



Advancing the Landscape of Clean Energy Innovation

February 2019

Foreword

We are pleased to submit our report, “Advancing the Landscape of Clean Energy Innovation.” In this report we describe today’s U.S. ecosystem of clean energy innovation from the perspectives of technological potential, investment patterns, institutional roles, and public policy.

The report identifies critical strengths and weaknesses of this ecosystem and offers recommendations for making that ecosystem more effective. It examines the different technology readiness stages through which innovation passes and the importance of feedback among those stages. It also discusses the significant opportunities to accelerate the pace of clean energy innovation that are presented by rapid advances occurring today across a myriad of technologies originating outside the energy sector.

We would like to emphasize three observations from our report.

- First, the U.S. has shown over many decades an unparalleled capacity to nurture energy innovation. This capacity reflects a rich and durable collaboration among government, universities, research institutions, industry, and entrepreneurs. This collaboration is grounded in the belief that energy innovation contributes importantly to economic growth, energy security, and environmental stewardship.
- Second, even with our capacity to innovate, and even with the emergence of innumerable technological opportunities, there are significant challenges in moving forward with clean energy technology. These challenges arise from the sheer size and complexity of existing systems, the degree to which these systems are embedded in our economy, and the high public expectations of safety and reliability they must meet. Energy systems traditionally have evolved incrementally.
- Third, these challenges can be met only by building on the collaborative strengths that our ecosystem has already demonstrated. Clean energy innovation depends on a national commitment to technological research; private-sector efforts to develop, apply, and commercialize products incorporating that research; and public policy.

In this report we convey the need for a comprehensive approach involving both public and private sectors in order to expand the current landscape of clean energy innovation and accelerate its processes. We hope that our report contributes to an understanding of the challenges presented and the approaches needed to address those challenges effectively. There is no final word on the subject. We see this report as a contribution to a continuing national dialogue and hope that it will stimulate further discussion, understanding, and action.

We are grateful for the opportunity that Breakthrough Energy and its partners have provided to explore this topic and recognize their commitment to advancing a meaningful and timely national dialogue. We hope that our report informs an appreciation of the complexity, reach, inherent dynamism, and promise of the U.S. clean energy innovation landscape and of the leadership that the United States can continue to provide.

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Executive Summary

The United States has been at the forefront of energy innovation for many decades. One of the most important reasons is the unique and extensive collaboration along the entire chain of innovation, from basic research to deployment, that engages the federal government, national labs and research institutes, universities, private sector, and state and local governments. This system has given the U.S. a global advantage for many decades.

The increasing focus on clean energy technology solutions and the potential for disruptive changes in energy systems points to the need for an objective review of the current clean energy innovation ecosystem. How does the clean energy innovation system work? What are its strengths and weaknesses? Is it up to the challenges? And how can it be improved and accelerated?

These are the questions that this study seeks to answer. Significant opportunities for clean energy innovation are presented by the changing U.S. energy supply profile; by advances in platform technologies such as digitalization and big data analytics; by expansion of electrification in the transportation and industrial sectors of the U.S. economy and the resulting electricity dependence of these sectors; by increases in urbanization and the emergence of smart cities; and by broad social and economic forces pushing to decarbonize energy systems in response to the risks posed by global warming and associated climate change.

Clean energy innovation supports multiple national goals: economic competitiveness, environmental responsibility, energy security, and national security. In serving these goals the need to address climate change is the challenge that calls most urgently for accelerating the pace of clean energy innovation.

Key features of energy systems, however, impede accelerated innovation. Energy is a highly capitalized commodity business, with complex supply chains and established customer bases, providing essential services at all levels of society. These features lead to systems with considerable inertia, focus on reliability and safety, aversion to risk, extensive regulation, and complex politics. Existing innovation processes face challenges as they work within these boundary conditions. The rapid pace of international energy investment, the commitments of most countries to Paris climate goals, and the ability of some countries such as China to rapidly increase clean energy investments challenge the preeminent position of the U.S. in clean energy innovation.

Successful clean energy innovation on a large scale in the U.S. requires alignment of key players, policies, and programs among the private sector, the federal government, and state and local governments. This report considers

these alignment needs through an assessment of the roles of these various groups. It also identifies critical clean energy technologies. It further suggests the value of regional efforts to advance innovation, and discusses ways in which federal tax policy could accelerate innovation. The report offers recommendations in each of these areas.

The Role of the Private Sector

The private sector is central to clean energy innovation, providing entrepreneurial vision, channeling financial resources, and connecting innovation to the rest of the energy system and the economy. At the same time, fundamental dynamics of the energy sector present significant challenges to clean energy innovation, stemming from basic industry characteristics and from the difficulty of capturing the full value of clean energy through market transactions alone. Innovators in clean energy face significant challenges in securing financial support and in demonstrating the compatibility of new technologies with existing systems. Over the past several years, venture capital has reduced its engagement in clean energy innovation, and traditional energy companies are exploring new models and mechanisms for innovation and investment.

While the initial stages of clean energy innovation are supported by a diverse, world-class set of U.S. research institutions, the innovation support system weakens as inventions move toward commercialization. The clean energy incubators that have emerged in recent years have so far tended to support software solutions. The availability of testing facilities for product demonstration is limited by the small number of facilities suitable for sustained testing and by their specialization.

Because of the energy system's long cycles of adoption, a broad range of approaches should be deployed to make it easier for adopters to understand, anticipate, and support the innovations that are being generated at the early stages of the innovation process. These efforts include, on the part of energy companies, open innovation, standardization of procurement requirements, encouragement of innovation testing either through dedicated evaluation staffs or through performance metrics, and active outreach to become familiar with innovations at the development stage or earlier. They include, on the part of innovators, early attention to the needs of adopters as indicated by expressed needs and by the past performance of innovation efforts.

Investments are needed from foundations and from federal, state, and local governments to expand the availability of open-access testbeds and strengthen the effectiveness of incubators in accelerating commercialization of innovative technologies. Some of these investments could fund research into best practices and performance results of incubators and testbeds and of state and local programs supporting innovation.

Because clean energy innovation incentivizes only modest financial investments at precommercial stages, and because strategic corporate investment is focused primarily on those innovations recognized as useful to business objectives, strategic philanthropic investors and coalitions of industry investors with long-term horizons could play an important role in identifying and supporting promising technology ventures that are otherwise not commercially viable in the near term.

Recommendations for Near-Term Actions

- Adopters of new technology, such as utilities, should consider a variety of approaches to support the innovations that are being generated at the early stages of the innovation process, including: open innovation; standardization of procurement specifications; encouragement of innovation testing (either through dedicated evaluation staffs or through performance metrics); and active outreach to become familiar with innovations at the development stage or earlier.
- Strategic philanthropic investors and coalitions of industry investors with long-term horizons should play an active role in identifying and supporting promising technology ventures that are otherwise not commercially viable in the near term.
- Foundations, as well as federal, state, and local governments, should make investments to expand the availability of open-access testbeds and incubators to accelerate commercialization of innovative technologies (e.g. Cyclotron Road).

Technologies with Breakthrough Potential

A shared agenda of primary technology objectives can help ensure that programs pursued by multiple stakeholders in the clean energy space are timely, durable, and mutually supportive. It can give entrepreneurs and creative innovators a framework for assessing the prospects of a particular area of initiative and the steps needed to sustain critical innovations over long time spans, and it can give corporate adopters, financial investors, and policymakers visibility into the evolving future of clean energy.

A four-step methodology is suggested for identifying breakthrough technologies to address national and global challenges and help meet near, mid- and long-term clean energy needs and goals. These steps consider technical merit, potential market viability, compatibility with other elements of the energy system, and consumer value. Application of these considerations to a list of 23 potential technology candidates yields a key technology shortlist:



Storage and battery technologies



Advanced nuclear reactors



Technology applications for industry and buildings as sectors that are difficult to decarbonize

- Hydrogen
- Advanced manufacturing technologies
- Building energy technologies



Systems: electric grid modernization and smart cities



Deep decarbonization/large-scale carbon management

- Carbon capture, use, and storage at scale
- Sunlight to fuels
- Biological sequestration

Recommendations for Near-Term Actions

- Federal investments in energy research, development, demonstration, and deployment (RDD&D) should be planned within a portfolio structure that supports potential breakthrough technologies at various timescales. There should be special focus on a critical subset of those technologies deemed to have very high breakthrough potential.
- Federal energy RDD&D portfolio investments should adopt a formal set of major evaluation criteria—such as technical merit, market viability, compatibility, and consumer value—with specific metrics for each criterion. These criteria should be used to prioritize programming and budget allocation decisions, as well as to develop public-private partnerships.
- Public and private sector stakeholders should collaborate in planning for and piloting of emerging technologies. A key component of these efforts is systems-level development plans that delineate technical challenges and risks; R&D pathways; cost and schedule assumptions; institutional roles (including public-private partnership opportunities); pathways to commercialization and diffusion; economic benefits; and consumer value.
- The Department of Energy (DOE) should lead a national effort to update the Basic Research Needs Assessments, originally initiated in 2001, to inform the assessments of emerging technologies with breakthrough potential, as well as the development of system-level roadmaps.

The Federal Government Role

The Federal government has long played a central role in supporting energy innovation. Through research grants, loan programs, tax incentives, laboratory facilities, pilot programs, and public-private partnerships, it has set the direction and pace of energy R&D, with profound impact on the national economy.

The principal agency funding clean energy innovation is the Department of Energy (DOE), which administers about 75 percent of all Federal energy R&D spending. DOE performs its role in partnership with its 17 national laboratories, academia, states, regions, other agencies, and the private sector. There are, however, several other Federal agencies with significant clean energy innovation budgets, including: the Department of Defense (DOD), the Department of Transportation (DOT), and the Department of Agriculture (USDA). Portfolios at these agencies are mission-focused, however, as opposed to being broadly based across all energy sectors.

As the primary Federal funder of energy R&D, DOE has played a critical role in changing the U.S. energy landscape over several decades. Shortly after its establishment in 1977, DOE characterized U.S. shale basins and supported the development of key drilling technologies that enabled horizontal drilling. It has had an ongoing and central role in developing supercomputing, an enabling technology for digitalization, artificial intelligence, smart systems, and subsurface characterization. Its investment in phasors and sensors support the smart grid. The Advanced Research Projects Agency — Energy (ARPA-E) — a DOE program —

has led to the creation of dozens of clean energy start-up companies which have raised more than \$2.6 billion in private-sector follow-on funding.

However, DOE's performance in advancing clean energy innovation would benefit from several institutional modifications. For example, the fuels-based organizational structure of the DOE, which has been in existence since 1979, is not optimized for modern energy systems and needs. It tends to lead to budget allocations by fuel, rather than prioritization by innovation potential.

The lack of long-term stable and predictable funding is also a concern for future R&D efforts at DOE. Although the Federal clean energy RD&D portfolio is significant (approximately \$6.4 billion in FY 2016 if expenditures by all Federal agencies and by DOE on basic science research are included), some prominent government and industry leaders have recommended the need for funding levels at two to three times the current levels based on the energy industry's current value to the economy (roughly \$1.37 trillion). While the Bipartisan Budget Act of 2018 (BBA) set new caps for discretionary spending that are as much as 25 percent higher than the Administration's budget — providing considerable headroom for near-term increases in spending for clean energy innovation — this agreement extends through FY 2019 only. The highly uncertain budget outlook for FY 2020 makes it difficult to plan an effective energy innovation portfolio focused on technologies with high breakthrough potential.

Recommendations for Near-Term Actions

- Congress and the Administration should initiate efforts to reorganize the Federal energy RDD&D portfolio and the Department of Energy toward a fuel- and technology-neutral structure that (1) aligns with the highest priority opportunities, (2) enables systems-level integration, and (3) avoids gaps in crosscutting programs.
- Congress and the Administration should consider dedicated funding sources for energy innovation as a means to ensure predictable and increasing levels of clean energy RDD&D funding based on international and cross-sectoral benchmarks.
- Federal policymakers should expand demonstration projects for key breakthrough technologies, while ensuring accountability via stage-gated project management, risk-based cost sharing, and assignment of demonstration project oversight to a single office within DOE.
- DOE and other agencies, as appropriate, should increase collaboration with the private sector and academia, including:
 - Instituting a multi-year and multi-agency portfolio planning process with broad-based stakeholder involvement from the private sector and academia.
 - Expanding use of prize authority to foster competition and open innovation.
 - Simplifying public-private partnerships with flexible financial vehicles like Technology Investment Agreements.

The Role of State, Local and Tribal Governments

State and city governments have regulatory authority over most of the myriad consumer, commercial, and industrial activities that collectively shape the country's patterns of energy use. They play central roles in advancing clean energy innovation, above all by creating markets for the application of clean energy technologies and encouraging diffusion of those technologies through supportive financial mechanisms.

Cities are crucial clean energy innovation testbeds. Urbanization trends make “smart cities” especially important as technology platforms for a clean energy future. Enhanced federal-state-city, public-private, and private-private partnerships can help unleash smart city innovation for tailored urban services, mobility, and standard-of-living improvements in the 21st century. “Smart” improvements could also provide significant value to rural communities by enabling decentralized generation and manufacturing, improving energy efficiency, and supporting economic development.

The contribution of state, local, and tribal governments to clean energy innovation could be further strengthened by development of program best practices and standardization, capacity and resource enhancement, increased funding, and modernization of ratemaking and business models. Programs that support and promote clean energy and energy innovation require significant state and local administrative resources and expertise; offices and officials that run them often have limited resources. Also, traditional ratemaking policies and methodologies at the state and local level can act as barriers to deployment of innovative energy technologies due to their reliance on proven track records associated with reliability and cost savings.

Recommendations for Near-Term Actions

- States should consider adopting technology-neutral clean energy portfolio standards and zero-emissions credits in order to strengthen markets for clean energy innovation — to include renewables and other forms of zero or low-carbon energy.
- State and local regulatory agencies should consider new ways in which existing ratemaking principles could be adapted to incentivize utilities to deploy established clean energy technologies, test emerging energy technologies, and realize value from behind the meter technologies.
- States should collaborate to identify best practices in the deployment of clean energy technologies, including financing mechanisms, consumer protections and equitable sharing of benefits among all socio-economic groups and geographic locations.

The Role of Regional Clean Energy Innovation Ecosystems

Many of the innovation opportunities and risks faced by the energy sector are highly regional in nature and are appropriately managed by strategies tailored to each region's specific needs. Strong regional relationships, for example, are observable among innovation, job creation, and technology deployment in the solar and wind energy industries.

Many energy innovation clusters in the U.S. are in the process of evolving into fully integrated innovation ecosystems. While federally funded RDD&D historically has not been well connected to state and regional economic development, activating these regional clusters to break down the barriers among federal, state, and local resources will create new synergies. National labs could serve as anchors for these efforts. While Federal support is important, regional leadership is critical. State and local governments, the private sector, universities, and philanthropies all have important roles in developing the particular strengths and shaping the particular contributions of regional innovation ecosystems.

Recommendations for Near-Term Actions

- Universities, private industry, philanthropies, state and local governments, and DOE should seek to expand and strengthen incubator capabilities within regional clusters to provide additional tools to enable innovators to conduct R&D and prototyping.
- DOE national laboratories, other federal laboratories, and Federally Funded Research Centers (FFRCs) can serve as anchors for regional clean energy innovation — and should be given sufficient flexibility in the expenditure of discretionary funds to support regional clean energy innovation options.

Mobilizing Increased Private Sector Investment in Energy Innovation

For U.S.-based entities, budget caps, reduced discretionary spending, and the Tax Cuts and Jobs Act (TCJA) will put downward pressure on Federal spending but will incentivize corporations to increase significantly business investments over the next decade (with estimates of up to \$15 trillion in incremental new investment, some of which could be targeted to energy innovation and infrastructure. Attracting these funds into clean energy innovation will depend on success in aligning the various elements of the innovation ecosystem discussed in this report: public policies that encourage a robust pipeline of research and that create markets for clean energy applications, combined with private-sector institutions that facilitate the commercialization of innovations.

The TCJA left unchanged the existing tax credits for renewable energy (wind, solar and geothermal), but did not extend the so-called “orphan” tax credits for fuel cells, combined heat and power projects, geothermal heat pumps, and new nuclear power plants. Most of these credits had expired at the end of 2016. The Bipartisan Budget

Act of 2018 (BBA), passed in February, modified and extended the nuclear power PTC; other credits were extended only through 2017 and their fate is uncertain.

In addition, the BBA included expanded provisions for carbon dioxide (CO₂) capture, utilization and storage (CCUS). The new 45Q provisions have the potential to significantly enhance the development and market diffusion of CCUS technologies and processes in both industrial and power applications, creating commercial opportunities both in the U.S. and abroad. The provisions provide greater market and financing certainty to help attract additional follow-on investment from the private sector.

Recommendations for Near-Term Actions

- DOE should set aside a small portion of its existing applied energy RDD&D funding to support accelerated de-risking of near-commercial innovative energy technologies and systems on an accelerated basis, to make these options more attractive for private capital investment.
- The new Section 45Q provisions expanding tax credits for carbon dioxide (CO₂) capture, utilization, and storage (CCUS) have the potential to significantly enhance the development and market diffusion of CCUS technologies and processes in both industrial and power applications, creating commercial opportunities both in the U.S. and abroad. Congress should consider additional measures to facilitate and accelerate CCUS deployment, including addressing uncertainties regarding long-term post-injection carbon management, monitoring, reporting and verification.

Chapter 1: Framing the Clean Energy Innovation Discussion

This chapter presents an overview of the opportunities and challenges faced by clean energy innovation in the United States today. It places the need for clean energy innovation in the context of national goals and broader technology trends. It notes the barriers to rapid diffusion of new technologies that are posed by a vast incumbent energy system, and the need for alignment of primary ecosystem components in order to overcome those barriers. This introductory discussion frames the chapters that follow, which discuss those primary components in greater detail and offer recommendations for strengthening their interaction.

FINDINGS

Framing the Clean Energy Innovation Discussion

- Growing energy-related challenges—climate change, national security, and competition for clean energy markets with other countries—point to a critical need for a U.S. innovation ecosystem that can accelerate the pace of energy sector transformation.
- Major trends creating both urgency and opportunities for clean energy innovation include: changes in the U.S. energy supply profile; digitalization, big data analytics, and smart systems; expansion of electrification in the transportation and industrial sectors of the U.S. economy and the resulting electricity dependence of these sectors; changes in demographics, increases in urbanization, and the emergence of smart cities; and broad social and economic forces pushing the energy sector toward decarbonization in response to the risks posed by global warming and associated climate change.
- Clean energy innovation also supports major national energy goals: economic competitiveness, environmental responsibility and greenhouse gas emissions reduction, energy security, and national security.
- Key features of energy systems, however, act against accelerated clean energy innovation. Energy is a highly capitalized commodity business, with deeply developed supply chains and established customer bases, providing essential services at all levels of society. These features lead to systems with considerable inertia, aversion to risk and focus on safety, extensive regulation, and complex politics. Existing innovation processes face challenges as they work within these boundary conditions.
- As energy systems increasingly adapt advanced technologies from adjacent industries, for example digitalization and nonstructural materials, many new and nontraditional players are entering the energy marketplace.
- The rapid pace of international energy investment, the role of central planning and greatly increased clean energy research, development and deployment, especially in China, and international commitments to Paris climate goals create conditions in which the U.S. could lose its current leadership position in clean energy innovation.
- Successful clean energy innovation on a large scale in the U.S. requires alignment of key players, policies, and programs within the federal government, state and local government, and the private sector — all of which need to work together to optimize investments in clean energy innovation.

TEXT BOX 1-1

Clean Energy

Clean energy: any process, product or system of products and processes, that can be applied at any stage of the energy cycle from production to consumption, whose application will reduce net greenhouse gas emissions, and can meet one or more of the following characteristics: reduced demand for water resources; reduced waste; reduced emissions of other air pollutants or reduced concentrations of contaminants in wastewater discharges.

Focus on the Future: Opportunities in Clean Energy Innovation

Energy powers the U.S. economy and its industrial base and is key to maintaining the health and well-being of U.S. citizens, enabling critical lifeline networks, interdependent infrastructures on which citizens rely, and emergency services. It also is a vital link to the global economy.

Four critical elements in the U.S. energy landscape set it apart from many other nations. First, the U.S. has a large energy resource endowment. It is now the world's number one producer of oil liquids and natural gas. It has large reserves of coal, and is converting its widely distributed renewable resources into useful energy. Second, the U.S. has an enormous energy market capable of supporting vast production and distribution assets and operations. Third, the U.S. has the best research universities in the world, continually developing discoveries and insights at the frontier of energy science. Fourth, the U.S. over many decades has sustained and funded a fruitful collaboration among universities, the government's national labs, and industry aimed at stimulating scientific discovery and bringing the insights of science into commercial application. These four elements have combined to provide an exceptionally dynamic energy innovation ecosystem.

The current report addresses key questions about the clean energy innovation ecosystem, including:

- How does clean energy innovation help meet national goals?
- How do the various elements of the clean energy innovation ecosystem interact, and can they be more productive?
- How does the United States leverage the clear strengths and advantages of its energy innovation ecosystem to establish a clean energy future?
- Is investment in clean energy innovation adequate to maintain our global leadership position?

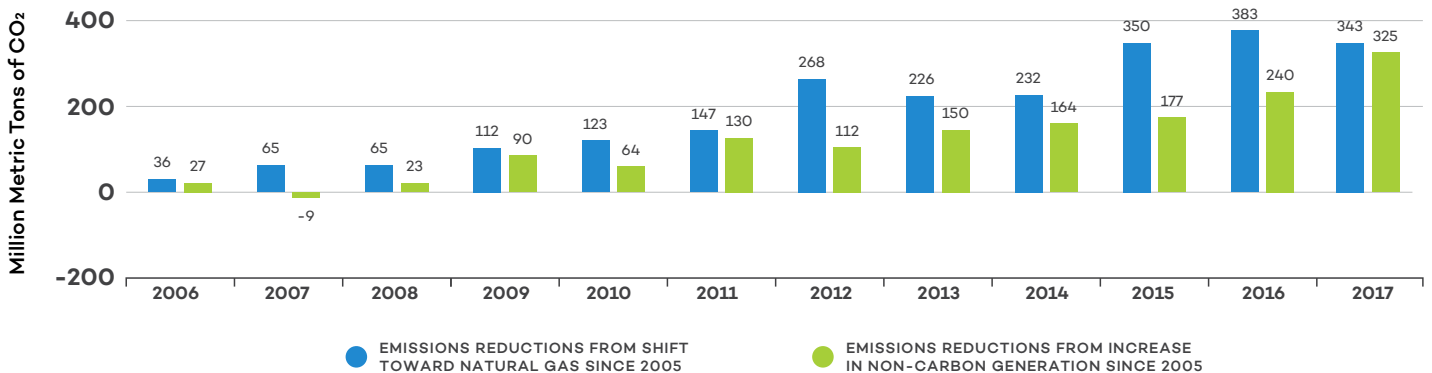
The Changing Energy Landscape

Today's changing energy technology landscape, coupled with recent dramatic advances in broad enabling technology fields, represents an opportunity to enhance and further invigorate the U.S. energy innovation ecosystem, create value and jobs, and help meet key policy goals. Several significant trends in energy markets are helping to shape these opportunities, including:

- changes in the U.S energy supply profile
- digitalization, big data analytics, and smart systems
- expansion of electrification in the transportation and industrial sectors of the U.S. economy and an increase in electricity-dependence in those sectors
- changing demographics, increased urbanization and the emergence of smart cities
- decarbonization through a changing fuel mix and increased energy efficiency

FIG. 1-1

U.S. CO₂ Emissions Reductions in Electricity Generation, 2006-2014



Fuel-switching to natural gas has resulted in a considerable reduction in CO₂ emissions from the U.S. power sector.

Source: EIA, 2018.

Innovation Has Changed the U.S. Energy Supply Profile

In the past decade, the technology-enabled unlocking of shale gas and tight oil resources in the U.S. has dramatically expanded available oil and natural gas resources, reduced the costs of producing them, and redefined the U.S. role in global oil and gas markets.

Domestically, the abundance of low-cost natural gas has resulted in a substantial shift away from coal to natural gas in the U.S. power generation sector. This shift has substantially reduced carbon dioxide emissions from the power sector (Figure 1-1).¹ Due to the greater operational flexibility of gas generation in contrast to coal generation it also has facilitated the integration into the power grid of generation from variable renewable resources such as wind and solar photovoltaic energy.

Internationally, increases in U.S. tight oil production have brought substantial diversification to international oil supply and have diminished the role of OPEC. The development of a U.S. export capacity for liquefied natural gas (LNG), enabled by low-cost shale gas production, has weakened the long-standing oil-linked LNG contracting conventions and has contributed to a growing spot market for global LNG. The potential growth of natural gas in Asia resulting from expanded LNG supplies could lead to emissions reductions from power generation similar to those seen in the United States.

Meanwhile, reductions in the costs of wind and solar technologies have improved their economics to the point where renewable power now represents the lowest cost option for new power generation capacity in some markets. In 2016, wind and solar units accounted for over 60 percent of new U.S. generation capacity.²

The rise of solar PV is particularly notable because of the technology's unique technical characteristics: it can be deployed effectively at every scale, from a single residential household installation involving kilowatts of generation capacity, to traditional utility-scale facilities involving hundreds of megawatts of capacity. This deployment flexibility, in combination with strong policy support, has resulted in the widespread growth of distributed solar generation. At the end of 2017

1. <https://www.eia.gov/environment/emissions/carbon/>

2. Energy Information Administration [EIA], "U.S. Electric Generating Capacity Increase in 2016 Was Largest Net Change Since 2011," Today in Energy, February 27, 2017, <https://www.eia.gov/todayinenergy/detail.php?id=30112>

“The rise of solar PV is particularly notable because of the technology’s unique technical characteristics: it can be deployed effectively at every scale, from a single residential household installation involving kilowatts of generation capacity, to traditional utility-scale facilities involving hundreds of megawatts of capacity.”

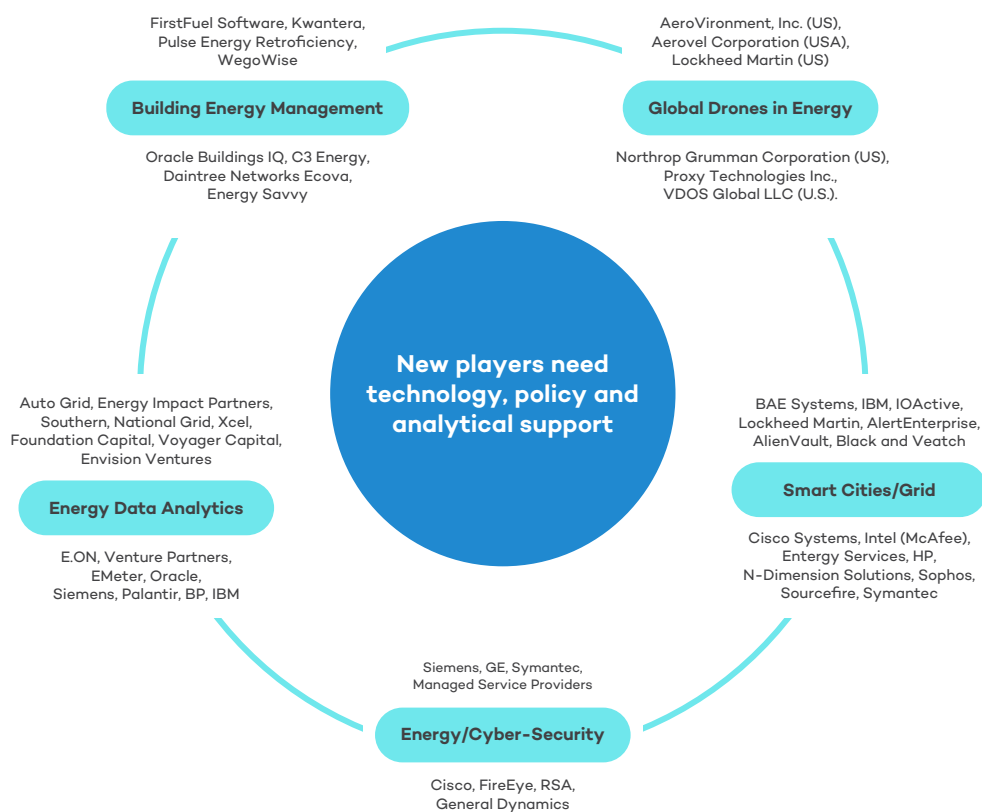
there were over 1.6 million solar installations in the United States,³ which include 16.2 gigawatts (GW) of “small-scale solar” (including residential and commercial rooftops) and 24.9 GW of utility-scale solar.⁴ These solar resources accounted for a little over one percent of U.S. power generation in 2017.

The spread of distributed solar generation combined with new digital technology has enabled two-way flows of electricity and created value in demand response across the system. It has allowed consumers to generate their own electricity from rooftop solar panels and to sell it back to the grid. The growing infrastructure of distributed solar PV facilities in the United States and other parts of the world is part of a broader trend towards an energy system that is more decentralized. In such systems, distributed generation, energy storage, and other smart energy devices consume and produce energy in a much more dynamic and system-responsive manner.

These changes have brought a range of new players into the energy marketplace as well as a range of new, system-based services, consumer products, and technologies to mitigate system risks (Figure 1-2).

FIG. 1-2

Emerging Clean Energy Innovation Spaces: Examples of Incumbents and New Players



3. “Solar Industry Data,” Solar Energy Industries Association, accessed February 27, 2018, <https://www.seia.org/solar-industry-research-data>

4. EIA, Electric Power Monthly, February 27, 2018, Table 6.1.A, https://www.eia.gov/electricity/monthly/epm_table_grapher.php?t=epmt_6_01_a

Non-traditional, technology-centric players are beginning to enter the clean energy space, which could unlock significant innovation opportunities throughout the energy value chain.

Source: Energy Futures Initiative (EFI), 2017

Digitalization, Big Data, and Smart Systems

The expansion of energy opportunities has been greatly facilitated by the rapid global growth of capabilities in digital information, analytics, and networks. Roughly 7.5 million internet-connected devices are added each day across the world, and by 2020 there are expected to be around 20 billion digital devices enabling the “Internet of Things” and the “Fourth Industrial Revolution” (Figure 1-3)⁵ — a world in which “anything that can be connected will be.”⁶ These changes, and those driven or supported by other key platform technologies, will continue to underpin breakthroughs in energy.

The global diffusion of digital technologies, combined with new capabilities to harvest vast amounts of data have unlocked a new era of advanced data analytical capabilities (e.g., machine learning, predictive analytics, natural language processing) to analyze large data sets and allow for better decision-making.⁷

This trend in big data analytics has led some to claim that “data is the new oil.”⁸ Additionally, big data analytics has unlocked significant potential in the use of software algorithms to perform tasks—visual perception, understanding and communicating with natural language and adapting to changing situations—that normally require human intelligence and leverage automation capabilities.⁹

Many of the functions of electric grid operators are improved by, and have the potential to be optimized by, automation. Distribution automation can greatly improve the speed, cost and accuracy of key functions required by smart grids. It uses digital sensors and switches with advanced control technologies to automate feeder switching, monitor voltage and equipment health—and also manage outages, voltages and reactive power.¹⁰

5. Gartner, “Gartner Says 8.4 Billion Connected ‘Things’ Will Be in Use in 2017, Up 31 Percent From 2016” (2017), <https://www.gartner.com/newsroom/id/3598917>

6. Jacob Morgan, “A Simple Explanation of the ‘Internet of Things,’” *Forbes*, May 13, 2014, <https://www.forbes.com/sites/jacobmorgan/2014/05/13/simple-explanation-internet-things-that-anyone-can-understand/#4f6aa33f1d09>

7. “Big Data Analytics,” IBM, accessed February 27, 2018, <https://www.ibm.com/analytics/us/en/technology/hadoop/big-data-analytics/>

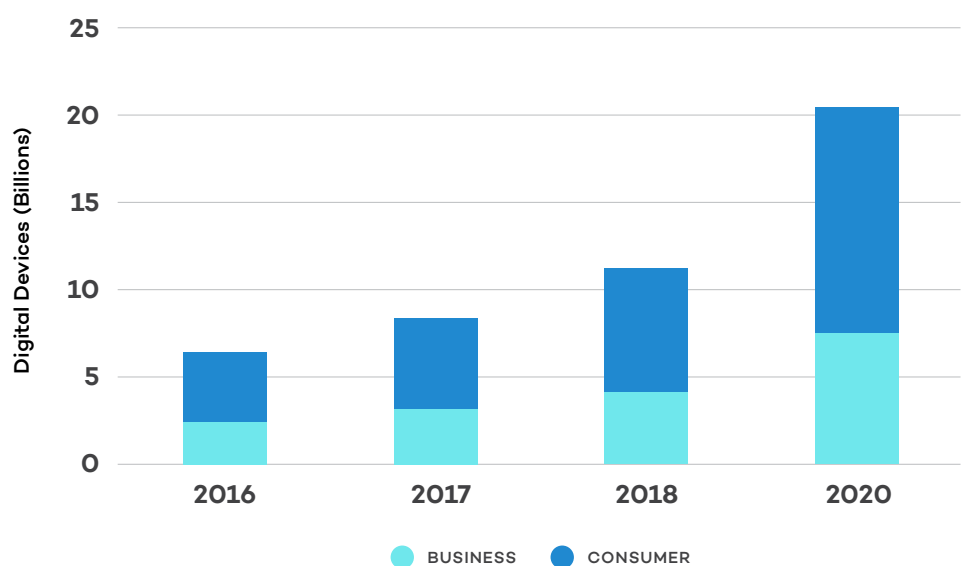
8. Matt Terry, “Jared Cohen Discusses Cyberpower and the New Digital Age,” *SIPA News*, May 2017, 59, <https://sipa.columbia.edu/news/jared-cohen-discusses-cyberpower-and-new-digital-age>

9. “Tech Breakthroughs Megatrend,” PwC, accessed February 27, 2018, <https://www.pwc.in/publications/tech-breakthroughs-megatrend.html>

10. DOE, *Distribution Automation: Results from the Smart Grid Investment Grant Program* (Washington, D.C., 2016), 4, https://energy.gov/sites/prod/files/2016/11/f34/Distribution%20Automation%20Summary%20Report_09-29-16.pdf

FIG. 1-3

Projected Number of Digital Devices Deployed Worldwide



The number of digital devices worldwide has increased dramatically since 2003; a trajectory that is expected to continue.

Source: *Energy Futures Initiative (EFI)*, 2017

The smart grid is enabled by trends in digital systems, which create two-way communication between electric utilities and customers. Smart meter infrastructure, sensors, and communication-enabled devices and controls support smart consumption, demand response, and distributed generation using real-time or near-real-time data. They also help improve system reliability by enhancing situational awareness and system responsiveness. Roughly 71 million advanced metering infrastructure (AMI) smart meters were installed in the U.S. by the end of 2016, covering 47 percent of the country's 150 million electricity customers (Figure 1-4). This was double the number of installations in 2010.¹¹

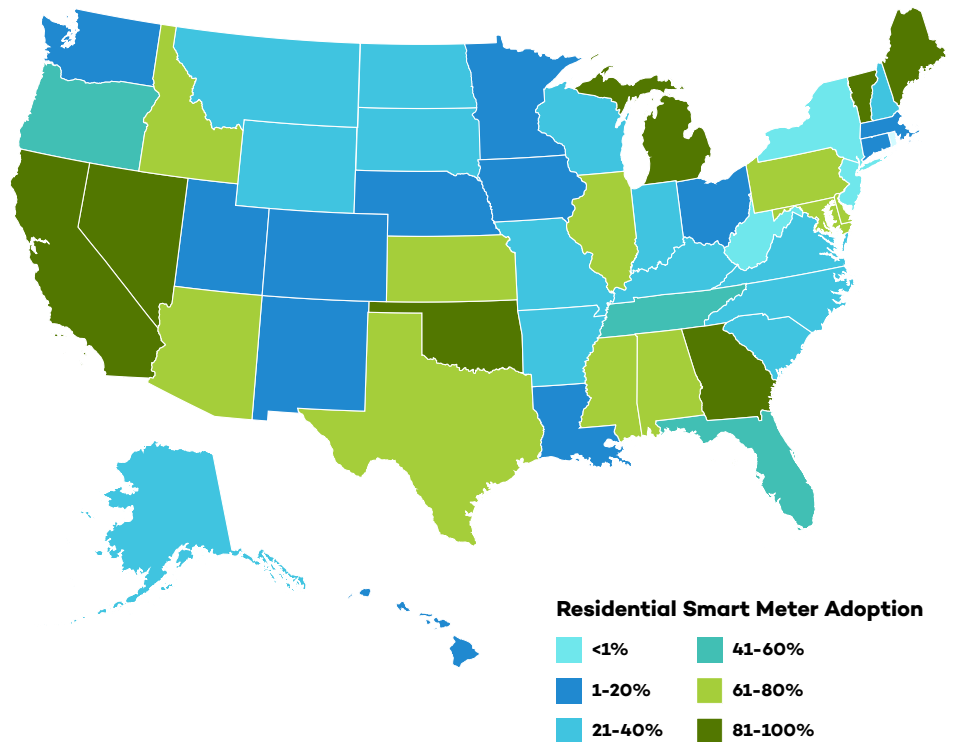
Artificial Intelligence (AI) is likely to unleash the next wave of digital disruption. Opportunities for machine learning and automated decision-making exist at every step of the energy value chain. In the face of increasing complexity of markets and networks of stakeholders and assets, AI can help the electricity sector better predict market behavior, balance operations in real time, maximize yield, and improve end-user experience.

Electrification and Electricity Dependence

The proliferation of digital and smart technologies and growing public interest in reducing carbon emissions are expanding electricity's role in the global economy. In 2016, for the first time ever, global investment in the electricity sector was higher than in all other energy sectors, including oil and gas, the historical owners of first place.¹²

FIG. 1-4

Residential Smart Meter Deployment, 2017



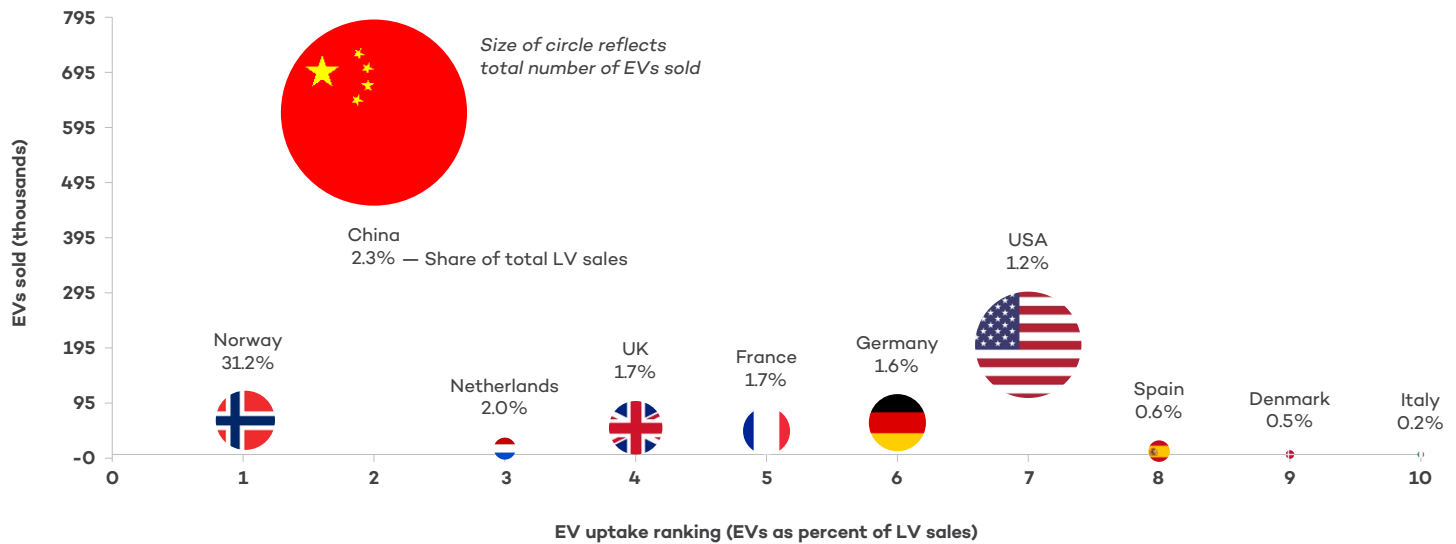
11. EIA, "Nearly Half of All U.S. Electricity Customers Have Smart Meters," Today in Energy, December 6, 2017, <https://www.eia.gov/todayinenergy/detail.php?id=34012>

12. IEA, World Energy Investment, 2017, accessed October 19, 2018, <https://www.iea.org/Textbase/npsum/WEI2017SUM.pdf>

Source: Energy Futures Initiative (EFI), 2018. Compiled using data from EIA, Today in Energy, December 6, 2017

FIG. 1-5

Comparison of EV Sales and Penetration by Leading Ten Countries, 2017



In 2017, the U.S. was the second largest purchaser of EVs, after China. However, six countries, including China, had greater EV sales as a percentage of their domestic market.

Source: IHS Markit "Reinventing the Wheel: Mobility and Energy Future" Service

While electrification is growing across industry, buildings, and other end-use sectors, the trend is most pronounced in the transportation sector. Although the global stock of electric vehicles — including battery-electric vehicles (BEV), plug-in hybrid electric vehicles (PHEV) and fuel cell electric passenger light-duty vehicles (FCEVs)—currently corresponds to just 0.2 percent of the total number of passenger light-duty vehicles in circulation, and 1.2 percent of light-duty vehicles sold in the U.S. in 2017, EV markets are growing rapidly. In 2016, the global EV stock exceeded two million, after surpassing one million in 2015.¹³

While the United States has been surpassed by China as the global leader in new EV sales (See Figure 1-5) the United States continues to see sharp increases in both electric light-duty vehicle sales and electric vehicle miles traveled.¹⁴ The total number of electric vehicles sold in 2016 (144,000) was nearly triple the number sold in 2012 (53,200).¹⁵ Projections for future adoption of these vehicles vary and may be influenced positively by smart mobility trends, such as connected and automated vehicles and ride sharing.

With this growing electrification, the U.S. economy and society are becoming significantly more dependent on electricity. All lifeline networks, as defined by the Department of Homeland Security (DHS), depend on electricity. Cybersecurity therefore will be an increasingly critical issue that must be addressed to protect the enormous value creation associated with electricity and all that it enables.

13. IEA, Global EV Outlook 2017: Two Million and Counting (Paris, 2017), 21, <https://www.iea.org/publications/freepublications/publication/GlobalEVO Outlook2017.pdf>

14. IEA, Global EV Outlook 2017, 5.

15. DOE, "U.S. Plug-in Electric Vehicle Sales by Model," accessed February 27, 2018, <https://www.afdc.energy.gov/data/10567>

Demographics, Urbanization, and the Emergence of Smart Cities

As of January 1, 2018, the U.S. population was 327 million. By midcentury, the total U.S. population is projected to reach 400 million. Although the growth rate in the U.S. has slowed over the last century, it is notable that the U.S. is the only major industrialized country in the world where population is expected to grow significantly over the next several decades.

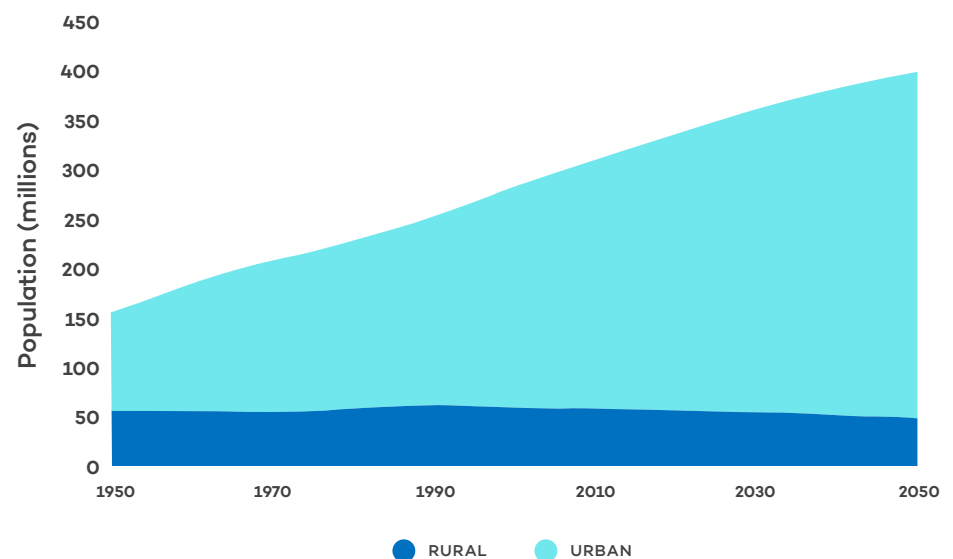
Population trends between urban and rural areas in the U.S. have differed markedly in the past (Figure 1-6). While the number of urban residents has increased approximately 500 percent since 1910, the number of rural residents has only increased by 19 percent.¹⁶ From 2000 to 2010, urban population growth increased by 12.1 percent, which outpaced the overall population growth rate of 9.7 percent. At present, only one-fifth of the U.S. population lives in rural areas.¹⁷ Projections to 2050 indicate an increasingly urban population, while rural areas could experience a slight population decline. Coastal areas of the U.S. continue to see the greatest population increases.¹⁸

Urbanization trends in the U.S. will likely increase the need for smart cities that draw on many technology areas, including networking and communications systems, the “Internet of Things,” cloud computing, and open data and big data analytics.¹⁹

On the other hand, urbanization raises issues about providing key, affordable services to rural areas that are disproportionately dependent on personal vehicles and trucks for the delivery of goods and services, where smart city technologies are not an option, where electric vehicles raise more concerns than in urban or suburban areas, and where many residents do not have access to broadband. This variability of impact suggests the need for regional solutions, strong support for universal broadband, and innovation in decentralized energy systems and additive manufacturing.

FIG. 1-6

Population Growth Projections for both Rural and Urban Areas



In the United States, urban areas are projected to see steadily increasing population growth, while rural areas may experience a population decline.

Source: Energy Futures Initiative (EFI), 2018. Compiled using data from United Nations, Department of Economics and Social Affairs, Population Division (2014).

16. EPA, “Urbanization and Population Change.”

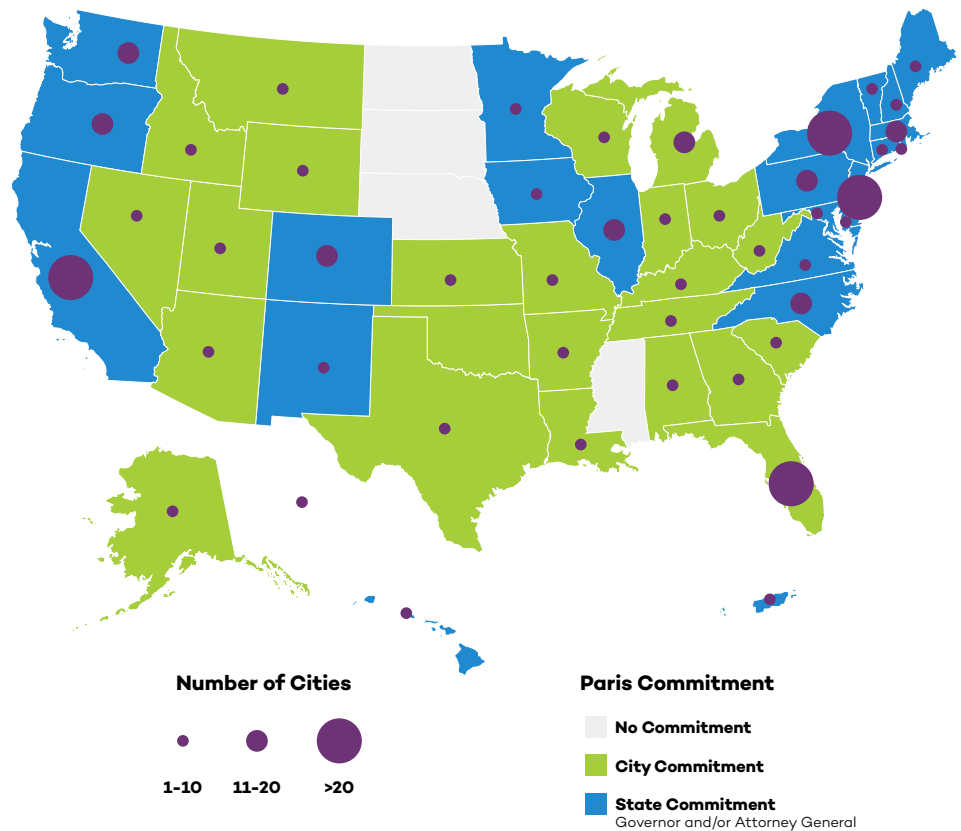
17. Census Bureau, “New Census Data Show Differences Between Urban and Rural Populations,” news release, December 8, 2016, <https://www.census.gov/newsroom/press-releases/2016/cb16-210.html>

18. U.S. Department of Commerce, National Oceanic and Atmospheric Administration [NOAA], “NOAA, U.S. Census Report Finds Increases in Coastal Population Growth by 2020 Likely, Putting More People at Risk of Extreme Weather,” March 25, 2013, <https://oceanservice.noaa.gov/news/weeklynews/mar13/population.html>

19. Lea, Smart Cities, 5-9.

FIG. 1-7

Sub-national Commitments to Meeting U.S. NDCs under Paris Agreement



There is a strong sub-national commitment to the Paris Agreement across the public and private sectors.

Source: Energy Futures Initiative (EFI), 2018. Compiled using data from U.S. Climate Alliance, Climate Mayors, and Office of the Attorney General for the District of Columbia.

Decarbonization

The U.S. has experienced a significant decline in CO₂ emissions in six of the last 10 years. The shift from coal to natural gas in power generation resulted in 1,254 million metric tons of avoided CO₂ emissions from 2005 to 2014, or about 61 percent of total avoided emissions over that period.²⁰ Developments in energy efficiency also have led to major drops in energy-related carbon emissions. At the household-level, energy efficiency expenditures led to \$140 in savings per capita in the United States since 2000.²¹ From 2009 through 2016, DOE issued 50 new or updated standards to make appliances, buildings, and equipment more efficient.²² Cumulatively, between 2009 and 2030, these standards are projected to reduce carbon emissions by over 2.5 billion metric tons, save consumers \$557 billion on utility bills, and reduce primary energy consumption by 42 quadrillion British thermal units (quads).²³

Overall U.S. CO₂ emissions in 2016 were 1.7 percent below their 2015 levels. U.S. CO₂ emissions today are back to the level of the early 1990s, although the economy has doubled in size since then.

20. DOE, Quadrennial Energy Review: Transforming the Nation's Electricity System: The Second Installment of the QER (Washington, D.C., 2017), 3-14. <https://www.energy.gov/policy/initiatives/quadrennial-energy-review-qer/quadrennial-energy-review-second-installment>

21. "Global Trends in Energy Efficiency," IEA, accessed February 27, 2018, <https://www.iea.org/topics/energyefficiency/globaltrends/>

22. Ernest J. Moniz, "Cabinet Exit Memo" (2017), <https://www.energy.gov/sites/prod/files/2017/01/f34/Department%20of%20Energy%20Cabinet%20Exit%20Memo.pdf>

23. DOE, Quadrennial Energy Review: Second Installment, 3-26.

The challenge of decarbonization will continue to be a major spur to clean energy innovation. Pursuant to the Paris Agreement of 2015 the U.S. committed to reduce greenhouse gas emissions 26 to 28 percent below 2005 levels by 2020.²⁴ While that goal no longer represents national policy, numerous sub-national entities in the U.S., including states and cities, have pledged to continue contributing to the U.S. goals (Figure 1-7).²⁵

Expressed commitments to carbon reduction have been made in the private sector as well. According to a joint publication of the National Association of State Energy Officials and Ceres, 60 percent of Fortune 500 companies have a clean energy, GHG emissions reduction, or energy efficiency goal and “120 major companies have agreed to set independently-verified, science-based GHG emissions reduction targets — equivalent to reducing GHG emissions 80% relative to 2005 levels by 2050.”²⁶ In December 2017, 32 oil and gas companies announced the Environmental Partnership, whose participants “believe that addressing environmental impacts is an important component of securing America’s long-term energy future.”

