these pose serious challenges for companies and investors, discouraging investment.
- **High Costs; Low Returns.** Capital costs for new energy supply and end-use technologies are generally higher per unit than their conventional competitors due to the cost of the performance advantages they offer and because they are just starting down the learning curve that their conventional competitors already traversed over many decades. Further, energy technologies typically produce or save low margin commodity fuels or power, generating low returns. Purchasers are also generally wary of high capital costs irrespective of lifetime savings, and this sensitivity is increased for a relatively new technology, which may have performance risk because of immaturity. Finally, some new technologies, such as large-scale electricity generators, fuels production, or manufacturing facilities, may require multi-hundred million to billion dollar investments for a single plant, a very difficult investment for most companies to mobilize.

- **Infrastructure.** The existing energy infrastructure has developed around incumbent fuels and technologies over the past century. New technologies that require new infrastructures can face a "chicken-and-egg" challenge. For example, vehicle purchasers want confidence that they will have ready access to fueling stations and may hesitate to purchase a vehicle that does not have such support; but without a large base of vehicles using such infrastructure, it is difficult to build and maintain the needed refueling capacity.

Table A1: Gestation times for R&D

R&D Activity	Years
Decision to Invest in R&D[89]	~ 2+
R&D[90]	~ 5–20+
Demonstration of Technology/System	~ 2–10+
Demonstration of Commercial Model	~ 2–5+
Resolution of Regulatory Issues[91]	~ 0–5+
Financing Manufacturing or Energy Plants	~ 2–5+
Market Penetration[92]	~ 10–20+

In contrast to energy R&D, the private sector can often capture high returns from R&D in pharmaceuticals, aerospace, and information technologies. Large investments may be required, but there can be large returns, such as for a new cancer drug. For energy, however, fuels and power are generally low cost commodities that do not provide high returns.

When R&D is completed and a technology is commercially available, it can still require decades to substantially penetrate the market and turn over the existing capital stock, as indicated in Table A2. This again motivates early and accelerated R&D and commercialization efforts, including large infrastructure investments to rebuild aging systems and to support new energy technologies.

Table A2: Approximate lifetime ranges for various capital stocks in the United States

Capital Stock	Lifetimes (yr)
Building Appliances[93]	~ 10–20
Cars[94]	~ 15–20
Industrial Equipment	~ 10–30+
Power Plants[95]	~ 40–60
Buildings[96]	~ 50–100+
Urban Form	~ 100s

Although the resulting low level of private investment may make sense from a corporate perspective, it is insufficient to meet the very large U.S. energy security, economic, and environmental challenges described above, many of which are of public—not private—benefit. Numerous studies have found that public returns on R&D investment generally are much larger than private returns.[97] This has often been highlighted for basic research, but has also been demonstrated for energy R&D. As noted above, a retrospective analysis by the National Academies of Sciences, Engineering, and Medicine found returns of about 20 to 1 for public investment in energy efficiency R&D for the portfolio of work they examined.[98] Subsequent analyses across a wide range of energy R&D investments have also generally found large returns.[99] The 31 new or updated appliance standards (substantially enabled by R&D) put in place from 2009 to 2015 are projected to cumulatively save by 2030 over $500 billion for consumers, 39 quads of energy, and 3 billion metric tons of CO_2 emissions.[100] The following challenges are among those that motivate public energy R&D investment:

- **Externality Costs:** Energy technologies impose a variety of costs, only some of them valued in the market. The public incurs substantial additional costs, such as for energy security (e.g., volatility of global oil supplies; OPEC market manipulation) energy reliability (loss of power in storms or other causes), health costs from air/land/water pollution, climate impacts from greenhouse gas emissions, and others as noted above. The substantial public benefits of reducing oil imports by R&D in energy efficient vehicles and new oil and other supply technologies were illustrated in Figure 5. That conventional energy technologies don't pay for all the costs that they impose on the public, such as energy security or health, reduces the price of energy from them and thus undercuts the market viability of advanced energy technologies that could help address these challenges. These costs are known as externalities and are recognized as a fundamental market failure by economists.