Major oil and gas companies are responding with new initiatives to advance innovation. Ten oil and gas companies have launched the Oil and Gas Climate Initiative (OGCI) and in 2016 announced a billion-dollar investment vehicle to “invest in technologies that have the potential to significantly reduce greenhouse gas emissions and are economically viable.”²⁷ (Figure 1-8)

FIG. 1-8

Global Oil and Gas Companies in the Oil and Gas Climate Initiative



“We, the leaders of the ten major oil and gas companies, are committed to the directions set out by the Paris Agreement on climate change. We support its agenda for global action and the need for urgency. Through our collaboration in the Oil and Gas Climate Initiative (OGCI), we can be a catalyst for change in our industry and more widely. OGCI aims to increase the ambition, speed and scale of the initiatives we undertake as individual companies to reduce the greenhouse gas footprint of our core oil and gas business – and to explore new businesses and technologies.”

Source: OGCI website

The appetite for clean energy innovation expressed in these commitments is likely only to grow and become more urgent. Analyses indicate a significant delta between current mitigation pledges and the level of mitigation needed to stay below the 2-degree limit.^{28, 29}

Figure 1-9 highlights the increased ambitions needed beyond the Paris Agreement NDCs to stay below the 2-degree Celsius limit,³⁰ underscoring the likely demand for new technologies and their accelerated deployment and diffusion by mid-century. The pace of clean energy innovation, already rapid, needs to be quickened, and the portfolio needs to be broadened.

24. United States of America, First Nationally Determined Contribution Submission, March 9, 2016, <http://www4.unfccc.int/ndcregistry/PublishedDocuments/United%20States%20of%20America%20First/U.S.A.%20First%20NDC%20Submission.pdf>

25. International Finance Corporation, “Climate Investment Opportunities Total \$23 Trillion in Emerging Markets by 2030, Says Report,” accessed February 27, 2018, [http://www.ifc.org/wps/wcm/connect/news_ext_content/ifc_external_corporate_site/news+and+events/news/new+ifc+report+points+to+\\$2423+trillion+of+climate-smart+investment+opportunities+in+emerging+markets+by+2030](http://www.ifc.org/wps/wcm/connect/news_ext_content/ifc_external_corporate_site/news+and+events/news/new+ifc+report+points+to+$2423+trillion+of+climate-smart+investment+opportunities+in+emerging+markets+by+2030)

26. Sandy Fazeli, Ryan Martel, and Alli Gold Roberts, Public-Private Partnerships to Advance Low-Carbon State Energy Policies: A NASEO- Ceres Issue Brief (Boston: Ceres, 2016), 2, https://www.naseo.org/data/sites/1/documents/publications/Ceres_NASEO_State_Energy_Policies.pdf

27. “OGCI Climate Investments,” Oil and Gas Climate Initiative, accessed February 27, 2018, <https://oilandgasclimateinitiative.com/investments/>

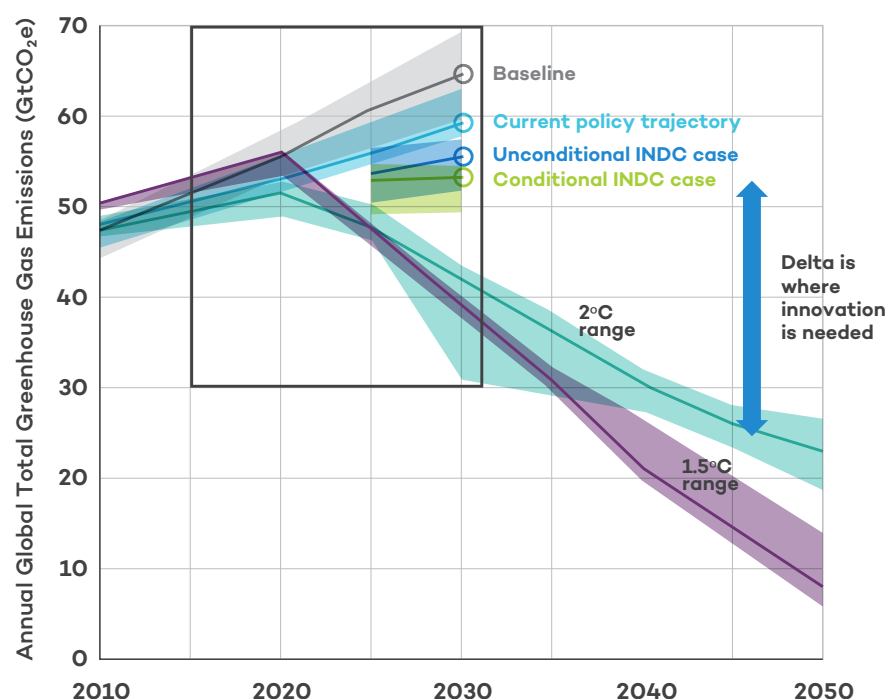
28. UN Environment Programme [UNEP], The Emissions Gap Report 2017 (Nairobi, 2017), <http://uneplive.unep.org/theme/index/13#egr>

29. Joeri Rogelj et al., “Paris Agreement Climate Proposals Need a Boost to Keep Warming Well Below 2°C,” *Nature* 534 (June 30, 2016): 631-639, doi:10.1038/nature18307

30. UNEP, The Emissions Gap Report 2017, 15.

FIG. 1-9

Meeting Deep Decarbonization Goals Will Require Significant Investments in Innovation



Model forecasts indicate that the world is not on a course to stay below the 2-degree Celsius limit with current INDC commitments. Significant innovation will be required to bridge the policy gap.

Source: Energy Futures Initiative (EFI), 2018. Modified from UNEP, *The Emissions Gap Report 2017*.

National Energy Goals

Clean energy innovation contributes materially to major national energy goals (see Text Box 1-2). Integration and diffusion of new technologies make energy systems more efficient and support productivity growth in the economy. Clean energy creates jobs. The 2018 U.S. Energy and Employment Report indicated that there were more than 1.9 million workers directly employed in Electric Power Generation and Fuels technologies in 2017; 800,000 of them were working in low-carbon-emission generation technologies, including renewables, nuclear, and advanced/low-emission natural gas. There were additionally 2.25 million jobs in energy efficiency, a category that includes the design, installation, and manufacture of energy efficiency products and services.³¹ Development of new energy technologies gives the U.S. products, systems, and expertise for export to vast world energy markets seeking ways of reconciling growing global energy needs with stringent climate policies. The technologies and infrastructure associated with clean energy innovation create flexibility and resilience in the energy system by diversifying energy resources and providing distributed points of supply and consumption.

31. <https://static1.squarespace.com/static/5a98cf80ec4eb7c5cd928c61/t/5afb0ce4575d1f3cdf9ebe36/1526402279839/2018+U.S.+Energy+and+Employment+Report.pdf>

TEXT BOX 1-2

National Goals*



Economic Competitiveness: Energy and its technologies for generation, transmission and distribution should enable the nation to, under a level playing field and fair and transparent market conditions, produce goods and services that meet the test of international markets while simultaneously maintaining and expanding jobs and the real incomes of the American people over the longer term. Energy technologies should enable new architectures to stimulate energy efficiency, new economic transactions, and new consumer services. Internationally competitive production of goods and services:

- maintain and expand jobs and real incomes of the American people over the longer term;
- stimulate energy system evolution, innovation, and improvement; and
- address energy inequities.



Environmental Responsibility: Energy technologies and associated infrastructures and supply chains should take into consideration a full accounting (on a life-cycle basis) of environmental costs and benefits, in order to minimize their environmental footprint.



Energy Security: Energy technologies and associated infrastructures and supply chains should be minimally vulnerable to most supply disruptions, both operationally and economically. They should mitigate impacts, including economic impacts, of disruptions by recovering quickly or with use of reserve stocks. Energy security should support overall national security and economic confidence and it should minimize opportunities for foreign influence.



National Security: Energy is essential for supporting and sustaining industrial output, government, emergency services, interdependent critical infrastructures, and the U.S. national security apparatus. These critical infrastructures include physical and information infrastructures that are required for communications, transportation, and almost every other element of economic and social activity. Electricity is especially critical for national security as it cannot currently be stored at scale.

**Modified from DOE, Quadrennial Energy Review: Energy Transmission, Storage, and Distribution Infrastructure, 1-19, 1-20*

“...the long-held preeminence of the U.S. in energy technology is challenged, for example, by China’s growing investment in clean energy innovation, which already surpasses the U.S. investment in several critical areas.”

Challenges Facing Clean Energy Innovation

The United States’ energy innovation ecosystem has sustained, modernized and transformed the country’s energy sources, systems, and services over many decades. It has made the U.S. the global leader in energy technology.

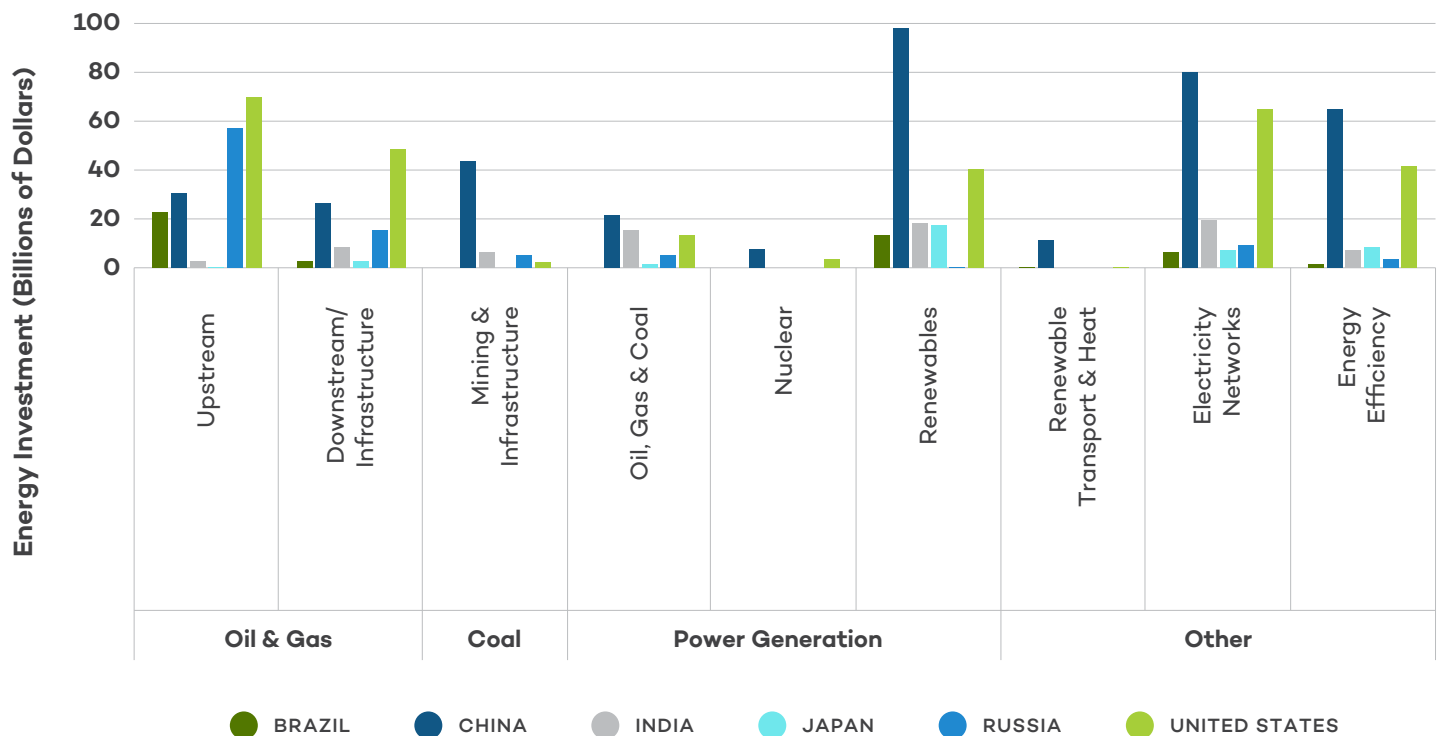
Along with the many forces favoring U.S. clean energy innovation come significant challenges. These challenges arise chiefly from the pervasiveness and strength of existing U.S. energy systems and from the complexity of the energy innovation process, and are especially daunting when considered in a global context. The long-held preeminence of the U.S. in energy technology is challenged, for example, by China’s growing investment in clean energy innovation, which already surpasses U.S. investment in several critical areas. (See Figure 1-10.)

Boundary Conditions of the Energy Sector

Energy is a highly capitalized, commodity business, with complex and extensive supply chains and established customer bases, providing essential services at all levels of society. These features lead to systems with considerable inertia, high levels of safety awareness and risk aversion, extensive regulation, and complex politics.

FIG. 1-10

Energy Investments by Resource and Country, 2017



The United State and China were major investors in energy resources in 2017. Chinese investment in power generation from renewables was over twice that of the United States.

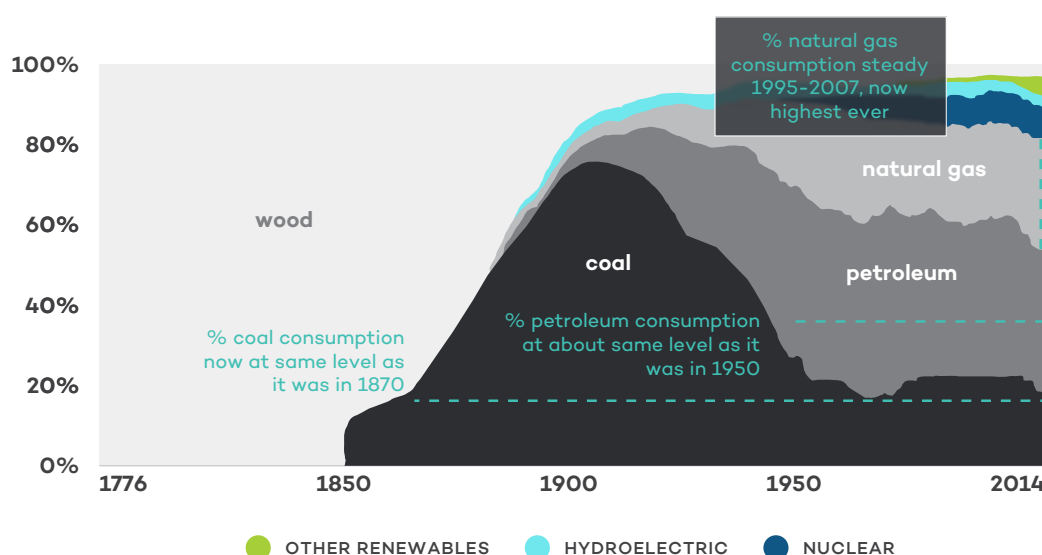
Source: Energy Futures Initiative (EFI), 2018. Compiled using data from IEA, World Energy Investment 2018.

These characteristics play a large role in shaping the structure of the sector's innovation pipeline, including the timelines involved and the roles played by individual stakeholders. Historically, transitions from dominant fuel sources take place on a multi-decadal scale (Figure 1-11). They occur within a framework of entrenched, high-value incumbent assets and service models that present significant barriers to market entry for new players. In comparison to other industries, the scope for disruptive change in energy systems due to innovation in technology or business model is limited.

The clean energy industry is operating in an uncertain policy environment, with significant inconsistencies between Federal and state programs, regulations and objectives. At a time of need for dramatic acceleration of the pace of innovation, these uncertainties could impede needed investments by the private sector.

FIG. 1-11

Share of U.S. Energy Consumption, 1850-2014



The U.S. fuel mix has changed dramatically since the middle of the nineteenth century, when coal was the primary fuel source for energy consumption. The percentage of coal consumption today is about the same as it was in 1870, the percentage oil consumption is about the same as it was in 1950, and natural gas, nuclear energy, hydropower, and other forms of renewable energy have gained a significant share of energy consumption and diversified the fuel mix.

Source: Energy Futures Initiative (EFI), 2018. Modified from EIA, *Today in Energy*, July 2, 2015.

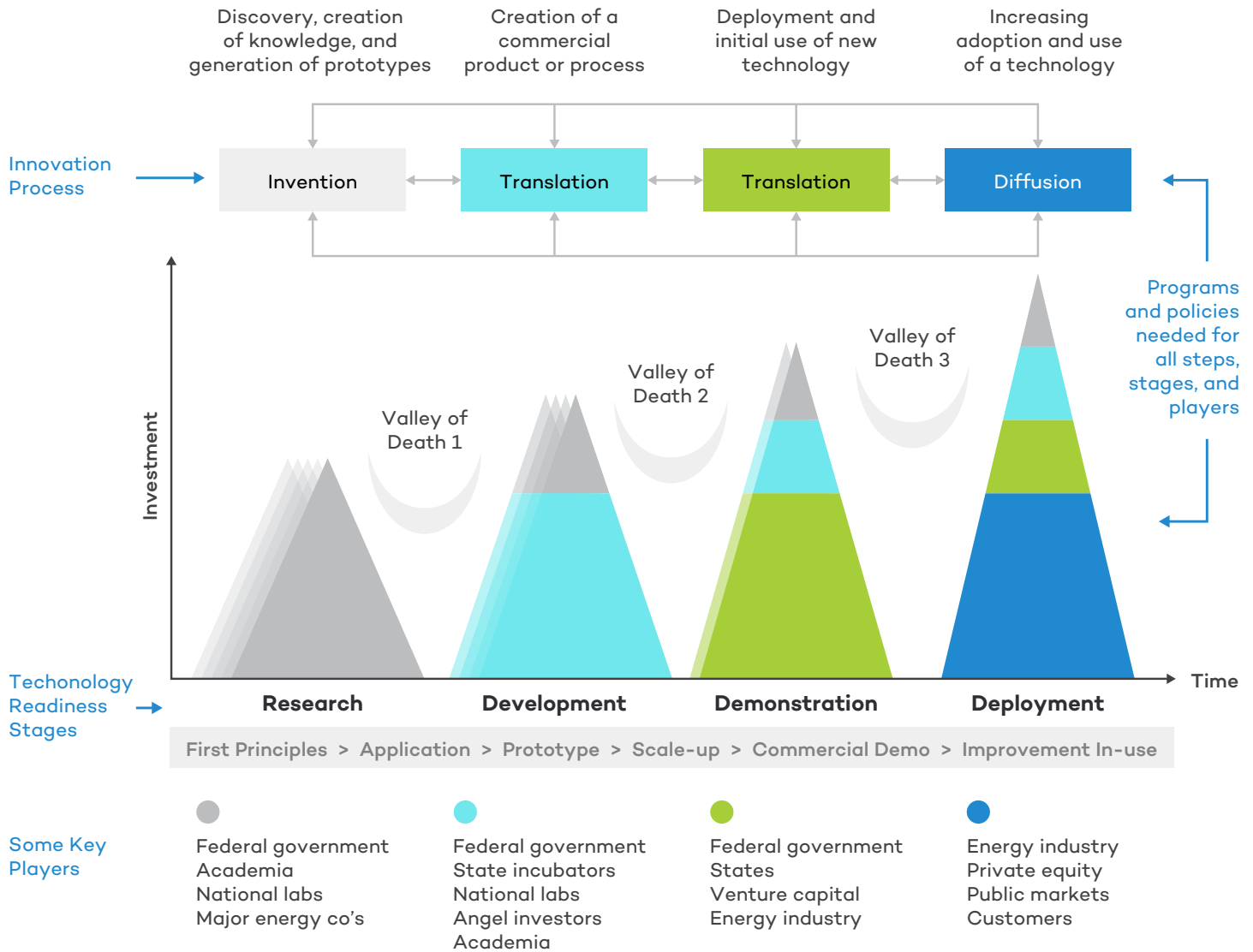
A Complex Innovation Process

Energy innovation involves the transformation of ideas, knowledge and capabilities into improvements in the value chain; changes in systems and interoperability of technologies; and advances in enabling technologies that facilitate improvements in cost and performance and that de-risk investment. Successful innovation occurs in both the public and private sectors, supported by institutional factors, including policies, regulations, business models, markets, management, and consumer knowledge and acceptance. Moving from invention, to translation, to adoption, to diffusion requires the alignment of many players, programs and policies (Figure 1-12),³² requires steeply escalating investments, and typically involves significant commercial risk.

32. Analysis modified from Ernest J. Moniz, "Stimulating Energy Technology Innovation." *Daedalus* 141, no. 2 (Spring 2012), 81-93, doi:10.1162/daed_a_00148

FIG. 1-12

Moving Innovations to the Marketplace



Innovations move into the marketplace through a system of invention, translation, adoption, and diffusion. Technology readiness stages of innovation include research, development, demonstration, and deployment. This system and these stages require collaboration among numerous players and the process can be highly non-linear, often involving a series of feedbacks initiated from learning by doing and using, which promotes continuous improvement from invention to diffusion.

Source: Energy Futures Initiative (EFI), 2018. Modified from Moniz, "Stimulating Energy Technology Innovation."

Moreover, the clean energy industry is currently operating in a highly uncertain policy environment. The implications of the new Federal tax law for the energy sector are not yet clear, and challenges to the Clean Power Plan remain unresolved. The recent imposition of a 30 percent tariff on imported solar cells and panels raises a range of issues about the flow of solar panels to installers and could have a significant impact on prices of solar systems in the U.S. These and other tensions and uncertainties about the balance and direction of national policies are impediments to private-sector investment.

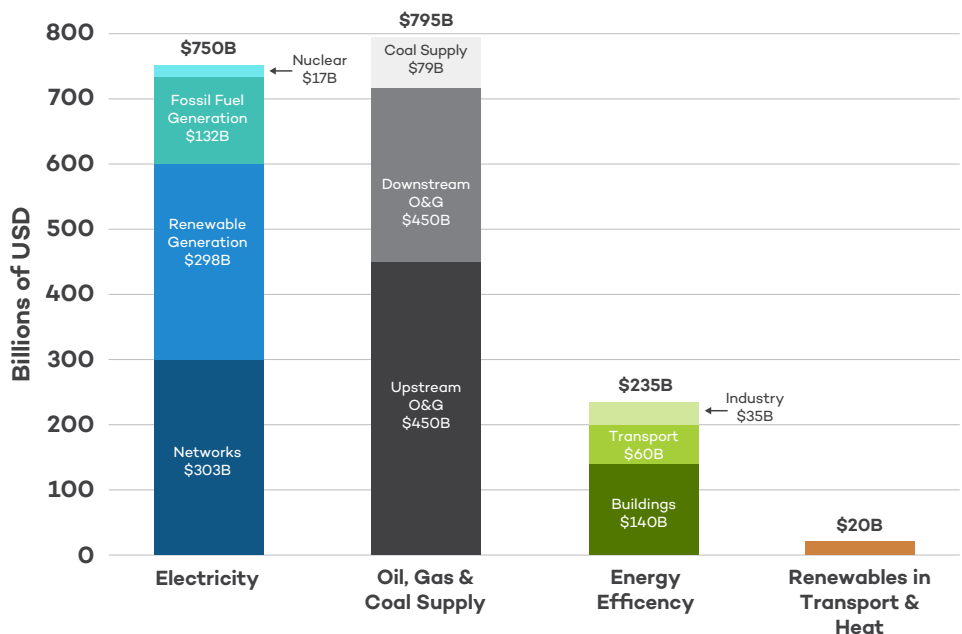
International Energy Investment

In 2017, global energy investment totaled \$1.8 trillion (Figure 1-13).³³ This level of investment may not be adequate, however, to meet rising demand. The International Energy Agency (IEA) estimates that between 2017 and 2040 roughly \$2.6 trillion of investment is needed annually in global energy supply and end-use sectors.³⁴ Electricity investments are likely to account for between one-half and two-thirds of this investment.

To meet its estimated electricity demand, China needs to add the equivalent of today's U.S. power system to its electricity infrastructure by 2040, while India needs the equivalent of the E.U.'s.³⁵ As a result, very large markets for energy technologies are emerging, worth between \$60-70 trillion in cumulative investment by 2040.³⁶ In 2016, China far outpaced the U.S. on nuclear, renewables, and efficiency investments (Figure 1-10).

FIG. 1-13

Global Energy Investment Totaled \$1.8 Trillion, 2017



In 2017, \$1.8 trillion was invested globally in the energy sector. The oil, gas, and coal supply sectors received \$45 billion more investment than the power sector.

Source: Energy Futures Initiative (EFI), 2018. Compiled using data from IEA World Energy Investment 2018.

33. International Energy Agency [IEA], World Energy Investment 2018: <https://www.iea.org/wei2018/>

34. Derived from \$60 trillion in cumulative investment in supply and end-uses in the New Policies Scenario, International Energy Agency [IEA], World Energy Outlook 2017: Executive Summary (Paris, 2017), 1-8, <https://www.iea.org/Textbase/npsum/weo2017SUM.pdf>

35. International Energy Agency [IEA], World Energy Outlook 2017: Executive Summary (Paris, 2017), 1-8, <https://www.iea.org/Textbase/npsum/weo2017SUM.pdf>

36. International Energy Agency [IEA], World Energy Outlook 2017: Executive Summary (Paris, 2017), 1-8, <https://www.iea.org/Textbase/npsum/weo2017SUM.pdf>

These 2016 investment figures represent clean energy technology deployment. China could also exceed U.S. levels of investment in clean energy innovation over the next five years. In late 2015, the United States, China and eighteen other countries announced their support for the Mission Innovation initiative, agreeing to double their government investment in clean energy research and development (R&D) over five years, and subsequently establishing an executive secretariat in London. A number of initiatives are moving forward in this context; for example, Mexico, Canada and the United States are leading an effort to accelerate advanced energy materials discovery by integrating high-throughput methods with artificial intelligence.

If China meets its Mission Innovation commitment to double its clean energy R&D investment, its spending on clean energy technology development and innovation in 2022 will equal or exceed that of the U.S., even assuming that the U.S. maintains its current level of clean energy R&D, which is in doubt. Moreover, countries like China with rapidly growing energy sectors and strong public roles in economic planning and resource allocation may find it less challenging than the U.S. to overcome energy incumbency and to align disparate players and capital sources.

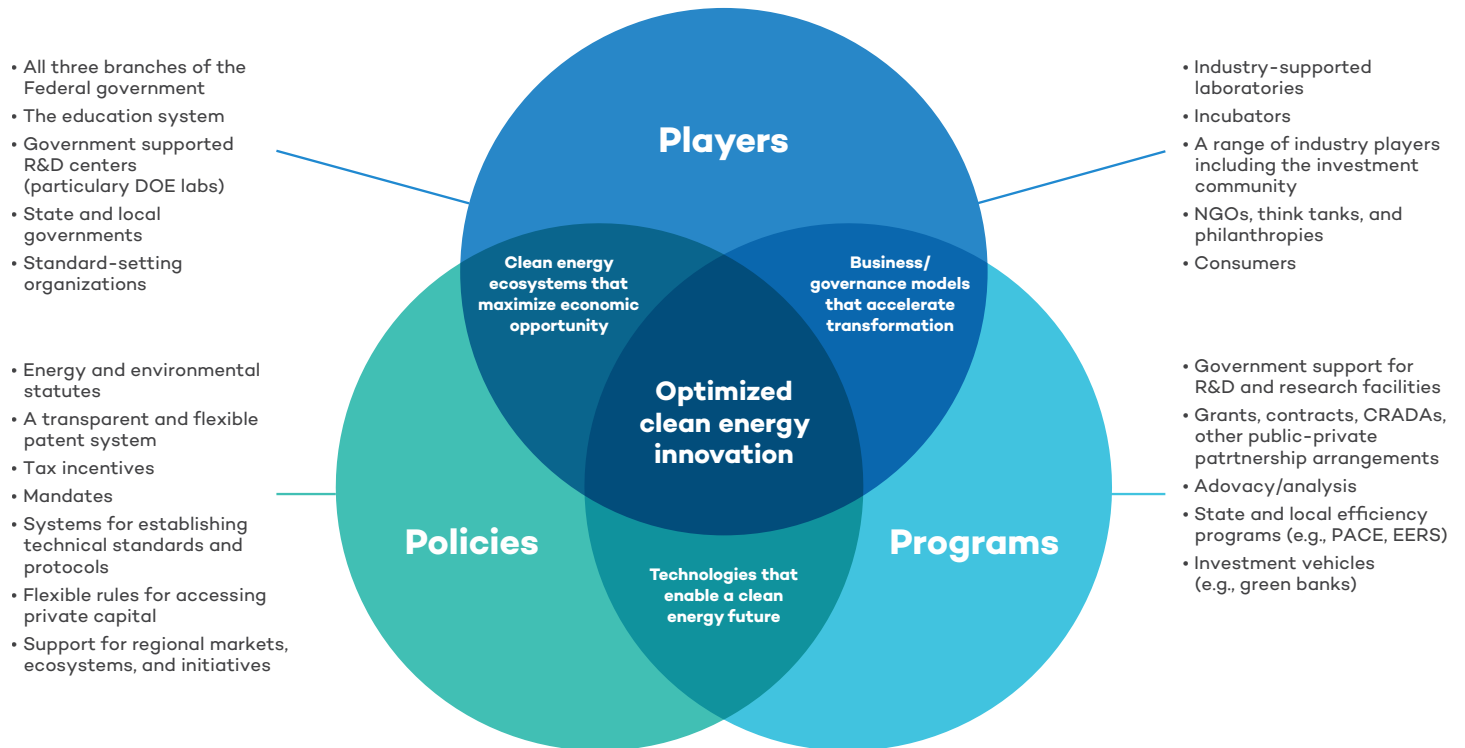
Aligning the Components of the Clean Energy Innovation Ecosystem

Continued leadership in clean energy innovation serves critical national energy goals. The strong global energy position of the U.S. today is attributable in part to decades of public and private research and investment. The emergence of shale gas and shale oil as significant additions to the U.S. energy supply is an example of this sustained interaction. DOE's early investments in shale basin characterization and key enabling technologies, such as horizontal drilling and polycrystalline drill bits, took several decades to come to fruition. Ultimately, these technologies experienced widespread diffusion, a situation that was enabled by demand, gas infrastructure, favorable policies on subsurface ownership rights and taxes, a robust independent producer industry, trial-and-error experimentation by private sector innovators, and a unique public-private partnership arrangement led by the Gas Research Institute.

Productive interaction of this kind requires alignment among the ecosystem's players, policies, and programs (See Figure 1-14).

FIG. 1-14

Aligning Players, Policies and Programs to Accelerate Clean Energy Innovation (Illustrative)



Source: Energy Futures Initiative (EFI), 2018

The following chapters in this report discuss how these components work together today, and how they can be better aligned. They address these opportunities under six headings:

- **The private sector role (Chapter 2):** patterns and dynamics of private-sector innovation and investment in clean energy innovation today, the challenges encountered in the innovation process, and ways in which institutions can further encourage entrepreneurship and innovation investment.
- **The portfolio of critical technologies (Chapter 3):** a screening of promising clean energy technologies and a preliminary selection of six technology areas that appear to have the potential for transformative change in U.S. energy systems.
- **The role of the federal government (Chapter 4):** means by which the federal government currently supports clean energy innovation through its research and development programs, and adjustments in policies, programs, and organization structures that could strengthen the innovation ecosystem's focus on critical technologies.
- **The state and local role (Chapter 5):** the critical role that state, local, and tribal governments play in creating markets for clean energy, in providing favorable regulatory environments for clean energy adoption, and in supporting the early-stage innovation process.
- **The regional role (Chapter 6):** the distinctiveness of regional clean energy innovation ecosystems and ways in which public and private institutions can collaborate to nurture and leverage particular regional strengths.
- **Incentivizing private sector investment (Chapter 7):** the potential impact of the Tax Cut and Jobs Act of 2017 on energy innovation investment, and opportunities for further incentivizing clean energy investment through federal tax and regulatory policy.

Chapter 2. The Private-Sector Role in Clean Energy Innovation

Clean energy innovation takes place primarily in the private sector. This chapter discusses the challenges faced by the private sector in effecting clean energy innovation, the patterns of innovation activity that have developed in response, and ways in which private sector efforts could be enhanced to accelerate clean energy innovation.

FINDINGS

The Private-Sector Role in Clean Energy Innovation

- The private sector is central to clean energy innovation, providing entrepreneurial vision, channeling financial resources, and connecting innovation to the rest of the energy system and the economy. At the same time, fundamental dynamics of the energy sector present significant challenges to clean energy innovation, stemming from basic industry characteristics and from the difficulty of capturing the full value of clean energy through market transactions alone.
- Investment patterns in the various stages of the innovation pathway reflect the private sector's adaptation to these challenges. At the research stage more than 90 percent of clean energy investment comes from DOE, not from the private sector. Reliance on private funding increases at later states of innovation. OEMs and energy companies are the primary funders of the development and demonstration stages of clean energy innovation. At the deployment stage the investment base broadens to encompass private equity, project finance, and a passive investment pool that includes sovereign wealth funds and green energy funds.
- Venture capital (VC) participation in clean energy innovation has declined significantly in recent years, as the length of time needed to gain widespread adoption of clean energy innovation and the regulatory complexity of energy innovation have become apparent. VC investments have moved toward application areas where relatively low-risk software can be deployed, and where market demand has been demonstrated.
- VC and corporate strategic capital leave a gap in investment coverage. Emerging investment vehicles with a strategic agenda of supporting clean energy innovation may fill this gap in the future. Notable examples are the Oil and Gas Climate Initiative (OGCI), Breakthrough Energy Coalition, and Energy Impact.
- Innovation challenges grow with each successive stage along the innovation pathway. While clean energy innovation at the research stage is supported by a diverse, world-class set of U.S. research institutions, the support system weakens as inventions move toward commercialization. The availability of testing facilities for product demonstration is limited by the small number of testing facilities suitable for sustained testing and by their specialization. The clean energy incubators that have emerged in recent years have tended so far to support primarily software solutions. Institutions providing entrepreneurial research fellowships are helping to strengthen the support system for more fundamental innovations.

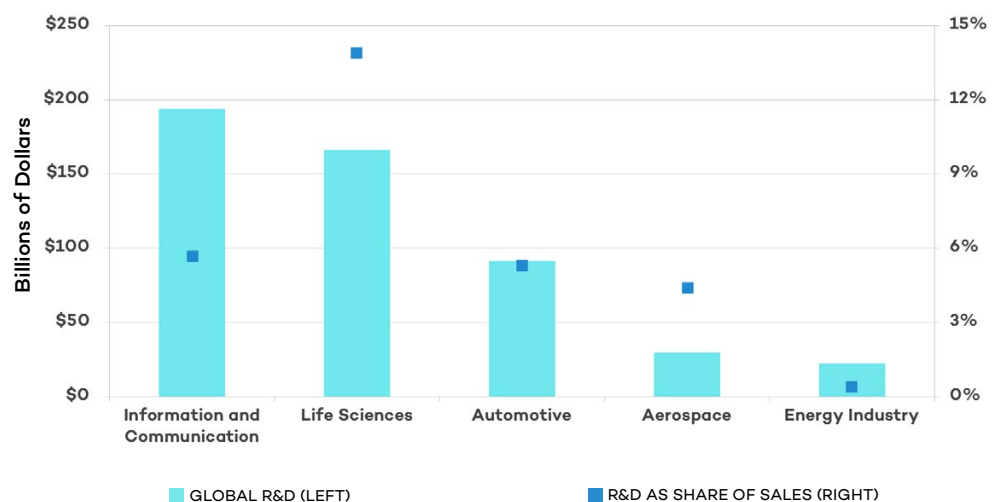
Private-Sector Challenges in Clean-Energy Innovation

The private sector plays a central role in clean-energy innovation. It provides entrepreneurial vision and initiative, channels financial resources, links technologies to needs, brings new concepts to commercial scale, markets them to customers, and provides the myriad commercial support services needed for innovation to take hold. However, private-sector market dynamics also present serious obstacles to clean-energy innovation. These obstacles reflect several fundamental features of energy systems.

- Energy systems are capital-intensive, complex, interconnected, and deeply embedded in the economy. Revenues of many trillions of dollars are supported by vast physical delivery systems and intricate supply chains based on business models that emphasize above all safety and reliability. These characteristics favor incremental rather than abrupt evolution. Compared to other large industries like pharmaceuticals, and information and communications, which are continually reshaped by innovation, global private research and development (R&D) spending levels in the energy industry are notably lower (Figure 2-1). The inertia inherent to large energy systems is evident as well in the long change cycles illustrated earlier in Figure 1-11.
- The complexity of the energy industry places strong intermediate institutions between innovators and end-use customers. Opportunities for leap-frogging these established institutions in order to forge new and disruptive customer relationships are limited. The path to significant penetration of new energy products and technologies lies almost exclusively through equipment suppliers and primary providers of energy.

FIG. 2-1

Global Industry Private R&D and R&D as Percentage of Sales, 2015



37. Data on global industry private R&D in 2015 for each industry segment (the light blue bars in the figure) are from "2016 Global R&D Funding Forecast," R&D Magazine, Winter 2016. "Energy Industry" includes utilities and oil and gas companies, the primary providers of energy. "Energy Industry" R&D includes R&D by utilities and oil and gas companies, the primary providers of energy. R&D regarding the use of energy by another industry (e.g., automotive) is included in that industry. Data on global R&D as a percent of global sales (the dark blue dots in the figure) were derived by dividing the above R&D figures by estimated global markets for each industry sector.

Global private R&D spending in the energy industry is substantially lower, both in dollars and in share of revenue, than in other major industries.

Source: IHS Markit analysis³⁷

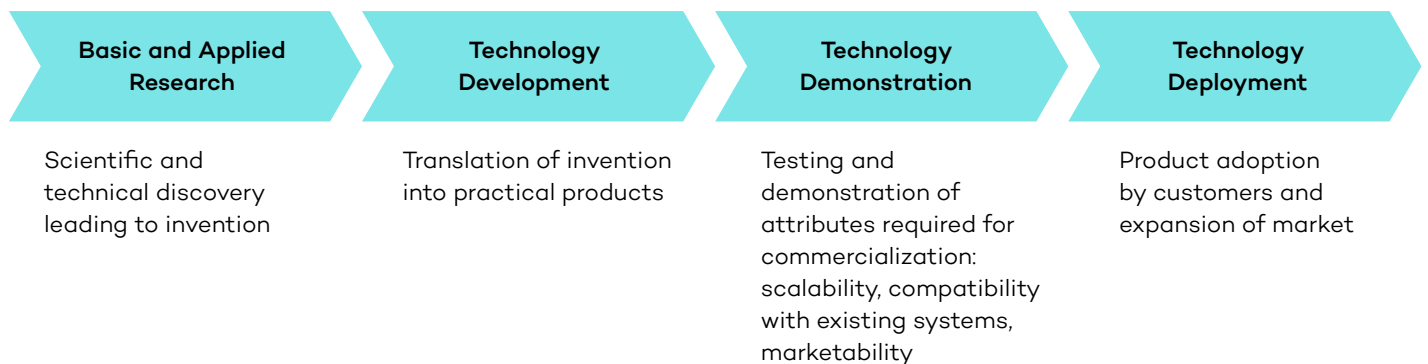
- Cost efficiency is critical to energy systems. Energy end products are relatively undifferentiated, leading to commodity pricing and significant price sensitivity in end markets and therefore throughout the energy supply chain. The fundamental stability of energy systems provides a platform over time for wringing inefficiencies out of business processes. Any significant technological innovation must attain sufficient production scale to demonstrate its contribution to cost efficiency.
- Reliability and safety are fundamental industry values. Requirements for safe, reliable energy delivery leave little room for error, and system mishaps bring high financial and reputational costs. Innovations must sustain a heavy burden of proof that they are safe and reliable in themselves and that they will not compromise in any way the safety and reliability of existing systems.

These barriers to energy innovation are especially formidable with respect to clean energy innovation. In an era of low U.S. fossil-energy prices, establishing a cost advantage for clean energy is challenging. The externalities of energy use that clean energy innovation is intended to mitigate usually are not manifest to the buyer as a cost, and the corresponding benefits of avoiding those externalities are not manifest as an economic gain.

The availability and distribution of financial resources, the roles of support institutions, and the interactions of innovators and adopters represent ongoing adjustments to these challenges. For purposes of the present discussion, the resulting patterns are described with reference to a succession of stages in the innovation process (see Figure 2-2.). The boundaries between stages are imprecise and fluid, and the results at each stage influence not only stages that follow but also stages that precede it. As with any iterative sequence, the process creates feedback loops and adapts to the teachings of experience. Nonetheless, each stage along the pathway has characteristic dynamics, and the path to commercialization leads through them sequentially.

FIG. 2-2

Technology Readiness Stages of the Innovation Process



Investment Patterns

Investment patterns change from one innovation stage to the next, with respect to both the source of investment (Figure 2-3) and the application of investment (Figure 2-4).³⁸

Basic and Applied Research

In the basic and applied research stage of clean energy innovation, the likelihood of commercial success is highly uncertain, and any paybacks envisaged are usually in the long term.

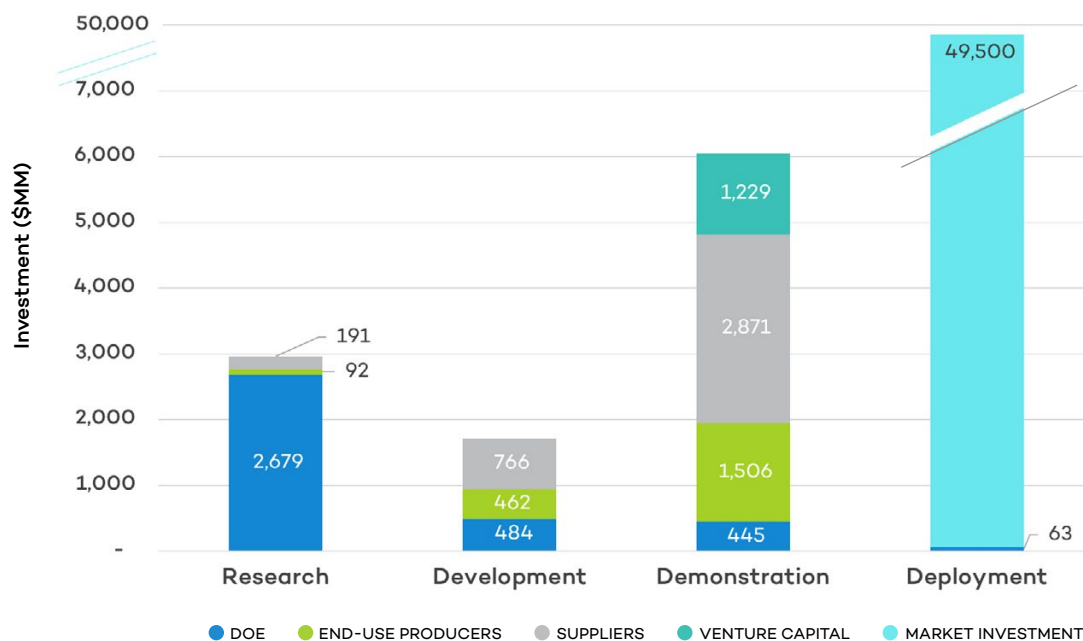
- DOE investment at this stage plays a paramount role, accounting for more than 90 percent of investment in 2016. It provides a source of constancy for funding at this early research stage, a stage where private-sector funding is limited by commercial uncertainty and tends to fluctuate in response to current industry business pressures. Most of the private-sector funding that does occur at this stage is provided in partnership with the federal government. The discoveries and inventions developed at this stage of innovation consequently depend heavily on the policy choices discussed in chapters 3 and 4.
- Major equipment suppliers in energy make some investment at this early stage, but it is a minor component of their overall research budgets, estimated to be about 5 percent of overall company R&D expenditures.³⁹
- More than half of spending at this stage is directed toward generation technologies, including next generation nuclear power, carbon capture, energy storage, and fuel cells. Other clean energy technologies that are the subject of both federal and corporate research at this stage include biofuels, transport electrification, grid optimization, and industrial process research. As noted in Chapter 3, these are areas of innovation that are likely to have the greatest impact toward attaining national clean energy goals, and are logically associated with the preponderance of federal investment found at this stage.

38. See discussion of sources and methods in Text Box 2-1.

39. The 5 percent figure is based on informal estimates provided during interviews with several leading original equipment manufacturers.

FIG. 2-3

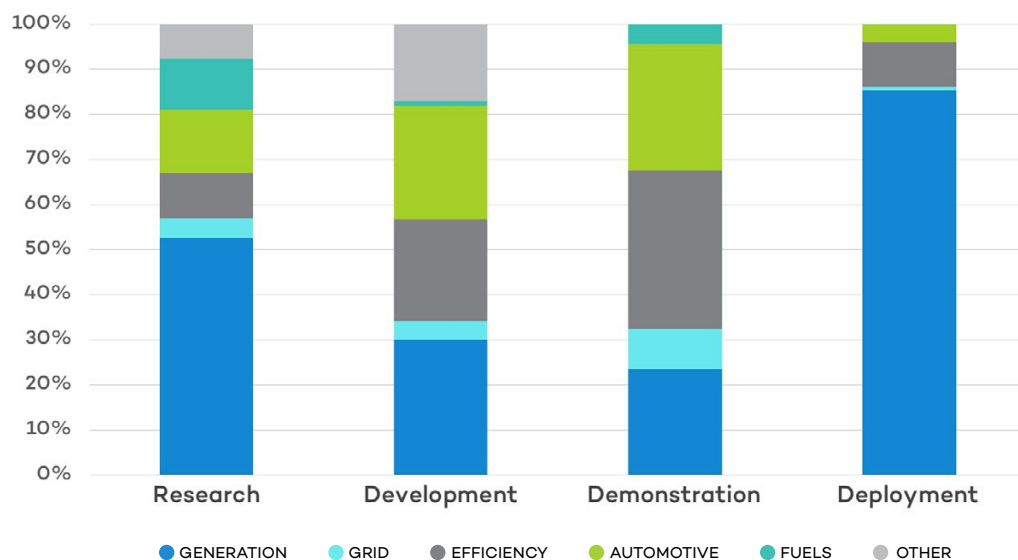
Investment Sources Across the Technology Readiness Stages of Clean Energy Innovation, 2016



Each stage along the clean energy innovation pathway draws on a different mix of capital resources.

FIG. 2-4

Share of Clean Energy Innovation Investments by Application and Technology Readiness Stage, 2016



Spending on intended end-use applications varies from stage to stage. Generation of electricity dominated technology deployment spending in 2016 and was prominent in the research stage. In the technology development and technology demonstration stages, efficiency and automotive end-uses account for significant shares of spending.

Source: IHS Markit analysis. See Text Box 2-1 for discussion of method.

TEXT BOX 2-1

Investment Estimation Method

The clean energy innovation investment figures provided in this chapter reflect judgments in four areas, as described below.

What investments are included? The following categories of investment are included: investments associated with renewable energy, including biofuels, biomass, waste-to-energy, geothermal, hydropower, wave and tidal energy projects, solar, and wind; energy smart technologies including smart meters, energy efficiency devices, and grid integration technology; electrified transport; electricity storage technology; fuel cells and hydrogen applications; carbon capture, storage, and utilization; and advanced nuclear technology. The primary application of these technologies is clean energy. Many other technologies that have indirect effects on energy consumption — by either making processes more efficient or providing general technological platforms that enable energy-specific technologies — are not included notwithstanding their relevance to clean energy. These adjacent technologies originate primarily in sectors other than energy and are so pervasive in the economy that their inclusion in the category of clean energy would make that category too large and amorphous to be analytically useful.

How is private investment calculated? Top-down numbers are derived from Bloomberg New Energy Finance and UN Environment Trends in Renewable Energy Investment. Bottom-up numbers are derived from public available R&D reports: FERC Form 1 reports in the case of utilities, and 10K and 20F forms and annual reports in the case of other private companies. The companies reviewed comprise all companies with material reported R&D expenditures in the following sectors: OEM and automation suppliers, renewable generation equipment providers, smart meter providers, building automation providers, lighting providers, and automotive. Information is cross-checked and supplemented by the following proprietary IHS Markit databases: Technology Smart Utility Meter Intelligence Service 2017, Technology Building Automation Equipment Report November 2017, and Technology CABA Intelligent Buildings Impact of IoT. With respect to companies that report R&D as a single category, that figure is allocated to clean energy according to business line contribution to total revenue and then adjusted to reflect relevant information provided in company press releases and other documents. Unless otherwise reported in company documents, 76 percent of overall R&D investment by US-based multinational companies is allocated to the U.S. Fifteen percent of overall R&D investment by non-US multinational companies is allocated to the U.S. if those companies have a U.S. R&D lab presence. These allocations are consistent with those used by the National Science Board's Science and Engineering Indicators, 2016. Calculations are informed also by interviews with industry experts active in technology development, including technology strategy managers, planning and strategy team leaders, and R&D team leaders.

TEXT BOX 2-1 (CONTINUED)

How is DOE investment calculated? DOE investments include expenditures traceable to the clean energy technologies listed above, documented in DOE's FY18 Budget in Brief. These investments total approximately \$3.6 billion in 2016 across all stages of innovation and are comparable to the investment numbers calculated for the private sector. Excluded is a portion of basic Office of Science research that is not attributable to specific technologies, certain non-attributed overhead expenses, and biological and environmental research. These excluded categories amount to nearly \$1 billion in expense, bringing the total 2016 DoE investment in clean energy to approximately \$4.6 billion, almost all of which is assignable to the research stage. Also excluded are loan guarantees made by DOE, typically at the demonstration and deployment stages, drawing on \$70 billion in loan guarantee authority. While these guarantees do not constitute direct investments, they enable investments by others and play a significant role in promoting later-stage innovation. Finally, the DOE investment figures used here exclude by definition investments made by state and other federal agencies. OMB calculates that clean energy investments by federal agencies other than DOE amount to approximately \$1.6 billion. Both the DOE loan guarantee program and non-DOE federal investments are discussed in chapter 4.

How are investments allocated among the various innovation stages? The different stages of innovation serve to distinguish major innovation tasks along a continuum; they do not fall within sharply defined boundaries. The term "research" can encompass an array of activities from fundamental science exploration through prototype design to ongoing experimentation with existing technology. For purposes of the current investment analysis the "Research" category is confined to inquiry that falls within the National Science Foundation's definition of Technology Readiness Level (TRL) 1. Innovation activities falling within TRL's 2–4 are grouped into the "Development" Category. The boundary between "Development" and "Demonstration" is also porous; the current analysis, for example, assigns all VC investment to the demonstration stage, since such investment typically follows the proof of concept that the development stage provides. Some VC investors may argue, however, that they are investing in development. These assignments are judgmental. Different reasonable judgments would yield somewhat different numbers, but would not alter significantly the investment patterns described or the investment dynamics addressed.

Technology Development

In the technology development stage, technologies that have shown promise in research must now prove themselves scalable and capable of commercial production. Design needs to be developed to the point where it is possible to assess whether the technology is capable of being manufactured or disseminated efficiently at acceptable cost. Commercial applications come into focus at this stage, but commercial risk assessment remains difficult. Experimental applications generate some hits and numerous misses. In some industries, notably information technology, a low success rate at this stage can be weighed against the high payback from those few applications that prove successful. In clean energy, however, the slow rate at which innovation can be absorbed and the complexity of integrating innovation into an existing system of energy delivery limit significantly the potential for rapid payback even for technically successful breakthroughs.

- DOE funding continues to play a significant, though lesser, role at this stage, notably through grants by the Advanced Research Projects Agency-Energy (ARPA-E).
- Corporations, both end-use producers and in particular equipment suppliers, whose competitive positions require continual innovation and improvement in their product offerings, assume a larger role. For these companies, the occasional misfires incurred in developing innovations that support their commercial objectives are an accepted cost of business.
- In 2016 generation, efficiency, and automotive applications claimed roughly equal shares of investment at this stage.

Technology Demonstration

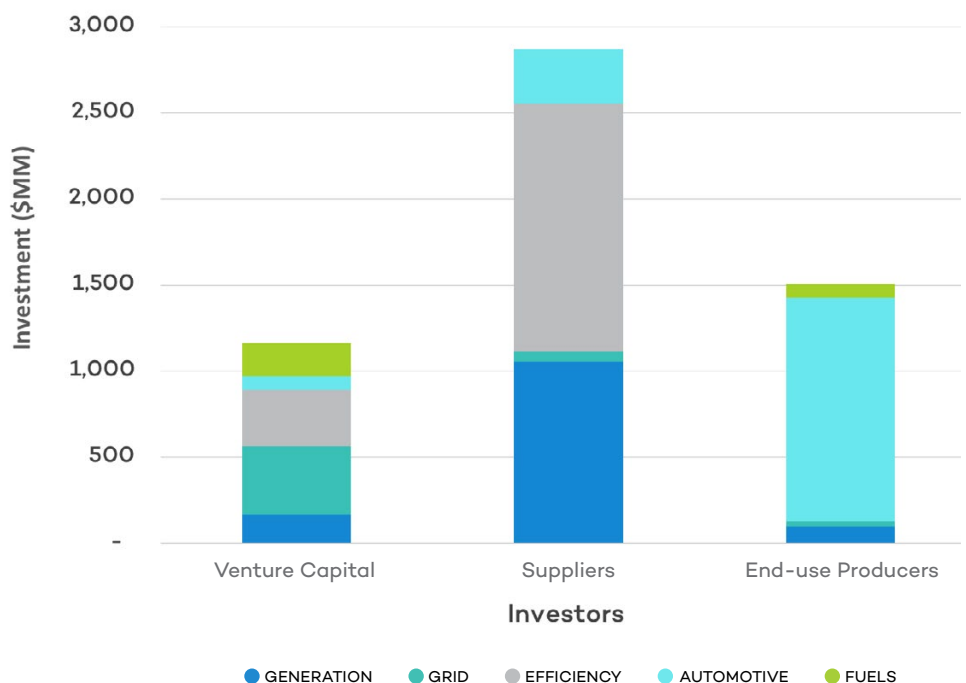
In the technology demonstration stage, new technologies must prove themselves scalable and capable of integration into the existing system. Product performance under a range of practical conditions is tested. Compatibility with existing customer assets and systems needs to be demonstrated, and safety and reliability need to be assured. A supporting business infrastructure needs to be put in place to manage the rapidly growing cash requirements characteristic of this stage and to begin developing the sales channels and customer relationships needed to achieve commercial viability. The aim of this stage is to bring the product or process to the point of adoption by actual users.

- The level of DOE funding for activities at this stage is approximately the same as at the technology development stage, but DOE's share of total investment for activities at this stage is less than 10 percent.
- Corporate investment grows substantially, particularly among equipment suppliers. This also is the stage at which VC assumes a significant role.
- By far the greatest share of private investment at the technology demonstration stage comes from potential adopters — the OEMs and other suppliers who might incorporate these innovations into their offerings to end-use producers, and the end-use producers themselves who might incorporate these innovations into their offerings to consumers (Figure 2-5). Some of this corporate investment is channeled through corporate venture funds and is reflected in VC spending, but most is channeled through internal R&D.

- Generation constitutes less than one-fourth of investment in technology demonstration — primarily relating to improvements in the efficiency of wind and solar generation. The preponderance of overall demonstration investment falls in the categories of automotive applications and end-use energy efficiency. Given this pipeline, it appears that deployment of clean energy innovations over the next several years will consist primarily of renewables build-out and improvement, devices and systems for increasing energy efficiency, and low-carbon automotive propulsion systems. Not surprisingly, these are the areas of clean energy that have received the most support over recent decades from public policy aimed at creating market demand, and where market dynamics have emerged that make such technologies potentially competitive and profitable.
- Supplier investments at this stage are weighted toward efficiency and generation. Efficiency projects include pilots for various building-efficiency devices like smart glass, advanced airflow sensors, and automation of building systems. Projects related to generation include advanced wind turbine designs and new manufacturing processes for silicon wafers. End-use producers by contrast invest comparatively little in these areas, depending on suppliers to test and validate innovations. The automotive category is an exception, in that the end-use producers are the dominant source of demonstration investment — reflecting the hands-on role that automobile manufacturers perform in piloting and testing such innovations as electric or autonomous vehicles.

FIG. 2-5

Clean Energy End-use Investment at the Demonstration Stage, 2016



In 2016, suppliers were the principal source of capital during the technology demonstration stage, with an end-use emphasis on generation and efficiency technology. The principal emphasis of end-use producers was in automotive applications.

Source: IHS Markit analysis, Corporate from SEC filings, FERC Form 1, Bloomberg New Energy Finance, and UN Environment Program

TEXT BOX 2-2

Types of Investors in Clean Energy Innovation

INVESTOR TYPE AND DESCRIPTION

Venture Capital (VC):

Early-stage investment in companies in return for ownership positions. Total VC activity in the U.S. is approximately \$75 billion annually, of which approximately 10 percent is deployed in the energy sector and less than 2 percent in the clean energy sector.

Strategic capital:

Corporate investment in technologies that provide competitive advantage or otherwise advance entity goals.

Private Equity (PE):

Fund managers purchasing companies with third-party funds, usually with the goal of improving company performance and realizing gains from those improvements. PE invests approximately \$200 billion annually.

Pension funds:

Funds making investments in order to support pay-out on defined-benefit retirement plans. In the United States, these funds hold \$25 trillion in assets.

ENGAGEMENT IN CLEAN ENERGY INNOVATION

Lack of success in clean energy investments despite previous strong interest has led venture to focus on more software within the energy space. New investment in early-stage clean energy innovation has declined from \$3.7 billion in 2008 to \$1.1 billion in 2016, interrupted by a spike to more than \$4 billion in 2011 in response to the stimulus of the ARRA.

The dominant source of funding in the applied research and technology demonstration phases of the innovation life-cycle. The assessment of value may encompass strategic objectives as well as the cash-flow potential of a particular technology. Investment by strategic capital in these early stages was approximately \$3.3 billion in 2016.

PE interest tends to focus on companies with established revenue streams with opportunities for business performance improvement. The typical five-year duration of a PE fund imposes a near-term to intermediate-term timeframe on value realization. PE firms are active primarily in the deployment phase of innovation, where they invested \$3.7 billion in 2016.

Pensions generally seek stable returns. Even those with clean-energy carve-outs tend to focus on the deployment stage, although there are exceptions. The California Public Employees' Retirement System, for example, has a fund focusing on early-stage investment.

TEXT BOX 2-2 (CONTINUED)

INVESTOR TYPE AND DESCRIPTION

Sovereign Wealth Funds (SWFs):

Funds with assets collected by governments, often from export of a natural resource, deployed to diversify the basis of a country's wealth. The worldwide asset base of these funds is in the range of \$8 trillion to \$9 trillion.

Other passive investors:

Entities such as banks, insurance companies, mutual funds, or university endowments.

Patient capital:

Often high-net-worth individuals who are willing for the sake of a larger objective to invest in enterprises with a longer pay-out period than other investors typically require.

ENGAGEMENT IN CLEAN ENERGY INNOVATION

SWFs generally have long investment horizons, and some can have higher risk tolerance if the project advances a national interest, especially developing home-country industries. Examples of clean-energy carve-outs focused on home-country investment include: Bpifrance (France); BDC Capital's Industrial, Clean and Energy Technology Venture Fund (Canada); Investinor (Norway); and the Early Stage Venture Fund of the National Research Foundation (Singapore). These carve-outs generally are not available for investment in the United States. SWFs typically are limited to investment in listed companies, which leads them to focus on the technology deployment stage of innovation.

Although these capital sources are primarily interested in economic return at acceptable risk, some have reserved funds for clean-energy investment. These investments apply primarily at the technology deployment stage.

What distinguishes the "patient capital" funders is their higher tolerance for risk in the service of broader social objectives. In this respect they resemble strategic investors, recognizing value beyond the intrinsic economic potential of the particular technology. Like strategic investors, they may be willing to invest in early-stage innovation, but their actual investment level at that stage in our 2016 benchmark year was very small.

Technology Deployment

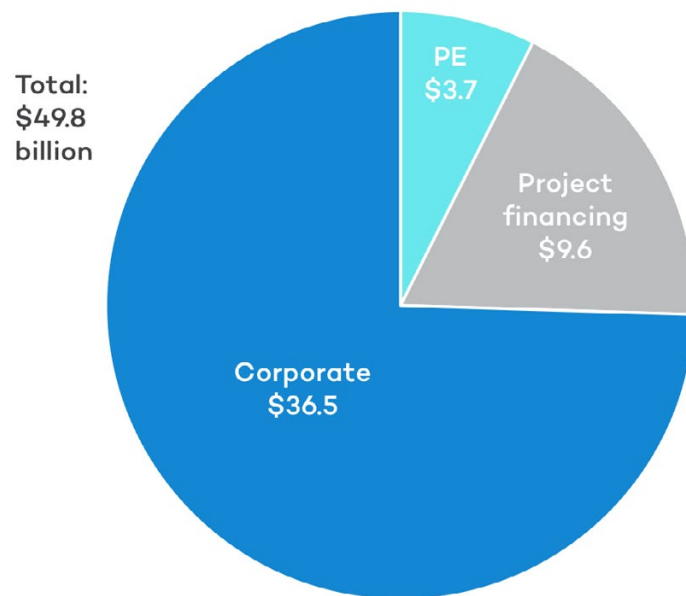
The technology deployment stage of the innovation pathway is where most private capital is invested. At this stage the scalability of the technology has already been demonstrated, and commercial risk can be assessed reasonably, but the investment needed to achieve commercial scale rises rapidly. The product must be adopted at a sufficient rate to achieve economic scale, and it must be supported by an array of basic commercial capabilities such as sales, contracting, accounting, and warranties. Because the diffusion of new technologies to multiple customers often involves multiple iterations of demonstration and testing, this deployment stage can overlap substantially with the previous stage. What is characteristic of this commercial deployment stage is the establishment of market position and the demonstration of economic viability. The aim of this stage is to expand beyond initial adoption and to diffuse the new product into a broader market. Equipment suppliers are no longer a significant factor, as at this stage they are selling the technology rather than investing in it, and VC has cashed out.

- This is the stage at which private equity funds primarily participate, usually acquiring companies with existing revenue streams and adding value by merging and refining business models. At this stage, funders are prepared in some instances to provide project financing on a non-recourse basis, typically where project revenue is reasonably assured through offtake purchase agreements.
- Most investment, however, comes from corporate balance sheets — either from retained earnings or from corporate equity and debt issuances (Figure 2-6). The funding for this type of corporate investment is raised from a variety of sources, most of them passive in the sense that they invest in the corporate entity that deploys investment funds rather than in the project or technology itself. Among these sources are sovereign wealth funds, pension funds, and most exchange-traded funds. Their participation in precommercial stages of innovation is limited by their obligation to invest prudently and, in most cases, to invest only in publicly listed companies. Even when a fund has identified cleantech as a category for emphasis, as Norway's sovereign wealth fund and California's state pension fund have done, they invest almost entirely in established clean tech corporations rather than in precommercial startups.
- A growing number of investment funds are factoring environmental, social, and governance (ESG) considerations into the composition of their portfolios. Arguing that firms with better ESG performance tend also to have better long-term financial performance, many of these funds include in their assessments a particular firm's exposure to risk from climate change, and in some instances the firm's expressed commitments to reducing its carbon footprint. While these funds help focus attention on corporate clean energy strategies, the metrics by which ESG assessments are made remain largely undefined and discretionary, and their impact on clean energy innovation is difficult to estimate. Similarly the number of green bonds aimed at supporting clean energy projects is rising, but the terminology is discretionary. Both ESG funds and green bonds aim to achieve returns competitive with other funds and bonds, so that while their growth indicates a potential pool of capital to support clean energy deployment, clean energy investments still need to meet the return standards imposed by capital markets generally.

- In 2016, more than 80 percent of investment in clean energy deployment occurred in electricity generation (Figure 2-4). This high ongoing level of investment is the payoff of decades of development in solar and wind technologies. The long cycle of innovation is evident here. Generation technologies that were in the research stage two to three decades ago have gained significant market share due to demand policies put in place mostly by states (and by Germany and China). They dominate deployment spending today. Generation technologies now in the research stage will not reach a similar level of investment until they have passed through the development and demonstration stages and have achieved an efficient scale. Like renewable generation, these future generation technologies will almost certainly require coordinated policy support in ensuring the market demand needed for that scale.

FIG. 2-6

Sources of Private Capital for Clean Energy Deployment, 2016 (Billions)



Corporate balance sheets provide the principal source of funding for deployment of clean energy technology, drawing on multiple sources of equity and debt capital.

Source: IHS Markit analysis; Corporate from SEC filings, FERC Form 1; VC from Crunchbase and CB Insights; PE from Crunchbase, Deployment from IHS Markit Technology, IHS Markit Energy Insight, Bloomberg New Energy Finance, and UN Environment Programme

Navigating the Private-Sector Innovation Pathway

The interaction between innovators and adopters sets the pace of innovation and creates the commercial opportunities that shape private investment. Clean energy innovation originates with invention by individuals, working alone or in collaboration with others, usually in a university or corporate context. An invention that occurs under direct corporate sponsorship will likely follow a path of development set by corporate R&D processes to the point where it is adopted, spun off, or abandoned. Most of the non-governmental resources devoted to clean energy innovation come from these corporate sources. Less than 20 percent of pre-commercial private-sector funding comes through venture capital funding of start-ups.

Corporate R&D represents strategic investment in capabilities that are expected in the long-term to enhance a company's value or otherwise contribute to its business objectives. Entrepreneurial start-ups, less constrained initially by the need to serve a corporate agenda, are fertile ground for new ideas. However, they face a challenging development path, and of course ultimately must demonstrate their value to a corporate adopter in order to achieve commercialization. The process by which entrepreneurs bring their innovations to that point takes much longer than most expect. Many lack an awareness of the business requirements of bringing a technology to market — raising money, managing cash flow, and building a business team. The basic management processes required of a start-up grow rapidly once it enters the development stage. One experienced entrepreneur and investor put it this way:⁴⁰

“Cleantech products require a lot more money and time to become established in a marketplace than anyone ever thought possible. You have to establish a manufacturing process, a sales force, customer service, warranty policies, on and on. Few start-ups realize how much internal infrastructure you need.”

Participants and observers of the innovation process stress the value of “tacit” knowledge — the know-how that is difficult to set forth explicitly in books and instruction manuals but comes instead from experience and from interaction with others engaged in the innovation process. Challenges frequently cited include finding incubators and test beds matched to the innovator's project, understanding the specific constraints imposed by regulations in some states or locales compared to others, and learning which investors are disposed to consider which kinds of projects. Many innovators express the need for a community of entrepreneurs to enrich and share this kind of knowledge.

The other major challenge entrepreneurs identify is the need to perform pilot tests in the field. This is a critical step in moving bench-scale prototypes to a reliable, commercial technology. In field tests, the entrepreneur sees how the technology is handled by field personnel, how it integrates into the existing system, and how it performs under real-world operating conditions. The specific testing needs of clean energy technologies vary widely. Energy efficiency software may require access to a large sample of different ratepayer classes through different seasons. New building materials may need stress tests to prove durability under load. These variations in testing needs create a challenge to find the right testing facility or partner for field trials.

40. This and other quotations in this chapter come from interviews conducted on a non-attributed basis with approximately 30 people active in the clean energy innovation field, including researchers, entrepreneurs, investors, and corporate technology executives.

TEXT BOX 2-3

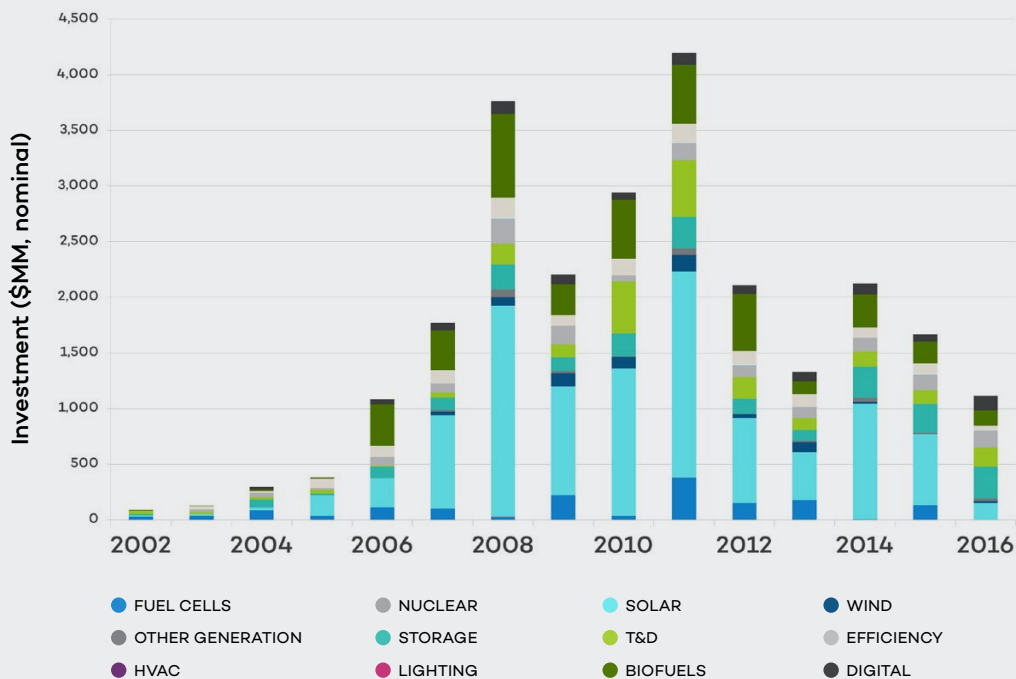
What's Happened to VC?

In contrast to suppliers and corporate adopters, who bring multiple strategic motivations to innovation investment, VC evaluates opportunities primarily based on expectations of stand-alone risks and returns. For this reason, although VC represents only 20 percent of the funding available for precommercial clean energy innovation, it is a reasonable market indicator of perceived intermediate-term commercial potential.

Over the past several years, discounting the temporary surge of investment prompted by the federal stimulus of the American Recovery and Reinvestment Act (ARRA) in 2009, VC investment in clean technology development has declined (Figure 2-7). The enthusiasm generated by the mid-2000s vision of clean tech as the next frontier of economic innovation has been tempered by the actual pace of innovation adoption in the sector, a pace that is misaligned with the typical venture expectation of achieving full value realization within five to ten years.

FIG. 2-7

Venture Capital Investment in Clean Energy by Category, 2002-2016



After rising rapidly during the early and mid-2000s and receiving an impetus from the stimulus of the ARRA, venture capital investment in clean energy technology has declined in recent years.

Notes: Includes corporate venture capital and strategic investment. Digital includes cross-cutting digital applications without a specific end-use application.

Source: IHS Markit analysis, CB Insights

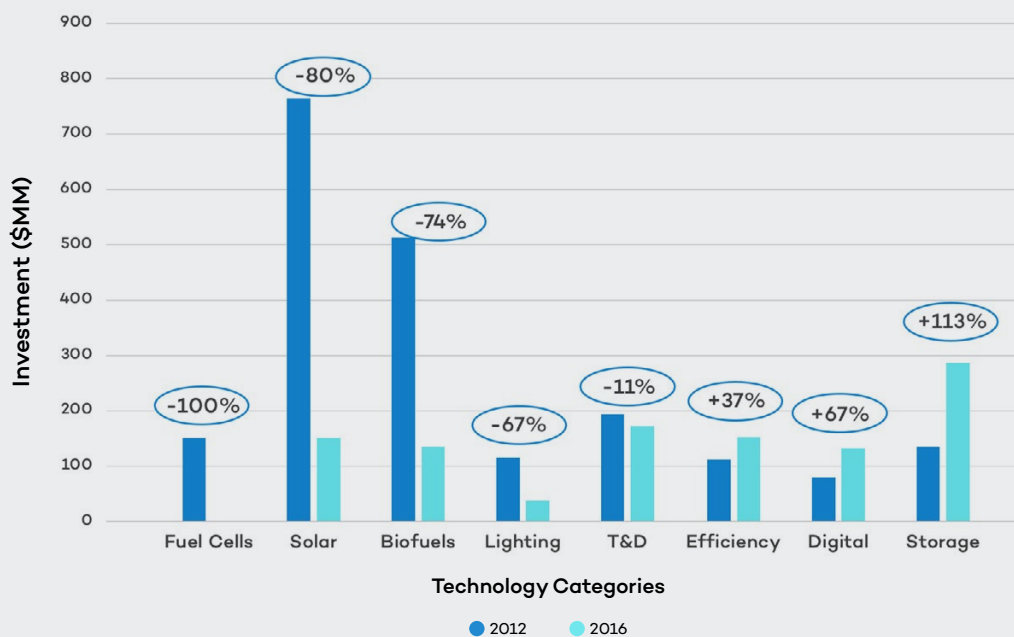
TEXT BOX 2-3 (CONTINUED)

VC investment not only has declined overall but also has shifted its technological emphasis (Figure 2-8). Between 2012 and 2016, investment interest in potential breakthrough technologies like fuel cells, solar, and biofuels has fallen. Meanwhile, investment interest has surged in the categories of energy efficiency, digital, and storage — in each of which innovation is dominated by software. This shift toward software applications seems to indicate a return to the comfort zone initially carved out by VC in the high-tech industry.

The venture model is suited to technologies that offer the prospect of value realization within a relatively short timeframe and the ability to scale rapidly. Software technologies possess these characteristics. Moreover, because of their relatively modest capital requirements, they allow a given level of investment to be spread over a number of activities with corresponding diversification of risk.

FIG. 2-8

Changes in Venture Capital Investment by Technology Category, 2012 vs. 2016



Venture capital investment between 2012 and 2016 not only declined, but also shifted its category emphasis toward efficiency, digital, and storage technologies.

Notes: Includes corporate venture capital and strategic investment. Digital includes cross-cutting digital applications without a specific end-use application.

Source: IHS Markit analysis, CB Insights

TEXT BOX 2-3 (CONTINUED)

Hardware innovation, by contrast, takes more time to develop, more time to demonstrate to the satisfaction of each potential customer, and more time to achieve market penetration in the face of increasingly efficient incumbent technologies, all the while requiring higher levels of investment at each stage. One of the active VC investors interviewed for this study captured a pervasive perspective regarding hardware innovation: “No one wants to invest in a cash-burning company that absorbs lots of capital. Once you’re in, it’s almost impossible to get out.”

One investor who considered backing a startup with a promising fuel cell technology described the prospects of taking the technology through the demonstration stage:

“This was a transformative technology, but we were told it would take five years to demonstrate it to the satisfaction of a single auto company, and then another seven years before it actually was put into use.”

As another experienced entrepreneur and investor put it during an interview, “The issues with the clean energy ecosystem come down to one word: patience.”

Testing, of course, needs to satisfy not only the innovator but also the potential adopter. Demonstrating a product's value and operability to the satisfaction of multiple customers adds expense and time. Then, once field tests have established the operational merits of the product to the potential user, the further hurdle remains of meeting the customer's procurement rules, which commonly are administered by a different internal organization than the one involved in evaluating test results. Regulatory certification requirements present an additional hurdle.

Adopters meanwhile face logistical challenges and business risks of their own. Evaluating technology requires facilities and experts. Integrating a new technology into an existing system involves cost, time, and inconvenience. The potential benefits of the new technology must demonstrably outweigh the cost of disrupting existing operations, workflows, and processes. There also may be concerns about the long-term viability of the supplier; a startup company might not be around in the future to support its technology.

Even when operations personnel see a potential benefit in the technology, internal institutional processes and performance metrics can discourage field trials. Decisions need to be made concerning how the field trial will be funded, who manages the trial, and who assigns value to the findings. Technology trials are often funded from operational budgets. The cost of such trials must compete for resources with the demands of existing operations to which performance targets for operations personnel are generally tied. In addition, such trials may involve distractions from ongoing operational responsibilities and potential disruption of ongoing operations. Finally, there is the ongoing risk involved in incorporating a new technology into the operations of an industry whose paramount concerns are reliability and safety. It's worth noting that many of these concerns apply not only to innovations offered by start-ups but also to those offered by internal corporate R&D groups. Energy companies innovate carefully.

Progress along the clean energy innovation pathway is propelled by the innovator but is enabled by the adopter. The innovation process is a feedback loop. Improving the flow of clean energy innovation requires understanding what adopters will deem deployable, what demonstrations they will need to make that finding, and how the technology can be developed in ways that satisfy those needs. In the words of one investor:

“When you innovate for consumer markets, you develop a new product and put it out there to see whether it sells. When you innovate for a supply chain, you find out what problem needs to be solved and you provide a solution. Energy is a supply chain; successful energy innovation needs to solve problems.”

For companies to be willing adopters of a clean energy technology, the technology needs to solve a problem big enough to make the effort and cost of adoption worthwhile. Matching a solution to a problem requires insight on the part of innovators and clear communication of business needs on the part of adopters. Public policy plays an important role in defining the problems that industry chooses to address. Demand-pull policies are often needed in order to make adopters receptive to clean energy solutions.

TEXT BOX 2-4

Corporate Open Innovation

Historically, many large corporations maintained large in-house research facilities (e.g., Bell Labs, Xerox PARC, DuPont Experimental Station) with extensive scientific and technical capabilities to perform research including development of prototypes for market development. Today's innovation landscape is very different — with the decline of large corporate in-house capabilities, with greater reliance on outsourcing and technology acquisition, and with an increasing role for individual and small-scale innovators seeking to develop new energy-related products and processes.

Increasingly, corporations have adopted “open innovation” models of R&D, drawing on innovations originated outside the corporate structure. Companies that might have invested heavily in basic research in the 1960s in order to secure a strong intellectual property (IP) advantage today focus instead on the cultivation and incorporation of multiple IP sources. Over the past decades, established companies have found greater value in adapting innovation to their distinctive configurations of competitive advantage than in securing IP in a particular technology. What technology a company offers has become less central to its business model than how it combines different technologies in a distinctive product offering.

As expressed by a corporate innovation executive interviewed for this study:

“We use every innovation resource we can, including our internal venture capital group to scout out opportunities outside our four walls. We welcome technology from anywhere; for us the critical innovations are how we put technologies together to serve our customers.”

This tendency has coincided with other trends, including deregulation, increasing international competition, and stringent Wall Street expectations of value maximization to steer

corporations away from investment in basic research. With open innovation, corporate investment can afford to wait until later stages of innovation, when the potential value and risks of an innovation become clearer.

As a corollary to reducing the corporate role in research, open innovation implies active engagement with startups at later precommercial stages. By expanding their innovation awareness upstream to encompass the early stages of applications research, adopters are present as an innovation takes shape, they can understand its potential, and they can anticipate and gain clarity on the risks it may present. By funding innovation at the development stage, and by facilitating demonstration tests, they also can lend credibility to the technology and assurances of staying power to other adopters who may be necessary in order to provide economic scale.

Several practices are helpful in reducing corporate barriers to adoption and making open innovation successful. Standardization facilitates the integration of new products into existing systems and helps clarify for entrepreneurs, as they develop their product, the technical hurdles they must clear. Collaboration between a potential adopter's operations and procurement organizations at an early point in the evaluation process reduces discontinuities and saves time. The distractions faced by the internal operating organization involved in managing trials can be eased by dedicated technology trial teams, separate from operations, that can manage the logistics of field trials and assess value using consistent metrics. Building a goal of a set number of field trials into the performance metrics of operational personnel has proven helpful in overcoming operational reluctance to disrupt existing processes and work flow. All of these measures require a purposeful commitment to innovation on the part of the adopter.

TEXT BOX 2-5

The Utility Innovation Model

As owners and operators of power generation assets and distribution networks, utilities play an essential role not only in the deployment of clean energy technology, but also in precommercial clean energy technology development and demonstration. They are the institutions in a position to perform field pilots to test technologies under deployment conditions, and to provide insights into how the product is used by the customer or how the technology integrates within existing delivery systems. As components of the energy system become more diverse and more distributed, while still requiring close coordination, this role of field evaluation and system integration becomes increasingly important.

As technology innovators or direct investors in early-stage innovation, however, utilities play only a modest role. Because of the regulated environment in which utilities operate, where cost recovery for technology development is limited, and because of the paramount industry focus on reliability, utilities must align their investment activities with the objectives and risk tolerance of their regulators, which vary from state to state. As one utility executive put it, “Policymakers have to buy into disruption before it can occur.”

The state regulatory environment is a critical variable in the level of R&D undertaken by utilities. Of the eight companies funding technology research at rates above the industry average (Figure 2-9), four operate in California and New York, where clean technology innovation is a significant state policy priority, and four operate in other states with regulatory bodies that historically are supportive of utility initiatives.

Utilities also sponsor research through the nonprofit Electric Power Research Institute (EPRI). EPRI receives funding from 90 percent of U.S. electric utilities, conducts studies in support of precommercial technology development ranging from surveys of the technology landscape, to field pilots testing how technologies perform under expected conditions, to developing best practices for operation. EPRI also convenes user groups for discussion of specific technology applications, providing important support to the technology demonstration and technology deployment phases of innovation.

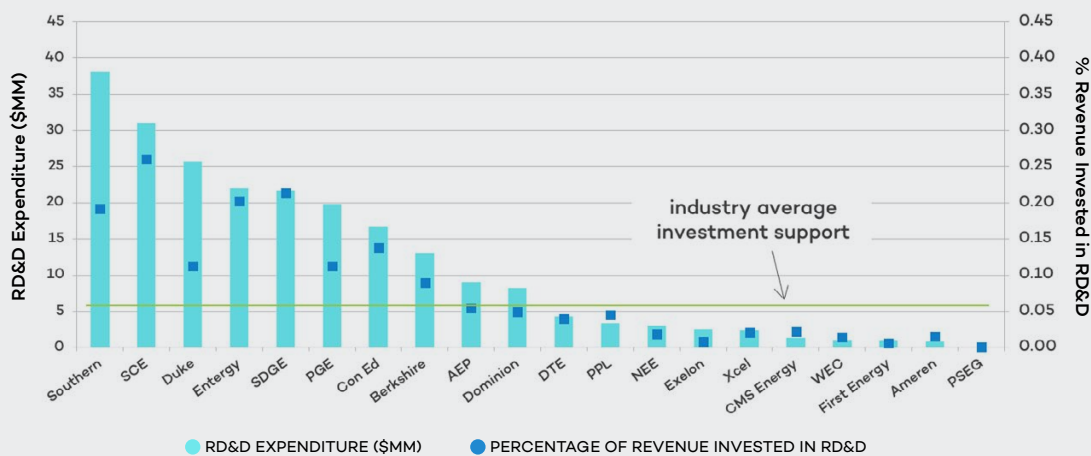
TEXT BOX 2-5 (CONTINUED)

Because the EPRI research agenda is set largely by the near-term research needs of member companies, it provides insight into the industry's principal areas of innovation interest. Funding in the areas of environment and electricity generation has decreased slightly over the past five years as issues with air quality standards, such as the Mercury and Air Toxics Standards and cross-state emission standards, have receded and as low-cost gas has displaced substantial amounts of coal generation. Funding for power delivery and utilization and nuclear studies has expanded slightly, reflecting concerns over renewable integration and member interest in next-generation nuclear power. Funding for early-stage technology innovation studies has been steady and very modest at an annual average of \$30 million (Figure 2-9).

Although not themselves significant sources of investment in early-stage technology development, municipal utilities and rural electric cooperatives provide important testing grounds for the adoption of clean technologies. Municipal utilities primarily serve metropolitan areas, while cooperatives serve large portions of rural America. Together they generate 5 percent of the nation's power, deliver 26 percent (most of it generated by others) to over 100 million customers, and own and maintain 42 percent of the nation's distribution network. State government regulatory commissions often have little or no jurisdiction over these utilities.

FIG. 2-9

U.S. Investor-owned Utilities Direct R&D Investment, 2016



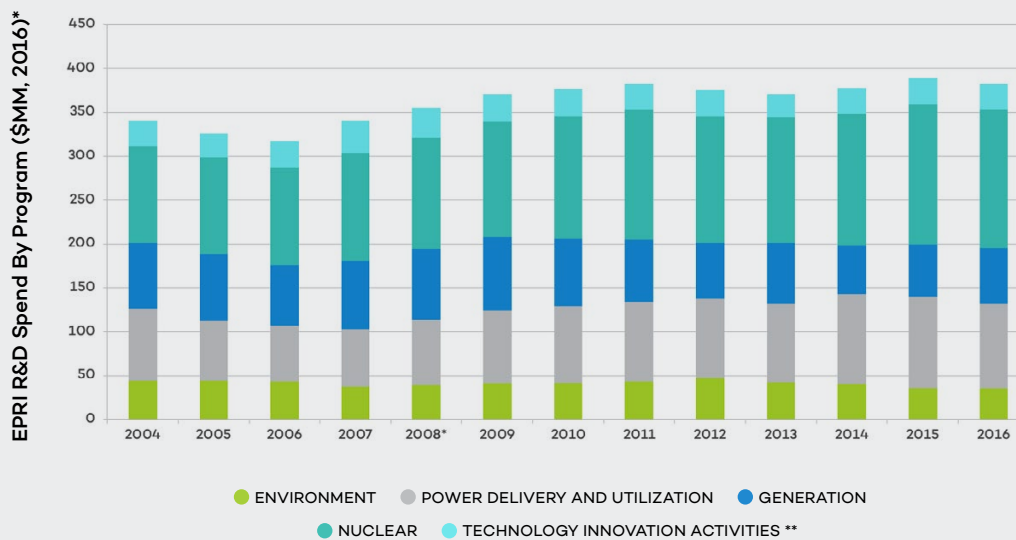
Source: IHS Markit analysis, based on review of FERC filings of 20 U.S. investor-owned utilities and subsidiaries.

TEXT BOX 2-5 (CONTINUED)

As not-for-profit entities overseen by municipal governments or citizen boards, cooperatives and municipal utilities have some of the lowest electric rates and highest reliability records in the United States. They lack the financial resources needed to invest in early-stage technology development, but once a technology has moved beyond proof-of-concept, these utilities often are among the most interested and willing to test emerging clean energy technologies, especially those that might provide cost savings. They were among the early testers and adopters of smart-meter technologies, and many have been at the forefront of installing renewable energy capacity, deploying energy storage technologies, engaging in grid modernization, and experimenting with electric rate structures.

FIG. 2-10

EPRI R&D Expenditure by Program, 2004-2016



EPRI has a large portfolio of R&D initiatives funded collaboratively by the utility industry. Annual spending on early-stage technology innovation averages \$30 million.

Notes: *Estimate; **Technology innovation activities are long-term R&D activities determined by EPRI assessment of industry strategic research needs.

Source: IHS Markit analysis

Institutional Support

Clean energy innovation is supported by an institutional structure that provides strong support to research but weakens as it moves to subsequent stages.

Research-stage Support

The research stage of clean energy innovation relies heavily on the U.S. university system, recognized as the best in the world. Universities sponsor energy research in basic science, technology, technology commercialization, the social science of energy use, and energy public policy. Universities and the DOE national laboratory system are the primary vehicles through which DOE's clean energy research funding is deployed. University partnerships with the national laboratories are common. Oak Ridge National Laboratory participates in a consortium of about 115 institutions of higher education. Other laboratories with five or more university partners include: the Fermi National Accelerator Laboratory, Idaho National Laboratory, National Energy Technology Laboratory, NREL, Savannah River National Laboratory, and Pacific Northwest National Laboratory.

Through legal mechanisms such as Cooperative Research and Development Agreements (CRADAs), the DOE national laboratories have played a significant role in taking technology from the research stage to technology development. Several studies of the DOE national laboratory system have noted the policy ambivalence that exists regarding laboratory participation in private research agendas. This ambivalence centers around an aversion to the federal government "picking winners," and a concern that the laboratories' enlistment in the commercial agendas of private companies might compromise the laboratories' public-interest mission of disinterested scientific and technical research. Most of these studies observe, however, that a key mission of the DOE is to "catalyze the timely, material, and efficient transformation of the nation's energy system,"⁴¹ and that the iterative feedback loops between basic and applied research require engagement between the DOE national laboratories and the private sector on a greater scale than occurs today.⁴² Recommendations for enhancing technology migration from the laboratories include more decentralized management of the laboratories, increased emphasis on technology transfer in DOE's laboratory performance metrics, and more flexible approaches in designing collaboration agreements, pricing laboratory facilities, and establishing rules of engagement for research partnerships.

In recent years, DOE has emphasized the need to migrate research from the discovery that occurs in university and national laboratory environments to a point where it can yield commercial applications. DOE's grants through its Energy Frontier Research Centers and ARPA-E typically involve major research universities in university-industry partnerships, often in collaboration with DOE's national laboratories. Similarly, DOE's energy research hubs are built around university-industry-national-laboratory partnerships to conduct multidisciplinary R&D focused on high-priority technology challenges.

An example of university-industry collaboration is the MIT Energy Initiative (MITEI). In this program, the university collaborates with major companies as research partners, each company associated with an agreed research portfolio and standardized IP arrangements. MITEI has an external advisory board that includes corporate funders, who help set broad direction and select research seed projects with pooled funding.⁴³

41. "Mission: Energy," Department of Energy, accessed March 21, 2018, <https://www.energy.gov/mission>

42. Laura D. Anadon et al., "The Pressing Innovation Challenge of the U.S. National Laboratories," *Nature Energy*, 1, no. 10 (September 12, 2016): 16117, doi:10.1038/nenergy.2016.117. See also Matthew Stepp et al., *Turning the Page: Reimagining the National Labs in the 21st Century Innovation Economy* (Washington, D.C.: Information Technology and Innovation Foundation, 2013), 42-54, http://www2.itif.org/2013-turning-the-page.pdf?_ga=2.53919264.903289316.1521667779-1704320746.1521667779

43. Ernest J. Moniz, "Stimulating Energy Technology Innovation," *Daedalus* 141, no. 2 (Spring 2012), 88-89, <https://hdl.handle.net/1721.1/70514>

The support provided to clean energy innovation by U.S. research institutions is an exceptional strength of the innovation ecosystem. The number and variety of institutions engaged is large and collaboration among them is productive. Increased emphasis is being placed on the commercialization prospects of the research developed. Collectively these institutions constitute a deep and resilient platform for the early stages of clean energy innovation.

Development-stage Support

In the development stage of clean energy innovation the primary support institutions are incubators. These organizations, often associated with research institutions and supported by state and local governments or philanthropies, provide startups with support and assistance in bringing a promising technology into the market. They provide critical support services — facility space, professional advice and networking, navigation through regulations, connection to funders, and understanding of government support programs. In addition to providing space and resources for development of the startup's technology innovation, they help it develop basic business skills such as planning cash flow, developing presentation materials, and raising funds. The number of incubators and technology accelerators has expanded rapidly in recent years. According to the Seed Accelerator Rankings Project, hundreds of entities calling themselves accelerators have emerged in the past five years.⁴⁴

44. "About," Seed Accelerator Rankings Project, accessed March 21, 2018, <http://seedrankings.com/#home>

45. The data for Figure 2-11, Text Box 2-6, and Table 2-1 were collected from the publicly available materials of the members of the organization Incubatenenergy as of October 2017, plus Cyclotron Road and the Los Angeles Cleantech Incubator (LACI). It comprises approximately 230 energy startups currently enrolled or being funded by those incubators. Based on information available on the incubator and company websites, each startup was characterized in three ways: (1) its technology category, selected from the root categories listed in Appendix A, (2) its subjective characterization as primarily a hardware or software innovation, and (3) its subjective characterization as a new energy system or an increment to an existing energy system. A startup offering was characterized as software if it provides primarily IP rather than a physical product. It was characterized as incremental if it serves primarily to make an existing energy apparatus or technology more efficient or to broaden marginally its applicability rather than to introduce a new technology.

46. The incubators in the analysis with high levels of state and local government support are Accelerator for a Clean and Renewable Economy (ACRE), Greentown Labs, Los Angeles Cleantech Incubator (LACI), Oregon Best, and Prospect Silicon Valley. Those with primarily private funding are CLT Joules, Elemental Excelerator, Innosphere, and Powerhouse.

These incubators have been associated primarily with the development of high-tech innovation, and the metrics and screening criteria they apply are influenced by that background. Incubators that aim at moving startups efficiently through the development process are likely to favor software. Hardware typically requires higher capital outlays than software, significantly longer lead times, and greater understanding of customer processes, infrastructure, and workflow. The array of the clean energy startups supported by incubators reflects this pattern (see Text Box 2-6: "What is Being Incubated?").⁴⁵

This inclination toward shorter-term startup efforts is particularly pronounced in incubators funded primarily from private sources, as opposed to those funded primarily from state or local sources. The latter group appears to have a higher concentration of hardware startups and a higher concentration of novel energy solutions (Figure 2-10).⁴⁶ This discrepancy in portfolios may reflect differences of purpose. Incubators founded with state and local sponsorship typically aim at supporting local innovation-based economic development. Compared to privately sponsored incubators, they may be more tolerant of long development lead times and more committed to breakthrough innovations that themselves provide a basis for economic development.

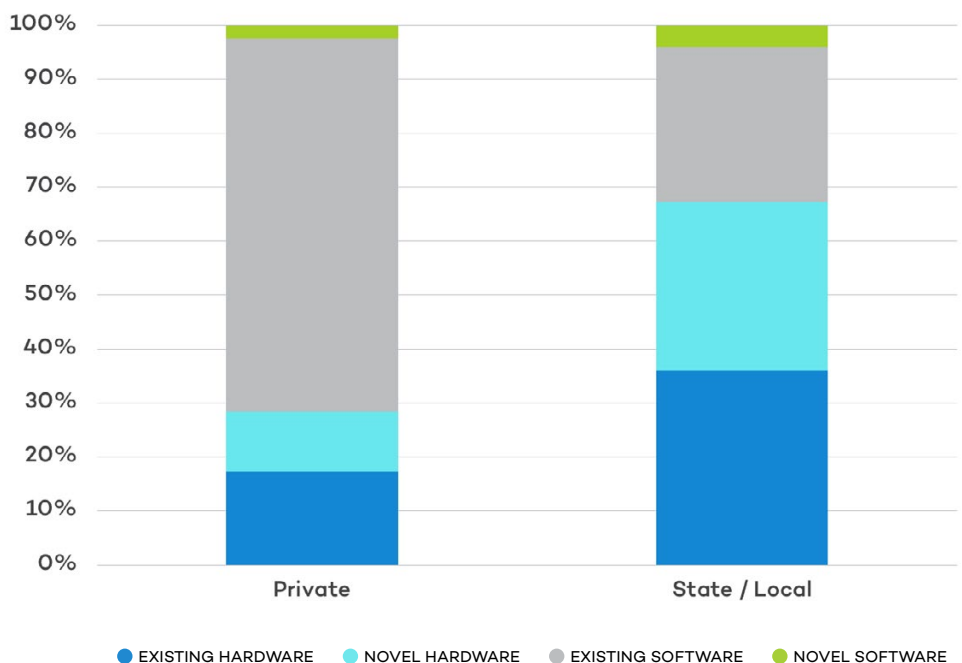
The basic incubator model aims at assisting entrepreneurs to develop successful startups. A somewhat different support model is represented by institutions that provide "entrepreneurial research fellowships." Cyclotron Road, based at Lawrence Berkeley National Laboratory in California, is perhaps the best-known example of this type. It identifies highly promising researchers and provides them with laboratory space and funding to support development of their technological ideas, providing an earlier intervention point than incubators, which typically support companies once they are already established. There are now three other institutions offering this type of fellowship: Innovation Crossroads at the Oak Ridge National Laboratory in Tennessee, Chain Reaction Innovations at the Argonne National Laboratory in Illinois, and the Runway Startup Postdocs program at the Jacobs Technion-Cornell Institute in New York.

In 2014, Cyclotron Road started awarding two-year fellowships to cohorts of individuals with advanced technical degrees, selected based on extensive energy research experience and promising technology visions. For example, the third cohort (for 2017-2018) of 10 fellows selected by Cyclotron Road came from a very competitive pool of 100 applicants.⁴⁷ By the end of their fellowships in late 2016, the fellows in the program's first cohort had all built prototypes or secured funding to do so, had collectively secured more than \$15 million in additional research funding or investment, and had created 30 high-tech manufacturing jobs.⁴⁸ The support model practiced by Cyclotron Road and similar organizations is to focus on talented individuals who otherwise would be unable to advance their technology, to help them develop a holistic commercialization plan incorporating technology, market planning, financing, and policy dependence. These organizations provide education in key commercial skills, mentorship, and networks of support with potential financiers, adopters, and fellow innovators and entrepreneurs.

Despite the growth in the number of technology incubators over recent years, only a small number nationwide are focused on clean energy, and those incubators accept only a small fraction of the innovators who apply for support. Although the track record of incubators is too recent to yield clear patterns, it appears that (with some exceptions) incubators, like VC, are more hospitable to software than to hardware solutions. To support technology migration through the technology development stage, more incubators are needed, as well as an increased willingness among incubators to support long-term breakthrough innovation.

FIG. 2-11

Startup Technology Portfolio by Incubator Type



Incubators developed under state and local sponsorship currently have a higher portion of startups focused on hardware than incubators developed under private sponsorship.

Source: IHS Markit analysis, drawing on data described in footnote 45

47. "Welcome, Cohort Three! Third Cohort of Innovators to Start at Cyclotron Road Next Week," news release, April 25, 2017, Cyclotron Road, Lawrence Berkeley National Laboratory, <http://www.cyclotronroad.org/journal/2017/4/25/welcome-cohort-three>

48. Nicole Systrom and Sebastien Lounis, Building a Home for Hard Science Innovators: A Retrospective on the Cyclotron Road Pilot: 2016 Annual Report – Cyclotron Road (Berkeley, CA: Lawrence Berkeley National Laboratory, 2017), 19, <https://static1.squarespace.com/static/543fdfece4b0faf7175a91ec/t/58cad7399de4bb7b62b0750f/1489688386385/2016-Cyclotron-Road-Annual-Report-Online.pdf>

Demonstration-stage Support

In the demonstration stage of innovation, as technology progresses from incubation to commercial product, test beds play an increasingly important role. These facilities provide access to the specialized equipment required to validate performance. For innovators they provide exposure to the processes and systems with which the new technology must integrate. For adopters they provide an opportunity for end users to develop operational familiarity with the new technology. By providing a platform for mutual accommodation of innovators and adopters, test beds can help overcome many of the hurdles that stand between research and deployment. As indicated by the sample of test beds listed in Text Box 2-7, “Examples of Clean Energy Testing Facilities,” the wide variety of testing needs posed by different technologies entails significant differences among testing facilities.

The complexity and locational specificity of energy systems require test venues that provide real-world conditions. Providing real-world conditions requires diverting facilities that are in actual use from their day-to-day missions. Even the test beds at DOE national laboratories are not designed for sustained late-stage demonstrations of this kind. For these reasons, demonstration has traditionally been the domain of industry and a bottleneck to innovators. Broadening that domain to accommodate innovators’ agendas will require more test facilities as well as closer collaboration between innovators and adopters during earlier stages.

However, test beds are expensive. To increase significantly the availability of test beds at utilities for carbon capture, next-generation nuclear power, and large-scale energy storage would cost hundreds of millions of dollars. It would likely require consortia of companies to share costs through an organization such as EPRI, or require government cost sharing of existing corporate facilities in return for broad third-party access to their testing programs. Significant expansion of this kind would need to be aligned with clear national research priorities of the kind described in chapter 3 of this report.

The pathway between technology invention and commercial adoption in an innovation ecosystem that attracts only modest interest from financial investors is challenging. During the development and demonstration stages, the need for innovation support grows but the support infrastructure thins out. Unless a concept gains early attention from a corporate adopter, it is likely to run out of resources.

TEXT BOX 2-6

What is Being Incubated?

Approximately half of the startups currently supported by energy innovation incubators fall into one of five technology categories, as summarized in Table 2-1. Within those five categories, 56 percent of the startups are concerned with software, and 85 percent are concerned with incremental improvements to existing energy solutions. The predominance of software in the most frequent technology categories is significant. Incubation works best with a critical mass of human capital in an environment surrounded by relevant skill sets and the opportunity to pivot from one idea to another to best take advantage of those skill sets. The most frequently occurring technology types stand the greatest chance of benefitting from the incubation environment and moving on to long-term private development. The clustering of incubator startups into a handful of technology categories is consequently self-reinforcing.

TABLE 2-1

Characterization of Technology Focus of Energy Incubator Startups

Top Five Technology Categories	Number of Startups	Percentage of Startups That Are:		Percentage of Startups Pursuing:	
		Hardware-Focused	Software-Focused	Novel Energy Solutions	Incremental Improvement to Existing Energy Solutions
Building Efficiency/ System Control	37	3%	97%	0%	100%
Grid Management/ Systems Operations	19	16%	84%	0%	100%
Advanced Materials	19	100%	0%	42%	58%
Distributed Solar	18	33%	67%	28%	72%
Building Conditioning/ Lighting	17	88%	12%	18%	82%
Totals	110	44%	56%	15%	85%

TEXT BOX 2-7

Examples of Clean Energy Testing Facilities

TEST FACILITY	PARTNERS	DESCRIPTION
Irvine Smart Grid Demonstration	Southern California Edison, DOE National Energy Technology Laboratory	End-to-end demonstration of multiple smart-grid technologies to test interoperability and efficacy of key elements of the grid, from the transmission level through the distribution system and into the home.
Walnut Station Test Facility	American Electric Power (AEP)	Research and testing services for various distributed energy resources and other enabling equipment, e.g., microturbines, fuel cells, advanced batteries, communications, protection and control equipment. Devices may be tested singularly or in combination with other devices and may operate with or without connection to the electric power grid. AEP engineers and technicians provide expertise in test formulation and implementation.
NIST Smart Grid System Testbed Facility	National Institute of Standards and Technology (NIST), Department of Commerce	Interconnected and interacting labs, contiguously located on the NIST Gaithersburg site, to accelerate development of smart grid interoperability standards. The combined platform for system measurements, characterization of protocols, and validation of standards aims to accelerate the development of interoperability standards against which innovators can develop their technologies.

TEXT BOX 2-7 (CONTINUED)

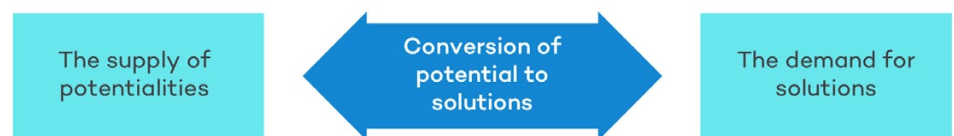
TEST FACILITY	PARTNERS	DESCRIPTION
National Carbon Capture Center	DOE National Energy Technology Laboratory, Southern Company (operator), AEP, Duke Energy, EPRI, Cloud Peak Energy, Clearpath	Facility enabling government, industrial, and university projects to conduct meaningful tests in an industrial setting. Post-combustion carbon dioxide capture technologies at various levels of maturity can be tested on multiple slip streams with a range of flue gas throughputs.
Washington Clean Energy Testbeds	Washington State, University of Washington Clean Energy Institute	Customized training and access to top-quality fabrication, characterization, and computational instruments for printing, coating, and testing materials and devices needed to achieve ultra-low cost solar cells and batteries, and for developing system integration hardware to optimize performance of devices and systems integral to the new energy landscape. Operates under a pay-per-use, open-access model, providing timely access to test facilities relative to the lengthier competitive application and approval process at public energy research and test-bed facilities.
Cold Climate Housing Research Center (CCHRC) Research and Testing Facility	U.S. Department of Agriculture-Rural Development, U.S. Department of Commerce Economic Development Administration, State of Alaska, Rasmuson Foundation	The CCHRC Research and Testing Facility consists of a 22,000 square foot building that incorporates cutting-edge building and energy technologies to promote and advance the development of sustainable shelter for Alaskans and other circumpolar people. Technology testing capabilities include adjustable foundations, ground source heat pumps, and solar thermal storage.

Strengthening the Private-sector Role in Clean Energy Innovation

The pervasive collaboration between industry and research institutions, and between public and private sectors, is a great strength of the U.S. clean energy innovation ecosystem. All markets, of course, and certainly energy markets, are affected by public policy. What is notable about clean energy innovation is that public policy is engaged not simply to regulate or channel the dynamics of the market but also to create and amplify the market. Within this policy framework a strong private-sector support system is needed to provide innovators with facilities, funding, coaching and community, business skills, and demonstration venues. The clean energy innovation ecosystem needs to link innovators and adopters in ways that acknowledge the bias toward stability and continuity of the existing energy system.

FIG. 2-12

Three Pillars of Energy Innovation



As these linkages are improved, financial sources of investment will find precommercial clean energy innovation more attractive. U.S. capital markets are among the most liquid and responsive in the world. The quantity of potential investment capital in the U.S. is ample in comparison with investment opportunities, as evidenced by the prevailing low cost of capital. Numerous potential funding sources are available in this space, and they have demonstrated the ability to respond flexibly in response to commercial performance.

The difficulty encountered by startups in securing funding at the various stages of the innovation pathway has less to do with capital scarcity than with the risk-reward prospects that startups present. It has been argued that innovative financial instruments — designed to categorize and allocate risk with greater precision than today's instruments provide — would facilitate funding, but unless the ultimate commercial prospects of innovations are improved through greater receptiveness by adopters, new financial instruments are likely to have only marginal impact on commercial risk calculations. As one investor put it, “It’s fine to know that a new product has financial backers, but what I really need to see are customers. To me a product’s potential is demonstrated by revenue far more than by equity.”