- **Market Shortcomings:** Many market shortcomings have been documented in the energy sector, particularly for energy efficiency, resulting in substantially lower levels of investment in energy efficiency technologies than economically appropriate. These include, for example, (1) the disconnect between the owner of a building who often does not want to pay for more efficient (and more expensive) equipment, and the renter of the building who must then pay higher energy bills (known as split incentives); (2) the frequent lack of energy metering by location or time, impeding knowledge of energy costs and the ability to take action; (3) the high transaction costs for improving the efficiency of an individual device, saving only low levels of energy; (4) the costs of conventional fuels and risks of cost increases that are often largely passed through to consumers by utilities, reducing the incentive for utilities to invest in energy technologies; and others.
- **Private R&D Investment Availability.** In addition to all of the above factors that discourage private sector R&D, many companies simply do not have funds to invest in R&D. Many of the most innovative companies are small, with limited resources, and all the companies face intense foreign competition, sometimes with competitors inappropriately receiving various direct and indirect supports. For example, analysis found and the Department of Commerce ultimately ruled that there were trade violations by extraordinary low Chinese PV prices—a factor contributing to the closure of many solar PV companies in the United States and Europe that closed during 2009-2014[101] and tariffs were put into place.[102] Such a survival situation leaves little room for R&D. Similarly, the National Research Council found that the intense market competition from low-wage producers of low-quality LEDs left innovative U.S. firms with little ability to support R&D.[103] Thus, the tilt in the market playing field can undercut even the ability of U.S. private innovators to support innovation.

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[20] An LED light costs about $2, has a lifetime of more than 20,000 hours, and uses about 8 watts of power for the equivalent light output of a standard 60 watt incandescent bulb. Its lifetime cost is then $2+20,000 h *0.008 kW*$0.10/kWh = $18, assuming a cost for electricity of $0.10/kWh. In comparison, an incandescent costs about $1, lasts 1000 hours, and requires 60 watts of power, giving an equivalent cost for 20 incandescent bulbs, required to provide light for the same length of time as 1 LED lamp, of 20*$1 + 20*1000 h *0.060 kW*$0.10/kWh = $140. Thus, over its lifetime, the LED saves roughly $140-$18=$122 compared to the equivalent series of incandescent bulbs. The total savings for the 200+ million sold to date is then 200E6*$122= $24 billion.

[21] This assumes, per figure 5, that oil imports range from about 4 million barrels per day at an EIA cost projection of $69 per barrel (2015$) to 2 million barrels per day at an EIA projected cost of $126 per barrel (2015$), thus totaling about $100 billion to 90 billion per year that could be offset with sufficient penetration of electric vehicles. Projections based on Energy Information Administration, "Annual Energy Outlook 2016", Table A.11 and nominal prices converted to 2015$ using the Table A20 GDP chain-type price index.

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[40] Meng Meng and Josephine Mason, "China to plow $361 billion into renewable fuel by 2020", Reuters, January 5, 2017

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46 Work at the scientific user facilities is free of charge for those who will publish their results in the open literature and at cost for the private sector who wishes to keep the results proprietary.

47 DOE supports innovation through open highly competitive processes, and also supports some innovation through non-competitive mechanisms

48 “Representative DOE Applied Energy Program Workshops”, Supplemental Information Appendix, “Quadrennial Technology Review 2015, http://www.energy.gov/under-secretary-science-and-energy/quadrennial-technology-review-2015-omnibus This review identified over 300 workshops during 2011-2015. The value of these workshops is evidenced by the strong participation by experts from industry, universities, National Labs, and others; if the workshops did not provide value, experts would quickly turn away as they don’t want to waste their time; instead, these workshops are conducted to engage the broad community and develop important information.

49 Researchers are willing to invest their time and effort to pursue public funds even though there are additional steps required with public funding to ensure that the process is fair, open, and transparent. Substantial effort goes into streamlining these processes and to design solicitations carefully to minimize the burden on applicants.

50 “Energy Frontier Research Centers”, http://science.energy.gov/bes/efrc/

51 See, for example, DOE, Quadrennial Technology Review 2015, Chapter 9, Section 9.2, https://energy.gov/under-secretary-science-and-energy/quadrennial-technology-review-2015 and DOE, “Science and Energy Plan, Fiscal Year 2016”, September 2015, See especially Appendix E, https://energy.gov/under-secretary-science-and-energy/downloads/science-and-energy-plan

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53 Office of Technology Transitions, http://www.energy.gov/technologytransitions/office-technology-transitions