Similarly, the widespread view that a “valley of death” lies between the different stages of the clean energy innovation pathway is misleading if it implies that financial sanctuary lies on the other side of the valley. The pathway of innovation rather becomes increasingly taxing in time and cost with each successive stage.

Moreover, long timelines and incremental absorption rates will always limit the role of financial capital in clean energy innovation, leaving strategic capital to play the dominant role. The main private sources of that strategic capital have been suppliers and (especially in the automotive industry) end-use providers. What this funding pattern does not cover are the long-term potential breakthrough innovations that are not on the business agenda of those corporations. For this

“With today’s power system in the U.S. you have 100+ years of optimization—reaching the right scale, the right technology mix, an efficient system of integration. It’s a mature, efficient, system. Bringing in cleantech requires major re-accommodation. It won’t happen on its own.”

reason, the entry of funding sources like the Breakthrough Energy Coalition, whose strategic objectives encompass breakthrough innovation for the sake of long-term national goals, but which also have the flexibility associated with financial capital can fill a critical gap in the clean energy innovation ecosystem. Even these funding sources, however, are unlikely to secure significant uptake of innovative clean energy technologies unless equipment suppliers, primary energy producers, and end-use customers have reason grounded in public policy to incur the attendant disruption and cost of adopting new clean energy solutions.

As the Chief Technology Officer of a leading energy equipment manufacturer put it: “Funds focused on cleantech haven’t done that well. What’s surprising about this is that people are surprised. With today’s power system in the U.S. you have 100+ years of optimization — reaching the right scale, the right technology mix, an efficient system of integration. It’s a mature, efficient, system. Bringing in cleantech requires major re-accommodation. It won’t happen on its own.”

To be sure, abundant examples exist of clean energy innovations that succeed in the market. Renewable energy, for example, is less expensive today than conventional sources of energy in some U.S. states, and is projected to be cheaper than conventional energy in many other areas of the country by 2020.⁴⁹ It is unlikely, however, that these technologies could have reached the economic scale that enables them to compete if they had not been supported by the public policy framework of research support and renewable portfolio standards that initially created a market for them and that continues to support them. The same could be said for the vast array of innovative devices and processes that are employed to support smart grids. The market for these devices has been created principally by public policy incentivizing energy efficiency and encouraging the integration of clean energy sources into the power system.

Many other clean technology innovations, especially those that support energy efficiency, do provide economic advantages that are captured in the course of normal market transactions. However, the payback periods may not seem compelling to consumers, and the energy savings offered may be a secondary consideration in comparison to other product attributes. Education programs and labeling regarding the relative energy consumption of appliances or HVAC, and the corresponding cost implications, have proven effective in encouraging adoption in some circumstances. Efforts are being made to develop deeper insight in this area. DOE, for instance, has offered awards to use behavioral insights to reduce the “soft” costs of residential solar such as customer acquisition and system installation.⁵⁰ The previous Administration’s Social and Behavioral Sciences Team conducted research in ways to activate consumer responses to climate change.⁵¹ Among topics examined were the impact of defaulting consumers to green options, and the effectiveness of a Home Energy Score that quickly allows prospective homeowners to assess the energy efficiency of a home.

Amid these challenges there are several respects in which private sector clean energy innovation processes could be facilitated and improved.

- The clean energy innovation community would benefit from technical information dissemination and technical assistance activities. Federally-funded National Network of Manufacturing Institutes and the Manufacturing Extension Partnerships can play an important role in assisting manufacturers, particularly small companies, in making investment decisions by providing information on deployment of state-of-the-art innovative technologies. DOE national laboratories also could play an increased role in this area.

49. Ryan Wiser et al., 2016 Wind Technologies Market Report (Washington, D.C.: U.S. Department of Energy, 2016), 57–62, https://www.energy.gov/sites/prod/files/2017/10/f37/2016_Wind_Technologies_Market_Report_101317.pdf

50. DOE, Energy Efficiency & Renewable Energy, “Education: Research Topics,” <https://energy.gov/eere/education/research-topics>

51. Executive Office of the President, National Science and Technology Council, “Social and Behavioral Sciences Team,” September 2016. <https://obamawhitehouse.archives.gov/sites/whitehouse.gov/files/images/2016%20Social%20and%20Behavioral%20Sciences%20Team%20Annual%20Report.pdf>

- Investments are needed to expand the availability of open-access test beds and incubator space to enable more rapid commercialization of innovative technologies. Additional support resources could make incubators more effective and help sustain startups after their incubator terms have expired. These additional resources include the following.
 - Assistance in steering innovators toward appropriate entrepreneurial research fellowships, incubators, and test facilities, and assistance in writing grant proposals and developing business plans.
 - Organization of venues and events to connect innovators, adopters, and investors through workshops, technology showcases, and conferences.
 - Research and analysis of best practices and performance results of incubators and test beds.
 - Support to state and local governments in designing effective clean energy programs, drafting legislation and regulations, and sharing governmental performance results and best practices.
 - Financial assistance to innovators in support of such basic family needs as health care insurance and daycare.
 - Technical and business advice and assistance to startups as they undertake the transition from incubators to commercial viability, and as they need to develop capabilities in manufacturing, sales, and finance. This support might involve assembling a pool of retired engineers and business managers willing to contribute time and expertise.
- In practice, it might prove useful to combine several of these support functions under a single institution that could serve as an “innovation center.” An innovation center located in a community committed to fostering technical innovation could catalyze a strong local or regional innovation culture by bringing together a combination of incubators, research fellowships, and the above support functions.
- An inventory should be developed of near-commercial innovative energy technologies in the innovation pipeline that could be readied for commercial deployment at scale. It might be possible to de-risk many of these projects through scale-up or demonstration through public-private partnerships using flexible financial vehicles such as DOE’s Other Transactions Authority. An illustration of how this can be accomplished can be found in DOE’s success in placing, quickly and effectively, significant levels of funding from the 2009 American Recovery and Reinvestment Act into programs such as the smart grid demonstration program.
- Nontraditional funding sources can add significant depth to the clean energy innovation ecosystem. For reasons discussed earlier in this chapter, the value of clean energy innovation ventures often is not fully reflected in the balance of commercial risk and reward presented. Strategic corporate investors may provide funding for some of these ventures to serve their strategic purposes. However, ventures that satisfy neither the criteria of financial investors nor the aims of corporate strategic investors may merit financial support for other reasons: to capture the learnings from a novel technical approach, to encourage interest in solving a particular problem, or to sustain a highly promising line of research. This is a role that private philanthropy, or philanthropically motivated investor groups, could potentially fill. This is not because they are patient in their expectation of economic return (which may never be realized in many instances), but because economic return is not their only investment aim.

TEXT BOX 2-8

Investors with a Cause

Recognizing the lagging investment in clean energy innovation, several partnerships of major potential investors have emerged in the past two or three years to provide a source of investment that is based on social as well as economic evaluations. The most prominent of these impact investment groups are noted below. These funds are global in scope and are too new to represent as yet a significant funding source for U.S. clean energy innovation, but given the relatively low level of innovation investment currently offered by the private sector, they have the potential to add significantly to the investment pool.

Oil and Gas Climate Initiative – *Inception: 2014.* The OGCI is a CEO-led initiative which aims to shape the petroleum industry response to climate change. The group comprises 10 oil and gas companies that together represent over one-fifth of the world's oil and gas production. They seek to pool their expert knowledge and develop strategic partnerships to limit climate change by increasing the development and deployment of carbon-mitigating technologies. Through OGCI Climate Investments, a \$1 billion fund to be deployed over 10 years, the group will support the development, deployment and scale-up of technologies and new business models with the potential to make a material impact on greenhouse gas (GHG) emissions. Innovation will be supported through collaborative investments in startups, support of demonstration projects, and deployment of successful technologies in the operations of member companies.

Breakthrough Energy Coalition – *Inception: 2015.* The Coalition is a diverse group of private investors: high-net-worth individuals, financial institutions and global corporations that are committed to funding technological solutions to meet the challenges of climate change. The Coalition aims to develop partnerships among governments and members to invest at early innovation stages and accelerate deployment of energy solutions at scale. The long-term perspective and the relatively risk-tolerant perspectives of coalition members relative to traditional financial investors is expected to help bridge the gap between basic science and commercially viable technology deployment. Breakthrough Energy Ventures is the investor-led fund of the Coalition. It takes a broad view of investment options, considering companies at all stages and sizes, across all technologies and geographies, provided the technologies meet the ultimate goal of enabling significant GHG reductions. The size of the fund is unspecified as yet.

TEXT BOX 2-8 (CONTINUED)

Energy Impact Partners – *Inception: 2015.* Energy Impact Partners is a private equity firm supported by a broad coalition of large utilities. It invests strategically in innovative technologies, services, and products throughout the electricity supply chain, from generation to consumption. It leverages the knowledge and experience of its investors to identify emerging technologies and business models relevant to the utility of the future. Through its investor utilities, it provides a market for those startup companies in which it invests. Its reported clean energy investment in 2016 and 2017, combined (counting the contributions of its syndicate partners), was a little over \$100 million.

Mission Innovation – *Inception: 2015.* Mission Innovation is a multinational initiative of 22 countries and the European Union to accelerate global clean energy innovation in transformative technologies through increased and coordinated public sector clean energy R&D, and greater information sharing among stakeholders. The group has identified a three-step approach to accelerating clean energy innovation: significantly increase government support for clean energy R&D, focus investment activity on high-impact technology challenges identified by member countries, and engage with the private sector to encourage increased levels of early-stage investment in these technologies.

RECOMMENDATIONS

The Private-Sector Role in Clean Energy Innovation

- Because of the energy system's long cycles of adoption, a broad range of approaches should be deployed to make it easier for adopters to understand, anticipate, and support the innovations that are being generated at the early stages of the innovation process. These efforts include, on the part of adopters, open innovation, standardization of procurement requirements, encouragement of innovation testing either through dedicated evaluation staffs or through performance metrics, and active outreach to become familiar with innovations at the development stage or earlier. They include, on the part of innovators, early attention to the needs of adopters as indicated by expressed needs and also by the past performance of innovation efforts.
- Investments are needed from foundations and from federal, state, and local governments to expand the availability of open-access test beds and the effectiveness of incubators in accelerating commercialization of innovative technologies. Some of these investments should fund research into best practices and performance results of incubators and test beds and of state and local programs supporting innovation.
- Communities interested in fostering technical innovation should consider establishing innovation centers comprising incubators, research fellowships, access to research facilities and expertise, and business mentorship programs.
- As discussed further in chapter 4, federally funded vehicles like the National Network of Manufacturing Institutes, the Manufacturing Extension Partnerships, and the national labs should collaborate in disseminating information on emerging clean energy technologies to the country's manufacturers. In addition, the federal government should maintain an inventory of technologies close to commercialization that could be accelerated by targeted public-private investment in scaled-up demonstration and testing.
- Strategic philanthropic investors and coalitions of industry investors with long-term horizons should play an active role in identifying and supporting promising technology ventures that are otherwise not commercially viable in the near term. This is recommended because clean energy innovation attracts only modest financial investments at precommercial stages, and because strategic corporate investment is focused primarily on those innovations recognized as useful to business objectives.
- Research institutions and nonprofits should be supported in pursuing social science insights into the motivations of adopters: how incentives can be designed to shape customer preferences in ways favorable to clean energy use, and how products can best be designed and presented to satisfy those preferences.
- Public policy (discussed in subsequent chapters) should be further strengthened and aligned to support both the supply and demand ends of the clean energy innovation ecosystem. The aim should be to create market forces strong enough to make rapid innovation profitable for innovators and investors and attractive to adopters, in the face of significant system inertia.

Chapter 3. Focusing the Energy Innovation Portfolio on Breakthrough Potential

This chapter proposes a set of criteria for identifying and prioritizing key breakthrough technologies. Twenty-three technology areas are highlighted for their breakthrough potential, and the criteria are applied to yield ten specific, high-value technology areas. The opportunities and challenges of each of these selected technology areas are discussed.

FINDINGS

Focusing the Energy Innovation Portfolio on Breakthrough Potential

- Federal and private clean energy innovation investment are complementary.
- Key platform technologies hold great potential to unlock significant clean energy innovation.
- A four-step process is used to identify breakthrough technologies that have potential to aid government, industry, and thought leaders in efforts to transform the energy sector:



Analyze key drivers of clean energy technology breakthroughs

Digitalization, big data, and smart systems
The difficult to decarbonize sectors (industry, transportation, and buildings)
Integration of platform technologies
Systems and supply chains

Develop selection criteria for breakthrough technologies

Technical merit
Market viability
Compatibility
Consumer value

Identify the universe of emerging energy technologies that have critical features across various timescales

Identify innovation areas with significant breakthrough potential

- Critical innovation areas identified are:
 - Storage and battery technologies
 - Advanced nuclear reactors
 - Technology applications of industry and buildings as sectors that are difficult to decarbonize: hydrogen; advanced manufacturing technologies; and building energy technologies
 - Systems: electric grid modernization and smart cities
 - Deep decarbonization/large-scale carbon management: carbon capture, use, and storage at scale; sunlight to fuels; biological sequestration

TEXT BOX 3-1

Energy Innovation Defined

Energy innovation is the transformation of ideas, knowledge, and capabilities into improvements in energy products and services. Innovations can include new system components, improvements in the value chain, changes in systems integration and interoperations of technologies, advances in enabling technologies that facilitate improvements in cost and performance, and other advances that lower investment risk. Successful innovation occurs in both the public and private sectors, supported by factors such as policies, regulations, business models, markets, and consumer knowledge and acceptance.

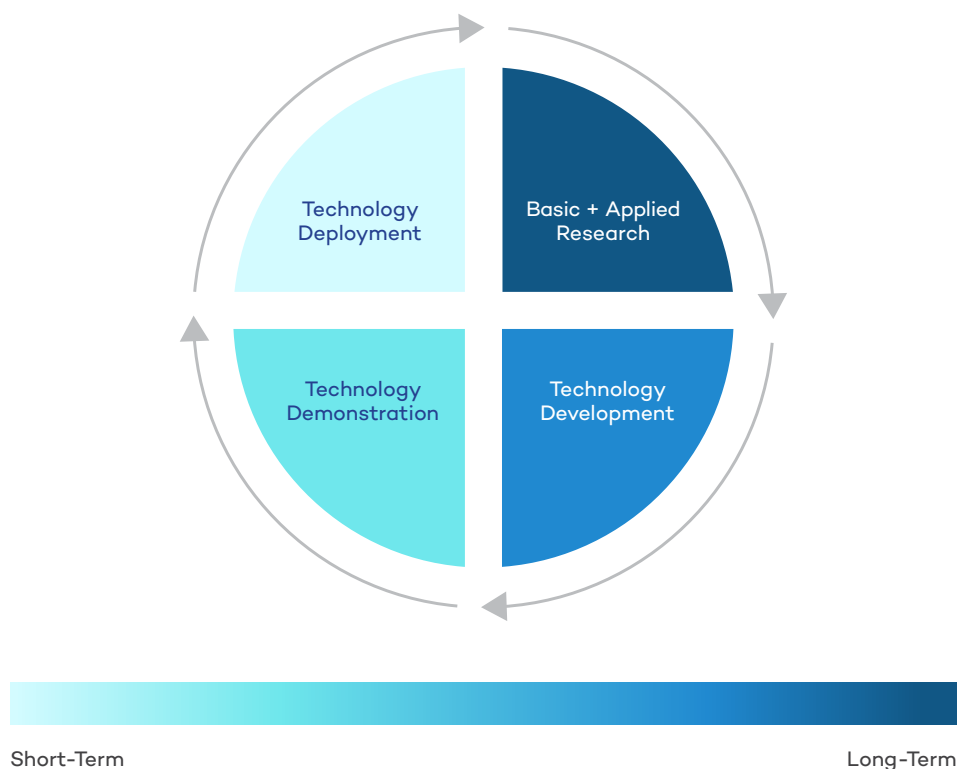
Clean Energy Innovation: the Need for a Focused Portfolio

Impediments to transformation in the energy sector are significant. As noted in Chapter 1, energy is a highly capitalized, commodity business, with complex and extensive supply chains and established customer bases, providing essential services at all levels of society. Energy systems consequently are characterized by considerable inertia, aversion to risk, extensive regulation, and complex politics. Breakthroughs in energy technologies, therefore, play out over long timescales — decadal, generational, and beyond. Consistent and sustained public and private sector funding in technology research, development, demonstration, and deployment (RDD&D) (Figure 3-1) is needed to span the innovation process of invention, translation, adoption, and diffusion over these timescales, and regulatory support is needed to ensure receptive markets.

In order to engage private and public resources effectively and collaboratively in reshaping energy systems toward cleaner technologies, it is important to identify a portfolio of potential breakthrough technologies that merit the long-term private and public commitments that will be required. Such a portfolio can provide a framework for prioritizing public resources, a roadmap for private innovation and entrepreneurship, and the comprehensive focus needed to effect long-term transformations in energy systems.

FIG. 3-1

The Basic Innovation Technology Readiness Stages



Technology readiness stages start with basic and applied research, and advances through the stages of technology development, demonstration, and deployment.

Source: Energy Futures Initiative (EFI), 2017

Drivers of Clean Energy Technology Breakthroughs

The portfolio of clean energy breakthrough technologies must address several challenges.

Zero-Carbon Power Generation

CO₂ emissions from power generation have declined substantially in the last decade (2016 emissions were 22.8 percent below 2006 levels)⁵² and there are a growing number of options for new large-scale, zero-carbon generation technologies. Much of the recent drop in emissions can be attributed to coal-to-gas fuel switching for power generation; natural gas has become the largest source of power generation in the United States (34 percent in 2016).⁵³ Without CCUS, though, gas-powered electricity generation will be too carbon intensive to meet midcentury emissions targets. Success in deeply decarbonizing the electricity sector is necessary for a low carbon economy.

Tough-to-decarbonize Sectors

There is a clear need to drive technology innovation in the end-use sectors that are tough to decarbonize. In developing the clean energy innovation breakthrough portfolio, there should be a prioritization around the following questions: Does a technology or process have significant potential to benefit the industrial, transportation, or buildings end-use sectors? Does the technology or process have significant benefits in terms of zero-carbon energy generation or large-scale carbon management?

- **Industry.** Reducing energy use and GHG emissions from the industrial sector is essential for any deep decarbonization strategy. The industrial sector consumes 22 percent of the nation's energy, making it one of the largest end-use sector emitters of GHGs. Significant innovation is needed to expand electrification in this sector, to reduce energy demand through additive manufacturing and artificial intelligence, to develop carbon-free sources for process heat (including the possible use of nuclear power or hydrogen combustion to generate that heat), and to capture CO₂ from various industrial processes for its subsequent utilization in products or permanent geological storage (termed carbon capture, utilization, and storage, or CCUS). Reducing emissions from the sector will require a combination of innovation in these four areas.
- **Transportation.** The overwhelming body of analyses concludes that significant emissions reductions are needed from the transportation sector for deep decarbonization. These reductions will necessitate the widespread electrification of the U.S. vehicle fleet, or use by that fleet of a fuel that does not emit CO₂ when burned.⁵⁴ The deployment of hybrid vehicles employing nickel-metal-hydride and lithium-ion batteries is continuing to expand, and plug-in hybrid electric vehicles (PHEVs) are beginning to gain market acceptance. More innovation is required, however, to accelerate the move to emissions-free transportation, including widespread deployment of electric vehicles that are 100 percent battery electric vehicles (BEVs) or hydrogen-fueled fuel cell electric vehicles (FCEVs).

52. U.S. Department of Energy, Energy Information Administration [EIA], Monthly Energy Review, February 26, 2018, Table 12.6, https://www.eia.gov/totalenergy/data/monthly/pdf/sec12_9.pdf

53. "Electricity Explained," Energy Information Administration, Department of Energy, last modified May 10, 2017, https://www.eia.gov/energyexplained/index.cfm?page=electricity_in_the_united_states

54. The White House, United States Mid-Century Strategy for Deep Decarbonization (Washington, D.C., 2016), 8-9, https://unfccc.int/files/focus/long-term_strategies/application/pdf/mid_century_strategy_report-final_red.pdf

“The rapid development of digital, data-driven, and smart systems—largely from outside the energy sector—has unlocked the potential of other platform technologies that could be scalable across the entire energy value chain. Leveraging these digitally-supported technologies can support a systems-level transformation of the energy sector, helping to reduce emissions, increase security, and improve overall system performance.”

Integration of Distributed Resources

Deployment of distributed energy resources, including community and rooftop solar photovoltaic (PV) systems, microturbines, storage, and demand management systems continues to grow. Grid operators are adapting to these trends through the application of digital communications and control technologies. These resources can help reduce carbon emissions by providing electricity from low- or zero-carbon technologies and by reducing demand. Some distributed energy resources (DER), such as distributed solar PV systems and energy-efficient equipment, can have a significant impact on system load, but may not be under the direct control of, or visible to, grid operators. Others, such as residential hot water heaters, have the potential to serve as DER or to provide demand response, but the technologies to do so currently have low penetration or are still nascent.⁵⁵

Large-Scale Carbon Management

Any effort to deeply decarbonize the energy and end-use sectors will require carbon management solutions. There are multiple pathways for large-scale carbon management. CO₂ may be converted into fuels, chemicals, or materials. It may also be stored in geologic formations, such as oil and gas reservoirs or saline formations. Even with accelerated efforts to develop new energy efficient and low-carbon energy technologies, carbon emissions will need to be managed at large scale in the coming decades. The research to establish the feasibility of large-scale carbon management is not, however, currently a significant element of the national energy innovation portfolio.

Integration of Platform Technologies

The rapid development of digital, data-driven, and smart systems — largely from outside the energy sector — has unlocked the potential of other platform technologies that could be scalable across the entire energy value chain. Leveraging these digitally-supported technologies can support a systems-level transformation of the energy sector — helping to reduce emissions, increase security, and improve overall system performance. Key platform technologies that hold the greatest potential to unlock significant clean energy innovation are: additive manufacturing, artificial intelligence, genomics, and blockchain.

- **Additive Manufacturing and Materials by Design.** The confluence of capabilities to model, design, engineer, and then synthesize and analyze new materials with desired properties has opened a new generation of materials for energy. Additive manufacturing, often referred to as “3-D printing,” allows for the creation of complex macroscopic shapes. When coupled with deposition of new and exotic complex materials, it can result in the creation of new classes of devices. The technique could have a transformational impact, reducing materials use and the weight of end products. Coupled with a materials-by-design approach, it will enable the mass production of complex structures of materials with application-specific properties not currently feasible with traditional manufacturing. Additive manufacturing also supports decentralized manufacturing, with significant potential for regional economic development.
- **Artificial Intelligence.** Pervasive sensing — driven by low-cost sensors — coupled to comprehensive models and high-performance computing, enables enhanced situational awareness, real-time simulation, and a new generation of autonomous control systems. Big data technology, coupled to emerging artificial intelligence and the use of algorithms to perform tasks in perception and control, opens the way for machine learning and automated decision-making to

55. U.S. Department of Energy [DOE], Quadrennial Energy Review: Transforming the Nation's Electricity System: The Second Installment of the QER (Washington, D.C., 2017), 3-24, <https://www.energy.gov/policy/initiatives/quadrennial-energy-review-qer/quadrennial-energy-review-second-installment>

optimize performance at every step of the energy value chain — predicting markets, balancing operations on critical time scales, and maximizing yield.

- **Genomic Science and Synthetic Biology for Energy Applications.** The revolution in genomic science has provided tools for understanding the structure, properties, and functionality of living systems from the simplest microbes, both natural and synthetic — to algae, the rhizosphere, plants, and higher organisms. This knowledge can be harnessed to manipulate and synthesize biological systems for an enormous range of purposes: from the design of energy crops and processes for the creation of fuels, to a more comprehensive understanding of the global carbon cycle and how it can be manipulated to mitigate climate change.
- **Blockchain.** Blockchain is essentially an information management system that streamlines many existing business processes, making them faster, cheaper, and more secure. Blockchain is already changing the way consumers conduct transactions, and represents a shift in the underlying model of business transactions away from a centralized structure of banks and firms to a decentralized system of customers and consumers. This may have significant impacts on the energy sector by lowering the barriers to entry for non-traditional energy suppliers and customers. These may include peer-to-peer energy traders or traditional suppliers engaging new sizes or types of customers.

Systems and Supply Chain Vulnerabilities

As the energy sector becomes more technology-centric, the supply chains for new technologies becomes more critical (Figure 3-2).⁵⁶ A core component of many of these trends is lithium, which is critical throughout information and communication systems. It enables computers and cell phones, smart devices, and most other mobile power technologies. The lithium supplies that enable these key technologies and innovations is part of a complex and concentrated global supply chain, and lithium demand is growing significantly.

Another major technology with a complex and distributed supply chain is the industrial control systems that are used to remotely monitor, analyze, and control the physical operations of one or more processes or facilities — and is key to automation. Decades of innovations in control system technology and increases in computing and networking capabilities have enabled the automation of many industrial processes, ranging from electricity generation, transmission and distribution to mass transit to manufacturing. Over time, more sectors in energy and across the wider economy will—directly or indirectly—rely on these, or similar, components.⁵⁷

The concern over supply chain security for these devices in the electricity sector led the Federal Energy Regulatory Commission (FERC) to issue Order No. 829 in July 2016, directing the North American Electric Reliability Corporation (NERC) to develop a new or modified Reliability Standard that addresses supply chain risk management for industrial control system hardware, software, and computing and networking services.⁵⁸ NERC complied with the order and FERC published a draft rule, adopting NERC's new standards, for public comment.⁵⁹ FERC is not the only Federal agency with an interest in this issue. It has also been reported that the National Security Agency has seen intrusions into critical industrial control systems by entities with the apparent technical capabilities “to take down control systems that operate U.S. power grids...and other critical infrastructure.”⁶⁰

56. James McCall, “Systems Analysis of Manufacturing Supply Chains,” Manufacturing Clean Energy (blog), Clean Energy Manufacturing Analysis Center, August 8, 2017, <http://www.manufacturingcleanenergy.org/blog-20170808.html>

57. Frost and Sullivan, Insights, Opportunities, and Trends in the Global Industrial Control Systems (ICS) Market, <https://www2.frost.com/frost-perspectives/insights-opportunities-and-trends-global-industrial-control-systems-ics-market/>

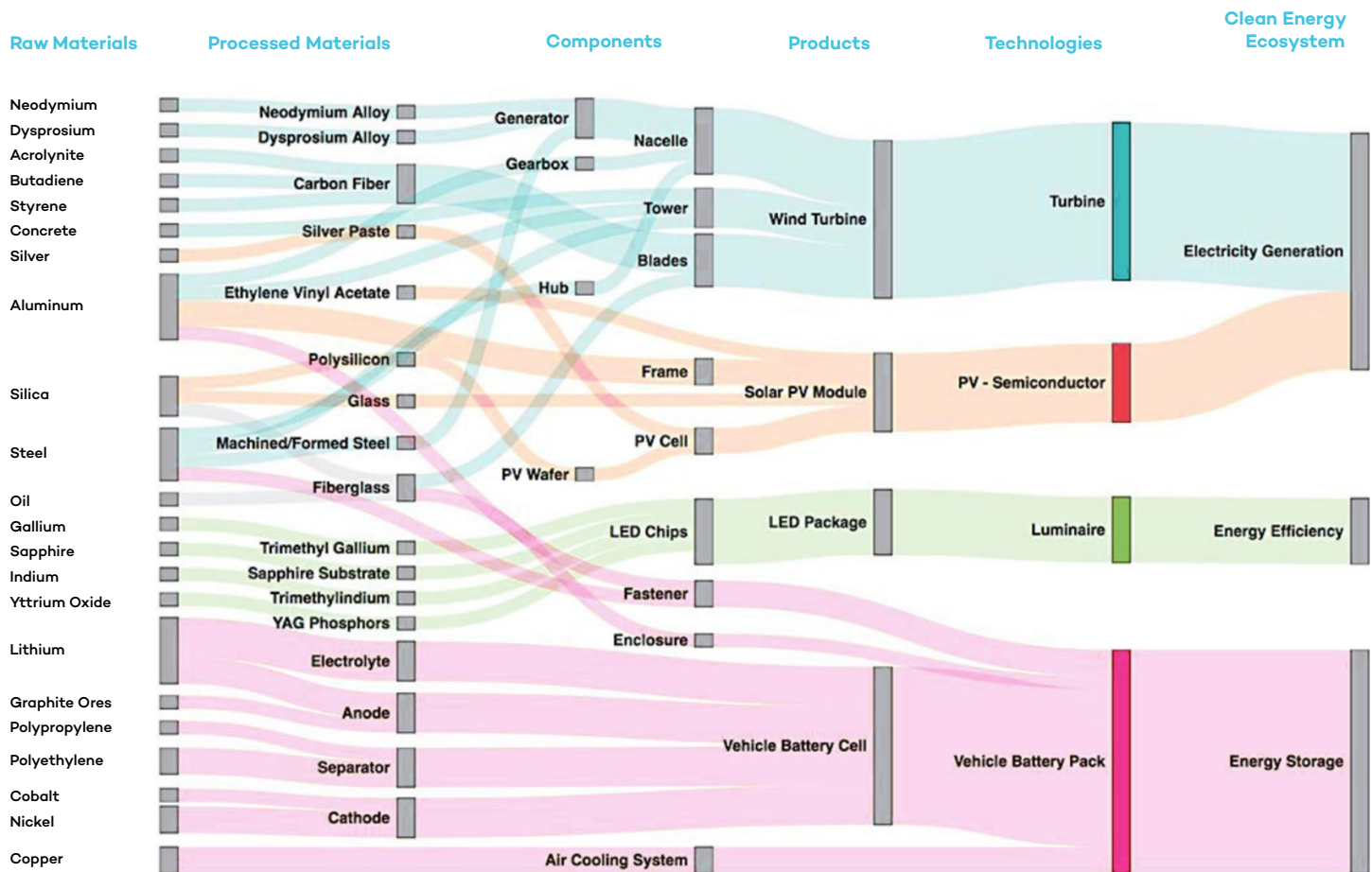
58. Revised Critical Infrastructure Protection Standards, 81 Fed. Reg. 49,878 (July 29, 2016) (Fed. Energy Reg. Comm’n, requiring the development of supply chain risk management standards, to be codified in 18 C.F.R. Part 40), <https://www.gpo.gov/fdsys/pkg/FR-2016-07-29/pdf/2016-17842.pdf>

59. Supply Chain Risk Management Reliability Standards, 83 Fed. Reg. 3433 (January 25, 2018) (Fed. Energy Reg. Comm’n, notice and comment on three standards to augment current reliability standards in 18 C.F.R. Part 40, to mitigate cybersecurity risks associated with the supply chain for bulk electric system cyber systems), <https://www.gpo.gov/fdsys/pkg/FR-2018-01-25/pdf/2018-01247.pdf>

60. Richard J. Campbell, Cybersecurity Issues for the Bulk Power System (Washington, D.C., Congressional Research Service, 2015), 9, <https://fas.org/sgp/crs/misc/R43989.pdf>

FIG. 3-2

Sankey Diagram of the Clean Energy Technology Supply Chain



The clean energy technology supply chain is vast and complex, but also includes numerous interconnections between raw materials and technologies.

Source: McCall, 2017. Clean Energy Manufacturing Analysis Center

Identifying Technology Breakthrough Priorities

The combination of extended time periods needed for fundamental energy innovations, the interaction of learnings at all stages of the innovation cycle, and the critical relationship between public and private sectors creates a need for a broadly understood portfolio of innovation objectives. A three-step selection process is proposed for identifying that portfolio:

1. Development of selection criteria for breakthrough technologies
2. Identification of the universe of emerging energy technologies, noting their impact potential across various time scales
3. Identification of innovation areas with significant breakthrough potential, utilizing the identified criteria

Selection Criteria

The selection criteria proposed are: technical merit, market viability, compatibility, and consumer value.

- **Technical Merit** includes energy or environmental performance, especially GHG reduction, leading to systems-level performance improvements. It also includes enabling innovations or knowledge and heuristic gains for cost, risk, and performance across a variety of technologies or systems.
- **Market Viability** includes manufacturability at scale with adequate and secure supply chains; a viable cost-benefit ratio for providers, consumers, and the greater economy; maturity to support very large scale-up; economic and environmental sustainability from a life-cycle perspective; significant market penetration; and revenue generation.
- **Compatibility** includes potential to interface with a wide variety of existing energy infrastructures (interoperability); potential to adapt to a variety of possible energy system development pathways (flexibility); potential to expand or extend applications beyond initial beachhead applications (extensibility); and the ability to minimize stranded assets.
- **Consumer Value** takes into consideration potential consumer preference issues, such as expanded consumer choice (by facilitating the introduction of new or improved products and services) and ease of use.

A broad list of candidate technologies has been developed and organized by energy supply (electricity and fuels), energy application (industrial, transportation and buildings), and cross-cutting technology areas (including large-scale carbon management, advanced materials, and high-performance computing). The table listing these technologies, provided in the appendix to this chapter, highlights the timeframe to potential commercialization.

The operational feasibility of obtaining the benefits of each candidate technology is subject to local infrastructure, resource availability, energy mix, strategy, regulations, and market structures. For a full analysis of technological potential, a range of factors must be considered, including emerging supply and demand scenarios, planned and existing infrastructure investments, needs for system flexibility, and natural competition.

For purposes of the current discussion, 23 emerging technologies have been identified qualitatively as having high breakthrough potential. Because these varied technologies are at widely different stages of development, they are mapped onto a near-, intermediate-, and long-term continuum. The mapping reflects the timeframe in which efforts pursued today can be expected to yield mature contributions. Even long-term items require attention in today's innovation portfolio; research groundwork must be laid now in order for these technologies to achieve their potential in the future.

The Breakthrough Technology Shortlist

Finally, the selection criteria—technical merit, market viability, compatibility, and consumer value—have been used to screen qualitatively for a select and critical subset of those technologies deemed to have high breakthrough potential.



Storage and battery technologies



Advanced nuclear reactors



Technology applications of industry and buildings as sectors that are difficult to decarbonize

- Hydrogen
- Advanced manufacturing technologies
- Building energy technologies



Systems: electric grid modernization and smart cities



Deep decarbonization: Large-Scale Carbon Management

- Carbon capture, use, and storage at scale
- Sunlight to fuels
- Biological sequestration

TABLE 3-1

Emerging Technologies with Breakthrough Potential

Application Area & Technology	Near Term (2025)	Intermediate Term (2035)	Longer Term (2050)
Electricity Supply & Distribution			
Heat Sources for Electricity Generation			
Coal with Carbon Reduction		Chemical looping; oxy-combustion; fuel cell carbon capture; subsurface CO ₂ management at gigaton scale; mineralization	Very large-scale CO ₂ utilization (fuels, products, sequestration)
Natural Gas Combined Cycle (NGCC)		Natural gas combined cycle with carbon capture	
Nuclear Fission		Advanced non-LWR, small-scale reactor technologies (e.g., high-temperature and fast reactors); advanced materials/fuels; modeling and simulation; used fuel degradation; alternative repositories; actinide burn-up; hybrid systems	Very high temperature reactors (power and process heat), especially SMRs
Heat-to-Electricity Conversion		Supercritical CO ₂ turbines; high-temperature-enabling materials for gas turbines	
Direct Electricity Generation			
Solar PV		Perovskites and other non-Si materials; systems integration with storage and energy management systems	
Storage		Non-lithium battery chemistry; flow batteries; solid state control systems; physical and cybersecurity	
Transmission and Distribution Systems	Interoperability standards; software and models; solid state components; cybersecurity	Grid architecture development; innovative control approaches; material innovations including wide bandgap semiconductors	
Fuel Supply & Distribution			
Oil and Gas Production			Methane hydrates
Alternative Fuels (Feedstocks and Conversion Technologies)			Affordable low-carbon drop-in fuels; sunlight-to-fuels
Hydrogen Production		Improved cost/performance of low- or zero-carbon H ₂ production pathways; improved materials	
Manufacturing & Industry			
Advanced Manufacturing Technology	Smart manufacturing (sensors, controls, automation); new-paradigm materials manufacturing techniques (e.g., electrolytic metals processing); and advanced additive manufacturing		
Process Heat			Hydrogen as a chemical reductant and as fuel for process heat for energy-intensive industries

TABLE 3-1 (CONTINUED)

Application Area & Technology	Near Term (2025)	Intermediate Term (2035)	Longer Term (2050)
Transportation & Mobility			
Electric Drive Vehicles			
Batteries		Advanced, non-Li Battery Technology	
Transportation System Management	Pathways to enhanced vehicle connectivity and automation; traffic management improvements; autonomous vehicles		
Built Environment			
Space Conditioning Technology		High efficiency electric heating systems (e.g., heat pumps that use refrigerants with low or zero Global Warming Potential)	
Systems Integration		Smart Cities systems integration of buildings, transportation and industry	
Large-Scale Carbon Management			
Terrestrial Sequestration		Sub-surface CO ₂ management at gigaton scale; mineralization	
Biological Sequestration	Research and field testing of alternative approaches for innovative, large-scale, biological sequestration approaches		
CO ₂ Utilization			Large-scale CO ₂ utilization alternatives (including conversion to fuels or products such as polymers and carbon fibers)
Cross-Cutting & Enabling Technology			
Enabling Science and Technology	Structural analysis of materials using X-ray light and neutron sources; novel nanoscale synthesis and fabrication techniques; advances in genomic and biological analytical and observational tools; modeling, simulation, and data analysis using high performance computing; advanced sensors and monitoring systems (e.g., drones)		
Energy/Water Nexus	Desalination		
Advanced Materials	Composite materials; earth-abundant substitutes; materials by design; materials in harsh environments		
High Performance Computing	Development of exascale computing capability including software		



Storage and Battery Technologies

The key characteristic of energy storage technologies is the ability to store electricity produced at one time for use at another time, balancing electricity supply and demand. Table 3-2 details criteria and challenges for storage and battery technologies.

TABLE 3-2




Selection Criteria and Challenges for Storage and Battery Technologies

Technology	Technical Merit	Market Viability	Compatibility	Consumer Value
Storage/ Batteries	Transformative role in multiple value chains – electricity (generation T&D, end use), transportation (all-electrified vehicles), buildings (flexibility, resiliency, reduce peak demand and demand charges) central to clean energy transition; transform grid, buildings and transportation value chains; many modalities and values — time, energy, and power; batteries “beyond lithium” emerging	Massive buildout in battery manufacturing capacity is underway — 10 percent of need. Costs and durability are limiting, and global lithium and other raw materials must expand	Wide range of batteries for power, energy, and conditioning. require improved power electronics; technology beyond batteries for grid and use sectors	Batteries are high value to energy providers and customers; countless applications throughout value chain; batteries make systems more flexible, higher quality, and more convenient
Challenge				
Huge scale-up: lithium and other energetic materials, battery manufacture; robustness, charge rate, energy density, and cost must improve				

“Storage, including batteries, can be used to address many challenges facing the power sector today, including integrating variable fuel sources into the grid, deferring capital investment in infrastructure, and improving economic dispatch, efficiency, and power quality.”

FIG. 3-3

Applications of Energy Storage in Electricity Value Chain

Electricity Value Chain			
Applications offered by Energy Storage	<ul style="list-style-type: none">• Electric Energy Time Shift• Renewable Integration• Ancillary Services	<ul style="list-style-type: none">• Voltage support• Transmission congestion relief• T&D upgrade deferral• Sub-station onsite power• Micro or remote grid	<ul style="list-style-type: none">• Time-of-use energy cost management• Power quality• Power reliability
Generation	Transmission	Distribution	End-use Application

Energy storage technologies have many applications throughout the power sector.

Source: Energy Futures Initiative (EFI), 2018; adapted from Harsh Thacker, “Business Case Analysis for Energy Storage Systems for Utilities in Asia Pacific,” Frost & Sullivan, September 2014

Storage, including batteries, can be used to address many challenges facing the power sector today, including integrating variable fuel sources into the grid, deferring capital investment in infrastructure, and improving economic dispatch, efficiency, and power quality (Figure 3-3).⁶¹ Batteries can also support transmission system balancing and coordination of distributed energy resources on distribution networks. In addition, they can be positioned in local communities or behind the customer meter to contribute to emergency preparedness and resiliency and can be used to reduce peak demand and reduce demand charges. Deployment of these technologies — along with other innovative solutions, including advanced control software — can enhance the grid’s capabilities and flexibility.

Lithium-ion systems dominate the current deployment landscape for grid-scale electric energy storage in the United States and demand is expected to grow (Figure 3-4). According to Lazard, lithium-ion systems provide an economical battery storage solution across multiple power sector use-cases, including peaker replacement and commercial behind-the-meter supply.⁶² This is mainly due to falling costs of lithium cells and modules and increasing battery performance in terms of charging efficiency and power quality.

This technology has potential for cost reductions due to emerging energy storage mandates and a burgeoning manufacturing capacity. There are many different lithium-ion chemistries that can be leveraged for grid-scale applications, each with differing power-versus-energy characteristics. Lithium-sulfur chemistries offer the potential for even greater energy densities than lithium-ion batteries. Various technology configurations exist, with some using nanomaterials and nanostructures that show enhanced results (e.g., higher energy density) compared to conventional batteries.

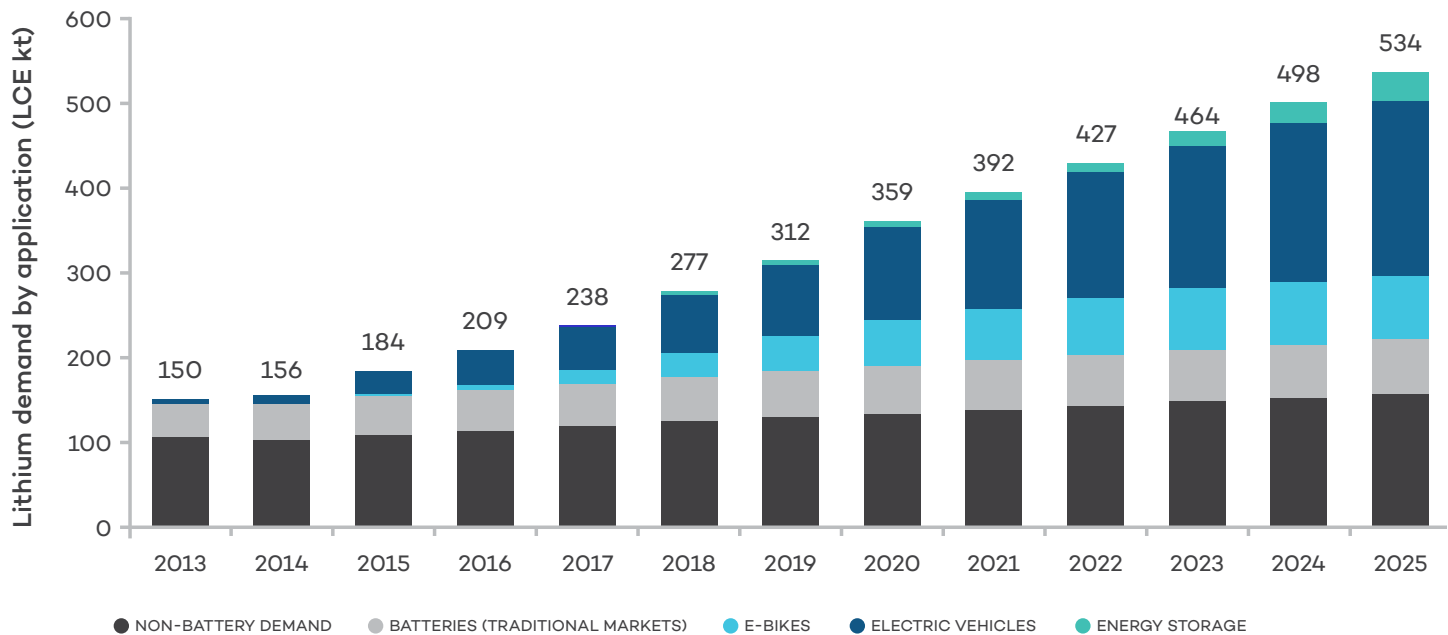
As lithium and battery storage grows in strategic importance to power generation, transportation, and digitalization, supply chains must be carefully analyzed. Rapid increases in demand for lithium for a range of batteries for electric grids, phones,

61. Harsh Thacker, “Business Case Analysis Energy Storage Systems for Utilities in Asia Pacific” (slides), Frost and Sullivan, September 10, 2014, slide 4, <https://www.slideshare.net/FrostandSullivan/business-case-analysis-apac-by-harsh-thacker>

62. “Levelized Cost of Storage: Version 3.0,” Lazard, November 2, 2017, <https://www.lazard.com/media/450338/lazard-levelized-cost-of-storage-version-30.pdf>

FIG. 3-4

Lithium Demand by End-use Application, 2013-2025



Lithium demand is expected to nearly double from 2018 to 2025, largely driven by electric vehicles but also from energy storage, e-bikes, and traditional battery markets such as consumer electronics and medical applications.

Source: Deutsche Bank, Inside EV

computers, vehicles could stress the supply chain (Figure 3-3).⁶³ The number of electric vehicles, globally, for example, could grow from 2 million in 2016 to between 9 and 20 million by 2020.⁶⁴ The growth of the global Internet of Things may nearly triple by 2020.⁶⁵ Major investments by an industry innovator, Tesla, and a major U.S. competitor, China — with 2021 targets of 35 gigawatt-hours (GWh) and 120 GWh, respectively — would carry global capacity to 270 GWh, enough for 30 million Prius type PHEVs (at 5-35 kilowatt-hours, or kWh, per vehicle), or about 3 million Tesla S class vehicles (at 80 kWh and more per vehicle). A global fleet of 4 million EVs of all types would require approximately 100,000 metric tons (MT) of lithium per year.

The electricity grid is another sector where demand for battery storage could be significant. According to the Energy Information Administration (EIA), the electric power industry has installed roughly 700 megawatts (MW) of utility-scale batteries on the U.S. electric grid — mostly in the last three years. As of October 2017, these batteries made up about 0.06 percent of U.S. utility-scale generating capacity. Another 22 MW of batteries were planned for the last two months of 2017, with 69 MW more planned for 2018.⁶⁶

Barriers to the implementation of batteries on the grid fit into five general categories: modeling, technological, financial, market, and regulatory. These all center around the lack of knowledge and experience of utilities and regulatory bodies in the utilization of — and capturing the many values of — batteries.

63. "Global Lithium Demand to Triple Over the Next 10 Years," Market Outlook, Lithium and Cobalt, Metalstech, accessed March 3, 2018, <http://www.metalstech.net/market-outlook/>

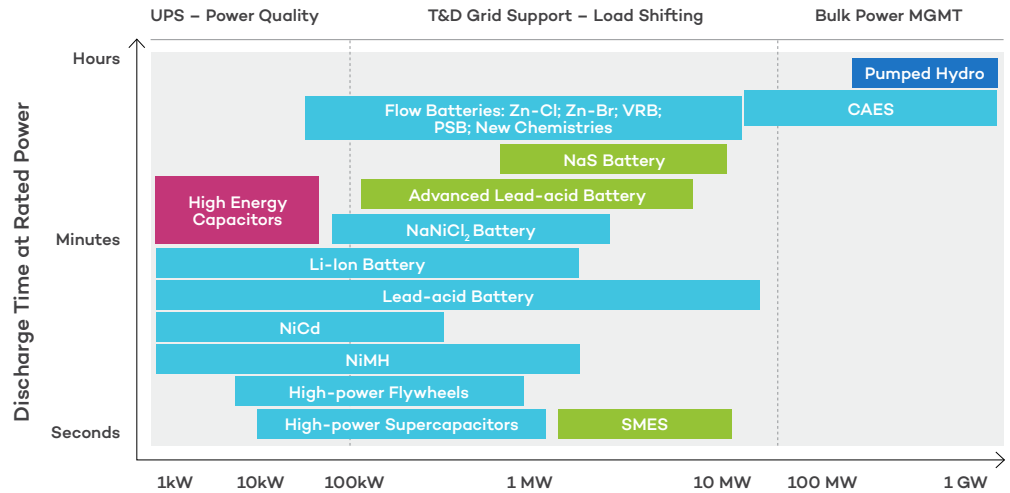
64. IEA, Global EV Outlook 2017, 6, <https://www.iea.org/publications/freepublications/publication/GlobalEVOutlook2017.pdf>

65. Gartner, "Gartner Says 8.4 Billion Connected 'Things' Will Be in Use in 2017, Up 31 Percent From 2016" (2017), <https://www.gartner.com/newsroom/id/3598917>

66. EIA, "Batteries Perform Many Different Functions on the Power Grid," Today in Energy, January 8, 2018, <https://www.eia.gov/todayinenergy/detail.php?id=34432>

FIG. 3-5

Select Battery and Storage Technologies by Application and Capability



Battery technologies have different capabilities and applications.

Source: Energy Futures Initiative (EFI), 2018; adapted from DOE and Sandia National Labs

A combination of RDD&D on batteries, as well as adoption campaigns by the utilities and public utility commissions, is needed to take advantage of the value of batteries throughout the grid.

Several chemistry options “beyond lithium-ion” are being explored, such as lithium-sulfur, lithium-air, sodium, magnesium, and redox-flow chemistries. Each comes with benefits and challenges (Figure 3-5).⁶⁷ Sodium-sulfur (NaS) batteries, for example, are a commercial technology with applications in distribution grid support, wind power integration, and other high-value grid services. U.S. utilities have installed about 9 MW of NaS batteries for peak shaving and firming wind installations, and have plans to install another 9 MW. NaS batteries have significant potential for broader use on the grid because of their long discharge times, their relatively high round-trip efficiencies, and their ability to quickly respond to control signals for regulation or improving power quality. However, NaS batteries use hazardous materials, including metallic sodium, which is combustible if exposed to water. Research needs include advances in chemistries, materials, and designs to reduce operating temperatures and improve safety features.

67. Sandia National Labs, “DOE/EPRI 2013 Electricity Storage Handbook in Collaboration with NRECA”, July 2013, <http://www.sandia.gov/ess/publication/doeepri-electricity-storage-handbook/>



Advanced and Small Modular Nuclear Reactors as Sources of Carbon-free Electricity and Process Heat for Industry

Nuclear energy can provide large-scale zero-emissions power generation, as well as clean energy support for industrial value chains. Table 3-3 details criteria and challenges for advanced and small modular reactor technologies.

TABLE 3-3

Selection Criteria and Challenges for Advanced and Small Modular Reactors

Technology	Technical Merit	Market Viability	Compatibility	Consumer Value
Advanced and Small Modular Reactors (SMR)	New route to clean power for grid and industry; heat and power; hybrid with renewables; advance beyond Light Water Reactors (LWR) — fast, high temperature	SMRs can change financial and applications dynamic	High reliability and resilience for grid and heat and power for buildings and industry; many tech options	Safety, cost, proliferation, security and environmental concerns must be satisfied
Challenge				
Public acceptance for large buildout, development and licensing				

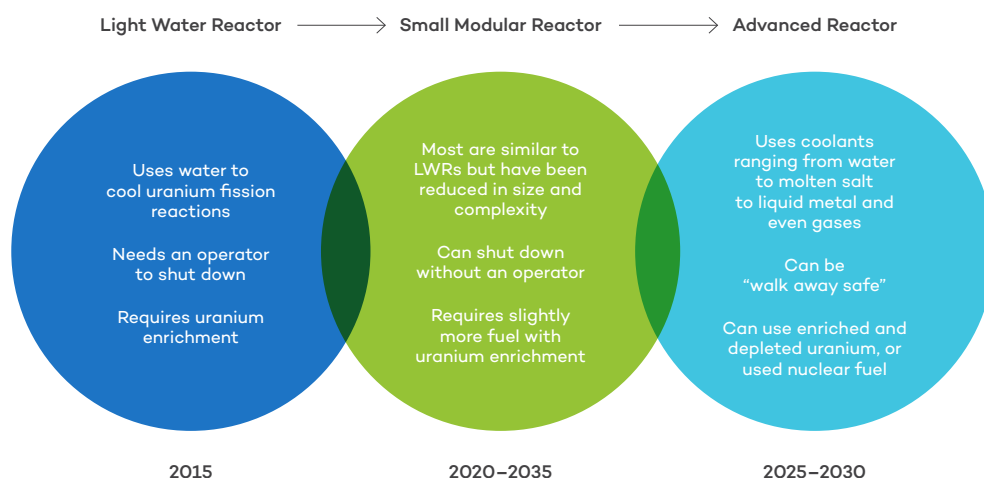
“Reliability and very high capacity factors are major assets of the current nuclear fleet, but safety, cost, nonproliferation, environmental, and security concerns must also be satisfied going forward. To have an impact, a global nuclear buildout will be needed as fossil-based systems are retired.”