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61 President’s Council of Advisors on Science and Technology, “ Report to the President on Accelerating the Pace of Change in Energy Technologies Through an Integrated Federal Energy Policy”, November 2010, https://www.whitehouse.gov/sites/default/files/microsites/ostp/pcast-energy-tech-report.pdf

[62] American Energy Innovation Council, http://americanenergyinnovation.org/ and specifically, "Restoring American Energy Innovation Leadership: Report Card, Challenges, and Opportunities", 2015, http://bpcaeic.wpengine.com/wp-content/uploads/2015/02/AEIC-Restoring-American-Energy-Innovation-Leadership-2015.pdf

[63] "Energy CO_2 Emissions Impacts of Clean Energy Technology Innovation and Policy," January 2017, Department of Energy, https://www.energy.gov/epsa/downloads/energy-co2-emissions-impacts-clean-energy-technology-innovation-and-policy

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[81] Manufacturing USA—The National Network for Manufacturing Innovation, https://www.manufacturing.gov/nnmi/

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[83] Within the manufacturing sub-sector, The Manufacturing Energy and Carbon Footprints analysis estimates that 7,228 TBtu, or 51% of the 14,064 TBtu of total delivered energy to the U.S. manufacturing sector, was wasted as efficiency losses in 2010.

[84] U.S. DOE Bandwidth Studies, accessed August 31, 2016. http://energy.gov/eere/amo/energy-analysis-sector#5

[85] This is an increase in R&D on hydrogen fuel production and represents an 74% increase compared to current funding levels. Funding increases for hydrogen fuel cells are contained in the vehicle efficiency section.

[86] National Academies of Sciences, Engineering, and Medicine, Climate Intervention Reports (2015): "Climate Intervention: Carbon Dioxide Removal and Reliable Sequestration", and "Climate Intervention: Reflecting Sunlight to Cool Earth", https://nas-sites.org/americasclimatechoices/other-reports-on-climate-change/climate-intervention-reports/

[87] In particular, see: Technology Assessment 6.B Advanced Materials Manufacturing of the Quadrennial Technology Review 2015, op. cit.

[88] See, for example, the case study of the Consortium for the Advanced Simulation of Light Water Reactors (CASL) in Chapter 6 Supplemental Information: Public-Private Consortia and Technology Transition Case Studies for system design, and see Chapter 3 for grid integration. of the Quadrennial Technology Review 2015, op. cit.

[89] The process for appropriating funds for an established public R&D activity begins with an agency and the administration developing a proposed budget in the March to January period, the President's budget submission to Congress in February, and Congress finalizing appropriations decisions in September for the new fiscal year beginning in October, a total of about 20 months. In practice, this process may take longer if funding is not appropriated by October 1, or due to other factors. For new areas of R&D for which there is not an established Congressional Authorization or Appropriation, the process may take much longer.

[90] Public supported R&D generally focuses on mid to longer term work and will typically require five years and often much more. For example, DOE supported R&D on solar PV and on wind turbines has been underway for over 30 years during which time the technologies have gone through many advances in order to achieve the results shown in Figure 4.

[91] The time required to meet regulatory requirements vary widely, but progress has been made in streamlining these processes in many cases. As examples, see:

- Nuclear Energy Institute, Fact Sheet, "Licensing New Nuclear Power Plants", October 2014, http://www.nei.org/Master-Document-Folder/Backgrounders/Fact-Sheets/Licensing-New-Nuclear-Power-Plants This identifies the development of a combined construction and operation license by the company of about two years, and the review by the Nuclear Regulatory Commission of about three years.
- Environmental Impact Statements under the National Energy Policy Act require a number of steps, as indicated by USDOE, "Environmental Impact Statement Explained", http://www.nei.org/Master-Document-Folder/Backgrounders/Fact-Sheets/Licensing-New-Nuclear-Power-Plants For active NEPA EIS activities, see: USDOE, Active NEPA Projects, http://energy.gov/nepa/active-nepa-projects

[92] As examples, consider the following:

- Buildings Sector. LED lighting went from cumulative sales of 400,000 in 2009 to about 200 million in 2015, and are projected by Goldman Sachs Equity Research to account for about 2/3 of the market by 2020, or about ~10 years. See: Jaakko Kooroshy, et al, "The Low Carbon Economy", Goldman Sachs Equity Research, Novenber 30, 2015, http://www.goldmansachs.com/our-thinking/pages/new-energy-landscape-folder/report-the-low-carbon-economy/report.pdf
- Transportation Sector. Market penetration times for major technology rollouts in the transportation sector required 23-33+ years after market entry. See: S. Plotkin, T. Stephens, W. McManus, (March 2013). "Vehicle Technology Deployment Pathways: An Examination of Timing and Investment Constraints." Transportation Energy Futures Report Series. Prepared for the U.S. Department of Energy by Argonne National Laboratory, Argonne, IL. DOE/GO-102013-3708. 56 pp. http://www.nrel.gov/docs/fy13osti/55638.pdf