Providing for a nuclear energy option, both nationally and globally, to provide clean, dispatchable baseload and scalable power in a complex and dynamic power grid environment is a critical goal. As the global energy system evolves toward a cleaner and more sustainable mix of generation sources, there will be an enduring fundamental need for stability and resiliency in all environments for macro and micro grids, both centralized and distributed. Reliability and very high capacity factors are major assets of the current nuclear fleet, but safety, cost, nonproliferation, environmental, and security concerns must also be satisfied going forward. To have an impact, a global nuclear buildout will be needed as fossil-based systems are retired.

Nuclear power technologies are evolving (Figure 3-6).⁶⁸ There are many advanced reactor concepts that utilize a variety of fuel-cycle strategies and can employ light-water coolant or any of multiple non-light-water coolants, such as liquid metals, molten salts, and helium. These options can offer safety, economic, proliferation risk, and operational advantages. Several of these advanced reactor technology options are capable of operation at temperatures of 880 degrees Celsius (°C) or higher, compared to the 300°C to 325°C outlet temperature of today's LWRs. Reactor outlet temperatures in this higher range provides heat that can be used as an energy source (termed process heat) in several industrial processes, such as the extraction of hydrocarbons from oil sands, the conversion of coal and biomass to high quality liquid fuels, petroleum refining, petrochemical and fertilizer production, desalination, and hydrogen production through thermal splitting of water. This makes these reactors very promising as a potentially significant contributor to deep decarbonization of industrial processes that otherwise would be very challenging. Currently, process heat for industrial processes is provided almost exclusively by the burning of fossil fuels and is the source of about 20 percent of total U.S. energy-related CO₂ emissions.⁶⁹

FIG. 3-6

Continuing Evolution of Nuclear



68. Samuel Brinton, "The Advanced Nuclear Industry," Third Way, June 15, 2015, <http://www.thirdway.org/report/the-advanced-nuclear-industry>

69. DOE, Quadrennial Technology Review 2015, Chapter 4: Advancing Clean Electric Power Technologies, Technology Assessments: High Temperature Reactors (Washington, D.C., 2015), 1, <https://www.energy.gov/sites/prod/files/2016/03/f30/QTR2015-4J-High-Temperature-Reactors.pdf>

Nuclear technologies are evolving beyond light water reactors to encompass both small modular reactors and numerous advanced reactor concepts.

Source: Energy Futures Initiative (EFI), 2017, compiled using data from Third Way, 2015

Advanced nuclear reactor concepts constitute a set of reactor technologies that are often referred to as Generation IV (or Gen IV) reactors, to distinguish them from early prototypes (Gen I), current commercial plants (Gen II), and advanced LWRs under construction or in consideration for construction (Gen III). The key attributes of Gen IV advanced reactors are improved economics, enhanced safety systems (largely or entirely passive in nature), reduced used fuel disposal requirements and proliferation risk, and “plug-and-go” fueling capability (longer cycles of up to 20 years between refueling). Two other important characteristics of several of the advanced reactor technology options are that they can be implemented at smaller scale (tens to hundreds of megawatts) and that they can be used to produce process heat.

The combination of these two characteristics makes these reactors potentially suitable for many industrial applications that are otherwise difficult to decarbonize, as noted above. The Gen IV advanced reactor technology options are generally of two types: thermal reactors that employ neutron moderators (hence the term slow neutrons) and fast reactors that emit neutrons from the fission process without neutron moderation. Individual thermal reactors employ various forms of cooling including water cooling. Fast reactors, by contrast, employ non-water cooling technologies.

SMRs range in size up to 300 megawatts electrical (MWe), employ modular construction techniques suitable for a manufacturing environment and can be constructed with major components shipped from factory fabrication locations to the plant site by rail or truck. SMRs also include designs that simplify plant site activities required for plant assembly. Advanced SMRs offer many advantages such as a relatively small size, reduced capital investment and dramatically shortened development times. Additionally, SMRs can be sited in locations not possible for larger nuclear plants, and offer provisions for incremental power additions. SMRs can be arrayed in hybrid configurations with a variety of renewables including concentrated solar power (CSP) and geothermal resources to supply heat, and PV, hydropower, and wind energy.

There currently are several companies that have raised private capital to invest in the pursuit of advanced reactor concepts. These efforts are largely leveraged from prior DOE-sponsored R&D in HTGR and molten salt reactor technologies. Several countries are supporting R&D on Gen IV reactor concepts. In 2001, they formed the Generation IV International Forum (GIF) to coordinate R&D “needed to establish the feasibility and performance capabilities of the next generation nuclear energy systems.”⁷⁰ In 2014, the GIF published a roadmap detailing R&D objectives for the next decade.

Several privately funded advanced reactor technology companies are currently working with the Canadian Nuclear Safety Commission (CNSC) in qualifying advanced reactor designs, consistent with the Gen IV Licensing Criteria established by the International Atomic Energy Agency. The CNSC employs a phased licensing review process that links various regulatory approvals to completion of engineering design milestones. This step-by-step approach provides greater regulatory certainty by harmonizing engineering design with safety objectives within each phase of the design process.

Packaging these technologies into small modular reactors can offer many advantages. As Figure 3-6 suggests, SMRs have the potential to provide a simpler path to nuclear energy and thereby change the dynamics of financing for nuclear power generation. SMRs can function with high reliability in electric grids from

70. “Generation IV International Forum,” accessed March 3, 2018, https://www.gen-4.org/gif/jcms/c_9260/public

small to large and (depending on the nuclear technology used) can provide heat for buildings and process heat for industrial manufacturing.

There are several areas of needed investment in R&D for advanced nuclear reactors, including better demonstration of performance and safety characteristics, fuels qualification, the establishment of a fuel-cycle pathway, and advanced materials development and qualification for high temperature applications. Another critical R&D need is a licensing framework. The Nuclear Regulatory Commission (NRC), with support from DOE, is currently working to develop a licensing framework for advanced reactor technologies, recognizing that the current NRC licensing process for LWRs is not directly applicable to safety issues for advanced reactor concepts.

DOE investments also provide guideposts for challenges faced by advanced reactors and SMRs. The DOE Advanced Reactor Technology Program is funding two cost-shared cooperative agreements supporting a high-temperature gas-cooled reactor (HTGR) technology and a molten salt reactor technology. DOE also supports R&D on sodium-cooled fast reactors (SFRs). HTGR reactors offer greater thermal efficiencies for electricity production — in the range of 40-50 percent compared to 32-34 percent for LWRs. They also can serve as a source of high-temperature process heat. SFRs boast the expectation of good safety performance. Both types of advanced reactors also have the potential of reducing water consumption requirements for electricity generation.⁷¹

In addition, DOE is pursuing advanced designs (including high-temperature and fast reactors) and is supporting licensing activities for SMRs. Advanced SMRs under development in the U.S. Address a variety of sizes, technology options, and deployment scenarios. These advanced reactors, envisioned to be in sizes ranging from a couple of megawatts up to hundreds of megawatts, can be used for both power generation and process heat. The SMR Licensing Technical Support Program works with industry partners, research institutions, the national laboratories, and academia to advance the certification, licensing, and siting of domestic advanced SMR designs, and to reduce economic, technical, and regulatory barriers to their deployment. Standardized manufactured designs will simplify the licensing process.

71. U.S. Government Accountability Office, Technology Assessment: Nuclear Reactors: Status and Challenges in Development and Deployment of New Commercial Concepts (GAO-15-562) (Washington, D.C., 2015), 21,<https://www.gao.gov/assets/680/671686.pdf>



Hydrogen as Clean Energy Carrier, Storage Medium, and Enabler of Decarbonized Industrial and Transportation Sectors

Hydrogen is one of the most abundant elements on earth but does not exist in a free state. The use of hydrogen produces no emissions except water. Hydrogen is an energy carrier, however, not a fuel, and requires a primary fuel for production. Table 3-4 details criteria and challenges for hydrogen technologies.

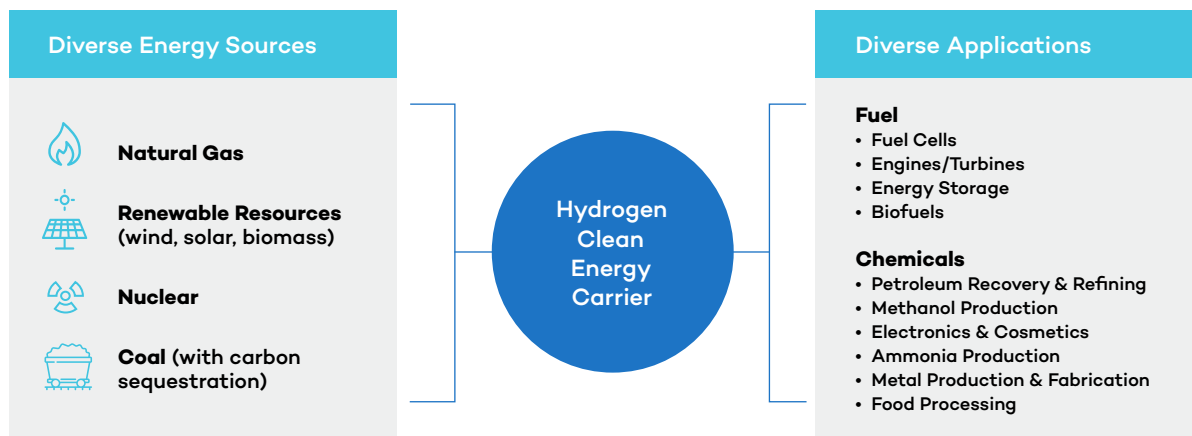
TABLE 3-4

Selection Criteria and Challenges for Hydrogen Technologies

Technology	Technical Merit	Market Viability	Compatibility	Consumer Value
Clean Hydrogen	Wide applicability – grid, transportation, buildings; energy storage for renewables; reductant and heat for manufacturing – chemicals, refining, steel	Current 11 million MT refining and chemicals; would require ~ 50+ million MT for transportation, 15 million MT for steel; fuel cell durability and cost are issues	Would require a robust distribution network; fuel cells + battery drive train = high quality LDV propulsion	With distribution network range and fill times consistent with current fleet
Challenge				
Massive buildout of clean hydrogen production, distribution, storage, and use; cost and safety must improve				

FIG. 3-7

Hydrogen is a Clean Energy Carrier



Hydrogen has broad applicability that includes an energy storage medium, clean energy carrier, and as a reductant and heat source.

Source: Energy Futures Initiative (EFI), 2018; adapted from U.S. Department of Energy

Hydrogen has very broad potential applicability in a low carbon environment, including in transportation, manufacturing, and electric power. Hydrogen utilized in fuel cells can provide power for a wide range of applications, from homes (1 to 5 kilowatts, or kW) to centralized power generation (1 to over 200 MW). Hydrogen has application as a chemical reductant and as a fuel for process heat throughout the manufacturing sector. Hydrogen can also serve as an energy storage medium to mitigate the intermittency of renewables (Figure 3-7).

Hydrogen is the staple of the chemical industry, supporting petroleum recovery and refining, methanol production, ammonia production, metal production and fabrication, food processing, and electronic and cosmetics production. In addition to these current uses, clean hydrogen can enable the decarbonization of these market sectors and is the primary option for fuel switching in a number of them.

Hydrogen also has strong potential in the transportation sector. Due to the high efficiency of hydrogen fuel cells, even when using natural gas-derived hydrogen without CCUS, a FCEV is expected to emit at least 50 percent less CO₂, compared to a current internal combustion engine (ICE) vehicle using gasoline. With hydrogen derived from sustainable, low-carbon sources, GHG reductions greater than 90 percent are achievable. Hydrogen fuel cells emit negligible criteria air pollutants (i.e., carbon monoxide, nitrogen oxides, ozone, particulate matter, sulfur dioxide, and lead), and while there may be emissions at the site of the hydrogen production depending on the production process used, the fuel cells themselves emit only water. High efficiency fuel cells combined with batteries and electrified drive trains can provide high quality propulsion, at scale, in light-duty vehicles (or LDVs – consisting of cars, sport utility vehicles, and light trucks). With a hydrogen distribution network, driving ranges and fill times for existing FCEVs would be comparable to those for the current ICE LDV fleet.

Current FCEV range is approximately 300 miles for 5 kilograms of hydrogen, compared to an average of 15 gallons of gasoline for the same distance in the current LDV fleet. This translates to about 50 million MT of hydrogen for FCEVs to supplant a 20 mile-per-gallon ICE gasoline fleet — which is equivalent to six times the current annual rate of hydrogen production in the United States.⁷²

There are numerous challenges to a hydrogen economy, many associated with infrastructure, the development of which is a long-term challenge. Figure 3-8 depicts a sector-specific roadmap for the production and delivery of hydrogen for transportation over time, starting with today's established methane reforming through various future renewable production options. The U.S. LDV fleet utilized approximately 127 billion gallons of gasoline in 2016.⁷³

Expansion of hydrogen use for the transportation sector would require that U.S. production of hydrogen increase to levels that are 5 to 15 times current production, depending on how far the scope of hydrogen use in transportation extended beyond LDVs. In the industrial sector, hydrogen use for steel production alone would require about 15 million MT per year. Hydrogen production and use at scale would require a more robust distribution network, but there are many potential pathways to hydrogen production and storage. A major industrialized country with a large population — Japan — is making a concerted effort to build a hydrogen-based energy economy.⁷⁴

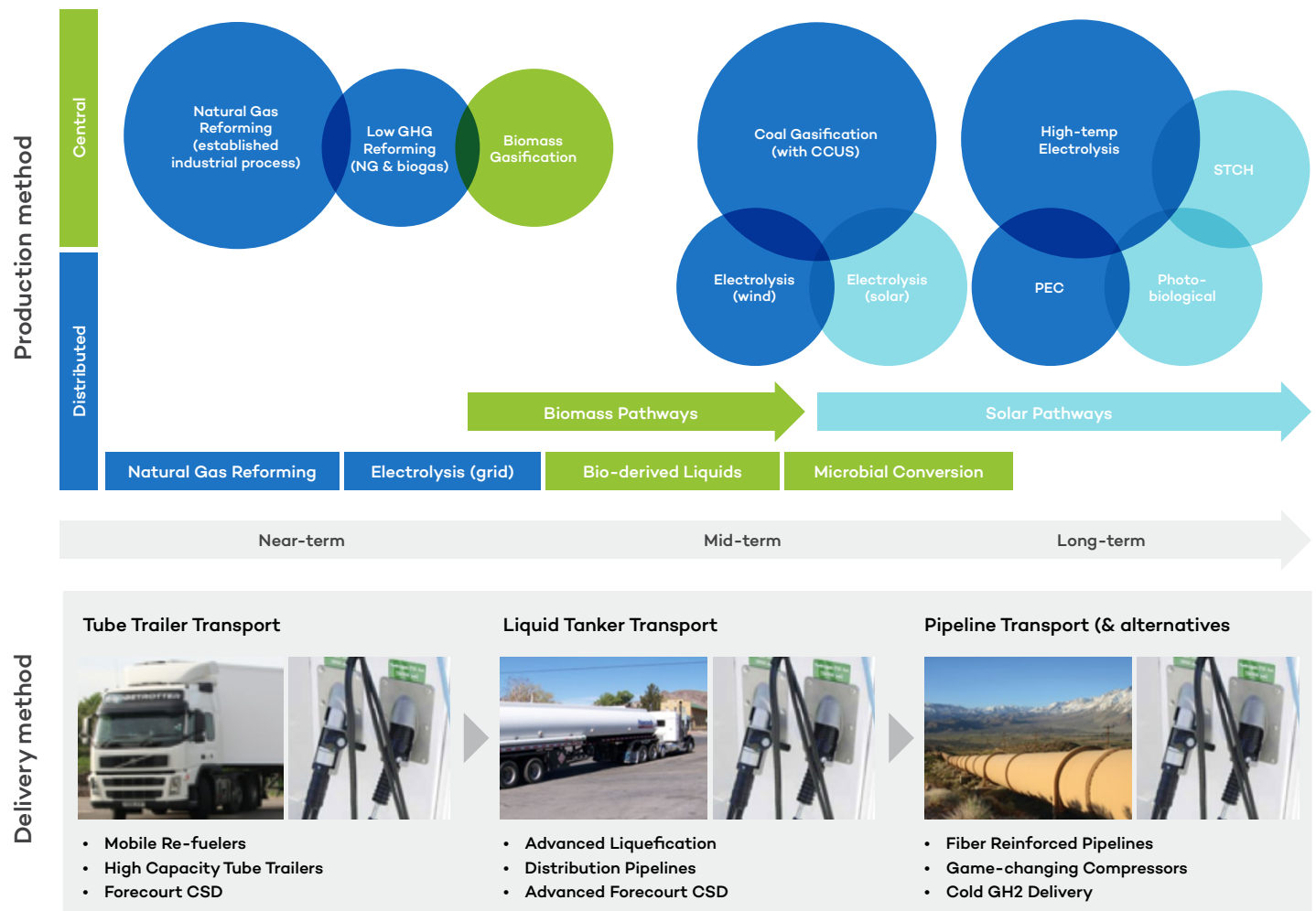
72. 9 million MT of hydrogen production annually in the United States, enough for 40 million FCEVs (DOE QTR, 2015, <https://www.energy.gov/under-secretary-science-and-energy/quadrennial-technology-review>); There were 243 million LDVs in 2015 (https://www.rita.dot.gov/bts/sites/rita.dot.gov/bts/files/publications/national_transportation_statistics/html/table_01_11.html).

73. Light-duty vehicle consumption of motor gasoline (row 41, data for 2016, converted from Btu to gallons of gasoline) from EIA, "Table 38. Light-Duty Vehicle Energy Consumption by Technology and Fuel Type," Annual Energy Outlook 2018, https://www.eia.gov/outlooks/aeo/supplement/excel/suptab_38.xlsx

74. Chisaki Watanabe, "Japan Is at Odds With Elon Musk Over Hydrogen Fuel Cells," Bloomberg Markets, last modified February 9, 2017, <https://www.bloomberg.com/news/articles/2017-02-09/japan-makes-big-push-for-hydrogen-fuel-cells-rubbished-by-musk>

FIG. 3-8

Example Hydrogen Production Pathway



Production and delivery of hydrogen for transportation through several generations.

Source: Energy Futures Initiative (EFI), 2018; adapted from U.S. Department of Energy



Advanced Manufacturing Technologies

Manufacturing utilizes 25 percent of the nation's energy, accounts for 11.6 percent of gross domestic product (GDP), employs 12.5 million people, and is the biggest end-use emitter of CO₂ (1.411 million MT direct emissions, 550 million MT indirect emissions).⁷⁵ Table 3-5 details criteria and challenges for advanced manufacturing technologies.

TABLE 3-5

Selection Criteria and Challenges for Advanced Manufacturing Technology

Technology	Technical Merit	Market Viability	Compatibility	Consumer Value
Advanced Manufacturing Technology	Complex suite to clean up top end use emitter; efficiency, innovation, fuel switching and CCUS	Improving efficiency and emissions is critical to industry; additive manufacturing and AI for integration and competitiveness	Very diverse suites of technology and applications complicates clean up; additive manufacturing has broad application	Efficiency + innovation improves competitiveness
Challenge				
Clean hydrogen will be a key, CCUS must be viable; investment to install e.g., additive manufacturing and AI				

Direct uses of energy in manufacturing includes producing steam and electricity for power generation and industrial processes (process heating furnaces, kilns, and dryers),⁷⁶ while indirect uses include electricity for processes that transform raw materials into useful products such as cement and ammonia (Figure 3-9).

Reducing both energy use and CO₂ emissions in the industrial sector is critical to economic vitality and to environmental goals. A significant fraction of emissions comes from a small number of energy-intensive manufacturers (iron ore, bauxite, petroleum, limestone, silicon dioxide, steel, aluminum, chemicals, cement, glass, paper) — 0.5 percent of plants account for 25 percent of emissions.

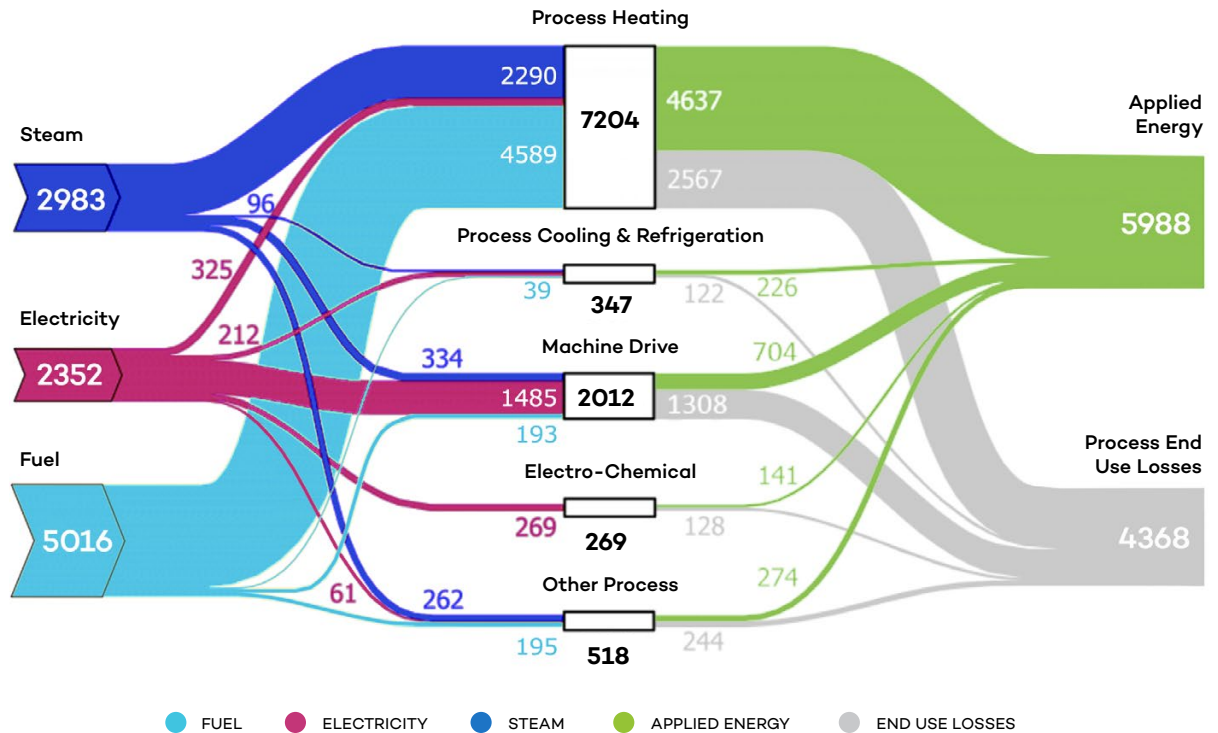
The manufacturing sector utilizes numerous and very diverse sets of component technologies. This diversity complicates the process of decarbonizing the manufacturing sector. Only a fraction of it is amenable to efficiency innovations such as smart manufacturing, or fuel switching and electrification. There are thermodynamic limits to the efficiencies that can be achieved, and alternative

75. DOE, "Energy Innovation Portfolio Plan, FY2018-FY2020," (January 2017); DOE, "Carbon Capture Utilization and Storage: Climate Change, Economic Competitiveness, and Energy Security" (2016). https://energy.gov/sites/prod/files/2016/09/f33/DOE%20-%20Carbon%20Capture%20Utilization%20and%20Storage_2016-09-07.pdf

76. DOE, Quadrennial Technology Review 2015 (Washington, D.C., 2015), 187, <https://www.energy.gov/quadrennial-technology-review-2015>

FIG. 3-9

Sankey Diagrams of Process Energy Flow in the U.S. Manufacturing Sector (Tbtu, 2010)



Process energy flows undertake several pathways in U.S. manufacturing.

Source: U.S. Department of Energy, 2010 Manufacturing Energy and Carbon Footprint

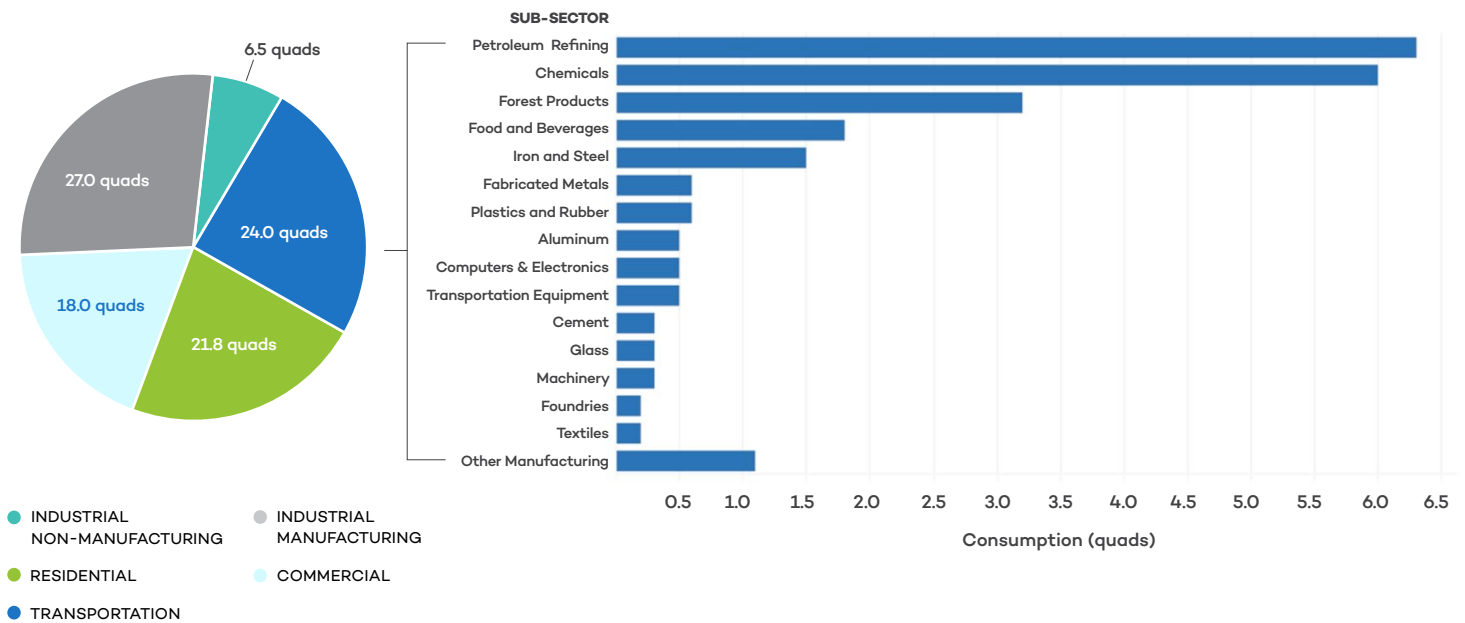
materials are not always available. Those manufacturing processes that are not amenable to efficiency improvements or electrification will require the development of CCUS and a buildout of the CCUS infrastructure.

As noted, switching to clean hydrogen for chemicals, refining, and iron and steel could eliminate major emissions from the sector. Figure 3-11 depicts opportunities for energy savings and associated emissions reductions from innovation in various industry subsectors.

Electricity and process heat generated from CHP can use 25 to 35 percent less primary energy than the combination of the energy required to produce electricity transmitted over the grid and the energy involved in the separate production of process heat. Innovation is needed to develop advanced process heating unit operations that provide improved properties, quality, or product value, at cost-parity to conventional techniques.

FIG. 3-10

Share of Energy Consumption by Industrial Manufacturing Sector and Sub-sector, 2015



Industrial manufacturing consumes a considerable amount of energy, much of which is driven by petroleum refining chemicals, and forest products sub-sectors.

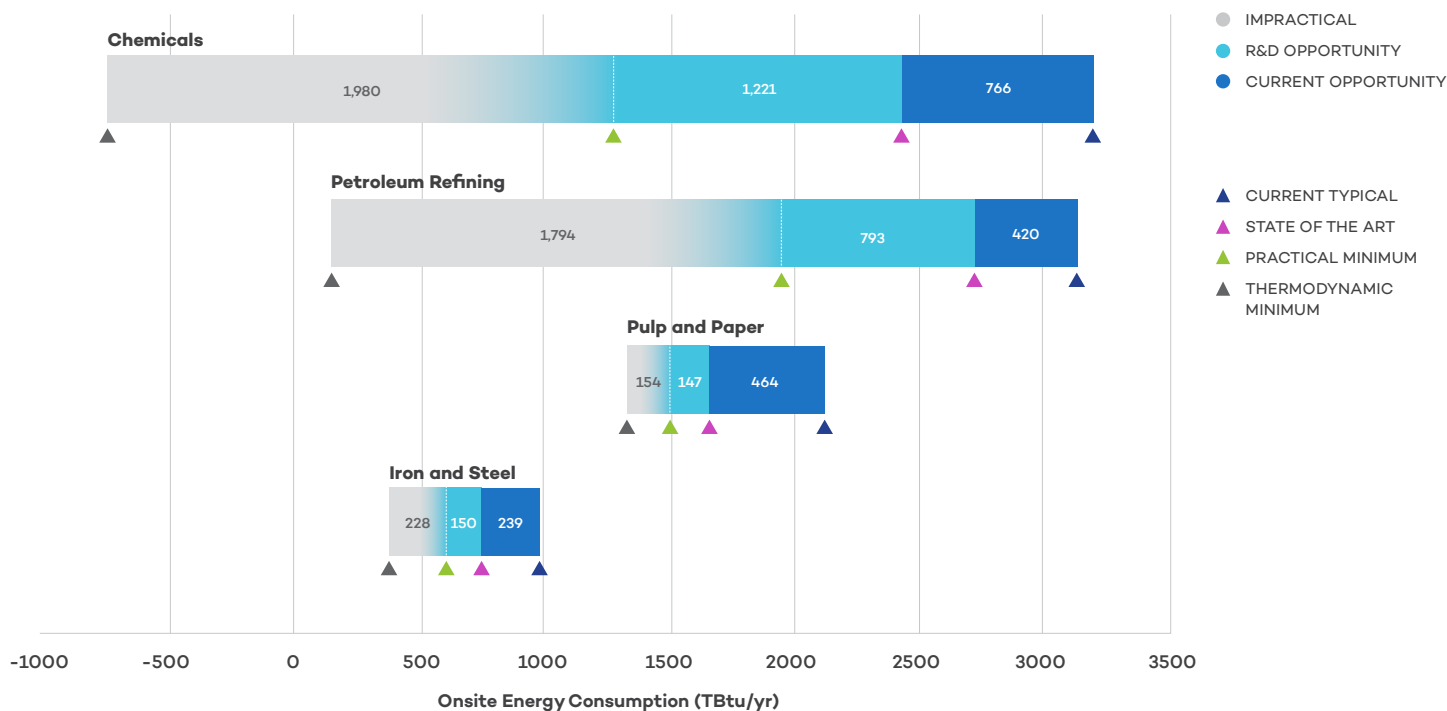
Source: Energy Futures Initiative (EFI), 2017; compiled using data from U.S. Department of Energy, 2015

Additional innovations that would reduce energy intensity and emissions from manufacturing include:

- developing new processes for carbon-intensive manufacturing, such as the manufacture of steel (with substitutes such as hydrogen for coke) and ammonia (with utilization of “clean” hydrogen)
- using advanced manufacturing techniques such as additive or roll-to-roll manufacturing and modified designs to exploit opportunities with advanced manufacturing techniques (e.g., fabricating better, more intricate structures rather than massive metal heat sinks)
- enabling alternatives for process heat and developing low-thermal-budget manufacturing technologies that reduce energy intensity by at least 50 percent compared to 2015 typical technology

FIG. 3-11

Bandwidth Diagrams Illustrating Energy Savings Opportunities in Four Energy-Intensive U.S. Manufacturing Industries



Opportunities for energy savings exist throughout the manufacturing sector including in the chemicals, petroleum refining, pulp and paper, and iron and steel sectors.

Source: U.S. Department of Energy

- developing and using advanced materials
- reducing the use of critical materials such as rare earth elements or developing substitutes for them
- improving the purification of used materials to enable re-use with no loss in performance
- recovering and re-using waste heat from processes
- improving controls and sensors, including high performance metrology for real-time in situ process control
- developing industrial combined heat and power (CHP), which offers opportunities for near-term solutions to cost-effectively reduce industrial energy use



New Energy Technologies for Buildings

The buildings sector accounts for about 76 percent of electricity use and 40 percent of U.S. primary energy use and associated GHG emissions. Reducing energy consumption for buildings is essential for meeting national energy and environmental challenges and reducing energy costs for residences, commercial enterprises, building owners and tenants. Table 3-6 details criteria and challenges for buildings energy technologies.

TABLE 3-6

Selection Criteria and Challenges for Buildings Energy Technology

Technology	Technical Merit	Market Viability	Compatibility	Consumer Value
Buildings	Improvements in technology and operations; key element in grid demand side management; core of smart cities	Intelligent design and supporting technology can revolutionize building energy use and emissions; rapid payback	Wide range of technologies, many with rapid turnover; very substantial upside	Efficiency, flexibility, and resilience have high consumer value
Challenge				
Very large legacy fleet; energy enterprise drivers for modernization and efficiency				

Opportunities for improved building efficiency are enormous. By 2030, building energy use could be cut more than 20 percent using technologies known to be cost effective today; emerging technology advances could cut energy use for buildings by more than 35 percent. Much higher savings are technically possible.

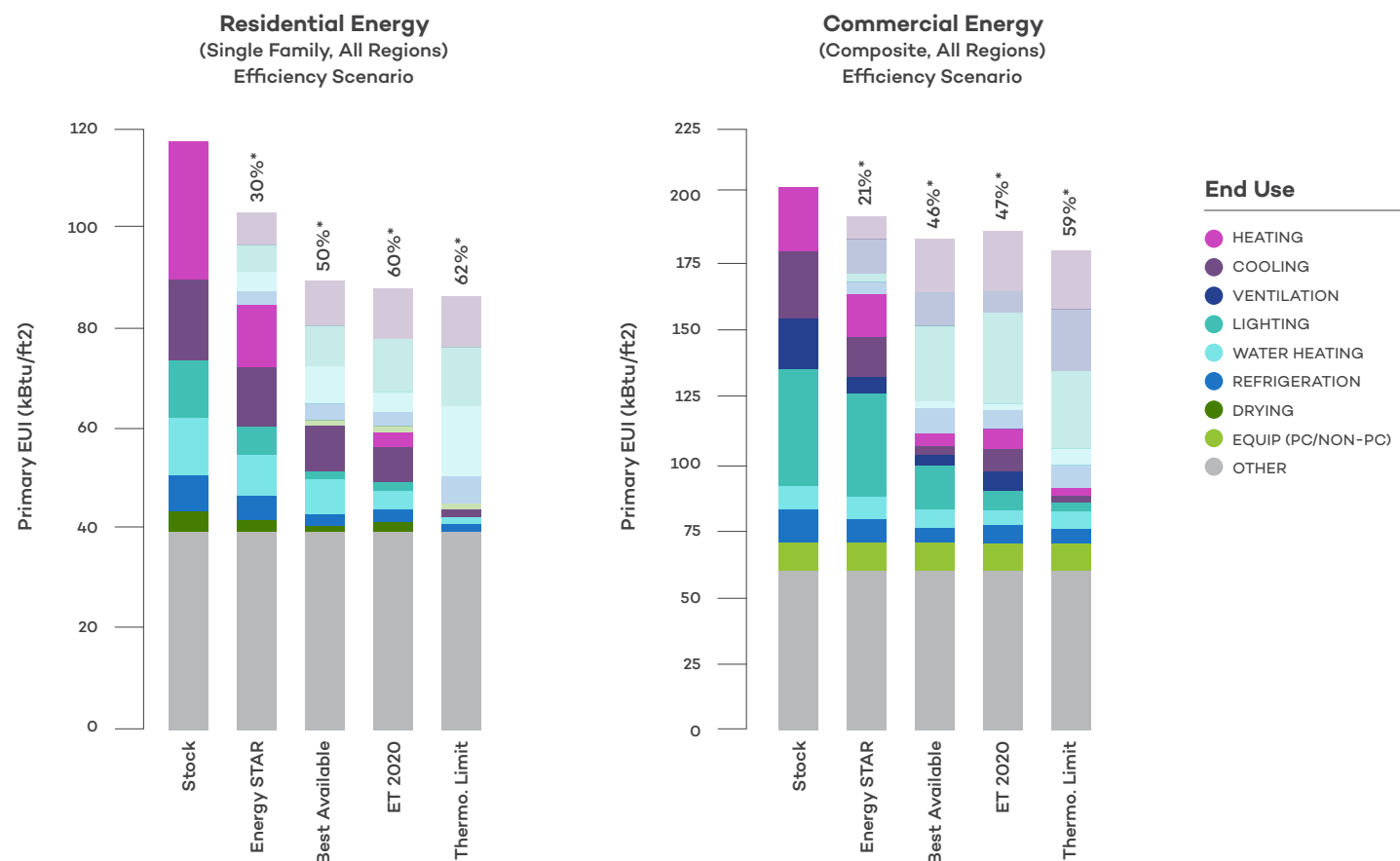
Building efficiency involves the performance of a complex system designed to provide occupants with a comfortable, safe, and attractive living and working environment. It requires integrating architecture and engineering designs, construction practices, and intelligent operation of the structures into the larger grid and energy ecosystem. Through advanced sensors and controls and integrated grid operational models, buildings can be key demand-side management elements for optimizing grid efficiency — and the core of a Smart Cities architecture.

The major components of energy consumption in buildings, and the fraction of total building energy they represent are:

- heating, ventilation, and air conditioning — 35 percent;
- lighting — 11 percent;
- major appliances (i.e., water heaters, refrigerators, freezers, and dryers) — 18 percent.

FIG. 3-12

Energy Savings Potential of Energy Star Technologies



Use of Energy Star Technologies could reduce residential and commercial energy consumption by 30 percent and 21 percent, respectively.

Source: Energy Futures Initiative (EFI), 2018; adapted from DOE Quadrennial Technology Review

The remaining 36 percent of building energy goes to a variety of other uses, including electronics (Figure 3-12).⁷⁷ In each case, there are opportunities both for improving the performance of system components (e.g., improving the efficiency of lighting devices) and for improving the way they are controlled as a part of integrated building systems (e.g., sensors that adjust light levels to occupancy and daylight).

Due to the long lifetime of the building stock, there needs to be a focus on retrofitting existing buildings. Efficiency improvements from retrofits can markedly change the environmental profile of buildings, especially when combined with the subsequent use of decarbonized electricity. Key research opportunities include the following:

- High-efficiency heat pumps that reduce or eliminate the use of refrigerants with Global Warming Potential, if they were to leak to the atmosphere
- Thin insulating materials
- Windows and building surfaces with tunable optical properties

77. DOE, Quadrennial Technology Review 2015, 144.

- High-efficiency lighting devices, including improved green light-emitting diodes, phosphors, and quantum dots
- Improved software for optimizing building design and operation
- Low-cost, easy to install, energy harvesting sensors and controls
- Interoperable building communication systems and optimized control strategies
- Decision science related to issues affecting purchasing and operating choices



Systems: Electricity and Smart Cities

Grid modernization and the emergence of smart cities are driving large-scale, systems-level changes to the infrastructure, operability, and technical capabilities of the power grid and urban areas. These changes are likely to revolutionize the way that people and digital technologies interact with such systems and hold the potential to unlock significant opportunities for clean energy innovation. The following section describes some of the disruptive technologies and processes that are helping shape power grids and cities of the future.

TABLE 3-7

Selection Criteria and Challenges for Energy Systems

Technology	Technical Merit	Market Viability	Compatibility	Consumer Value
Systems: Grid Modernization and Smart Cities	Revolutionizes the interactions and interoperability of myriad grid technologies and the optimized functionalities of urban centers	Provides a foundation for innovations in energy systems, and urban commercial, transport, industrial, and residential systems and processes	A fundamental requirement for beneficial access to the burgeoning set of energy and urban human systems; enabled by big data and AI	Links customer needs to the emerging innovations in electrification and urban systems
Challenge				
Multidimensional sensors and model based operational systems; inherent cyber and physical vulnerabilities of large complex systems; standards to assure stability and resilience with exponential growth				

The electric grid is transitioning from a physical structure with one-way flows of electricity, monopoly utilities, and limited consumer options to an architecture that encompasses a range of actors, needs, and actions. This transition is due primarily to information, communications, and grid-control technologies. This modernization is making the grid “smarter” and more resilient as two-way

communication between electric utilities and customers enhance situational awareness of system operations.

These “smart grid” technologies include advanced sensors known as Phasor Measurement Units that allow operators to assess grid stability, as well as advanced digital meters that give consumers better information and automatically report outages. These technologies also include relays that sense and recover from faults in substations automatically; automated feeder switches that re-route power around problems; and batteries that store excess energy and make it available later to the grid to meet customer demand.⁷⁸

“Smart cities” are complex ecosystems of citizens, city authorities, local companies, industries, and community groups collaborating through advanced technologies.⁷⁹ Sensors and data management capabilities enable control of the flow of traffic, water, energy and people, substantially increasing the carrying capacity and efficiency of those systems. In the transportation sector, cars, trucks, planes, ships, trains, and their supporting infrastructures are becoming smarter and more connected due to digital platforms that offer vehicle-to-vehicle and vehicle-to-infrastructure connections. Intelligent traffic networks enabled by these technologies will monitor real time traffic flow and will use artificial intelligence to reduce congestion and emissions and improve safety and commute times. These integrated systems will support a mixed-fuel and mixed-mode fleet and provide a facile interface to walking and cycling environments.

Grid modernization is resulting in reduced frequency and duration of power outages, as well as improved grid security and reduced peak loads. Other results include increased integration of renewables, lower operating costs, and potentially new services. Distributed Energy Resources (DER) help reduce carbon emissions by enabling low- and zero-carbon emitting technologies, and by reducing demand. DER represent a wide range of generating technologies and programs that reside on a utility’s distribution system or on the premises of an end-use consumer.⁸⁰ As smaller power sources, they can be aggregated to provide power necessary to meet regular system demand. As the grid continues to modernize, DER such as storage and advanced renewable technologies can help facilitate the transition to a smarter and more customer-responsive grid. Deploying DER in a widespread, efficient, and cost-effective manner requires complex integration with the existing electricity grid.

As the world’s population becomes more urbanized, there is a pressing need for — and growing opportunity to — increase the efficiency, efficacy, and resilience of these growing global centers. This includes the concerted use of emerging platform technologies, a healthy mix of central and distributed energy resources, integrated mobility technologies, smart buildings and infrastructure, and integrated commercial sectors to efficiently move goods and provide services.

Key to smart city developments is multilevel communications networks that couple together the sub-elements of public infrastructures in an open data structure that facilitates all the activities of a city — commercial, industrial, residential, retail, health, education, entertainment, food, and many more. These systems include low-power and low-cost wide area networks — open data systems that offer the speed, computation power, and storage capabilities that enable more functionality to a wider number of users. For example, open internet protocols leveraging Internet of Things devices and big data analytics can support more information processing of local activities (e.g., traffic data, customer transactions), which would feed back into new business models and research areas, as well as new public sector initiatives and services that improve the lives

78. “Grid Modernization and the Smart Grid,” Office of Electricity Delivery and Energy Reliability, Department of Energy, accessed March 3, 2018, <https://energy.gov/oe/activities/technology-development/grid-modernization-and-smart-grid>

79. Lea, Smart Cities, 3.

80. DOE, Quadrennial Energy Review: Second Installment, 3-24.

of citizens.⁸¹ Embedded microgrid energy system structure, including storage, will hybridize the buildings system and provide a more efficient and resilient response to challenges and interruptions, including natural disasters and intrusions.

Many challenges exist to system-level changes, including flat electricity demand, business models that are not fully developed, customer buy-in, “prosumers,” as well as the deployment of enabling infrastructures, appropriate valuation of new services, outdated regulatory structures, and the presence in the market of large-scale incumbents.

Added to these challenges is the reality that advances in innovative internet technology have resulted in an exponential increase in cybersecurity vulnerabilities across all sectors.

According to one report, “an advanced threat actor with the appropriate attack vector will get in regardless of what defenses are in place.”⁸²

Cybersecurity for the energy sector has emerged as one of the most important issues of our time. Cyber adversaries are becoming more knowledgeable about how to exploit various aspects of electric grid infrastructure and are developing new capabilities that significantly increase the risk of cyber-induced power outages. Russian attackers targeted multiple electric utilities in Ukraine in 2015 and 2016, which resulted in service disruptions to customers during both events. Reports suggest that these intrusions were predominantly designed to test their attack tools against real-life power systems.

In 2017, a cyber attack framework called “Crashoverride” was discovered as the first-ever malware that targets electric grids, and the fourth capability tailored to attack industrial control systems, alongside Stuxnet, Blackenergy 2, and Havex.⁸³ In 2016, the “Mirai” botnet attack infiltrated hundreds of thousands of internet-connected devices worldwide, including home routers and security cameras, to disrupt a broad swath of global Internet infrastructure.⁸⁴ Chinese-linked actors, between 2009 and 2016, have successfully attacked multiple governments, organizations, and companies, with a recent focus on managed IT service providers. These attacks have harvested intellectual property, sensitive business information, and information on routers, servers, and computer passwords of major firms across all critical infrastructure sectors — including energy.⁸⁵

Smart grids (and components such as sensors, controllers, and meters), big data analytics, increased automation, and two-way flows of information will only increase the energy sector’s exposure to cyberattack. The development of smart cities, grids, and systems will stall unless significant advances are made in cybersecurity.

Successfully overcoming the cybersecurity issues associated with these technology-centric systems-level transformations is fundamental to ensuring the future of the energy system. Every effort to prevent, track, and respond to attacks is key to maintaining cybersecurity in energy. Additionally, innovations in technology, process, and policy are critical to all current and future efforts. A key focus for addressing these challenges is blockchain technology — essentially a secure and immutable information management system — which offers significant opportunities for the development of smarter systems. It also opens new opportunities to create decentralized energy systems and markets by diminishing the risks associated with distributed generation, demand-side management, metering, billing, and clearing.

81. Lea, *Smart Cities*, 9.

82. Idaho National Laboratory, Mission Support Center, *Cyber Threat and Vulnerability Analysis of the U.S. Electric Sector* (Idaho Falls, 2016), 35, <https://energy.gov/sites/prod/files/2017/01/f34/Cyber%20Threat%20and%20Vulnerability%20Analysis%20of%20the%20U.S.%20Electric%20Sector.pdf>

83. Dragos, *CRASHOVERRIDE: Analysis of the Threat to Electric Grid Operations* (Hanover, Maryland, 2017), 4, <https://dragos.com/blog/crashoverride/CrashOverride-01.pdf>

84. Zane Ma et al., “Understanding the Mirai Botnet,” *Proceedings of the 26th USENIX Security Symposium* (Berkeley: USENIX Association, 2017), <https://www.usenix.org/system/files/conference/usenixsecurity17/sec17-antonakakis.pdf>

85. PwC UK and BAE Systems, *Operation Cloud Hopper* (London: PwC, 2017), 4, 14, <https://www.pwc.co.uk/cyber-security/pdf/cloud-hopper-report-final-v4.pdf>



Deep Decarbonization: Large-scale Carbon Management

Large-scale carbon management is a key component of deep decarbonization and will be vital for the achievement of global climate goals. There are very few emissions pathways that offer hope to stay below the 2°C limit without some form of large-scale carbon management. Most IPCC models require carbon capture and sequestration (CCS) to stay below the 2°C limit⁸⁶ and 87 percent require carbon removal.⁸⁷ The following section describes some large-scale carbon management options — large scale CCUS, sunlight to fuels, and biological sequestration — and concomitant challenges associated with these technologies and processes.

TABLE 3-8

Selection Criteria & Challenges for Large-Scale Carbon Management Technology

Technology	Technical Merit	Market Viability	Compatibility	Consumer Value
Large-Scale Carbon Management	A required option for many decarbonization challenges; very large-scale test	Will keep many energy production and end use options open	A wide variety of unit operations and contexts	Availability at cost and scale provides many customer options
Challenge				
Viability and safety at energy system scale must be established				

86. Glen P. Peters, et al., "Key Indicators to Track Current Progress and Future Ambition of the Paris Agreement," *Nature Climate Change*, 7 (2017): 118-122, <https://jacksonlab.stanford.edu/sites/default/files/nclimate3202.pdf>

87. Michael Obersteiner, et al., "How to Spend a Dwindling Greenhouse Gas Budget," *Nature Climate Change*, 8 (January 2, 2018): 7-10, <https://www.nature.com/articles/s41558-017-0045-1>

Carbon Capture, Utilization, and Storage (CCUS)

CCUS is a process that captures CO₂ emissions from sources — such as coal-fired power plants or industrial facilities — and either reuses or stores CO₂ in ways to keep it from entering the atmosphere. The scale involved in carbon capture is enormous; a single 500MW coal plant emits well over 100 million tons of CO₂ in a 50-year lifetime.

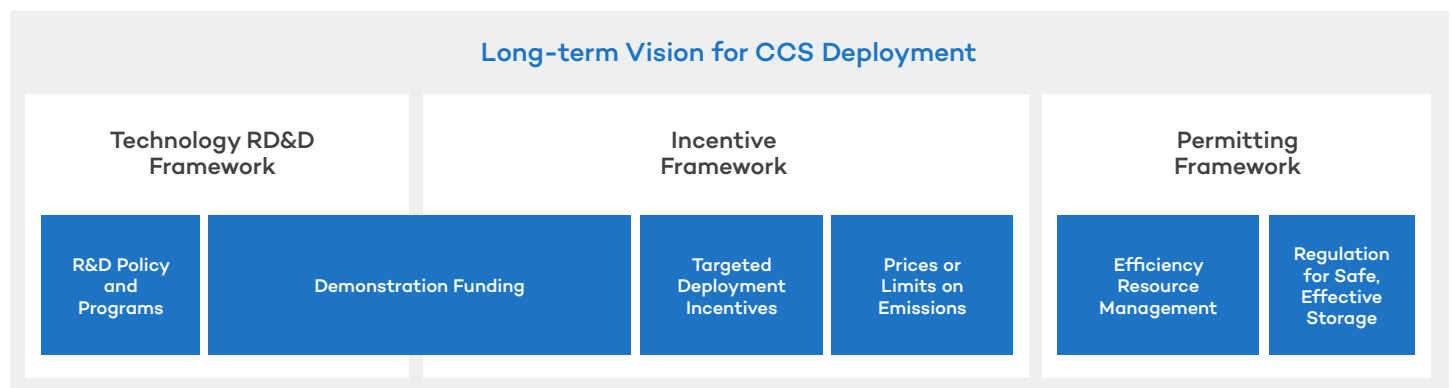
Storage can use geologic formations that have stored oil, natural gas, brine, and CO₂ over millions of years. Up to this point the storage method most frequently employed has been injection into partially depleted oil fields in order to increase oil recovery. This method, known as enhanced oil recovery (EOR), not only succeeds in sequestering CO₂, but also creates value through the additional oil production it supports. The economics of this method are, therefore, subject to fluctuations in the price of oil.

The use of fossil fuels in a future world with significant carbon constraints will require a viable CCUS option to deploy at scale. For industry (the end-use sector with the greatest CO₂ emissions), CCUS will be required for the intermediate to long term. The various options for producing hydrogen from fossil resources or biological carbon resources also generate CO₂ streams that must be accommodated through CCUS. A long-term vision for CCUS deployment is critical (Figure 3-13).

CCUS has been challenging to deploy at commercial scale. The U.S. currently has nine large-scale integrated CCUS projects (defined as having the capacity to capture upwards of 500,000 metric tons of CO₂ per year and combining both capture and storage capabilities). Three of these projects began operation in the 1970s and '80s; the remainder began operation between 2010 and the present. Apart from a 2017 retrofit of Archer Daniels Midland's Illinois ethanol refinery, which stores captured CO₂ in an underground saline aquifer, all of the currently operating projects rely on the economics of EOR. Total capture and storage capacity from these projects amounts to 22 million metric tons of CO₂, a minuscule percentage of the approximately 5 billion metric tons of CO₂ emitted annually in the United States.

FIG. 3-13

Drivers and Supportive Policies are Essential



Carbon capture and sequestration can play a critical role in the pursuit of a low-carbon future, but will require proper policy support.

Source: Energy Futures Initiative (EFI), 2018; adapted from Levina, E., International Energy Agency

TABLE 3-9

Large-scale U.S. Integrated CCUS Projects in Operation Today

Project	Location	Online Date	CO ₂ Source	Disposition	000 Mt/yr
Terrell Natural Gas Processing Plant	Texas	1972	Gas processing	EOR	500
Enid Fertilizer	Oklahoma	1982	Fertilizer plant	EOR	700
Shute Creek/ LeBarge	Wyoming	1986	Gas processing	EOR	7,000
Century Plant	Texas	2010	Gas processing	EOR	8,400
Air Products Steam Methane Reformer	Texas	2013	Refinery	EOR	1,000
Coffeyville Gasification Plant	Kansas	2013	Fertilizer plant	EOR	1,000
Lost Cabin Gas Plant	Wyoming	2013	Gas processing	EOR	900
Parish Petra Nova	Texas	2016	Power plant	EOR	1,600
Illinois Industrial	Illinois	2017	Ethanol refinery	Saline aquifer	1,000
Total CCUS capacity					22,100

Among the large power plant CCUS projects undertaken over the past decade Petra Nova's success in achieving operational status is the exception; most have found it difficult even with federal support to attract long-term financing under the weight of cost, legal challenges, and regulation. The problem of cost may be ameliorated by recent increases in tax incentives. "45Q" federal tax credits for carbon capture have been increased substantially, from \$20 per Mt for secure geological storage and \$10 per Mt for EOR, to \$50 and \$35 respectively.

Another challenge to CCUS deployment in the U.S. is the lack of midstream infrastructure capacity. In order to connect power plants and other CO₂ sources east of the Mississippi River to potential storage and EOR sites in the Midwest, it's estimated that 10,000 to 30,000 miles of CO₂ pipeline would need to be added to the 5,000 miles currently available. Further difficulties are presented by federal standards for wells, which are far more stringent for geological sequestration than for EOR.⁸⁸

Sunlight to Fuels

The atmospheric carbon capture innovations discussed below, including growing biomass and using it to produce electricity in plants coupled with CCUS, or direct CO₂ capture from the atmosphere through physical or chemical means – will require long-term and very large storage facilities. New technologies and a stronger science base will be needed to take advantage of the much larger underground capacity for storage potentially available beyond the use of saline aquifers. To put this in perspective, 1 ppm of CO₂ in the atmosphere corresponds to 7.8 billion MT of CO₂; the Great Pyramid of Giza weighs 5.2 million MT; so 1 ppm of CO₂ in the atmosphere would be an amount of CO₂ with a weight that is equivalent to 1,500 Great Pyramids.^{89, 90}

88. Pipeline estimates from J.J. Dooley, R.T. Dahowski, and C.L. Davidson, Comparing Existing Pipeline Networks with the Potential Scale of Future U.S. CO₂ Pipeline Networks, Pacific Northwest National Laboratory, February 2008. CCUS projects from IHS Markit analysis, IHS Markit Climate and Carbon service.

89. Calculated from data in "Table 3. Common Conversion Factors," Carbon Dioxide Information Analysis Center - Conversion Tables, accessed March 3, 2018, <http://cdiac.ess-dive.lbl.gov/pns/convert.html#3>

90. Encyclopedia Britannica Online, s.v. "Pyramids of Giza" (weight converted to metric tons), accessed March 3, 2018, <https://www.britannica.com/topic/Pyramids-of-Giza>

“...‘clean hydrogen’ could be used as a chemical reductant to convert deconstructed biomass into a range of fuels utilizing current petrochemical refineries and infrastructure — creating a carbon-neutral fuel cycle.”

The ability to generate commercial high-energy fuels directly from sunlight holds great promise as an innovation that could help transform the energy sector. Solar fuels could supplant fossil fuels by providing a storage mechanism for solar energy, as well as a liquid fuel to feed into the existing infrastructure for industry, power, and vehicles. Through the process of photosynthesis, plants and some microbes convert sunlight into energy-rich chemical fuels, using the abundant feedstocks of water and CO₂. The process of using photosynthesis to make fuels via energy crops, at the current stage of development, is inefficient from an energy perspective and has high land-use and water requirements.

Recognizing the potential of sunlight to fuels, DOE established the Joint Center for Artificial Photosynthesis in 2010 with the goal of demonstrating a scalable, manufacturable solar-fuels generator using Earth-abundant elements that, with no wires, would robustly produce fuel from the sun 10 times more efficiently than the current baseline activities.

Currently it is possible to photo-electrochemically split water to produce hydrogen and oxygen, but it is not yet commercially viable. In a two-step process, this “clean hydrogen” could be used as a chemical reductant to convert deconstructed biomass into a range of fuels utilizing current petrochemical refineries and infrastructure — creating a carbon-neutral fuel cycle.

The goal is to combine these functions into a single cell, avoiding the complexities of the chemical manufacturing chain, and ultimately achieving much higher efficiencies. But the conversion of CO₂ to methane with the evolution of oxygen is an 8-electron, 8-proton multistep process that must be mediated by catalytic systems not currently in existence. In addition, the electrochemical forces that dissociate water and CO₂ also cause the photoactive surfaces to degrade rapidly. Creating the needed innovations in technology will require a range of activities including design advances, new materials, catalyst and materials integration, modeling, device development, test-bed prototyping and testing.

With functioning prototypes in hand, pursuit of the goal of achieving 10 times the efficiency of natural photosynthesis can be attempted. The simplicity and power of these systems would make them ideal for global deployment in both developed and emerging economies, providing a clean and sustainable energy option.

Biological Sequestration

Leveraging existing processes of biological carbon storage may offer significant benefits in terms of large-scale deep decarbonization. Biological sequestration absorbs CO₂ through the growth of vegetation and the continued storage of carbon in organic materials.⁹¹ These types of projects are key, as the largest flux of carbon between the atmosphere and land occurs via photosynthesis in plants.⁹²

In December 2016, the DOE Secretary of Energy Advisory Board (SEAB) approved a report on CO₂ utilization, which described, among other things, a framework for how enhancing photosynthesis, in principle, has potential for large-scale carbon management (at the level of gigatons of CO₂ per year).⁹³ The report recommended harnessing the natural biological carbon cycle by exploring ways to:

- Increase the photosynthetic efficiency of crops for food, bioenergy, feed, and fiber, as well as trees used for bioenergy, reforestation and afforestation, with no marginal increase in resource inputs, such as fresh water, fertilizers, and pesticides, and preferably with reductions in each of these.

91. Gordon Smith, et al., “Biological Sequestration: Forestry and Agriculture,” Carbon Offset Research and Education, Stockholm Environment Institute and Greenhouse Gas Management Institute, accessed March 3, 2018, <http://www.co2offsetresearch.org/consumer/trees.html>

92. Tim White, “Carbon Cycle and Atmospheric CO₂,” Earth 350: The Critical Zone, Pennsylvania State University, accessed March 3, 2018, https://www.e-education.psu.edu/earth530/content/l3_p4.html

93. DOE, Secretary of Energy Advisory Board, Report of the Task Force on CO₂ Utilization (Washington, D.C., 2016), 37–45, <https://www.energy.gov/sites/prod/files/2016/12/f34/SEAB-CO2-TaskForce-FINAL-with%20transmittal%20ltr.pdf>

- Evaluate the benefits and limitations of marine macroalgae as a bioenergy feedstock for both land-based energy and liquid transportation fuels.
- Identify approaches to reduce the decomposition of soil organic carbon and the impact of emissions of nitrous oxide (a GHG) by considering the biology and chemistry of soil carbon decay. Examples include creating roots that go deeper in the rhizosphere with higher lignin content.
- Optimize crops and land-management technology that stabilize organic carbon over longer time frames, including accelerating the transition to no-till agriculture, sustaining no-till land after the transition is made, and extending the period in which forests are net CO₂ sinks.
- Intensify research in understanding the ecological impact of harnessing the natural biological carbon cycle, including using systems modeling to understand the net global carbon impact.⁹⁴

The scientific community needs a better understanding of the fundamental mechanisms controlling carbon sources and sinks. In the past two decades, much progress has been made in understanding historical trends in atmospheric CO₂. Additionally, biogeochemical modeling of carbon in oceans and terrestrial systems continues to advance. However, current carbon cycle research still cannot quantitatively address several key questions, including the following:

- What are the fundamental processes controlling the behaviors of carbon sinks and sources in ocean and terrestrial systems?
- How will human activities and changing climate conditions affect these processes?
- Will current carbon sinks persist or become carbon sources in a warmer, higher-CO₂ world?
- How long will biologically sequestered carbon remain stored?

Next Steps in Portfolio Development

Reshaping the energy innovation portfolio will require significant resource mobilization and coordination throughout the innovation process. Of paramount importance to developing an effective portfolio is taking stock of the full suite of resources available and understanding unique strengths and capabilities of various technological options. The following section details some of the critical components required to create an ideal enabling environment for clean energy innovation to flourish. It also describes the importance of roadmaps to maximize technological potential.

Creating the Environment for Innovation

High-level consensus and collaboration across Federal and state governments, universities, laboratories, and the private sector—and in many cases the international community—is foundational to overcoming today's challenges to realizing the energy technologies of the future. This is because, in most cases, the complexity of the scientific problems to be overcome is too challenging for a single investigator or research team.⁹⁵

A prime example of successful high-level collaboration is the DOE's Energy Frontier Research Centers (EFRCs), which were established to overcome today's

94. DOE, Task Force on CO₂ Utilization, 43-44, <https://www.energy.gov/sites/prod/files/2016/12/f34/SEAB-CO2-TaskForce-FINAL-with%20transmittal%20ltr.pdf>

95. "Energy Frontier Research Centers (EFRCs)," Office of Science, Department of Energy, last modified October 17, 2016, <https://science.energy.gov/bes/efrc>

TEXT BOX 3-2

Energy Innovation Defined

1. How do we control material properties at the level of electrons?
2. How do we design and perfect atom- and energy-efficient synthesis of revolutionary new forms of matter with tailored properties?
3. How do remarkable properties of matter emerge from complex correlations of the atomic or electronic constituents and how can we control these properties?
4. How can we master energy and information on the nanoscale to create new technologies with capabilities rivaling those of living things?
5. How do we characterize and control matter away — especially very far away — from equilibrium?

toughest scientific challenges for energy technology breakthroughs by combining the talents of the country's scientific community. Their genesis is in the 2007 Basic Energy Sciences Advisory Committee report, *Directing Matter and Energy: Five Challenges for Science and the Imagination*, the culmination of a series of Basic Research Needs workshops sponsored by DOE beginning in 2001.

The report outlined five grand challenges for basic energy science and articulated the need for mechanisms to fund a type of research that “is inherently multidisciplinary and will require sustained efforts over long periods of time before society will reap the benefits.”⁹⁶ The research at each EFRC must address one or more of these five interrelated grand challenges that define the roadblocks to progress and the opportunities for transformational discovery that were identified by the research community (Text Box 3-2).⁹⁷

These integrated, multi-investigator centers are addressing key scientific questions that could lead to significant advances in energy technologies, including carbon capture and sequestration, predictive modeling of materials, catalysis, and energy storage. Engaging a wide community of scientists in a series of workshops, the program moved the Office of Basic Energy Science research portfolio more into Pasteur's Quadrant⁹⁸ of use-inspired science — an approach fitting to DOE's energy mission.

Other DOE-initiated, multidisciplinary energy science research centers are the Energy Innovation Hubs and the Bioenergy Research Centers (BRCs). The Hubs bridge the gap between basic and applied research. Each Hub addresses a single critical national energy need, such as the Sunlight to Fuels Hub. The BRCs are large, multi-institutional, multidisciplinary research centers focused on developing the basic science needed to realize commercially viable cellulosic biofuels.

The Mission Innovation framework, announced in November 2015, is another model for leveraging the insights from the global scientific community. A global initiative with 22 countries and the European Union, Mission Innovation is designed to dramatically accelerate global clean energy innovation by doubling R&D investments in five years — \$30 billion by 2021 — and significantly increasing private sector participation.

It is key that increased collaboration among scientists, as well as strong commitments from across the innovation ecosystem, are supported by an innovation agenda that includes major goals, challenges, and direction. Navigating these issues is key to identifying technologies with the greatest breakthrough potential. More frequent high-level discussions and engagements across the energy innovation ecosystem will help direct the innovation agenda and result in more technology breakthroughs.

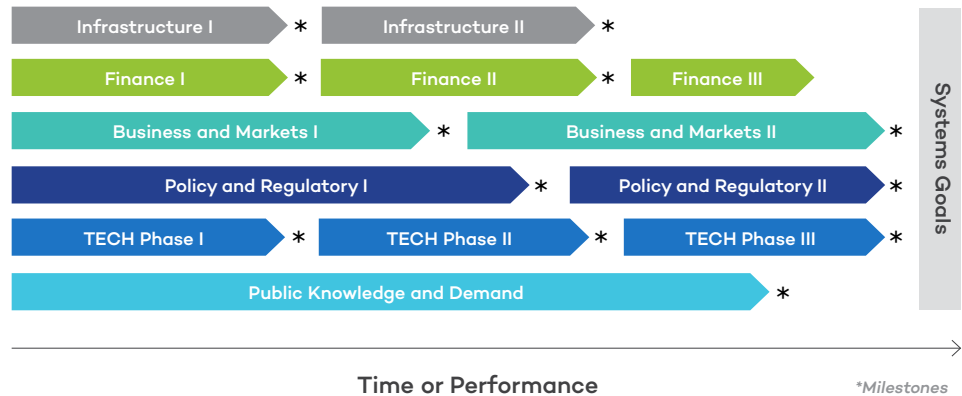
96. DOE, Basic Energy Sciences Advisory Committee, Subcommittee on Grand Challenges for Basic Energy Sciences, *Directing Matter and Energy: Five Challenges for Science and the Imagination* (Washington, D.C., 2007), 109, https://science.energy.gov/-/media/bes/pdf/reports/files/Directing_Matter_and_Energy_rpt.pdf

97. DOE, Quadrennial Technology Review 2015, 323.

98. Donald E. Stokes, *Pasteur's Quadrant: Basic Science and Technological Innovation* (Washington, D.C.: Brookings Institution Press, 1997).

FIG. 3-14

Generalized Technology Roadmap



Roadmapping can play a critical role in identifying development pathways for priority clean energy technologies.

Source: Energy Futures Initiative (EFI), 2018; adapted from U.S. Department of Energy.

Road-Mapping Technologies with Breakthrough Potential

Realizing the potential of a specific priority technology requires a roadmap that lays out the developmental pathway both in temporal terms and in terms of the progressive performance needed from all the elements of a functioning system. The analyses in a roadmap set multidimensional goals, milestones, and strategies. These analyses include all challenges and opportunities in an interconnected and self-consistent analysis of performance, cost and schedule. They include technologies, infrastructure, and supporting institutional factors such as policies, business models, markets, standards, and regulations. These analyses inform strategic commitments and investments, also identified in a roadmap. Figure 3-14 provides a high level, simplified depiction of such a roadmap.

A system-level development roadmap consistently incorporates all challenges and opportunities to advance the technology to commercialization. The assessment of challenges should consider:

- cost to commercialization
- technical risk and expected value of risk (i.e., risk times cost)
- timescale to commercialization
- demands on infrastructure, resources, and the supply chain
- capabilities needed to execute a successful innovation program
- likelihood of market-only-driven innovation and access to alternatives
- potential customer concerns relative to adoption of a successful innovation
- compatibility with markets, policies, and regulations

Opportunities may include:

- public/private partnership opportunities to share risk and cost in order to overcome barriers or accelerate a market-only-driven innovation process
- potential benefit-cost ratios and financial return on public investment
- forms of public investment (e.g., cost sharing, credit enhancement, tax incentives, purchase commitments, market mandates)
- level of public financial obligation (for both Federal and non-Federal public funding)
- market acceptance potential
- affordability across various customer classes and socio-economic consumer groups

The systems-level development roadmap is a critical element in the advancement of potentially breakthrough technologies. The roadmap can help identify and quantify the key technical challenges and risks, and also provide a forecast of the timeframe and resource requirements. Additionally, it can help identify the needed stage-gating of the innovation process, including milestones for updating comparative assessments against other innovation options, and off-ramps and other decision points.

While the roadmap itself may be a dynamic document subject to ongoing change, the roadmapping process can ensure that all the elements of the innovation process are thoroughly considered in the R&D program. Roadmapping creates an institutional mechanism to obtain inclusiveness and transparency in addressing various viewpoints on the key innovation issues. It also provides a framework to ensure that the entire innovation process through commercialization has been fully considered, the key players in the value chain identified, and their roles defined.

RECOMMENDATIONS

Reshaping the Energy Innovation Portfolio for Breakthrough Potential

- Investments in energy RDD&D should be planned within a portfolio structure that facilitates a broad range of investment in transformational innovation across both time scales and technologies. This can help address key needs of a transforming energy sector, including developing and supporting science and energy RDD&D programs based on a fuel-neutral and technology-neutral structure organized by electricity, fuels supply, and end use applications.
- Portfolio investments should adopt a formal set of major evaluation criteria: technical merit, market viability, compatibility and consumer value, with specific metrics for each criterion. These criteria should be used to prioritize programming and budget allocation decisions as well as develop public-private partnerships.
- A robust portfolio of potential breakthrough technologies at various timescales should be supported. There should be special focus on a critical subset of those technologies deemed to have very high breakthrough potential:
 - Storage and battery technologies
 - Advanced nuclear reactors
 - Technology applications of industry and buildings as sectors that are difficult to decarbonize:
 - Hydrogen
 - Advanced manufacturing technologies
 - Building energy technologies
 - Systems: electric grid modernization and smart cities
 - Deep decarbonization/large-scale carbon management:
 - Carbon capture, use, and storage at scale
 - Sunlight to fuels
 - Biological sequestration
- Lithium, cobalt, graphite and other critical materials are becoming strategic resources for enabling a clean energy future. Their supply chains should be closely monitored by an impartial entity that interfaces with both public and private stakeholders. Regular updates should be publicly available.
- Increased interaction among broad stakeholders through planning, roadmapping, and piloting of emerging technologies can increase technology breakthrough potential. These efforts should provide systems-level development plans that delineate technical challenges and risks, R&D pathways, cost and schedule assumptions, institutional roles (including public-private partnership opportunities), pathways to commercialization and diffusion, economic benefits, and consumer value.
- DOE should lead a national effort to update the Basic Research Needs Assessments, originally initiated in 2001, to inform the assessments of emerging technologies with breakthrough potential as well as the development of system-level roadmaps. The updates to the Basic Research Needs Assessments should reflect the changing dynamics of the economy and energy markets, as well as the changes and new opportunities afforded by the emergence of new platform technologies. This updating and possible expansion could be partly carried out through Mission Innovation.

Emerging Energy Technology Options and Identification of Potential Breakthrough Ideas (Breakthrough Candidates Indicated in Green)

Assumes all RD&D Activities are Implemented Concurrently, Targeted to Initial Commercialization in the Timeframes Specified			
Application Area & Technology	Near Term (2025)	Intermediate Term (2035)	Longer Term (2050)
Electricity Supply & Distribution			
Heat Sources for Electricity Generation			
Concentrated Solar Power	Capital cost reduction	Hybrid systems	
Geothermal	Modeling, simulation, & technology validation; gas cleanup; advanced materials	EGS with application of hydraulic fracturing; mineral recovery and hybrid systems; membrane processes	
Coal with Carbon Reduction	Second generation coal/CCS pilot plants; CCS retrofit demonstration; international partnerships	Chemical looping; oxy-combustion; fuel cell carbon capture; subsurface CO ₂ management at gigaton scale; mineralization	Very large-scale CO ₂ utilization (fuels, products, sequestration)
Natural Gas Combined Cycle (NGCC)		Natural gas combined cycle with carbon capture	
Nuclear Fission	LWR advanced fuels for safety; LWR cost reduction; LWR life extension; SMRs design and licensing	Advanced non-LWR, small-scale reactor technologies (e.g., high-temperature and fast reactors); advanced materials/fuels; modeling and simulation; used fuel degradation; alternative repositories; actinide burn-up; hybrid systems	Very high temperature reactors (power and process heat), especially SMRs
Nuclear Fusion			Science development and cost reduction for tokamak technology; development of non-deuterium-tritium fusion concepts
Biopower	Biogas processes	Utility scale bio-power with CCS	
Heat-to-Electricity Conversion	Ultra-supercritical steam turbines; thermionics; Allam cycle	Supercritical CO ₂ turbines; high-temperature-enabling materials for gas turbines	
Direct Electricity Generation			
Solar PV	Low cost manufacturing techniques; soft cost reduction	Perovskites and other non-silicon materials; systems integration with storage and energy management systems	
Onshore Wind	HPC model development to improve wind farm design and operation; high-resolution short-term resource modeling	Materials and manufacturing technologies for large and segmented wind turbine blades	
Offshore Wind	Demonstration Projects to test alternative concepts (e.g., tethering), applications (icing conditions), and cost reduction opportunities	Deepwater offshore wind platforms	

CHAPTER APPENDIX (CONTINUED)

Direct Electricity Generation (Continued)			
Nuclear Power	Small modular reactor design and licensing	Advanced reactors, large and small, for heat and power	Generation IV reactors
Water Power (Hydro and Marine Hydrokinetic)	Marine hydrokinetic component technology; supporting research, monitoring and modeling of hydro systems	Materials and turbine designs; modularization	
Fuel Cells	Improved membranes processes and materials		
Storage	Full system designs to address cost	Non-lithium battery chemistry; flow batteries; solid state control systems; physical and cyber-security	
Transmission and Distribution Systems	Interoperability standards; software and models; solid state components; cybersecurity	Grid architecture development; innovative control approaches; material innovations including wide bandgap semiconductors	Technologies and tools to interpret and visualize data and enable faster controls
Distributed Energy Resources	Advanced “smart” technologies	Controllers for integrated systems, such as smart buildings and microgrids	
Electricity Systems Integration	Internet of Things (IOT); high fidelity models, tools and simulators; common modeling framework; nontraditional contingency planning; technologies to assess system trust	Resilient and adaptive control systems; integration of artificial intelligence, automated and distributed decision-making	
Fuel Supply & Distribution			
Oil and Gas Production	Water quality management; water recycling; oil spill mitigation technology	Understanding induced seismicity; CO ₂ fracking fluid	Methane hydrates
Oil and Gas Transmission and Distribution	Methane leakage controls		
Alternative Fuels (Feedstocks and Conversion Technologies)	Feedstock cost reduction; improved cellulosic conversion technology	Improved biochemical and thermo-chemical conversion pathways; high-value bioproducts and bio-based inputs to chemicals	Affordable low-carbon drop-in fuels; sunlight-to-fuels
Hydrogen Production	End-to-end fuels infrastructure cost reduction	Improved cost/performance of low- or zero-carbon H ₂ production pathways; improved materials	Utilization approaches for high energy intensity manufacturing
Hydrogen Fueling Infrastructure	H ₂ fueling demonstrations, including point-to-point, to test storage and safety systems	System design for H ₂ distribution infrastructure for integrated transportation and industry applications	

CHAPTER APPENDIX (CONTINUED)

Manufacturing & Industry			
Advanced Manufacturing Technology	Smart manufacturing (sensors, controls, automation); new-paradigm materials manufacturing techniques (e.g., electrolytic metals processing); advanced additive manufacturing	New production methods, including replacement and recycling of critical materials	
Industrial Energy Efficiency	Expanded CHP applications; process intensification; roll-to-roll processing	Industrial CCUS applications	
Transportation & Mobility			
Light Duty ICE Vehicles			
Engines & Fuels	Flex-fuel engines; simulation, sensors, controls, materials, and engine waste heat recovery; co-optimization of fuels and engines	Low-carbon drop-in fuels	
Vehicle Technology	Light-weighting		
Heavy Duty ICE Vehicles			
Engines & Fuels	Heat recuperation; autonomous freight hauling	Hydrogen-fueled engines with point-to-point fueling infrastructure	
Vehicle Technology	Aerodynamics improvement; driver assist		
Electric Drive Vehicles			
Batteries	Lithium-ion cost, performance, and weight improvements; alternative lithium sourcing (e.g., brines)	Advanced, non-lithium battery technology	
Electric Drive Systems	Improved power electronics and controls; motors, system controls	Continued cost reduction	
Charging Infrastructure	Standardization; fast charging technology	Very-fast charging technology; wireless charging	
Fuel Cell Vehicles	Improved efficiency (75 percent) and durability; storage for 300-mile range	Reduced cost and increased durability; improved on-board hydrogen storage	
Transportation System Management	Pathways to enhanced vehicle connectivity and automation; traffic management improvements; autonomous vehicles		
Built Environment			
Space Conditioning Technology		High efficiency electric heating systems (e.g., heat pumps that use refrigerants with low or zero Global Warming Potential)	
Lighting	Long-term durability testing; more efficient, high power density LEDs	Efficient, durable, low-cost OLEDs; efficient quantum dot materials	

CHAPTER APPENDIX (CONTINUED)

Built Environment (Continued)			
Cooling Cycle Technologies	HFC replacements	Alternative thermodynamic cooling cycles (e.g., solid state)	
Building Shells	Thin insulating materials for deep retrofit; improved metrics for energy performance of building shells	Tunable PV systems (e.g., PV windows)	
Systems and Controls; Integrated Systems	More flexible power management systems; communications protocols; more efficient circuitry; improved sensors and controls;	Wide-band-gap semiconductors; wireless sensors and controls; control algorithms	
Systems Integration	Interoperable building communications systems and optimized control strategies; decision science affecting consumer choice	Smart Cities systems integration of buildings, transportation and industry	
Large-Scale Carbon Management			
Terrestrial Sequestration	Large-scale integrated demonstrations of sequestration in alternative geologic media	Sub-surface CO ₂ management at gigaton scale; mineralization	
Biological Sequestration	Research and field testing of alternative approaches for innovative large-scale biological sequestration approaches	Large-scale demonstrations of most promising biological sequestration approaches with potential gigaton-scale application	
CO ₂ Utilization		CO ₂ fracking fluid	Large-scale CO ₂ utilization alternatives (including conversion to fuels or products such as polymers and carbon fibers)
Carbon Capture Cross-cut (Re-cap from Above)	Second generation coal/CCUS pilot plants; CCUS retrofit demonstration; international partnerships	Natural gas CCUS; industrial CCUS; chemical looping, oxy-combustion; fuel cell carbon capture	
Cross-Cutting & Enabling Technology			
Enabling Science and Technology	Structural analysis of materials using X-ray light and neutron sources; novel nanoscale synthesis and fabrication techniques; advances in genomic and biological analytical and observational tools; modeling, simulation, and data analysis using high performance computing; advanced sensors and monitoring systems (e.g., drones)		
Energy/Water Nexus	Desalination		
Advanced Materials	Composite materials; earth-abundant substitutes; materials by design; materials in harsh environments	Advanced materials and materials interaction to enable additive manufacturing	
High Performance Computing	Development of exascale computing capability including software		Large-scale quantum computing

Chapter 4. The Role of the Federal Government in the Energy Innovation Ecosystem

This chapter discusses the scale, scope, and balance of the Federal clean energy research, development, demonstration, and deployment (RDD&D) portfolio. This portfolio has produced significant successes that have helped shape the nation's energy system, both now and for the future. The chapter notes some of these successes and focuses particularly on the Department of Energy (DOE), which provides roughly 75 percent of federal clean energy research and development (R&D) funding. This chapter also examines DOE's structure in the context of the modern energy sector and suggests alternative programs and organizational structures that could enhance the contributions of the federal government to energy system transformation.

FINDINGS

The Role of the Federal Government in the Energy Innovation Ecosystem

- Three-quarters of Federal investment in clean energy innovation in FY 2016 was administered by the DOE. Other agencies with significant clean energy innovation budgets include the Department of Defense (DOD), the Department of Transportation (DOT), and the Department of Agriculture (USDA). Portfolios at these agencies are mission-focused, as opposed to being broadly based across all energy sectors.
- The fuels-based organizational structure of the DOE, which has been in existence since 1979, is not optimized for modern energy systems and needs. It tends to lead to budget allocations by fuel, rather than prioritization by innovation potential.
- Implementation processes for the Government Performance and Results Act (GPRA) impose rigid strictures on the way R&D program offices establish performance measures. The resulting metrics are focused on very near-term (2-year to 3-year) performance and processes and do not adequately measure innovation. Adopting and implementing a high-performance, applications-based energy innovation portfolio, with greater emphasis on technology roadmapping, will require greater attention to multiyear program planning.
- The funding available for federal energy R&D programs after 2020 is currently a matter of great uncertainty. The Bipartisan Budget Act of 2018 (BBA) sets new caps for discretionary spending that are as much as 25 percent higher than the Administration's budget, providing considerable headroom for near-term increases in spending for clean energy innovation. Long-term prospects, however, are unclear as the budget agreement applies for only 2 years.

Setting the Scope and Scale of the Federal Clean Energy Innovation Portfolio

For nearly a half century, different Administrations and Congresses have supported a broad energy innovation R&D portfolio. They have also pursued policies, regulations, tax incentives, public-private partnerships, and other approaches to incentivize private sector financing to commercialize the innovations from these efforts. This has led to deployment of technologies at scale that align with key national needs.

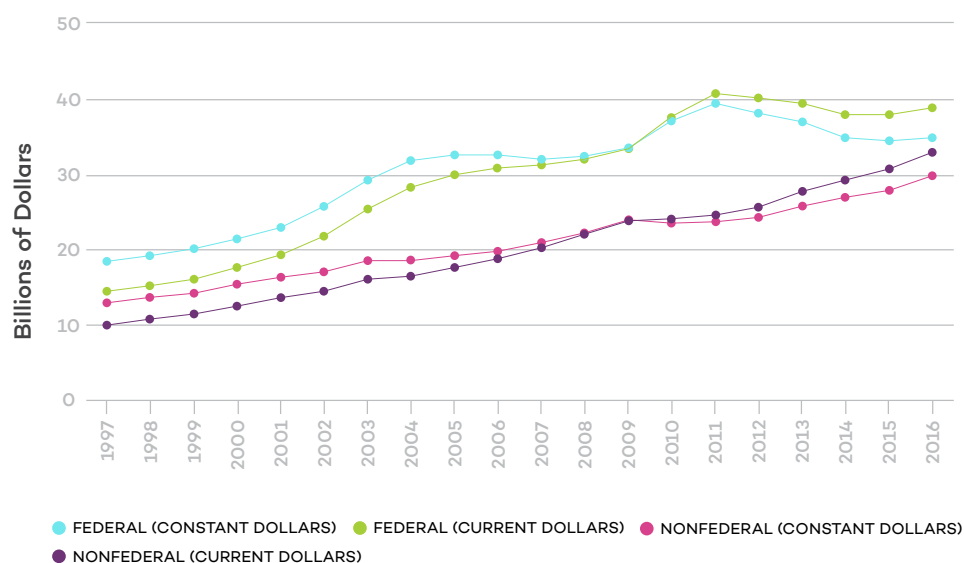
There are compelling reasons for a sustained and substantial Federal role in clean energy innovation. First, the Federal government has a central role in supporting four national goals relevant to energy: national security, energy security, national economic competitiveness, and environmental responsibility. The challenge of climate change adds an additional element of urgency in advancing these overarching Federal responsibilities.

The Federal government is also a major supporter of academic research (Figure 4-1), a critical link in the Nation's innovation chain and the foundation of its intellectual infrastructure. In the U.S. Energy Employment Report released in May, 2018, 70 percent of employers reported having a somewhat or very difficult time hiring skilled employees; in professional and business services, this number was 75 percent. The educational pipeline supported by academia — with significant support from the Federal government — is critical for a clean energy future.

Finally, many technologies that are transforming how energy is produced, transported and consumed have been supported by Federal technology investments (see Text Box 4-1) in areas critical to a clean energy future, such as digitalization and data analytics.

FIG. 4-1

Federal and Nonfederal Funding of Academic R&D Expenditures, FY 1997-2016



Source: National Science Board, Science & Engineering Indicators 2018

TEXT BOX 4-1

The Role of the Federal Government in the Oil Innovation Ecosystem: Basic Research in Enabling Technologies

An industry analysis, *EOR: Past, Present and What the Next 25 Years May Bring*, highlighted the key role of technology in oil production, noting that technology innovation in the 1990s “marked extraordinary technological improvements in exploration, drilling and production.” It went on to say that at the 30th anniversary of the Offshore Technology Conference, there was “a display of technology that would have seemed like science fiction a decade earlier.” The article highlighted among others, these technologies: conversion of Star Wars laser defense technology to drilling; a downhole factory that combined fiber optics, artificial intelligence and robotics; and cross-borehole seismic tomography. The Federal government’s early research in these areas is detailed below and illustrates the key role it plays in the energy innovation ecosystem.

Star Wars defense laser technology. More officially known as the Strategic Defense Initiative, this program for air and missile defense, as well as satellites and satellite weapons, was developed by the Department of Defense in the 1980s with assistance from scientists and physicists at DOE National Laboratories, such as physicist Lowell Wood at the Lawrence Livermore National Laboratory.

Fiber-optics. Development and experimentation for fiber optics began with the U.S. Army Signal Corps in 1958. A federal funding contract for development went to Corning Glass Works for the period of 1963–1970. In 1975, the U.S. government decided to link the computers at the NORAD Headquarters using fiber optics. Federal funding of many research programs related to fiber optics continued until 1985.

Robotics. The National Science Foundation (NSF) began funding engineering, computing, sensors, machine movement, and computer vision prior to the 1970s, but the first grant for a project on a “robot” was awarded in 1972. One of the first key inventions was the Adaptive Suspension Vehicle (ASV) developed at Ohio State University, with funding from NSF and the Defense Advanced Research Projects Agency (DARPA). NSF has been a key supporter of robotics research in the subsequent decades.

Artificial intelligence. U.S. Government began investing in deep learning (the forerunner to artificial intelligence) in the 1960s.

Cross-borehole seismic tomography and miniature geophone tools. DOE National Laboratories collaborated with the Oil Recovery Technology Partnership and provided the computing power necessary to improve 3D imaging. DOE National Laboratories also developed 4D seismic technology and a multi-station borehole seismic receiver.

Supercomputing, a related and enabling technology of all of these. The federal government has pursued a long-standing commitment to the development of supercomputing. One of the first industry developments resulted from a partnership between Harvard and IBM with the ASCC project. Cray and the iterations of Seymour Cray’s many companies competed in parallel with the IBM/Harvard partnership, and still competes with other prominent companies such as Intel, Hewlett Packard, and AMD, among others. DOE has long pushed the frontiers of supercomputer development for its science, energy, and nuclear weapons missions.

The Central Role of the Department of Energy in Clean Energy Innovation

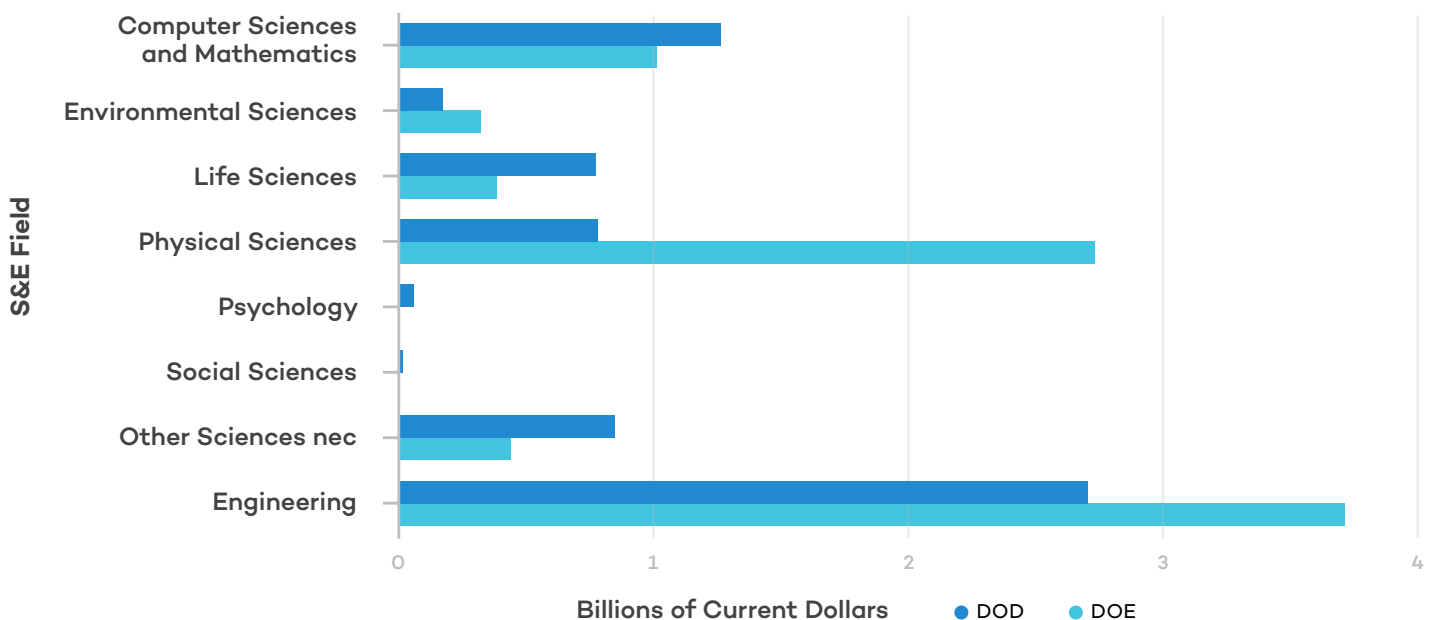
While other agencies have mission-specific energy portfolios (discussed later in this chapter), the agency with primary responsibility for clean energy innovation is the DOE. In FY 2017, DOE administered roughly \$4.8 billion, or 75 percent of the Federal government's \$6.4 billion, in spending on clean energy innovation. DOE performs its role in partnership with its 17 national laboratories, academia, states, regions, other agencies, and the private sector.

DOE's investments in clean energy innovation have played a critical role in changing the U.S. energy landscape over several decades. DOE characterized U.S. shale basins shortly after its formation in 1978. It has had an ongoing role in developing supercomputing, an enabling technology for digitalization, artificial intelligence, and smart systems. Its investment in phasors and sensors support the smart grid. The Advanced Research Projects Agency–Energy (ARPA-E) — a DOE program—has supported a range of clean energy start-up companies. Additionally, the DOE's Loans Program Office (LPO) was instrumental in seeding the U.S. utility scale photovoltaic market (See Text Box 4-2).

DOE's research and development activities, in fact, account for a substantial portion of all Federal science and engineering research. Figure 4-2 compares DOE's and DOD's obligations for research by funding for science and energy fields. While DOE is a much smaller agency, its support for computer science and mathematics is close to that of DOD's. Additionally, its support of the physical sciences dwarfs DOD's, and its support for engineering exceeds DOD's by around \$1 billion.

FIG. 4-2

DOD, DOE Obligations for Research by Major S&E Field, FY 2015



Source: National Science Board, *Science & Engineering Indicators 2018*

TEXT BOX 4-2

DOE's LPO: Launching the U.S. Utility-scale Photovoltaic Market

LPO was instrumental in launching the utility-scale solar photovoltaic (PV) solar industry in the United States. In 2009, there were only 22 MW of installed utility-scale PV capacity domestically, and the U.S. Energy Information Administration (EIA) forecast only 126 MW of total utility-scale PV solar capacity to be installed by 2015.¹ Solar developers were unable to secure the necessary financing for construction of large projects, even with firm offtake contracts and substantial equity in hand.

In 2011, LPO provided more than \$4.6 billion in loan guarantees to support the first five utility-scale solar PV facilities larger than 100 MW. Since then, the private sector has taken over and individually financed at least 45 more utility-scale PV projects, resulting in a 531% increase in installed capacity.² By 2015 there were over 12,000 MW of solar PV capacity installed at utility scale, two orders of magnitude greater than EIA's 2009 prediction. Many of the banks that financed these projects, such as John Hancock, Bank of America, and Citigroup, were banks that worked with LPO through the Financial Institution Partnership Program (FIPP) in financing the first five utility-scale PV projects.

The launch of the domestic utility-scale PV industry demonstrates the critical role LPO plays in reducing risk for innovative technologies and creating a financing model that can be adopted by the private sector.

1. EIA, 2009. Available at: <https://www.eia.gov/outlooks/archive/aeo09/supplement/supref.html>

2. DOE, 2016. Available at: <https://www.energy.gov/lpo/articles/mesquite-solar-highlights-how-doe-loan-guarantees-helped-launch-utility-scale-pv-solar>

Aligning the DOE Energy Innovation Portfolio and Management Structure with Breakthrough Technology Opportunities

The DOE is a \$30 billion cabinet-level Federal agency. About \$10 billion, or one-third of its budget, is allocated to energy and science activities, with the remaining two-thirds devoted to nuclear weapons programs and environmental cleanup of the nuclear weapons complex. In FY 2017, DOE administered \$4.8 billion, spanning the energy innovation process from invention to translation and ultimately, adoption. DOE supports:

- basic energy research managed by the Office of Science, including the chemical and materials research in its Basic Energy Sciences program and the genomics science and biological systems research in its Biological and Environmental Research program; and the Fusion Energy Sciences program in the Office of Science
- ARPA-E
- the programs in the Office of Fossil Energy, other than management of the Strategic Petroleum Reserve and other oil reserves
- the programs in the Office of Electricity Delivery and Energy Reliability; the programs of the Office of Nuclear Energy, other than the safeguards and security program at Idaho National Laboratory and the nuclear waste management program
- the programs of the Office of Energy Efficiency and Renewable Energy, other than the grant programs to states and local governments (e.g., weatherization assistance)
- the Loan Programs Office, which is essentially self-funded and provides loans and loan guarantees for early deployments of a wide range of innovative technologies, including advanced technology vehicle manufacturing

Fuels-Based Organizational Structure, An Outdated 1970s Approach

The current organizational structure of the energy technology programs at DOE is largely fuels-based, as are the portfolios of these programs. DOE's appropriations account structure and budget planning also track this fuels-based organizational framework. DOE's organizational structure, with some modifications (the Office of Electricity Delivery and Energy Reliability was created as a separate organization in 2005), has been in existence since 1979, when a reorganization was put in place by Charles Duncan, the second Secretary of Energy. This structure was established in response to pressing issues of that day, such as oil embargoes and a perceived dearth of natural gas resources.⁹⁹ It does not align well with modern energy sector needs, capabilities, and opportunities.¹⁰⁰

The first step in reshaping DOE's energy innovation portfolio is to redefine it along a new applications-based structure that puts energy production, distribution, and applications in logical groupings that enable comparative analyses and prioritization among technologies serving similar needs. Such a portfolio structure could be organized by electricity supply, fuels supply (including the use of hydrogen as an energy carrier), and end use applications (in transportation, buildings systems, and industry). The basic research programs that underpin all these elements would remain unchanged. Comparing the same FY 2017 budget estimates under the current structure with this possible alternative structure provides a significantly different perspective on priorities, as shown in Figure 4-3.

99. <https://www.energy.gov/fe/about-us/our-history>

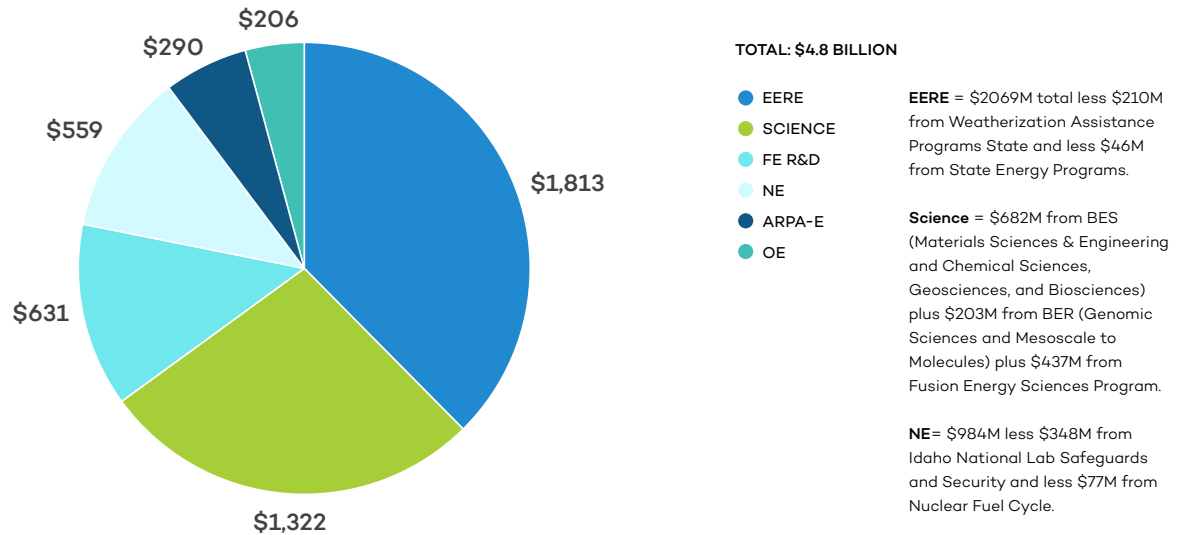
100. The original DOE organizational structure, instituted by Secretary James P. Schlesinger, was organized by stage of technology readiness, i.e., energy science, energy technology, and resource applications.

This alternative structure reveals significant underinvestment in heat-to-power conversion (only \$32 million in FY 2017) and storage technologies (only \$20 million in FY 2017) compared to the large investment (\$1.629 billion) in electricity generation technologies. Drawing final conclusions on the appropriate priorities requires further analysis through the application of the evaluation criteria described in chapter 3; however, working from an applications-based portfolio enables portfolio gaps to be more easily identified.

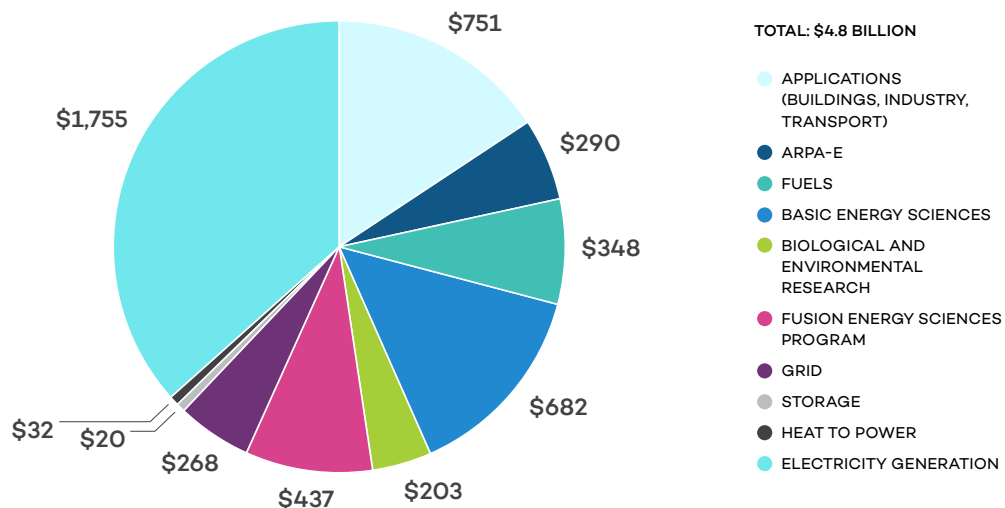
FIG. 4-3

Comparison of DOE Budget Structures by Organization and Application

DOE Budget Structure by Organization (\$millions)



DOE Budget Structure by Application (\$millions)



Source: EFI, 2017. Compiled from DOE Fiscal Year 2018 Budget Documents

“...the ability to set and re-order priorities to respond to the changing innovation landscape, to meet emerging needs, and to take advantage of new opportunities is hampered by the rigidities of the current fuel-centric portfolio structure.”

The current DOE portfolio and budget structure, with its organization by fuel source (e.g., coal, oil, gas, nuclear, renewables), is mirrored in DOE's current program management structure. Redesigning and rebalancing the portfolio to meet technology priorities with the greatest breakthrough potential raises questions as to whether the current organization can effectively meet the changed and changing needs of the energy sector.

Several other key questions are indicated in Figure 4-4. For example, the current organization separates fuel supply from transportation. Is it missing opportunities that would be captured by a more holistic approach to transportation fuels?

Another example: in the current organizational structure, the energy efficiency mission is in the office responsible for renewable energy. Efficiency in end uses is not fuel specific (it is in power generation but that is a separate issue). This placement raises the question: Are opportunities being missed to improve efficiency in all end uses?

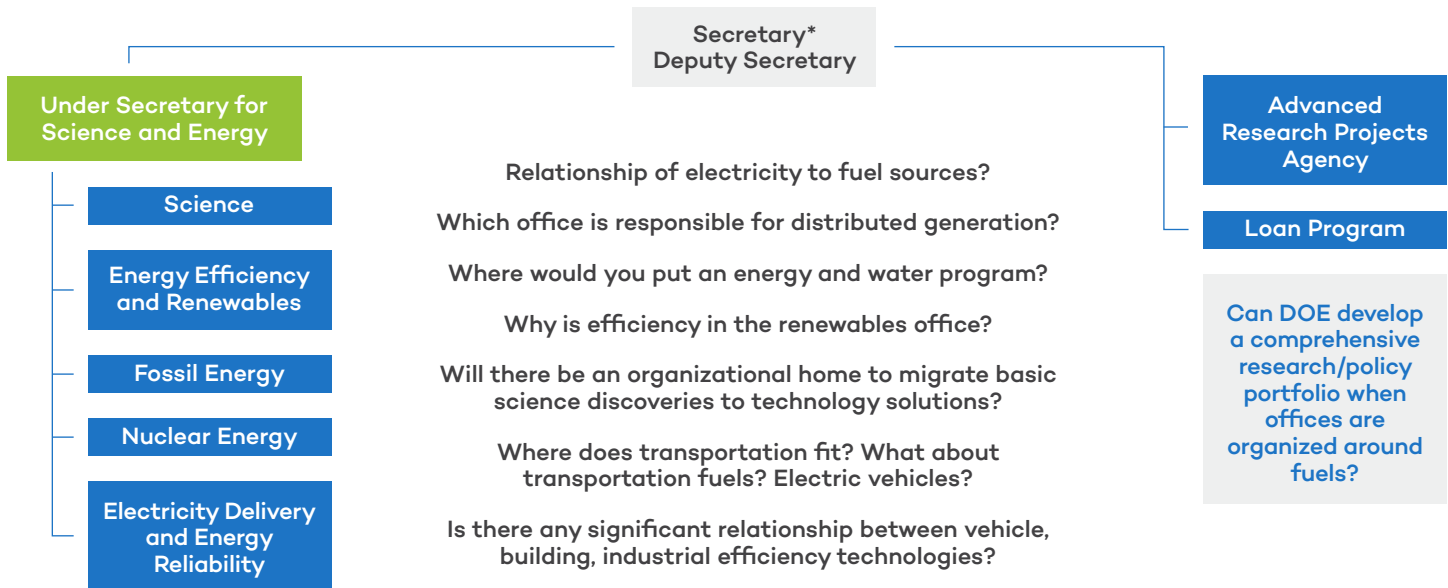
The current structure also is focused mostly on discrete technologies as opposed to energy systems supported by a portfolio of technologies. The current fuels-based organizational structure makes it difficult to support systems that have little to do with particular fuels, or that affect multiple fuels.

Other issues raised by DOE's organizational structure shown in Figure 4-4 include the following:

- Key cross-cutting science and technology issues, such as distributed generation or heat-to-power technologies, do not have a programmatic or organizational “home.”
- The technology-specific subprograms and suborganizations do not facilitate systems-level RDD&D, such as smart transportation and smart cities.
- Key platform technologies (e.g., digital devices and artificial intelligence) that can contribute across a range of technologies and provide significant support for systems receive little or no focus in the energy technology offices.
- Regional differences and needs are not systematically identified and addressed.
- Energy efficiency technologies, by being housed with renewable energy, are separated from other key fuel sources, generators, and delivery systems, resulting in a fragmented approach.
- The critical contribution of advanced manufacturing technologies to the value chain of all energy technologies is not fully realized, because the relevant program is structured as a subprogram element of energy efficiency technology.
- Hydrogen technology and hydrogen production technologies are subsumed as a subprogram element within the vehicle fuel cells program. As a result, the broader potential for hydrogen as an energy carrier for multiple other applications is not supported.
- Large-scale carbon management has no programmatic home and consequently receives inadequate attention.
- Most importantly, the ability to set and re-order priorities to respond to the changing innovation landscape, to meet emerging needs, and to take advantage of new opportunities is hampered by the rigidities of the current fuel-centric portfolio structure.

FIG. 4-4

Questions Raised by Current DOE Organizational Alignment



The DOE organizational structure raises several questions regarding the efficacy of its current alignment.