[93] James D. Lutz, Asa Hopkins, Virginie Letschert, Victor H. Franko, Andy Sturges, "Using National Survey Data to Estimate Lifetimes of Residential Appliances", Lawrence Berkeley National Laboratory, October 2011, LBNL- Report 81616. http://eetd.lbl.gov/publications/using-national-survey-data-to-estimat See also, for example: ATD Home Inspection, "Average Life Span of Homes, Appliances, and Mechanicals", http://www.atdhomeinspection.com/advice/average-product-life/

[94] Stacy C. Davis, Susan W. Diegel, Robert G. Boundy, "Transportation Energy Data Book, Edition 34", ORNL, August 2015, ORNL-6991. http://cta.ornl.gov/data/tedb34/Edition34_Full_Doc.pdf This lists the average lifetime of vehicles as 16.9 years, which has been given a range here of 15-20 years.

[95] Energy Information Administration, "Age of Electric Power Generators Varies Widely", June 16, 2011, http://www.eia.gov/todayinenergy/detail.cfm?id=1830

[96] Jennifer O'Connor, "Survey on actual service lives for North American buildings", Woodframe Housing Durability and Disaster Issues conference, Las Vegas, October 2004, http://cwc.ca/wp-content/uploads/2013/12/DurabilityService_Life_E.pdf

[97] See, for example: Robert Solow, "Technical change and the Aggregate Production function", Review of Economics and Statistics 39, pp.312-320, 1957; Edward Denison, Trends in American Economic Growth 1929-1982, Brookings Institution, Washington, DC, 1985; Ishaq Nadiri, "Innovations and Technological Spillovers", NBER Working Paper #4423, National Bureau of Economic Research, Washington, DC, 1993;

[98] National Research Council, "Energy Research at DOE: Was It Worth It? Energy Efficiency and Fossil Energy Research 1978 to 2000", Committee on Benefits of DOE R&D on Energy Efficiency and Fossil Energy, Board on Energy and Environmental Systems, Division on Engineering and Physical Sciences, National Research Council, National Academies of Sciences, Engineering, and Medicine, National Academy Press, Washington, DC, 2001. https://www.nap.edu/catalog/10165/energy-research-at-doe-was-it-worth-it-energy-efficiency

[99] See, for example, the retrospective benefits studies listed at: http://www.energy.gov/eere/analysis/program-evaluation-eere-planned-and-completed-evaluations and http://www.energy.gov/eere/analysis/policy-and-analysis-publications

[100] U.S. DOE, Office of Energy Efficiency and Renewable Energy, "Saving Energy and money with Appliance and Equipment Standards in the United States", https://energy.gov/sites/prod/files/2016/10/f33/appliance_and_equipment_standards_factsheet-100516.pdf

[101] From 2009 through 2014, some 112 solar energy companies, primarily in the United States and the European Union, were identified as bankrupt, closed, or acquired by competitors under suboptimal conditions. See, for example: Eric Wesoff, "Rest in Peace: The Fallen Solar Companies of 2014", December 6, 2014, http://theenergycollective.com/eric-wesoff/2165821/rest-peace-fallen-solar-companies-2014

[102] See, for example: "Commerce Finds Dumping of Imports of Certain Crystalline Silicon Photovoltaic Products from China and Taiwan and Countervailable Subsidization of Imports of Certain Crystalline Silicon Photovoltaic Products from China" http://enforcement.trade.gov/download/factsheets/factsheet-multiple-certain-crystalline-silicon-photovoltaic-products-ad-cvd-final-121614.pdf

[103] National Research Council, "Assessment of Solid-State Lighting, Phase Two", National Academies of Sciences, Engineering, and Medicine, Committee on Assessment of Solid-State Lighting, Board on Energy and Environmental Systems, Division on Engineering and Physical Sciences, National Academy Press, Washington, DC, 2016. http://www.nap.edu/24619

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