Source: Energy Futures Initiative (EFI), compiled from DOE organization chart on DOE website on November 20, 2017

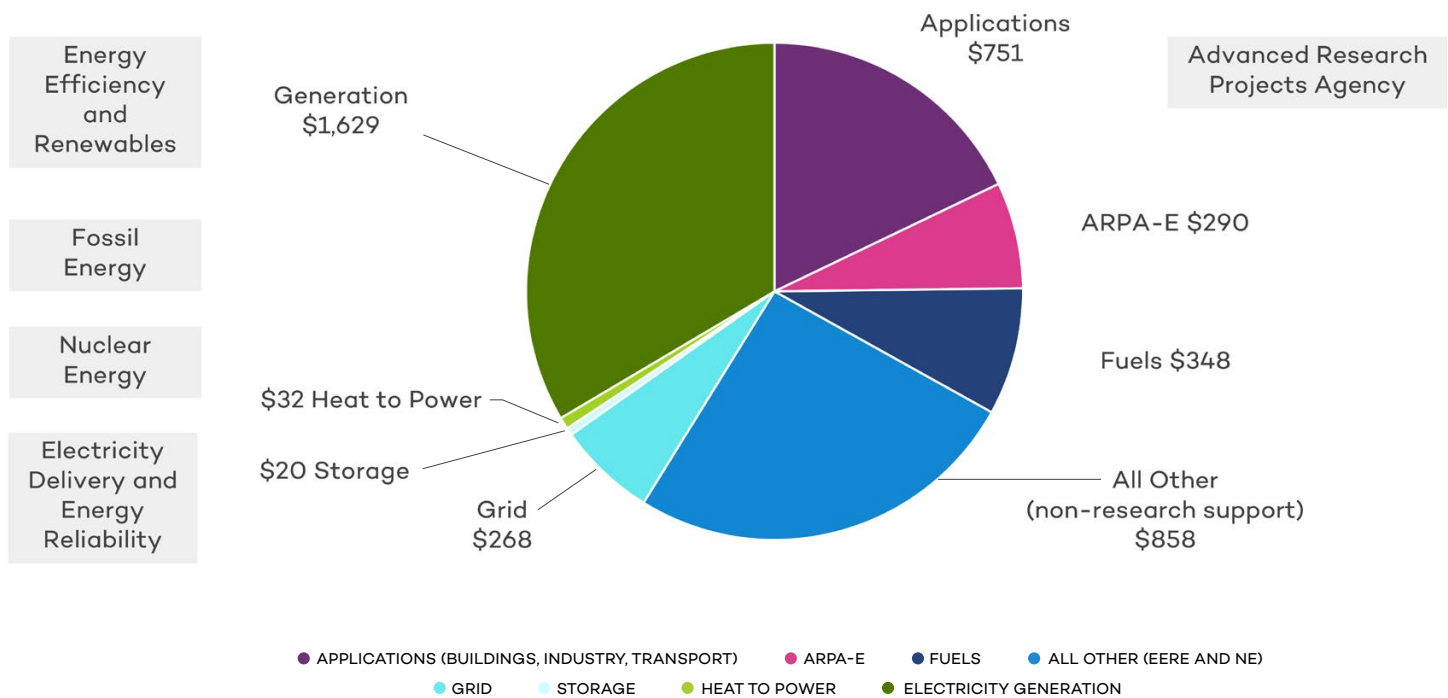
A fuels-based organizational structure tends to encourage budget prioritization by fuel rather than by innovation potential. Figure 4-5 shows that the current fuels-based structure also tends to favor funding for electricity generation technologies relative to fuels and electricity grid system issues.

DOE's current internal budget planning process works from baseline targets established by historical funding levels; funding is internally allocated among the various fuels-based organizations based on these targets. The process allows for some reallocation of priorities at the departmental level, generally if individual organizations within the Department propose to exceed their baseline targets for some new or enhanced activity. However, there is a perceived disincentive for significant portfolio restructuring proposals from the "bottom-up," as the organization risks receiving little or no incremental resources and is being told instead to fund the proposed new or expanded activities at the expense of its ongoing programs. A similar dynamic exists at a higher organizational level between DOE and the Office of Management and Budget (OMB).

The program analysis and prioritization process at DOE has been significantly improved in recent years with the development of the Quadrennial Technology Review (QTR), a formalized process of cross-cutting analysis involving all relevant DOE offices and a strong role for the national laboratories in advancing "big ideas" and in providing inputs into the overall strategic planning process. Two QTRs have been carried out, in 2011 and 2015. It is not clear whether there will a QTR in 2019 but rapid changes in the energy sector and energy technologies suggest a strong need. Moreover, the QTR process is not currently implemented within a portfolio framework and there remains a lack of formal evaluation criteria of the kind discussed in chapter 3 for technologies supported by DOE.

FIG. 4-5

Current DOE Fuels-based Organization and Budget



A fuel-based organizational structure tends to favor generation technologies over other areas such as grid and storage.

Source: Energy Futures Initiative (EFI), 2017; compiled from U.S. Department of Energy FY 2018 Budget Documents

“Despite strategic and portfolio planning for programmatic cross-cuts and flexibility, fuel-based programs tend to “retreat to their corners” when budget and appropriations stresses occur. Also, while the national laboratories are well suited to take a strategic view of cross-cutting issues, their roles in DOE program and budget planning is limited.”

Despite strategic and portfolio planning for programmatic cross-cuts and flexibility, fuel-based programs tend to “retreat to their corners” when budget and appropriations stresses occur. Also, while the national laboratories are well suited to take a strategic view of cross-cutting issues, their role in DOE program and budget planning is limited. The national laboratories are contractors, and laboratory personnel are classified as contractor employees, with the exception of the National Energy Technology Laboratory which is a wholly owned Federal laboratory. Contractors are restricted from direct participation in the internal governmental budget-making and could have conflicts of interest if they were to participate in DOE budget decisions.

Multiyear Portfolio Planning and Stage-gated Performance Measurement

DOE's program offices for applied energy R&D currently conduct multiyear planning to various degrees, but the effort is primarily focused on one year at a time. This is due to the nature of the annual budget process within the Administration (led by OMB) and the annual appropriations process in Congress.

In 2012, Congress enacted a requirement that the DOE's annual budget request include proposed funding levels for a five-year period.¹⁰¹ The purpose of this requirement, as stated in the Senate Report on its Energy and Water Development Appropriations Bill, 2018, "is to ensure that the Secretary is proposing a current budget that takes into account realistic budget constraints in future years, and that Congress has full visibility into the future implications of current budget decisions across the Department's energy programs."¹⁰² However, OMB guidance sets out yearly budget estimates largely on a "current services" basis (i.e., allowing only for increases for inflation, if that), structured according to fuel-based appropriations accounts, thereby inhibiting efforts to plan for changing priorities and modernization.

Adopting and implementing a high-performance, applications-based energy innovation portfolio, with greater emphasis on technology roadmapping will require greater attention to multiyear program planning. One way to address the uncertainties of future budgets is to plan for alternative budget scenarios, enabling greater transparency in the assessment of a range of investment levels and performance outcomes.

Better portfolio planning also requires improvements in program performance management. The Government Performance and Results Act (GPRA) implementation process imposes rigid strictures on the way R&D program offices establish performance measures. These strictures yield metrics that are focused on the very near term (i.e., 2 years to 3 years) and metrics that are process oriented and do not measure innovation. The performance measures to meet GPRA requirements do not provide adequate measurement of innovation progress.

Possible approaches to improving performance measurement include:

- adoption of metrics, as part of the roadmapping process, that delineate cost and technical performance;
- adoption of metrics for deployment programs focused on market outcomes;
- development of longer-term performance measures to replace the short-term focus of GPRA; and
- setting aside a very small portion of program budgets (less than 1 percent) to fund ongoing impact and evaluation studies.

Finally, more effective execution of the portfolio requires better definition of stage-gates, with clearer articulation of the performance objectives for each stage of innovation. Different players are involved at different stages of the innovation process, and clearer performance measures will enable more effective entrance and exit strategies. A recent report from the Hamilton Project of the Brookings Institution addressed the issue of technical standards (i.e., performance measures) in pharmaceutical and energy research:

101. Energy and Water Development and Related Agencies Appropriations Act, 2012 § 304, 42 U.S.C. § 7279a.

102 S. Rep. No. 115-132, 61 (2017), <https://www.congress.gov/congressional-report/115th-congress/senate-report/132/1>

“As a new technology progresses toward a marketable product, companies must prove that the technology can be produced economically. In order to appeal to investors, they must also demonstrate that the product will meet the performance targets required by the market. For drugs, clinical research is needed to demonstrate safety and efficacy of the product. Investors can use the three stages of FDA-approved clinical trials as a benchmark for progress toward marketability...Energy products, on the other hand, have no such benchmarking system to allow investors to quickly assess the level of risk.”¹⁰³

The study notes that the closest analogy is the technology readiness level (TRL) scale first developed by the National Aeronautics and Space Administration (NASA), but also notes some limitations in the ability of the TRL scale definitions to fully capture risk. Most notably, the report cites the lack of a certification process for TRLs and the absence of a gatekeeper.

Facilitating More Effective Public-Private Partnerships

DOE energy innovation funding is executed largely through basic research grants, contracts, and cooperative agreements. Most cooperative agreements — and many contracts — are cost-shared by the non-Federal participants. As part of the implementation of the American Recovery and Reinvestment Act (ARRA) funding in 2009, DOE increased support for collaborative R&D arrangements, such as Energy Frontier Research Centers and Innovation Hubs, but the basic three mechanisms for support remained unchanged. Government contracts, especially when applied to non-profit and university partners, can introduce rigidity into the innovation process. Cooperative agreements have more flexibility, but also can be restrictive when applied to multiparty collaborative research projects.

DOE has another, more adaptable statutory mechanism to support public-private partnerships in the form of its Other Transactions Authority (OTA). This authority permits the use of Technology Investment Agreements (TIAs) that are not subject to the same level of requirements in the Department of Energy Acquisition Regulation (DEAR) applicable to grants, contracts and cooperative agreements. The streamlining of administrative requirements makes TIAs more cost efficient, and the ability to tailor project-specific terms for intellectual property enables more effective public-private partnerships. DOE also has authority to award prizes, which has been used in a few limited circumstances. Increased use of TIAs and prizes could increase the flexibility and effectiveness of DOE's support for its energy innovation portfolio.

Reconsidering the DOE Role in Later-Stage Innovation

Innovation is a complicated and interactive process. As summarized in a recent international study of energy innovation:

“The innovation process involves many stages — from research through to incubation, demonstration, (niche) market creation, and ultimately, widespread diffusion. Feedbacks between these stages influence progress and likely success, yet innovation outcomes are unavoidably uncertain. Innovations do not happen in isolation; interdependence and complexity are the rule under an increasingly global innovation system.”¹⁰⁴

The processes of invention, translation, adoption, and diffusion are interdependent. As suggested by Figure 3-1, the innovation process is a cycle that continually iterates, as the research stage of innovation absorbs learnings from the development, demonstration, and deployment stages. Limiting Federal support

103. Anna Goldstein et al., Promoting Energy Innovation with Lessons from Drug Development (Washington, D.C., Brookings, 2017), 10-11, <https://www.brookings.edu/research/promoting-energy-innovation-with-lessons-from-drug-development/>

104. Arnulf Grubler et al., “Policies for the Energy Technology Innovation System (ETIS),” in Global Energy Assessment – Toward a Sustainable Future, ed. Thomas B. Johannsen et al. (Cambridge: Cambridge University Press, 2012), 1669, <http://www.iiasa.ac.at/web/home/research/Flagship-Projects/Global-Energy-Assessment/GEA-Summary-web.pdf>

to only the research stage weakens the cycle by making development and demonstration less likely. It also provides an opportunity for other countries to fill the gap and reap the commercial benefits of U.S. research.

The FY 2018 federal budget proposed by the Administration “focuses Federal activities on early-stage R&D and reflects an increased reliance on the private sector to fund later-stage R&D, including demonstration, commercialization and deployment where the private sector has a clear incentive to invest.”¹⁰⁵ This perspective is the latest installment in a long-standing debate over the role of the Federal government in supporting development, demonstration and deployment programs and projects. The establishment of the DOE in 1977 included an Assistant Secretary for Resource Applications to oversee commercial deployment activities. Several years later, the Reagan Administration proposed to limit DOE’s role to early-stage, high-risk, but potentially high payoff research. This concept evolved during the Administrations of George H. W. Bush, Bill Clinton, and George W. Bush into a policy of supporting RD&D through the “proof of concept” stage. The Energy Policy Act of 2005, passed by a Republican-led House and Senate and signed by a Republican President, explicitly authorized DOE to conduct “a balanced set of programs of energy research, development, demonstration and commercial application.”¹⁰⁶

The Administration’s FY 2019 budget request stated, “The Budget...reflects an increased reliance on the private sector to fund later-stage demonstration and commercialization activities.”¹⁰⁷ Considerable analysis indicates that prior efforts to reduce Federal energy R&D investment did not trigger compensating increases in private sector investment.¹⁰⁸ Indeed, there is compelling analytical evidence that public investment in energy R&D creates an “additionality effect,” particularly with respect to small firms.¹⁰⁹

The ARRA, enacted to provide broad economic stimulus in the wake of the Great Recession, included a significant, one-time infusion of \$32.7 billion in federal funds to jump-start an accelerated innovation agenda (see Text Box 4-3). The results illustrate the beneficial outcomes that may arise from policy-making which balances short-term responses with a long-term outlook. By allocating a portion of the recovery package to the clean energy innovation agenda, Congress and the Administration acknowledged the importance of clean energy innovation and the radiating effects it could have on the entire economy.

105. U.S. Office of Management and Budget [OMB], Major Savings and Reforms: Budget of the U.S. Government, Fiscal Year 2018 (Washington, D.C., Government Publishing Office, 2017), 35, <https://www.whitehouse.gov/wp-content/uploads/2017/11/msar.pdf>

106. http://www.nationalacademies.org/OCGA/109Session1/public-laws/OCGA_149954

107. <https://www.whitehouse.gov/wp-content/uploads/2018/02/budget-fy2019.pdf>

108. “Matt Hourihan, If Government Scales Back Technology Research, Should We Expect Industry to Step In? (Washington, D.C.: AAAS R&D Budget and Policy Program, 2017), 5, <https://www.aaas.org/news/new-brief-could-industry-fill-gaps-following-federal-rd-cuts>

109. Bettina Becker, “Public R&D Policies and Private R&D Investment: A Survey of the Empirical Evidence,” *Journal of Economic Surveys*, 29, no. 5 (December 2015): 922-923, <https://onlinelibrary.wiley.com/doi/abs/10.1111/joes.12074>

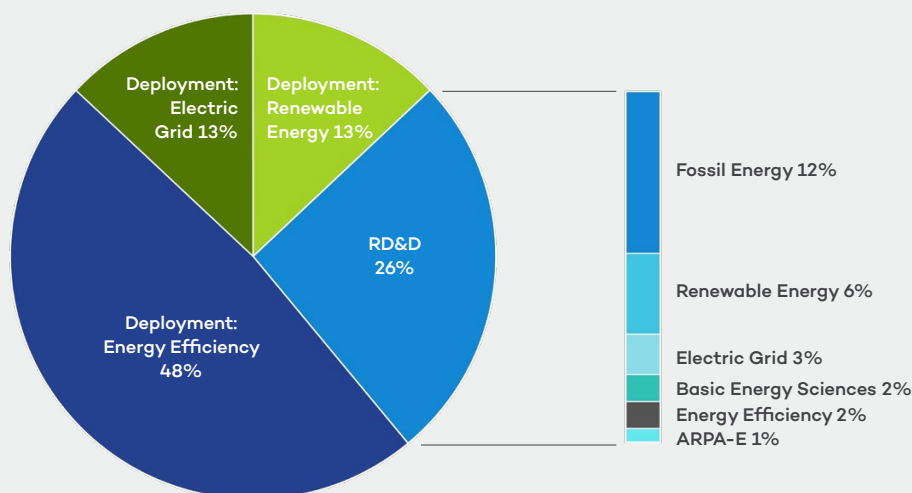
TEXT BOX 4-3

Case Study on the Impacts of Later-stage ARRA Funding at National and Select State Levels

The ARRA provided \$32.7 billion to DOE for energy innovation research and clean energy projects throughout the United States. Most of these funds (74 percent) supported later-stage deployment activities, while 26 percent were allocated for RD&D across multiple programs (Figure 4-6). Of the nearly \$8 billion for RD&D at DOE, approximately half went to fossil energy technologies, with an emphasis on carbon capture and advanced coal combustion technologies.

FIG. 4-6

ARRA Funds for DOE RD&D and Deployment Activities



ARRA funds allocated across the innovation spectrum led to notable achievements in several areas:

- **Innovative Research:** ARPA-E projects garnered more than \$200 million in follow-on private sector funding one year after its initial round of funding.
- **Energy Efficiency:** More than 650,000 low-income households received weatherization and energy efficiency retrofits, which saved families an average of \$437 per year on energy bills.
- **Transportation:** Provided grants to 70 private companies and researchers in 30 states, contributing to the rise of an advanced vehicle industry through the opening of 30 new vehicle component plants, dramatic battery (100-mile range) cost reductions from \$33,000 to an estimated \$10,000 by 2015, and an increase in EV charging stations from 500 to more than 18,000 by 2012.
- **Renewable Generation:** Funded more than 20,000 projects with the capacity to provide power for more than one million households, which allowed for a greater integration of renewables onto the grid.
- **Smart Grid:** Provided seed money for projects in 49 states and two territories, and deployed 1,300 phasor measurement units, 16.6 million smart meters, smart relays, automated feeder switches, and storage batteries. Overall electric grid benefits from ARRA funding included a 50 percent improvement in distribution system reliability, 3 percent increase in distribution system efficiency, 30 percent reduction in peak loads, 50 percent reduction in operational costs, greater customer awareness and management of electricity consumption, reduced emissions, automation, quicker service restoration, and better sensing of the operational health of the grid.

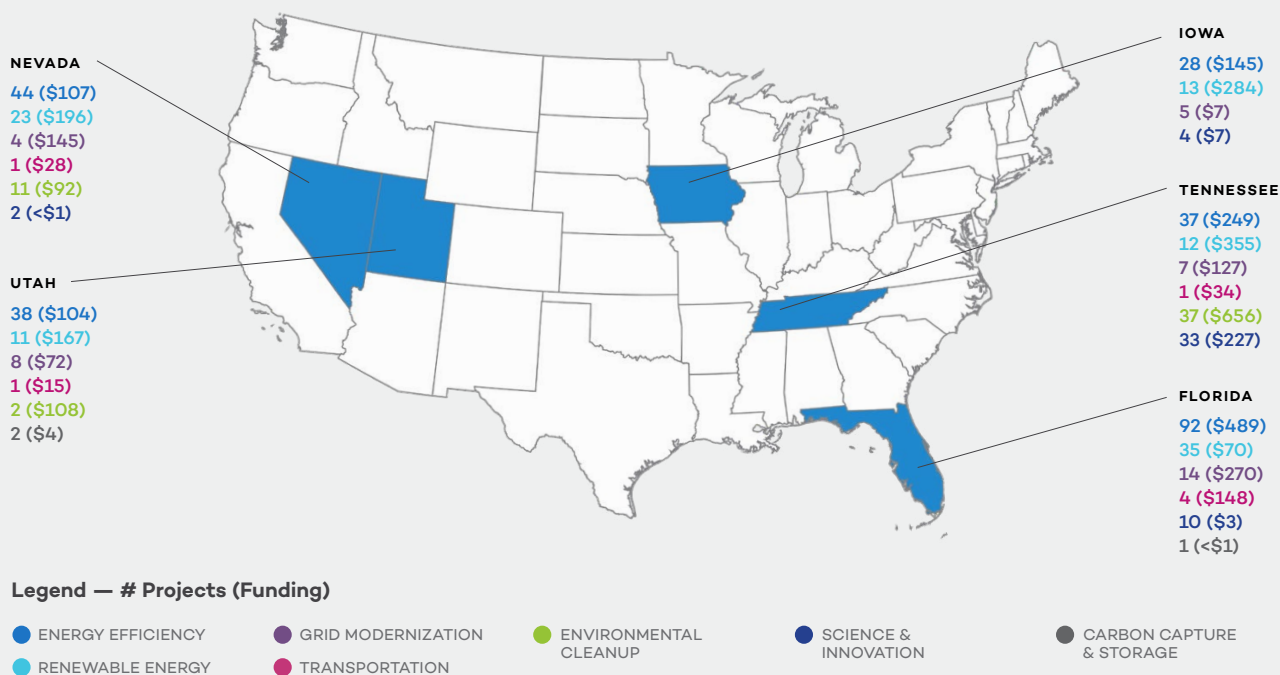
TEXT BOX 4-3 (CONTINUED)

- **Workforce:** Helped prepare the next generation energy workforce through more than 50 smart grid workforce development projects.
- **Disaster Planning:** Assisted with the development of energy assurance plans for natural disaster events in 47 states and 44 cities.

The infusion of Federal funds into the energy sector also helped spur cost-sharing projects between government and industry. For example, DOE entered into joint partnerships with over 200 electric utilities and organizations to invest \$9.5 billion in 99 projects focused on efforts such as grid modernization and cybersecurity. At the state level, funds were used for a wide variety of projects (Figure 4-7).

FIG. 4-7

ARRA Funding for Select State-level Energy Innovation Projects



Sources: "2009 American Recovery and Reinvestment Act," Information Center, Office of Electricity Delivery and Energy Reliability, DOE, accessed March 7, 2018, <https://energy.gov/oe/information-center/recovery-act>

AEIC, Restoring American Energy Leadership: Report Card, Challenges, and Opportunities (Washington, D.C., Bipartisan Policy Center, 2015), 8, <https://www.americanenergyinnovation.org/wp-content/uploads/2015/02/AEIC-Restoring-American-Energy-Innovation-Leadership-2015.pdf>

DOE, Department of Energy: Recovery Act State Memos [Discrete memos for Florida, Iowa, Nevada, Tennessee, and Utah] (Washington, D.C., 2010), <https://www.energy.gov/recovery-act-state-summaries>

DOE, Department of Energy: Successes of the Recovery Act (Washington, D.C., 2012), https://www.energy.gov/sites/prod/files/RecoveryActSuccess_Jan2012final.pdf

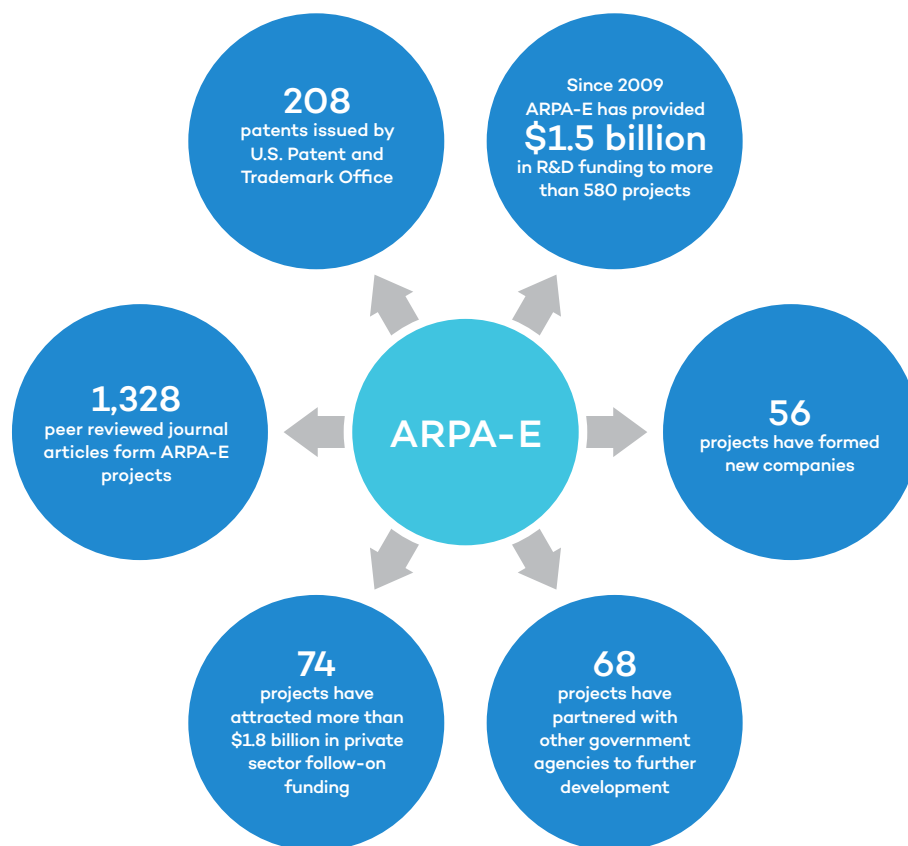
DOE, Office of Electricity Delivery and Energy Reliability, A Glimpse of the Future Grid through Recovery Act Funding (Washington, D.C., 2015), https://www.energy.gov/sites/prod/files/2015/10/f27/OE%20ARRA%20Grid%20Modernization%20Highlights%20october2015_O.pdf

ARPA-E, which was established by the America COMPETES Act of 2007 pursuant to a recommendation by the National Academy of Sciences, Engineering, and Medicine in the *Rising Above the Gathering Storm* report, has been given more program flexibility than other DOE programs, largely in the area of program management. This flexibility has proven to be valuable. Since its initial funding in the 2009 ARRA, ARPA-E's success has been widely acknowledged (Figure 4-8).¹¹⁰ ARPA-E currently is funded, however, at less than a third of the level recommended by the report of the National Academies of Sciences Engineering and Medicine that originally recommended its establishment.

Budget constraints have limited ARPA-E's funding to only a few percent of the proposals the program receives, leaving hundreds of high-potential opportunities unsupported and unrealized. The persistence of suboptimal award rates in a high-performance program led Congress to support a doubling of the National Institute of Health (NIH) research budget. That same circumstance is present today at ARPA-E.

FIG. 4-8

ARPA-E Key Facts



ARPA-E has already achieved significant milestones since its initial funding in 2009.

Source: Energy Futures Initiative (EFI), 2018. Modified from ARPA-E, U.S. Department of Energy.

110. U.S. Department of Energy [DOE], The Advanced Research Projects Agency—Energy: Overview (Washington, D.C., 2017), 1, <https://arpa-e.energy.gov/sites/default/files/arpa-e%20Fact%20Sheet-09172018.pdf>

Strengthening Federal and State Government Support for Large-scale Demonstration Programs at DOE

Technology demonstration projects represent a critical stage in energy innovation process; but they also pose one of the most difficult challenges in the energy

innovation policy. The track record of DOE-funded demonstration projects is mixed. For example, in the carbon dioxide capture, utilization, and storage (CCUS) program, some large-scale demonstration projects (e.g., industrial CCUS and the utility-scale Petra Nova CCUS project) have been very successful. Others (e.g., Mississippi Power's Kemper County energy facility, which was mostly funded by the private sector as a commercial plant even though it represented an unusually large scaling from a laboratory-scale project) experienced significant cost overruns. Still others (e.g., FutureGen) never advanced to the construction phase.

A recent study identified key reasons for including demonstration projects in the energy innovation portfolio:

- Such projects provide the opportunity to integrate numerous and diverse components and subsystems that might interact in unexpected ways.
- They allow for technologies that need to be integrated into tightly-coupled systems, such as the electricity grid, to be debugged in more controlled settings than beta-testing them with the public.
- They reduce economic risk for follow-on projects — providing confidence for investors, particularly in risk-adverse markets such as electricity.
- They reduce institutional risks along with technical and economic risks, facilitating acceptance to regulators and the public.¹¹¹

DOE normally relies on private-sector partners to manage cost-shared demonstration projects, especially when the DOE cost share is relatively small (such as the Kemper facility). However, DOE is appropriately held accountable if cost-shared demonstrations are poorly executed. Moreover, within DOE, demonstration project oversight is currently exercised by the individual R&D program offices with varying degrees and quality of oversight. Execution of cost-shared demonstrations could be significantly enhanced by extending some or all of the same procedures and oversight to these projects as have been successfully adopted for other major DOE projects, such as application of the stage-gated process embodied in DOE Project Management Order 413.3B.¹¹²

Another possibility is to consolidate DOE oversight of cost-shared demonstrations in a single office staffed with project management experts. A similar consolidation was successfully implemented within the DOE National Nuclear Security Administration.

A related issue is the cost-sharing policy applied to demonstration projects. Section 988 of the Energy Policy Act of 2005 requires at least 50 percent non-Federal cost sharing for a demonstration or commercial application activity. This provision provides flexibility for adjustment in the cost-sharing formula to take into consideration of technical risk.¹¹³ However, DOE lacks a formal methodology for setting risk-adjusted cost sharing, and it is not clear whether such determinations can also include assessment of market risk such as the level of a project's exposure to competitive power markets.

Demonstration projects are essential to energy innovation. Implementation reforms can improve project success rates and strengthen the critical Federal role as an initiator, accelerator, and “de-risier” of innovation via demonstration. In any portfolio of demonstration projects, which by definition carry risk, a few will not succeed (although even those will provide important lessons for the future). The issue of the need for demonstration projects as part of the innovation process and the issue of effective project execution are distinct. The need for continual improvement in execution does not weaken the case for the Federal role in demonstration projects.

111. David M. Hart, *Across the “Second Valley of Death”: Designing Successful Energy Demonstration Projects* (Washington, D.C.: Information Technology and Innovation Foundation, 2017), 5–6, <http://www2.itif.org/2017-second-valley-of-death.pdf>

112. DOE, Office of Project Management, Program and Project Management for the Acquisition of Capital Assets, DOE O 413.3B, Version Chg 4 (MinChg): 10-13-2017 (Washington, D.C., 2017), <https://www.directives.doe.gov/0413.3-BOrder-b-chg4-minchg/@images/file>

113. Energy Policy Act of 2005 § 988, 42 U.S.C. § 16352.

TEXT BOX 4-4

The National Labs

The DOE National Laboratory System, comprising 17 world-class research institutions located around the country, is the research and development network through which DOE pursues its mission “to ensure America’s security and prosperity by addressing its energy, environmental, and nuclear challenges through transformative science and technology solutions.” The system began with World War II research on nuclear weapons, but has expanded and evolved over succeeding decades to encompass a much broader set of issues:

- Basic research into the physical sciences
- Development of new energy technologies
- Nuclear security and science and engineering support for other security agencies
- Environmental cleanup of the Cold War nuclear production legacy sites
- Collaboration with academia and industry to spur innovation that contributes to national prosperity

Today the system has an annual budget of approximately \$13 billion and employs 20,000 full-time scientists and engineers.

One of the labs, the National Energy Technology Laboratory, has federal employees and is directly managed by DOE. The remaining 16 are federally funded research and development centers (FFRDCs) funded and overseen by DOE but managed and operated by industrial, academic, or nonprofit institutions. This governance model, used initially in the Manhattan Project, today gives DOE responsibility for strategic direction of research programs but places execution of the programs in the hands of competitively selected private contractors responsible for meeting performance standards set by DOE. Management and leadership of the labs may change from time to time, but the accumulated knowledge and expertise of the research staffs are retained. The labs are differentiated by specific missions — some are single-purpose and some multi-purpose — and by the specialized capabilities and facilities each has developed. These facilities are complementary, and the association of labs in a collaborative system enhances their ability to tackle major science and technology-based issues within DOE’s mission space. The DOE National Labs also perform a considerable amount of research for other government agencies and for private industry because of the labs’ unique capabilities.

National labs play an important role in the innovation ecosystem by providing world-class research facilities that are too expensive and specialized to be developed by universities or most companies acting alone, and by providing sustained attention to scientific issues with long time horizons and multidisciplinary complexity. Notably, five of the world’s ten fastest supercomputers are housed in the national labs. Through various collaborative programs the labs also help connect the early scientific discovery emphasized by research universities with the needs of industry for near-term solutions. Their engagement with universities includes support for postdoctoral students and research opportunities for graduate students and undergraduates. The national labs play a vital role in building U.S. scientific human capital, supporting approximately 2,300 postdoctoral researchers and providing research and internship opportunities to nearly 3,000 undergraduate students and more than 2,000 graduate students. National lab facilities are used by more than 30,000 researchers annually.

TEXT BOX 4-4 (CONTINUED)

17 National Laboratories		
Laboratory	Location, steward, year founded	Examples of unique facilities
Ames Laboratory	<ul style="list-style-type: none"> • Ames, IA • Office of Science • 1947 	<ul style="list-style-type: none"> • Sensitive Instrument Facility • Critical Materials Institute • Powder Synthesis Facility for Additive Manufacturing
Argonne National Laboratory	<ul style="list-style-type: none"> • Argonne, IL • Office of Science • 1946 	<ul style="list-style-type: none"> • Advanced Photon Source • Leadership Computing Facility • Tandem Linear Acceleratory System • Center for Nanoscale Materials
Brookhaven National Laboratory	<ul style="list-style-type: none"> • Upton, NY • Office of Science • 1947 	<ul style="list-style-type: none"> • Accelerator Test Facility • Center for Functional Nanomaterials • National Synchrotron Light Source II • Relativistic Heavy Ion Collider
Fermi National Accelerator Laboratory	<ul style="list-style-type: none"> • Batavia, IL • Office of Science • 1967 	<ul style="list-style-type: none"> • Fermilab Accelerator Complex
Idaho National Laboratory	<ul style="list-style-type: none"> • Idaho Falls, ID • Office of Nuclear Energy • 1949 	<ul style="list-style-type: none"> • Advanced Test Reactor • Fuel Manufacturing Facility • Space and Security Power Systems Facility • Biomass Feedstock National User Facility
Lawrence Berkeley National Laboratory	<ul style="list-style-type: none"> • Berkeley, CA • Office of Science • 1931 	<ul style="list-style-type: none"> • Advanced Light Source • The Molecular Foundry • National energy Research Scientific Computing Center • Joint Genome Institute
Lawrence Livermore National Laboratory	<ul style="list-style-type: none"> • Livermore, CA • National Nuclear Security Administration • 1952 	<ul style="list-style-type: none"> • National Ignition Facility • National Atmospheric Release Advisory Center • High Explosives Applications Facility • Forensic Science Facility
Los Alamos National Laboratory	<ul style="list-style-type: none"> • Los Alamos, NM • National Nuclear Security Administration • 1943 	<ul style="list-style-type: none"> • Plutonium Science and Manufacturing Facility • Los Alamos Neutron Science Center • National High Magnetic Field Laboratory
National Energy Technology Laboratory	<ul style="list-style-type: none"> • Pittsburgh, PA; Morgantown, WV; Albany, OH; Houston, TX; Anchorage, AK • Office of Fossil Energy • 1910 	<ul style="list-style-type: none"> • Energy Conversion Technology Center • Advanced Alloy Development Facility • Materials and Minerals Characterization Facility • Geological Science and Engineering Facility • Mobile Environmental Monitoring Laboratory

TEXT BOX 4-4 (CONTINUED)

Laboratory	Location, steward, year founded	Examples of unique facilities
National Renewable Energy Laboratory	<ul style="list-style-type: none"> • Golden, CO • Office of Energy Efficiency and Renewable Energy • 1977 	<ul style="list-style-type: none"> • Battery Thermal and Life Test Facility • Controllable Grid Interface Test System • Solar Energy Research Facility • Wind Structural Testing Laboratory
Oak Ridge National Laboratory	<ul style="list-style-type: none"> • Oak Ridge, TN • Office of Science • 1943 	<ul style="list-style-type: none"> • Spallation Neutron Source • Building Technologies Research and Integration Center • Carbon Fiber Technology Facility • Center for Structural Molecular Biolog
Pacific Northwest National Laboratory	<ul style="list-style-type: none"> • Richland, WA • Office of Science • 1965 	<ul style="list-style-type: none"> • Atmospheric Radiation Measurement Climate Research Facility • Environmental Molecular Sciences Laboratory
Princeton Plasma Physics Laboratory	<ul style="list-style-type: none"> • Princeton, NJ • Office of Science • 1951 	<ul style="list-style-type: none"> • National Spherical Torus Experiment-Upgrade • Laboratory for Plasma Nanosynthesis • Magnetic Reconnection Experiment
Sandia National Laboratories	<ul style="list-style-type: none"> • Albuquerque, NM; Livermore, CA; Tonopah, NV; Carlsbad, NM; Kauai, HI • National Nuclear Security Administration • 1949 	<ul style="list-style-type: none"> • Z Machine • Combustion Research Facility • Microsystems and Engineering Sciences Applications Complex
Savannah River National Laboratory	<ul style="list-style-type: none"> • Aiken, SC • Office of Environmental Management • 1951 	<ul style="list-style-type: none"> • Shielded Cells Facility • FBI Radiological Evidence Examination Facility • Atmospheric Technology Center
SLAC National Accelerator Laboratory	<ul style="list-style-type: none"> • Menlo Park, CA • Office of Science • 1962 	<ul style="list-style-type: none"> • Stanford Synchrotron Radiation Lightsource • Facility for Advanced Accelerator Experimental Tests • Linac Coherent Light Source
Thomas Jefferson National Accelerator Facility	<ul style="list-style-type: none"> • Newport News, VA • Office of Science • 1984 	<ul style="list-style-type: none"> • Continuous Electron Beam Accelerator Facility

Making the DOE Loan Programs More Flexible

The DOE Loan Programs Office (LPO) has built up an impressive record of performance, including launching the utility-scale solar PV industry, helping revitalize domestic manufacturing of energy-efficient autos, and building a \$30 billion portfolio of 30 projects. Indeed, the LPO has established such an effective approach to due diligence and risk management that OMB has recommended to another loan-granting agency that it have the LPO manage its loan granting process (Figure 4-9).

The LPO has leveraged \$50 billion of total investment, with a more favorable loan loss record (2.2 percent) than the commercial banking industry and a net return to the Treasury of over a billion dollars so far.¹¹⁴ The LPO currently has \$39 billion in credit authority to be deployed.

Greater flexibility in the implementation of DOE loan and loan guarantee programs could enable DOE's current \$39 billion in loan and loan guarantee authority to leverage up to \$100 billion of investments in innovative energy infrastructure. This could be done using currently available credit authority and without the need for new appropriations. This leveraging also would support the Administration's infrastructure objectives of a 10-year, \$1 trillion national infrastructure investment initiative by lowering the risk profile for private investors.

Energy-related Innovation Support at Other Federal Agencies

Although DOE has the largest budget responsibility for federal energy innovation spending, DOD, DOT, and USDA, as well as NASA and the Environmental Protection Agency (EPA), also conduct important energy innovation programs in support of their missions.¹¹⁵ Although targeted on by their specific mission areas, these various R&D programs and projects address several common technical issues. Examples include improvements in battery performance, reductions in the cost of biofuels, development of "smart" energy-efficient transportation systems, and engine and combustion technologies that can operate on alternative fuels.

Increasing the level of Federal investment and accelerating the pace of innovation opportunities like these in energy will require more effective coordination and integration of Federal agency energy R&D activities. This will be especially important as systems-level innovation becomes more prominent in the innovation portfolio. There are several interagency coordination mechanisms in place to ensure that energy-related R&D activities are well-organized with multiple mission objectives in mind. Typically, these coordination mechanisms are developed and implemented at the level of the individual programs in each agency. The three-agency Memorandum of Understanding (MOU) among DOE, USDA and DOD for biofuels is an example of this.

A broader example of interagency coordination occurred in the context of the 2015 U.S. commitment to Mission Innovation — a pledge to double the level of Federal investment in clean energy innovation. This commitment was reflected government-wide in the FY 2017 budget request, which called for a 20 percent increase in Federal investment in energy innovation across 12 Federal departments and agencies — totaling \$7.7 billion. The FY 2018 budget passed by Congress includes a roughly 10 percent increase in DOE Mission Innovation-related energy R&D programs. International collaborations on targeted clean energy technologies are also moving ahead under the Mission Innovation umbrella (e.g., initiatives on North American advanced materials and CCUS).

114. Sixty percent of the 2.2 percent default rate is attributable to Solyndra, which failed for market reasons, when Chinese solar panels flooded the U.S. domestic market. Notwithstanding this widely publicized loss, the loan program has achieved an impressive loan loss record.

115. Federal agency energy-related R&D programs are discussed in detail in separate working papers that supplement this report.

FIG. 4-9

DOE's Loan Programs Office Portfolio: Diverse, Regional, High Impact, Late Stage Innovation

Idaho (1): Front End Nuclear Facility (Advanced nuclear/\$2 B)

Illinois (1): Ford (Advanced vehicles manufacturing /\$5.9 B)

Indiana (2): Abound Solar (Solar manufacturing/\$400 M); VPG (Advanced vehicles manufacturing/\$50 M)

Michigan (6): Ford (Advanced vehicles manufacturing/\$5.9 B)

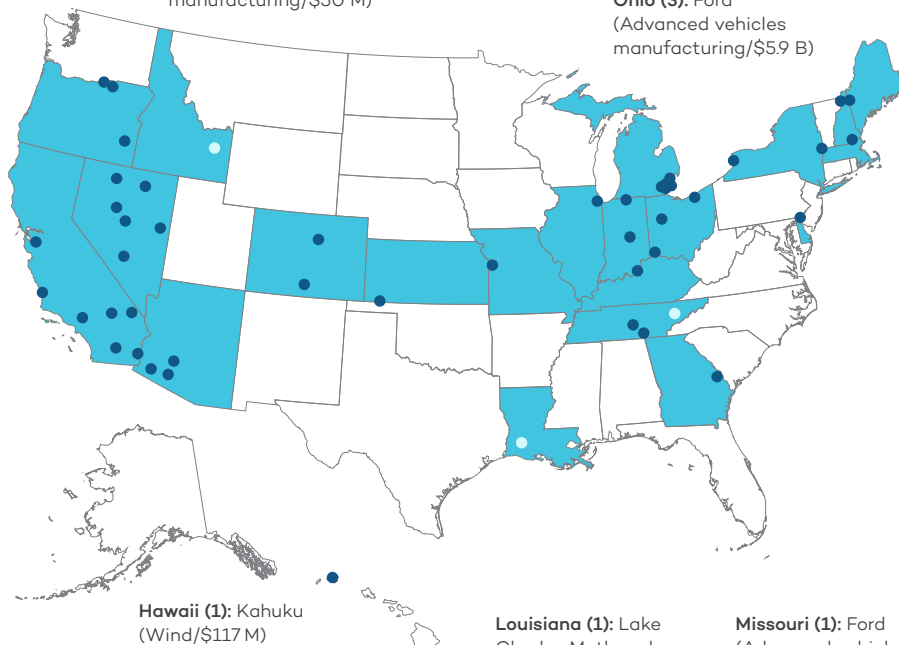
New Hampshire (1): Granite Reliable (Wind/\$169 M)

Maine (1): Record Hill (Wind/\$102 M)

Oregon (3): Shepherds Flat (Wind/\$1.3 B); USG Oregon (Geothermal/\$97 M)

Nevada (6): Blue Mountain (Geothermal/\$98.5 M); Crescent Dunes (CSP/\$737 M); One Nevada Line (Storage & Transmission/\$343 M); Ormat Nevada (Geothermal/\$350 M)

California (8): Antelope Valley Solar Ranch (Solar PV/\$646 M); Blythe Solar Power Project (CSP/2.1 B); California Valley Solar Ranch (Solar PV/\$1.2 B); Desert Sunlight (Solar PV/\$1.5 B); Genesis (CSP/\$852 M); Ivanpah (CSP/\$1.6 B); Mojave (CSP/\$1.2 B); Tesla (Advanced vehicles manufacturing/\$465 M)



Hawaii (1): Kahuku (Wind/\$117 M)

Arizona (3): Agua Caliente (Solar PV/\$967 M); Mesquite 1 (Solar PV/\$337 M); Solana (CSP/\$1.45 B)

Colorado (2): Abound Solar (Solar manufacturing/\$400 M); Alamosa (Solar PV/\$90.6 M)

Louisiana (1): Lake Charles Methanol (Advanced fossil/\$2 B)

Kansas (1): Abengoa Bioenergy (Bioenergy and biofuels/\$132.4 M)

Missouri (1): Ford (Advanced vehicles manufacturing/\$5.9 B)

Massachusetts (1): 1366 Technologies (Solar manufacturing/\$150 M)

New York (2): Ford (Advanced vehicles manufacturing/\$5.9 B); Stephentown Spindle (Storage & Transmission /\$25 M)

Delaware (1): Fisker (Advanced vehicles manufacturing/\$529 M)

Kentucky (1): Ford (Advanced vehicles manufacturing/\$5.9 B)

Tennessee (3): Alcoa Inc. (Advanced vehicles manufacturing/\$259 M); Nissan (Advanced vehicles manufacturing/\$145 B)

Georgia (1): Vogtle (Advanced nuclear/\$3.4 B GPC, \$3.1 B OPC, \$1.8 B MEAG)

● EXISTING CONDITIONAL COMMITMENT
● EXISTING LOAN GUARANTEE AGREEMENT

Source: Energy Futures Initiative (EFI), 2018; compiled using data from DOE, 2018

The Quadrennial Energy Review (QER) is another multiagency initiative. This government-wide analysis is designed to ensure that energy investments and policies, across 22 agencies with energy missions and interests, are developed and coordinated to meet and maximize national goals of security, competitiveness, and environmental responsibility. This process, recommended by the President's Council of Advisors on Science and Technology in late 2010, produced two installments of comprehensive analyses, garnering bipartisan support for both the QER process and the recommendations that resulted. One-third of the recommendations in the first installment of the QER were reflected fully or partially in law, at a time when obtaining bipartisan support for many policies and investments has been challenging.

Department of Defense

Next to DOE, DOD maintains the largest portfolio of investment in Federal energy innovation. Technological innovation has been critical to retaining U.S. superiority in national security, and advances in energy technology have played a key role in this.

Table 4-1 shows the total R&D funding at DOD. Unfortunately, the budget for energy R&D activities is not separately identified within this total. The energy R&D portfolio is driven by mission requirements, which are not always synonymous with competitive commercial energy market objectives. DOD does, however, seek to work to ensure that new energy innovation options are cost effective relative to mission needs, and DOD-funded innovation does have significant commercial benefit.

In FY 2016, DOD consumed 77 percent of total Federal energy used, which is a decline from the previous year and the lowest percentage figure on record. DOD energy needs fall roughly into two broad categories: energy needed to run its global installations and facilities, and operational energy to fuel its various missions abroad. Jet fuel is by far the dominant source of energy and because of that, within DOD, the Air Force alone represents almost one-half of DOD's total energy usage.

TABLE 4-1

DOD Research, Development, Testing, and Evaluation (RDT&E) (Budget Authority, Billions of Dollars)

Defense RDT&E	T2017 Enacted	2018 Request	Percent Increase
Science and Technology	14.0	13.2	(5.7)
Development	55.1	64.0	16
Management Support	4.6	6.1	33
Total	73.8	83.3	12.9

Source: Based on John F. Sargent, Jr., *Federal Research and Development Funding: FY2018 (R44888)* (Washington, D.C., Congressional Research Service, 2018), 14; figures reflect both Base and Overseas Contingency Operations Funding

Innovation at DOD generally has involved cooperative, sometimes competitive, interactions among individuals and organizations within both the public and private sectors — academic, other non-profit, or commercial. Innovations have included significant military “spin-offs” to the civilian sector; they have also included, especially in recent years, “spin-ons” from the civilian sector to the military sector. Thus, much innovation has ultimately proved “dual use,” even if this was not obvious at the time of the initial technology development.

DOD procurement programs and DOD facilities offer significant opportunity as an early market for innovation. Specific DOD energy R&D initiatives include:

- **The DOD Installation Energy Test Bed** that evaluates new energy technologies in building energy efficiency management, microgrids, energy management technologies and systems, and renewable electricity generation
- **The National Network for Manufacturing Innovation**, implemented in coordination with DOE and the Department of Commerce
- **The Rapid Innovation Fund** to address nascent technologies that could yield significant benefits to DOD procurement
- **The Defense Innovation Unit Experimental (DIUx)**, which provides investment capital to innovators addressing DOD problems

There are numerous examples of high-impact results from DOD investments and programs (see Case Study in Chapter 1). The Defense Advanced Research Projects Agency (DARPA) — a small DOD agency known for working with academic, government, and corporate partners on breakthrough technologies — has helped transform military capabilities through innovations such as precision weapons, stealth technology, and autonomous systems. It has also created technological spinoffs for civilian society such as the internet, automated voice recognition, language translation, and Global Positioning System (GPS) receivers small enough to embed in consumer devices.

Another important program at DOD, in view of the trends described in chapter 1, is the DIUx: inspired by DARPA, it is a small-scale DOD entity — with about 50 staff. DIUx was established to accelerate commercial innovation to solve DOD problems, with expedited contracting procedures that utilize DOD’s Other Transactions Authority. It focuses on building bridges with the researchers and technologists in Silicon Valley to leverage its expertise and currently has five focus areas:

- **Artificial Intelligence:** leveraging artificial intelligence and machine learning for operational impact
- **Autonomy:** adopting and countering autonomous systems
- **Human Systems:** countering emerging biological threats
- **Information Technology:** making combat information accessible to forces
- **Space:** developing on-demand access to space, persistent satellite capabilities and broadband space data transfer¹¹⁶

116. “Five Focus Areas,” Team, Defense Innovation Unit Experimental, Department of Defense, accessed March 7, 2018, <https://www.diu.xmil/team>

As of September 30, 2017, DIUx had awarded \$184 million in contracts for 59 pilot projects and two follow-on production contracts.¹¹⁷ So far, however, funding for this unit has been limited. The budget request for this program for fiscal year 2018 was \$54 million.

An example of coordinated efforts of DOD agencies with other partners is the Integrated High-Performance Turbine Engine Technology program. This effort lasted 18 years, and involved the Air Force, Army, Navy, DARPA, NASA, and industry. Its objective was to conduct science and technology research that would advance the engineering of gas turbine engines used in military aircraft. The program made many significant advances that have been successfully deployed in, for example, aircraft such as the F-35 Joint Strike Fighter.¹¹⁸

Department of Agriculture

There is substantial direct and indirect energy use in the agricultural sector (Figure 4-10). Energy costs can comprise one-third to one-half of cash expenses for grain crops. Direct energy use to support farm operations (i.e., crops and livestock) comprises 60 percent of such expenses, mostly in the form of fuels to operate machinery (e.g., tilling, spraying, harvesting), and to provide ventilation, irrigation, and grain drying.

Only a small amount of energy use on farms is electricity — a few percent for grain crops; slightly more for confined animal feeding operations requiring ventilation, such as for poultry. Agriculture is heavily reliant on fuels such as diesel, gasoline, propane and liquefied petroleum gas. Forty percent of farm energy use is indirect energy used to manufacture bulk agricultural chemicals, including fertilizer and pesticides.¹¹⁹ This energy use may be further divided into process energy (the heating, cooling, and pressurization needed for manufacturing) and the inherent (chemical) energy in the chemicals themselves.

USDA offers loans and grants to support deployment in agriculture of clean-energy technologies (such as renewable generation of electricity) and to support expansion of biofuel capacity. It also funds research into elements of the biomass value chain, including conversion technologies for fuels and sustainable practices for management of forest biomass. In partnership with DOE, USDA conducts research into plant genomics to improve drought tolerance and pathogen resistance. The overall budget for these research activities at USDA is modest, less than \$5 million per year. DOE has pursued complementary programs for reducing the carbon intensity of ammonia production, as making ammonia accounts for 90 percent of the energy used in producing fertilizer.

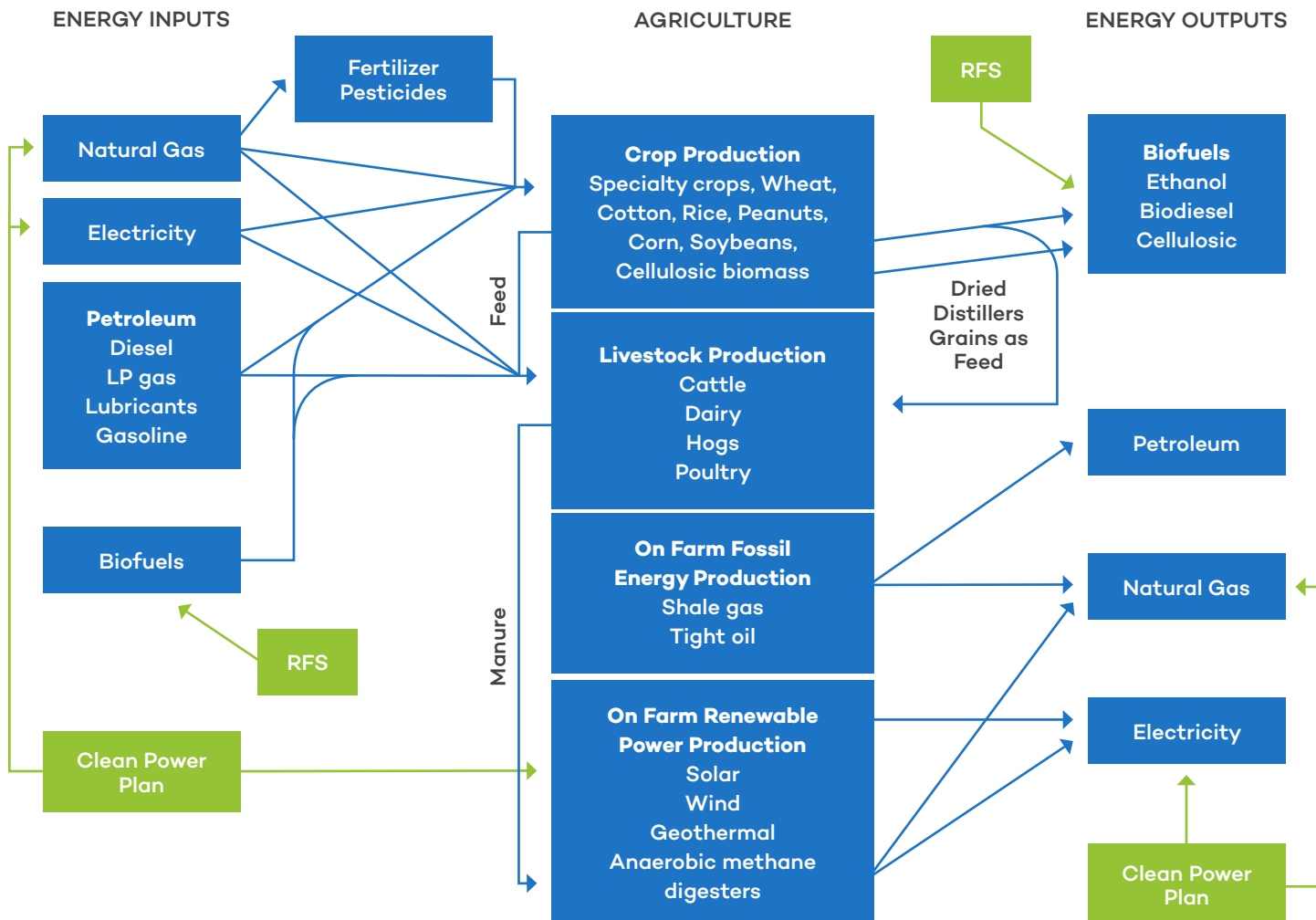
117. U.S. Department of Defense, Defense Innovation Unit Experimental, DIUx Quarterly Results: Q4 2017 (Washington, D.C., 2017), 2, <https://www.diu.xmil/download/datasets/1372/DIUx%20Q4%20FY2017.pdf>

118. John Alic, "Defense Department Energy Innovation: Three Cases," in *Energy Innovation at the Department of Defense, Assessing the Opportunities*, ed. Daniel Sarewitz and Samuel Thornstrom (Washington, D.C., Consortium for Science, Policy and Outcomes, 2012), 17, <http://bipartisanpolicy.org/wp-content/uploads/sites/default/files/Energy%20Innovation%20at%20DoD.pdf>

119. This component of energy use is often assigned to industry, specifically the chemical manufacture sector.

FIG. 4-10

Agriculture and Energy



Source: USDA, 2016

TABLE 4-2

USDA Support for Energy Programs (Budget Authority), FY 2017

Program	FY 2017
Bioenergy for Advanced Biofuels	\$14 MM
Rural Energy for America Grants	\$33 MM
Rural Energy Saving Program	\$8 MM
High Energy Costs Grants	\$10 MM
Biomass Research and Development	\$3 MM

Source: Data on FY 2017 actual levels from United States Department of Agriculture: FY 2019 Budget Summary (Washington, D.C., 2018), 35, 39, 68

As seen in Table 4-2, much of the Federal support related to energy in the agriculture sector focuses on technology adoption.

The Bioenergy for Advanced Biofuels Program promotes the development of cellulosic biorefinery capacity. The Rural Energy for America Program, a mandatory program from the 2014 Farm Bill, offers grants for deployment of renewable energy and energy efficiency technologies on farms. USDA also provides financial assistance across several programs (including the Rural Energy Saving Program) in the form of loans and loan guarantees for similar purposes. The High Energy Costs Grants help with the construction of energy generation, transmission, storage, and distribution facilities in eligible areas. The Department also provides direct payments to producers of advanced biofuels from second-generation feedstocks (e.g., from cellulosic material, agricultural waste materials, and biogas).

Innovation in the biofuels industry has sought needed chemical engineering improvements for converting second-generation feedstocks into fuels. Several of the strategies rely on enzyme-catalyzed saccharification and/or fermentation. Complementing its deployment focus for biofuels, the USDA supports the Biomass Research and Development Initiative (BRDI), at \$3 million in FY 2017, which has a focus on R&D. The BRDI is a collaborative program with the DOE in the technical areas of feedstocks development, biofuels and bio-based products development, and, biofuels development analysis.¹²⁰

In 2017, DOE and USDA jointly issued a funding opportunity announcement that \$6 million from USDA (from fiscal 2016 and 2017) and \$3 million from DOE would be made available to continue focus on these three areas and support the development of cost-competitive cellulosic biofuels.¹²¹

The National Program for Biorefining of the USDA Agricultural Research Service (ARS) has the goal of integrating new biorefining capacity with existing agriculture; the biorefinery concept promises to improve economic efficiency and has shown in the case of sugar feedstocks that co-production of ethanol and electricity for export is profitable. The Biorefining Program's nine currently-supported projects advance three program components focused on biochemical refining, biodiesel, and pyrolysis. The Program has supported novel methods for conversion of feedstocks such as cellobiose-fermenting yeast for production of cellulosic ethanol at lower cost.¹²² ARS is also funding genetic improvement work on feedstocks such as perennial grasses, biomass sorghum, energy cane, and lipid seeds.

120. "Biomass Research and Development Initiative (BRDI)," National Institute of Food and Agriculture, U.S. Department of Agriculture, accessed March 7, 2018, <https://nifa.usda.gov/funding-opportunity/biomass-research-and-development-initiative-brdi>

121. U.S. Department of Agriculture [USDA], "USDA Announces \$6 Million for Sustainable Energy Research," news release, June 5, 2017, <https://nifa.usda.gov/announcement/usda-announces-6-million-sustainable-energy-research>

122. USDA, Agricultural Research Service, National Program 213: Biorefining — National Program Annual Report: FY 2016 (Beltsville, MD, 2017), <https://www.ars.usda.gov/ARSUserFiles/np213/NP213%20FY16%20Annual%20Report%20Final.pdf>

Department of Transportation

Not surprisingly, DOT's research agenda is heavily focused on innovation for transportation systems. In November 2016, DOT designated national fueling corridors in strategic locations along major U.S. highways for plug-in electric vehicle charging and for hydrogen, propane, and natural gas stations. DOT's goal is to support the strategic deployment of advanced fueling infrastructure by the end of 2020.¹²³

The DOT has a 2017 R&D budget of approximately \$875 million, aimed principally at improving the performance and efficiency of U.S. transportation, which would clearly affect energy consumption. These efforts are complemented and coordinated with a roughly similar amount of research spending on transportation by DOE. Topics of research include vehicle battery and electrification, vehicle systems and efficiency, advanced combustion, biofuels, fuel cells, and upgrades to the national air traffic control system. The scale of DOT's R&D programs is detailed in Table 4-3.

TABLE 4-3

DOT R&D Programs (Budget Authority, Millions of Dollars), FY 2017

Agency	FY 2017 Annualized
Federal Aviation Administration	361.6
Research, Engineering, and Development	[165.7]
Federal Highway Administration	313.9
Highway Research and Development	[76.9]
Intelligent Transportation Systems	[71.5]
National Highway Traffic Safety Administration	86.4
Federal Railroad Administration	40.1
Federal Transit Administration	27.9
Pipeline and Hazardous Materials Safety Administration	21.4
Office of the Secretary	13.9
Federal Motor Carrier Safety Administration	9.0
TOTAL R&D	874.2

Source: DOT, FY 2018 Congressional Budget Justifications
(Note: Totals may not add due to rounding)

Importantly, through the National Highway Traffic and Safety Administration, DOT also administers and enforces Federal fuel efficiency standards. This program, instituted in the 1970's, has spurred the adoption of numerous technologies, including fuel injection, front-wheel drive, four-valve cylinders, and improved automotive design and manufacturing. Further improvements in technology and design will be needed to achieve increasingly stringent Federal standards.

123. DOT, RD&T Strategic Plan, 76.

DOT's transportation sector innovation focuses, in part, on more fuel-efficient vehicles and freight transport. It also includes the development of alternative fuels, in concert with improving technologies such as hydrogen fuel cells and adapting existing platforms such as internal combustion engines for natural gas or higher blends of ethanol. In addition to hardware innovation, DOT focuses on policy measures to reduce automobile usage and to address modal shifts toward mass transit — critical areas of focus, but with limited application in rural America.

DOT's stakeholders in the transportation sector face many challenges shared by other sectors of the economy, including aging systems, increased weather-related damages, threats from cyberattacks, and new and growing demands from consumers. DOT analysis has concluded that the U.S. transportation system has not kept up with increased travel demand, and that there is congestion across all transportation modes. The average urban commuter in U.S. metropolitan areas, for example, spends an estimated 42 hours per year in traffic delays, which costs the economy \$160 billion annually in wasted time and fuel.¹²⁴ The amount of freight hauled by truck and rail is expected to increase by more than 40 percent from 2015 to 2045, potentially adding to congestion.¹²⁵ Challenges are also growing for air travel. For example, increasing demand and more severe storms have led to more flight delays and cancellations. According to one study, one in five flights was delayed or cancelled in the United States in 2007, resulting in an estimated economic cost of \$33 billion per year.¹²⁶

New research and policy areas for DOT include unmanned aircraft systems, automated vehicles and other unmanned ground vehicles, the Internet of Things, and on-demand ride services. According to DOT, these emerging technologies have the potential to advance the Department's mission of "providing safe, clean, accessible, and affordable transportation."¹²⁷ Much of this work, with respect to connected vehicles, automation, and big data is done as part of DOT's Intelligent Transportation Systems Joint Programs Office.¹²⁸

In December 2016, DOT announced that it would fund \$300.3 million in grants to 32 University Transportation Centers (UTCs) across the country, to help address transportation-related challenges including better mobility of people and goods, reduced congestion and improved safety. Other challenges DOT wants to address include extending the durability and useful life of transportation infrastructure, environmental protection, and preservation of the existing transportation system.¹²⁹ Funding for the UTC program was renewed in 2015 under the Fixing America's Surface Transportation (or FAST) Act. The program is authorized to award \$72.5 million to \$77.5 million per year in grants to UTCs through FY 2020.¹³⁰ Also, in 2016, DOT conducted a "Smart City Challenge," pledging up to \$40 million to one city to fully integrate advanced transportation technologies — self-driving cars, connected vehicles, and smart sensors.¹³¹ Seven finalists leveraged DOT's funding to raise approximately \$500 million in additional funding from a diverse group of mostly private-sector partners. (See chapter 5 for more information).

In January 2018, DOT announced an effort to leverage innovative data analysis techniques to advance transportation safety, including two new pilot programs that will help integrate traditional datasets with big data sources. One pilot project will merge vehicular crash, highway design, and vehicle speed data (from GPS-enabled devices) to better assess how operating speeds contribute to the likelihood of accidents. A second pilot program will use vehicle crash data from the Waze mobile app to determine whether this data can be used as a reliable indicator of traffic accidents and thereby estimate crash risk based on such roadway hazards.¹³²

124. David Shrank et al, 2015 Urban Mobility Scorecard (College Station, TX: Texas A&M University, 2015), 17, <https://static.tti.tamu.edu/tti.tamu.edu/documents/mobility-scorecard-2015.pdf>

125. U.S. Department of Transportation [DOT], Bureau of Transportation Statistics, "DOT Releases 30-Year Freight Projections," press release no. BTS 13-16, March 3, 2016, <https://www.bts.gov/newsroom/dot-releases-30-year-freight-projections> [Note: Percentage calculated from data in Table 1]

126. Michael Ball et al, Total Delay Impact Study: A Comprehensive Assessment of the Costs and Impacts of Flight Delay in the United States, Final Report — October 2010 (College Park, MD: NEXTOR, 2010), vii, 32, https://isr.umd.edu/NEXTOR/pubs/TDI_Report_Final_10_18_10_V3.pdf

127. DOT, Research, Development, and Technology [RD&T] Strategic Plan: 2017-2021 (Washington, D.C., 2016), 13, <https://www.transportation.gov/sites/dot.gov/files/docs/USDOT-RD%26T-Strategic-Plan-Final-011117.pdf>

128. DOT, ITS Strategic Plan: 2015-2019, (Washington, D.C., 2014), v-vi, <https://www.its.dot.gov/strategicplan.pdf>

129. DOT, "U.S. Transportation Secretary Foxx Announces \$300 Million for University Transportation Center Grants," press release, December 5, 2016, <https://www.transportation.gov/content/us-transportation-secretary-foxx-announces-300-million-university-transportation-center-0>

130. DOT, RD&T Strategic Plan, 23.

131. DOT, RD&T Strategic Plan, 64.

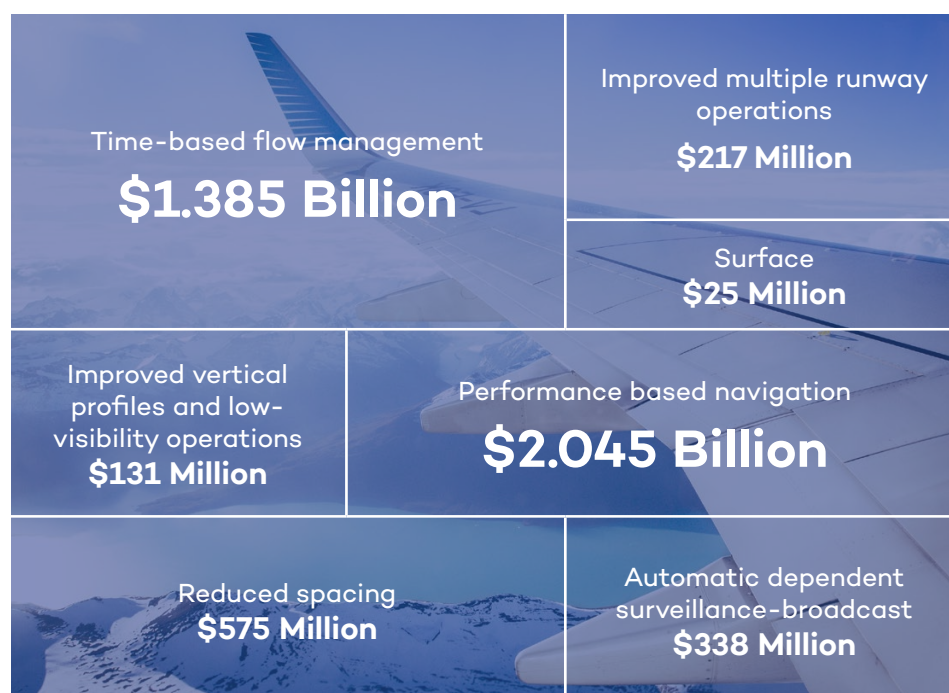
132. DOT, "USDOT Announces Safety Data Initiative, Pilot Programs to Apply Innovative Analysis to Transportation Safety," press release, January 8, 2018, <https://www.transportation.gov/briefing-room/dot0318>

DOT's "Every Place Counts" initiative has convened Federal advisors, state agencies, local officials, and community organizations to explore design approaches for the next generation of U.S. transportation systems — as the current generation of systems will reach the end of its lifespan in the next few decades. These are long-term designs for infrastructures that support communities that are connected, economically prosperous, and environmentally and physically healthy. DOT's NextGen project is tasked with the modernization of America's air transportation system by transforming its radar-based air traffic control system to a more efficient satellite-based system. According to DOT, NextGen "is delivering benefits today that increase efficiency and flexibility while reducing aviation's environmental footprint and enhancing safety" (Figure 4-11).¹³³

New opportunities are emerging to maximize RDD&D resources and activities in the transportation sector. One example involves the Federal Highway Administration (FHWA), which is helping to fund a first-of-its-kind cooperative research initiative known as the Infravation program. The Infravation program allows U.S. entities, such as academic institutions and businesses, to participate in RDD&D activities with international entities to promote transportation sector innovation. Funding for the program currently amounts to \$11 million for nine different projects. A second example involves the Twinning Initiative, co-developed by the FHWA and European Commission. This initiative pools resources between two projects that are similar in scope and objectives to maximize resource effectiveness for mutual benefit. This concept is expected to be applied frequently over the next five years and has already been successfully used for projects involving urban freight, sustainable pavements, and warm-mix asphalt.¹³⁴

FIG. 4-11

Savings from DOT's NextGen Program (Including Efficiency)



133. "Innovation," DOT 50th Anniversary, U.S. Department of Transportation, last modified June 7, 2016, <https://www.transportation.gov/transition/mission-history-goals>

134. DOT, RD&T Strategic Plan, 17.

Source: DOT website, accessed May 26, 2018

“Federal tax incentives have been a continuing source of support for the early commercial deployment of innovative energy technologies. For example, section 29 of the Internal Revenue Code, which provided a tax credit for the development of unconventional natural gas, was critical in launching the domestic unconventional natural gas industry.”

Many of the above RDD&D initiatives provide fertile ground for collaboration between DOT and DOE. In 2016, DOT and DOE signed a memorandum of understanding (MOU) to develop a joint action plan covering a range of increasingly interrelated topics between the transportation and energy systems. These topics include Smart Cities, connected and automated vehicles, alternative fuels, and electric vehicle research.¹³⁵

Other Federal Support for Energy Innovation

Other agencies provide targeted support for energy innovation as part of their broader missions and portfolios. The National Science Foundation (NSF) has a total budget of about \$7.5 billion, supporting basic research and education programs across the entire physical spectrum of the physical sciences and engineering disciplines. It is estimated that about \$0.5 billion (6.7 percent of the NSF budget) supports a portfolio of investments in fundamental science and engineering research with potential applicability to energy. Most NSF funding supports principal investigators in universities, but NSF also supports university-based research centers designed to foster cross-disciplinary initiatives in various areas of science, technology, and energy innovation.

NASA has a total budget of about \$19.5 billion supporting a broad mission in space science and exploration, including astronomy, earth observations from space, and human spaceflight. NASA supports R&D related to energy innovation as an important enabler of spaceflight and space power technologies. It also provides support for aeronautics R&D. This program, with a budget of \$650 million, aims to expand the boundaries of aeronautical knowledge for the benefit of the Nation and the broad aeronautics community. The aeronautics R&D program includes integrated research in airspace operations and safety, advanced air vehicles, integrated aviation systems, and transformative aeronautics concepts.

Refocusing Future Federal Tax Policy to Spur Innovation

Federal tax incentives have been a continuing source of support for the early commercial deployment of innovative energy technologies. For example, section 29 of the Internal Revenue Code, which provided a tax credit for the development of unconventional natural gas, was critical in launching the domestic unconventional natural gas industry.

The Tax Cuts and Jobs Act of 2017 left intact the current production tax credits for wind and solar, as well as the investment tax credit for solar energy. The Bipartisan Budget Act (BBA) extended other energy tax incentives, including the extension of the current production tax credit for new nuclear power generation facilities, as well as existing credits for energy efficiency, fuel cells, alternative fuel infrastructure, and biofuels. Finally, the BBA provided a new program of tax incentives (in section 45Q of the Internal Revenue Code) for carbon capture, utilization and storage.

While the particulars of the renewable energy production tax credit (PTC) and solar investment tax credit (ITC) remain unchanged, the value of these credits will be reduced due to other changes in the Tax Cut and Jobs Act.

- The lower corporate tax rate will reduce the amount of funding that can be raised for renewables projects from third-party investors who are looking to share the tax benefits from the project (termed tax-equity investors). Their tax benefit consists of both the tax credit for the project (worth about 30 cents per

135. DOT, RD&T Strategic Plan, 14.

dollar invested) and depreciation (prior to the Act, worth about 26 cents per dollar invested). With a reduction of the corporate tax rate from 35 percent to 21 percent, depreciation on any given project will be worth less. For this reason, the amount of tax equity that can be raised, as part of the financing for the project, will decrease. It is estimated that tax equity currently accounts for between 50 and 60 percent of the capital financing of a wind farm and between 40 and 50 percent of the capital financing of a typical solar project.

- The Act also includes a base erosion anti-abuse (BEAT) tax that may also reduce incentives for tax-equity investments. This is because the purchase and use of renewable tax credits reduces the value of tax liability that is protected from the BEAT tax. Additionally, the structure of the BEAT tax makes it difficult for tax-equity investors to know if they will receive all the tax credits they were expecting when they close a tax-equity deal.¹³⁶

There are several other provisions in the Act that might negatively impact innovation, such as a cap on interest deductions for larger companies, and a requirement that revenues from prepaid power contracts be reported as lump sum.

The Act contains other provisions that will positively affect the financing for innovative technologies. While the reduction by the Act of the corporate tax rate from 35 percent to 21 percent, as noted above, may reduce the amount of tax equity raised for renewable energy projects, this reduction, which is intended to spur increased capital investment across the board, may stimulate R&D investment. The Act also allows pass-through entities to exclude 20 percent of otherwise taxable income from taxation; this provision also benefits Master Limited Partnerships, which are important for some energy technologies. In addition, the Act provides for faster write-off of new equipment, allowing 100 percent expensing of the cost of equipment, both new and used. Finally, it should be noted that the Tax Cut and Jobs Act leaves unchanged the research and experimentation tax credit, applicable to all industries and R&D investment. The subsidy value of this credit is estimated to be \$13.26 billion over the next 10 years.¹³⁷

Energy Tax Policy Options

Congress has periodically addressed energy tax policy issues, and likely will continue to do so in future years. This may provide a window of time to explore and analyze alternative tax policy options that are more targeted to incentivize innovation, for future consideration by the Administration and Congress.

There are two broad policy issues to be considered in the assessment of future Federal energy tax policies to support innovation:

- What are the relative merits, and appropriate mix, between tax incentives and direct investment in targeted cost-shared R&D, as an enabler of private sector investment in energy innovation; and
- What is the most beneficial design framework of a future energy innovation tax policy?

On the first issue, there is analytical evidence that “R&D tax credits have a positive effect on private R&D investment.”¹³⁸ There are valid arguments to be made that a program of targeted Federal direct investment in R&D is more cost efficient than a broad-based tax incentive because it minimizes the possibility of rewarding actions that might otherwise be taken in the absence of the incentive. On the other hand, a tax incentive can encourage demand pull for energy innovation by lowering the cost

136. Keith Martin, “Final U.S. Tax Bill: Effect on Project Finance Market,” Norton Rose Fulbright, December 16, 2017, <http://www.nortonrosefulbright.com/knowledge/publications/160375/final-us-tax-bill-effect-on-project-finance-market>

137. OMB, Analytical Perspectives, FY 2018, 140.

138. Becker, “Public R&D Policies and Private R&D Investment.”

of initial commercial introduction, thereby creating more incentive for innovators to move forward toward commercialization. There also is evidence that “both policy tools may be more effective if performed in a coordinated way and that the tax credits are the more effective short-run policy option, while direct subsidies are the more effective medium to long-run policy.”¹³⁹

On the second issue, Federal energy tax incentives historically have been structured as technology or fuel specific, i.e. designed to support a particular fuel or technology. Energy tax incentives also have been typically put in place for a finite period, and subject to periodic Congressional review and reconsideration. In several instances, caps are imposed on the quantity of whatever qualifies for the tax credit. A case in point is the current consumer tax credit for the purchase of electric vehicles; the credits are capped at specific volume limits for each automaker after which the credit is reduced and ultimately eliminated. The current production tax credit for wind energy projects is another example, it has a specific phase down schedule based on the date when a qualified project enters service. The limitations on time or quantity are influenced as much or more with a view toward reducing the “budget score” for the overall tax legislation, rather than from a detailed analysis of what is needed to encourage early commercialization and move down the learning curve.

A new approach for an innovation-focused tax policy to encourage initial commercial deployment of new energy technologies and systems could be fashioned based on the following principles:

- It should be as broad-based and technology-neutral as possible, allowing innovation across the entire breadth of the energy landscape to qualify; the incentive should not pre-select a particular fuel or technology;
- It should reward performance rather than investment, with a clearly defined performance metric;
- It should not be designed to support a specific market share target, but instead be limited, based on time or quantity, based on a reasonable projection of the deployment learning curve, with a clear exit strategy that avoids the potential for creating a permanent subsidy; and
- It should reward early adopters, through some combination of bonuses to early adopter and reduced benefits to later adopters. A phase-down schedule also would enable the exit strategy.

A new, innovation-focused energy tax policy could be designed either as a tax credit or as a tax adder. A technology-neutral tax credit could be established based on the degree of improvement in system energy efficiency, reduction in water use, or reduction in emissions of greenhouse gases or other pollutants. The credit could encourage innovation across all fuels and technologies. One example is the Section 45Q for carbon capture and sequestration. The credit is technology and fuel neutral, as it would provide a specific per ton credit for carbon removed from the environment from any source, including carbon already diluted in the atmosphere. Another example is the legislative proposal, the Technology-Neutral Tax Credit Act (H.R. 7196; Reed, R-NY), introduced in the last Congress. A refocused, innovation-based set of tax incentives could leverage significant new private investment in early deployment at a cost within the current budget envelope of the current tax credits. A future innovation-based tax incentive with an annual cost in the range of about \$6 billion (slightly less than the FY 2017 budget cost of current energy tax credits) could be phased in as the current renewable energy deployment credits begin to expire.

139. Becker, “Public R&D Policies and Private R&D Investment,” 936.

An alternative tax policy approach to incentivizing technology-neutral energy innovation would be to set a tax charge on fuels or technologies. The charge could penalize those fuels or technologies that are relatively energy inefficient; another approach would be to set a charge based on the externality cost of an energy source that is not otherwise reflected in its market price. The “gas guzzler” tax on fuel inefficient vehicles (now expired) was one such approach; it was intended to complement CAFE standards by encouraging automakers to manufacture, and consumers to purchase, vehicles that were more fuel efficient. Another approach is an economy-wide carbon charge. An economy-wide carbon charge would not only incentivize accelerated deployment of low-carbon and carbon free energy solutions, but it also would incentivize acceleration across the full range of research, development, demonstration and deployment. A number of studies indicate that there would be benefits from an economy-wide, broad-based carbon charge as a central driver of innovation in clean energy technology and the most efficient way to internalize the cost of carbon emissions.¹⁴⁰ There are a number of design issues that would need to be addressed in fashioning a specific proposal, including the size of the charge, how it might vary over time, and the use of the incremental revenues garnered by the charge. Legislative proposals were introduced in both Houses in the last Congress (H.R. 6463 and 7172; S. 2368 and 3791), with both Republican and Democratic sponsors, to establish a national carbon charge program, with proceeds rebated to consumers on a per capita basis.

The Looming Impact of Discretionary Spending Caps

Virtually all Federal agency energy RDD&D investment is currently classified as discretionary spending. Annual budget levels for this spending are set within a framework of statutory spending caps for defense and non-defense discretionary spending. There have been strong political divisions in recent years over the appropriate level for discretionary spending, particularly for non-defense spending, leading to significant differences in targets for spending from year to year.

The statutory caps for discretionary spending — the so-called sequester caps — were set for a 10-year period through FY 2021 in the Budget Control Act of 2011 (BCA), but have been modified by subsequent budget acts, annual Congressional Budget Resolutions, and the Bipartisan Budget Act (BBA), as shown in Figure 4-12.

The Administration's proposed FY 2018 budget would have reduced the non-defense caps by \$54 billion below the BCA cap, with a corresponding increase for defense spending. After much disagreement and two short government shutdowns, Congress finally adopted revised spending caps for FY 2018 and FY 2019 in the Bipartisan Budget Act (BBA), enacted in early February 2018. The Administration's proposed FY 2019 budget initially re-proposed substantial reductions in the BCA budget cap for non-defense spending, with a last-minute adjustment that still fell short of the revised FY 2019 cap set in the BBA.

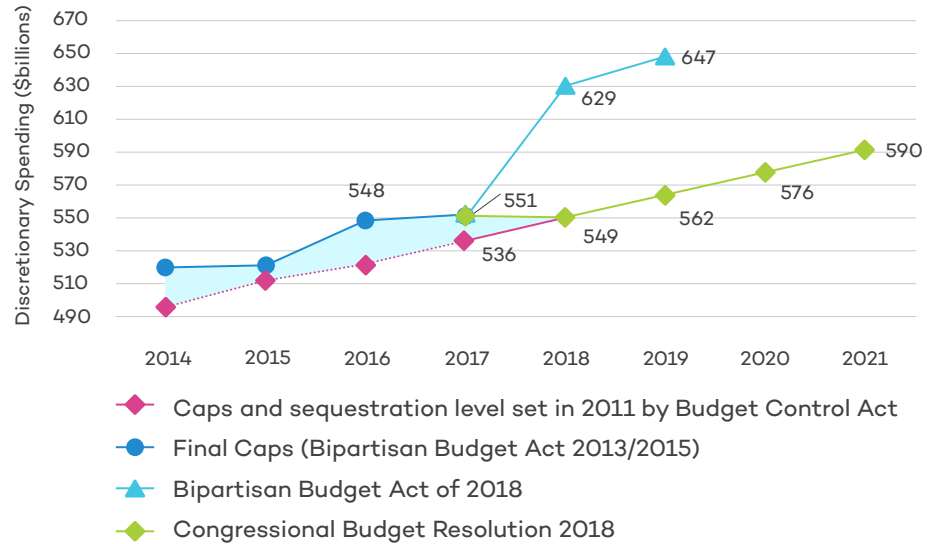
The large magnitude of the differences between Administration and Congressional fiscal policy, combined with the uncertainties created in the process of budget deliberations, have significant adverse implications for clean energy RDD&D, and for the ability of the U.S. to meet key competitive, security and environmental goals. The magnitude of the swings in the non-defense spending cap levels — increases in FY 2018 and FY 2019 but much lower levels beginning in FY 2020 —

140. Citations to individual studies are too numerous to cite here. Collections of studies on this topic can be found at www.rff.org and www.mitei.org

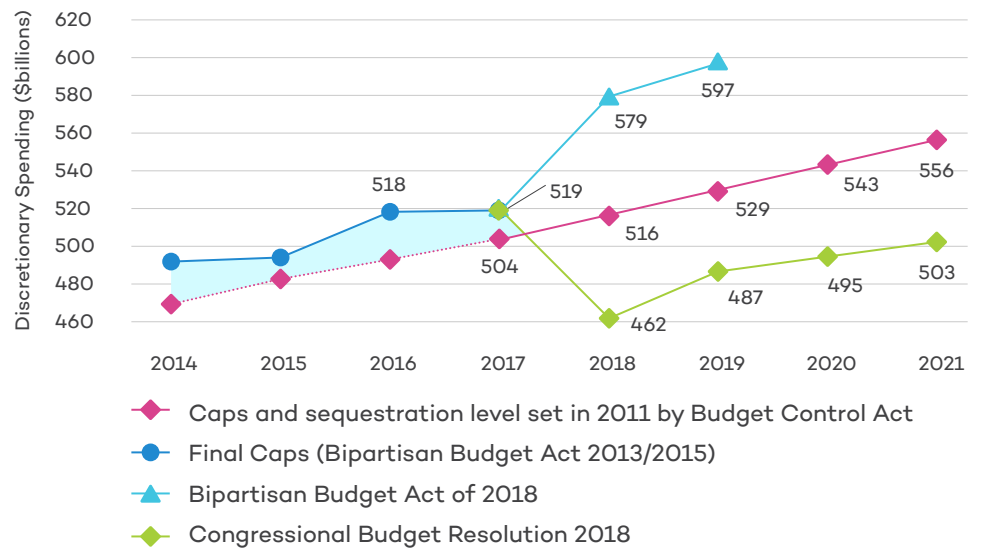
FIG. 4-12

Discretionary Spending Caps (\$ Billions)

Defense Caps



Non-Defense Caps



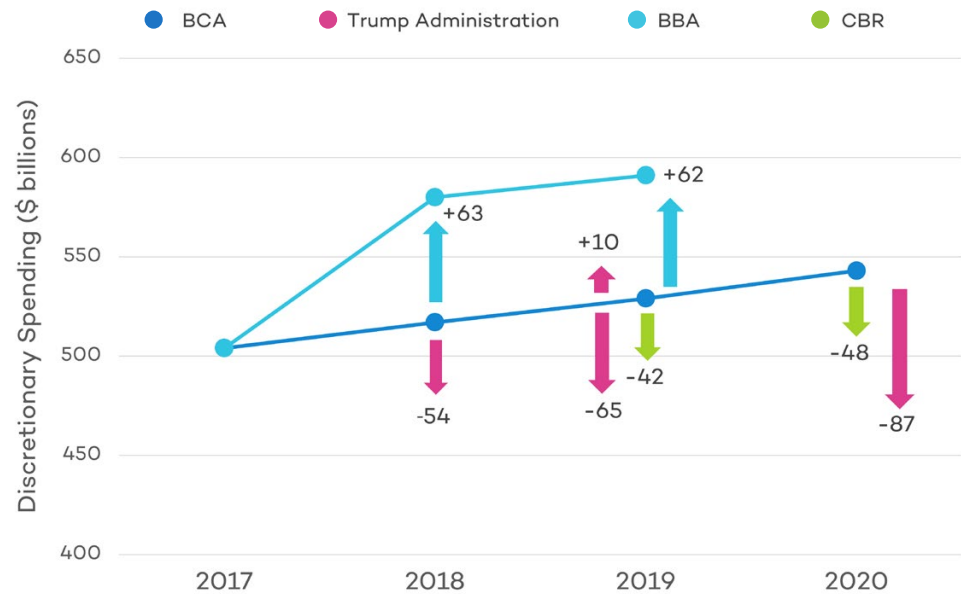
The CBR exerts considerable downward pressure on non-defense discretionary spending, including for clean energy innovation.

Source: Energy Futures Initiative (EFI), 2017, compiled from Budget Control Act of 2011 and Congressional Budget Resolution for FY 2018

is virtually unprecedented in the Federal budget process (see Figure 4-13). This is creating substantial uncertainty for program managers and industry partners in developing a balanced R&D portfolio and implementing multiyear research programs and projects.

FIG. 4-13

Range of Potential Changes in the Non-Defense Discretionary Spending Caps



There are significant differences in the top-line caps on non-defense discretionary spending. BCA = Budget Control Act, BBA = Bipartisan Budget Act, CBR = Continuing Budget Resolution.

Source: Energy Futures Initiative (EFI), 2018, compiled from Budget Control Act of 2011, Congressional Budget Resolution for FY 2018, Bipartisan Budget Act of 2018, and Tax Cuts and Jobs Act of 2017

“Federal policymakers — and the thought leaders that support them — must make decisions about the importance of clean energy innovation for meeting critical imperatives for the Nation’s security, for its global competitiveness, and for climate change mitigation in an environment of high uncertainty and budget constraints.”

The Administration’s FY 2018 budget proposal for DOE came in below the Congressionally-established budget caps, cutting DOE applied R&D programs by nearly half and eliminating entirely both ARPA-E and the DOE loan and loan guarantee programs. The final FY 2018 appropriations bill enacted by Congress, however, had a quite different outcome, actually increasing DOE’s R&D funding. The final bill provided funding increases of 16 percent for DOE’s Office of Science and 10 percent in total for all of DOE’s applied energy R&D accounts, including a 15 percent increase for ARPA-E. The current balances of lending authority in the DOE loan programs remained unchanged.

Federal policymakers — and the thought leaders that support them — must make decisions about the importance of clean energy innovation for meeting critical imperatives for the Nation’s security, for its global competitiveness, and for climate change mitigation in an environment of high uncertainty and budget constraints.

141. Calculated from data in American Association for the Advancement of Science, "Trends in Federal R&D as % of GDP, FY 1976-2017," June 2016, <http://www.aaas.org/sites/default/files/RDGP%3B.xlsx>

142. Calculated as the sum of three figures: (1) net sales, receipts, and operating revenues for Petroleum and coal products [NAICS 211], (2) net revenue for Electric power generation, transmission and distribution [NAICS 2211], and (3) net revenue from Natural gas distribution [NAICS 2212], all for 2016 Q4 through 2017 Q3. The data for NAICS 211 is in U.S. Census Bureau "Quarterly Financial Report" accessed March 6, 2018, <https://www.census.gov/econ/currentdata/dbsearch?program=QFR&startYear=2016&endYear=2018&categories=324&dataType=101&geoLevel=US¬Adjusted=1&submit=GET+DATA&releaseScheduled=->. The data for NAICS 2211 and NAICS 2212 is in U.S. Census.

143. American Energy Innovation Council [AEIC], A Business Plan for America's Energy Future (Washington, D.C.: Bipartisan Policy Center, 2010), 5, http://americanenergyinnovation.org/wp-content/uploads/2012/04/AEIC_The_Business_Plan_2010.pdf

144. AEIC, The Power of Innovation: Inventing the Future (Washington, D.C.: Bipartisan Policy Center, 2017), 9-10, <http://americanenergyinnovation.org/wp-content/uploads/2017/06/AEIC-The-Power-of-Innovation-Inventing-the-Future.pdf>. [Note: The number that AEIC used for energy sales, from data in the Energy Information Administration (EIA) Short-Term Energy Outlook for February 2017, derives from total U.S. end-use energy expenditures in the EIA State Energy Data System.]

145. <https://docs.house.gov/meetings/AP/AP00/20180516/108312/HRPT-115-HR-FY2019-EnergyandWater.pdf>

146. <https://docs.house.gov/meetings/AP/AP10/20180507/108254/BILLS-115HR-SC-AP-FY2019-EnergyWater-SubcommitteeDraft.pdf>

147. <https://www.congress.gov/115/crpt/srpt258/CRPT-115srpt258.pdf>

148. <https://www.appropriations.senate.gov/imo/media/doc/FY2019%20Energy%20&%20Water%20Development%20Appropriations%20Act,%20Report%20115-258.pdf>

The Administration's FY 2019 budget again proposed substantial reductions in funding for DOE science and energy programs — an overall reduction of 31 percent — notwithstanding the increased headroom in the revised non-defense discretionary spending cap set in the BBA. The FY19 budget proposal, once again, would have terminated ARPA-E and the DOE loan programs. Action in the House and Senate Appropriations Committees has rejected these cuts and instead provides modest increases of 3–4 percent in FY 2019 funding relative to the FY 2018 enacted levels. Final action is pending.

The budget outlook for FY 2020 will cause further uncertainty for planning an effective energy innovation portfolio. Even with the most optimistic scenario (i.e., some form of continuation of the BBA caps into FY 2020 and beyond), the longer-term outlook for discretionary spending, including Federal investment support for energy innovation, remains highly constrained. Federal policymakers and the thought leaders that support them must make decisions about the importance of clean energy innovation for meeting national imperatives in an environment of high uncertainty and budget constraints.

Although the Federal clean energy RD&D portfolio is significant (approximately \$6.4 billion in FY 2016), some prominent government and industry leaders have recommended the need for funding levels at two to three times the current levels. One such estimate results from matching the historic scale of Federal R&D support across the board (an average of just under 0.91 percent of gross domestic product, from 1997 to 2016)¹⁴¹ to the current value of the energy industry to the economy (roughly \$1.37 trillion).¹⁴² Using this benchmark, Federal R&D for energy should be \$12.5 billion per year. A similar level has been advanced by the American Energy Innovation Council (AEIC), a group of 10 of the nation's most preeminent corporate leaders. In 2010, the AEIC called for a tripling of Federal investment in energy research, development, and demonstration (RD&D), to a minimum of \$16 billion per year.¹⁴³ In its most recent report, the AEIC again called for this level of Federal investment in energy RD&D, recommending that Federal investment reach 1.6 percent of energy sales, which the AEIC stated would "bring spending on energy innovation closer to, although still well short of, other advanced technology sectors."¹⁴⁴

Congress is taking its own measure on the role of the Federal government in supporting development, demonstration and deployment. The House of Representatives Appropriations Committee report on FY 2019 appropriations for DOE states that:^{145, 146}

"Early-stage research and development has an appropriate place in a balanced research portfolio. However, the Committee believes that a focus on only early-stage activities will forego the nation's scientific capabilities in medium- and later-stage research and development and may not fully realize the technological advancements possible under the Department's applied energy activities."

The Senate Appropriations Committee report on its version of the FY 2019 bill is more definitive about the limitation of a strategy focused on only early-stage research and the need for an energy innovation strategy that includes later-stage R&D, as well as demonstration and deployment activities, stating that:^{147, 148}

"The Committee believes that such an approach will not successfully integrate the results of early-stage research and development into the U.S. energy system and thus will not adequately deliver innovative energy technologies, practices, and information to American consumers and companies. The Committee directs the Department to implement mid- and late-stage research and development activities as directed in this report in a timely manner."

TEXT BOX 4-5

The American Energy Innovation Council on Federal Support for Energy Innovation

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

Source: The Power of Innovation: Inventing the Future, AEIC, 2017

Seeking Federal Funding Certainty for Direct Federal Investment in Innovation

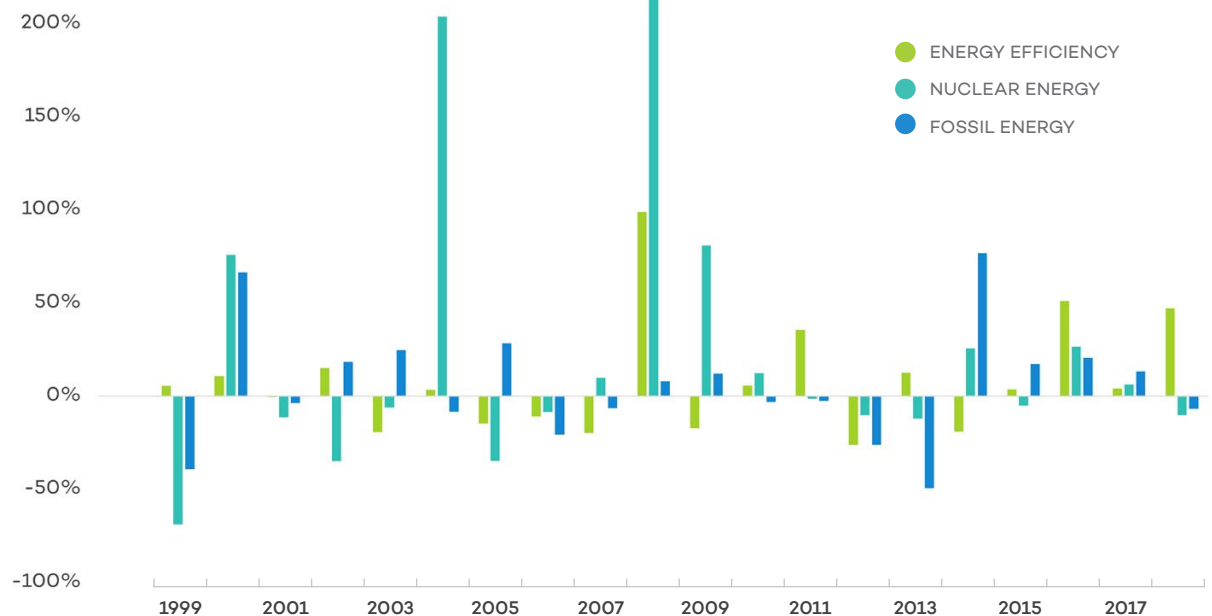
The process of annual appropriations introduces large uncertainties into the process of planning and executing the portfolio, due to the uncertainties and delays associated with annual budget cap negotiations and the resulting dependence on stop-gap Continuing Resolutions. Large swings in year-on-year funding (as illustrated in Figure 4-14) — evidencing an underlying lack of a consensus on innovation policy — is also a significant factor leading to inefficiencies in the way Federal energy R&D funds are deployed.

There have been several alternative funding models that have achieved better innovation performance than likely would have been attained if funded through annual appropriations. The DOE Clean Coal Technology Program in the 1980s and 1990s, for example, was funded through advance appropriations that automatically became available in future fiscal years. This led to greater certainty in cost-sharing arrangements and more successful demonstration project outcomes. The practice of advanced appropriations has since been prohibited by Congress, except in a few grandfathered circumstances. More recently, in 2015, DOE was able to obtain a special funding mechanism for modernization of the Strategic Petroleum Reserve (SPR). The Bipartisan Budget Act of 2015 authorized annual appropriations totaling \$2 billion for SPR modernization, offset by the sale of SPR oil. While annual funding levels are set in appropriations acts, the use of a dedicated offset isolates the program from the uncertainties and constraints of the non-defense discretionary caps.

In 2016, Congress enacted the 21st Century Cures Act, which sought to increase funding for NIH research programs by authorizing an increment of annual appropriations totaling \$4.8 billion over 10 years, outside of the discretionary spending caps. The funds were intended to increase the level of annual funding normally appropriated to NIH. To comply with budget scoring rules, the new funding (outside the cap) was partially offset by the sale of oil from the SPR. However, the

FIG. 4-14

Volatility in Funding for Select DOE Programs (Annual Percent Change)



Funding volatility throughout DOE can hinder clean energy innovation and increase uncertainty for portfolio planning.

Source: Energy Futures Initiative (EFI), 2017. Compiled from AAAS, 2017, U.S. Department of Energy R&D

Trump Administration FY 2018 budget proposed to circumvent this Congressional intent by seeking \$495 million in incremental appropriations while cutting the base NIH appropriation by \$5 billion (from roughly \$35 billion to \$30 billion).¹⁴⁹

Another idea that has been advanced from time to time is to divide Federal discretionary funding into an annual operating budget and an investment (or capital) budget, each with separate rules. The investment budget could be shaped within a multiyear framework, enabling more efficient and effective application of funds. State and local governments typically employ separate capital budgets, but since the late 1960s, the Federal government has operated under unified, cash-basis budgeting.

The approach most likely to lead to stable multiyear funding for energy technology investment is the establishment of a special fund with two key characteristics:

- it is financed through a dedicated revenue source and not dependent on annual appropriations drawn from the General Fund of the Treasury; and
- it either scored as a net zero with respect to domestic discretionary spending caps or is operated outside the caps entirely but subject to Congressional oversight.

The Ultra Deepwater and Unconventional Natural Gas and Other Petroleum Fund, enacted by a Republican-controlled Congress in 2005, and financed from Federal oil and gas royalty receipts, was such a fund. This Fund was not only financed solely from royalties, it also was not subject to annual appropriations, although

149. OMB, Appendix: Budget of the U.S. Government, Fiscal Year 2018 (Washington, D.C.: Government Publishing Office, 2017), 435-436, <https://www.govinfo.gov/content/pkg/BUDGET-2018-APP/pdf/BUDGET-2018-APP.pdf>

Congress exercised oversight through review of the annual program plan. Because the research program was intended to provide new technologies to expand natural gas and petroleum production from Federal lands, it offered the possibility to eventually become self-sustaining.

Another approach to providing stable funding would be to institute a national public benefits charge on electricity, implemented through some form of “wires charge” or upstream charge on fuels for electricity. Another model that could be considered would be a non-governmental entity to manage the R&D program but funded through a governmentally-controlled charge. The Gas Research Institute (GRI) and the Electric Power Research Institute (EPRI) provide examples of R&D funding approved by Federal and state regulators, respectively:

- GRI was a non-profit, non-governmental entity established by the natural gas industry in 1976. It was funded by a mandatory surcharge placed by the Federal Energy Regulatory Commission (FERC) on natural gas volumes in interstate commerce. At its peak annual funding level in the early 1990s, the GRI annual budget was more than \$200 million, financed by a surcharge of about 1.5 cents per thousand cubic feet of gas transported by interstate pipeline companies. The mandatory surcharge was phased out over a seven-year period by FERC beginning in 1998. The Gas Technology Institute (GTI) is the successor organization to GRI and is currently funded from voluntary contributions from natural gas utilities. GTI revenues totaled \$103 million in 2016.
- EPRI is a non-profit, non-governmental entity established by the electric power industry in 1973. It was originally funded through a voluntary charge placed on sales revenues and approved by state public utility commissions. The suggested charge was 0.1 mills per kilowatt-hour (kWh) of electricity. EPRI restructured its program around 2000 to a business model that was project-based, with voluntary cost sharing from interested companies on a project-by-project basis. Revenues in 2015 totaled approximately \$407 million. Based on the prior charge regime, in 2016 EPRI's budget would have been \$3.76 billion, if 0.1 mills had been collected for every kWh consumed at retail nationwide.

Movement toward a more assured funding structure for energy innovation could provide a significant boost to the pace and effectiveness of the innovation process. Much work would need to be done to develop a new funding mechanism that would be supported by stakeholders and acceptable under current budget scoring rules.

RECOMMENDATIONS

Regarding the Role of the Federal Government in the Energy Innovation Ecosystem

- The critical collaboration between public and private sector players would be strengthened by several adjustments to the current scope and administration of federal clean energy activities. Private sector commitments to develop and adopt new clean technologies draw heavily on the foundational scientific insights and risk mitigation provided by federal energy innovation programs.
- Establishment of a reliable source of DOE R&D funding. This step would facilitate planning on the part of universities, labs, and the private sector, and permit researchers and entrepreneurs to commit to the multi-year undertakings needed for advances in clean energy. Dedicated sources of federal R&D funding should be evaluated. These can be employed to more directly engage industry to ensure alignment of policies, programs, and players.
- A long-term increase in such funding to the levels recommended in previous studies based on international and cross-industry benchmarks — approximately twice today's level. This increase would accelerate economy-wide engagement in clean energy invention and development.
- Expansion of DOE loan programs to support late-stage demonstration and early deployment of clean energy innovations by the private sector. The program could leverage \$100 billion of incremental energy investment without requiring new appropriations.
- Implementation of administrative and legislative reforms to increase the impact of the department's R&D programs. These reforms include:
 - Organizational and budgeting alignment around critical energy applications and highest priority opportunities, to reflect the need for systems-level integration and to avoid gaps in programs that span multiple fuels.
 - A multi-year and multi-agency portfolio planning process with broad-based stakeholder involvement.
 - Greater use of flexible financial vehicles like Technology Investment Agreements and prize competitions to simplify public-private partnerships.
 - Strengthened management of demonstration projects through stage-gated project management, risk-based cost sharing, and assignment of demonstration project oversight to a single office.
 - Clearer performance standards at each stage of the innovation process to assist potential investors in evaluating risk.
 - Systemic assessment of clean energy innovation progress and the impact of Federal programs.

Chapter 5. The Role of State, Local, and Tribal Governments in Clean Energy Innovation

This chapter reviews the principal forms of state, local, and tribal government support for clean energy innovation and identifies opportunities to improve current programs. It considers the essential roles that state and local governments play in the development of clean energy ecosystems and markets. It describes the utilization, at both these levels of government, of tools such as mandates, improved approval processes, and financing programs. It also examines how tribal and rural lands are serving as test beds for clean energy technology, providing an important link in the chain of clean energy innovation. Finally, this chapter discusses federal support for state, local, and tribal government initiatives.

FINDINGS

The Role of State, Local, and Tribal Governments in Clean Energy Innovation

- Using a variety of tools, notably mandates, financing programs, and cap-and-trade greenhouse gas programs, state and local governments are creating markets for clean energy technologies. State renewable portfolio standard (RPS) programs in 29 states and Washington, D.C. cover 56 percent of total U.S. electricity sales. Twenty-four states and Washington, D.C. have adopted energy efficiency resource standards.
- State and local commitments to the Paris Climate Agreement could create a large market for future clean energy innovation. The states, cities, and businesses that have made these commitments represent more than half of U.S. gross domestic product (GDP).
- Barriers to optimizing these programs and policies include considerable variations among state and local government policies and practices; the complexity of financing programs; the administrative and resource burdens associated with some of these programs; the consequences of standards, regulations, and ratemaking practices that have not kept pace with innovation and the market; and legacy programs that may hinder the flexibility and adaptability of a modernized energy system.
- Traditional ratemaking policies and methodologies at the state and local level can act as barriers to deployment of innovative energy technologies.
- Clean energy technologies are an important feature of the numerous smart city initiatives currently underway in urban areas. These technologies also offer solutions to challenges faced by rural and remote communities.
- Federal programs created to promote innovation at the state, local and tribal levels require improvements in design, implementation, and funding in order to achieve their stated objectives.

State and local governments play a central role in the clean energy innovation ecosystem. State and local regulations and incentives have supported the deployment of solar and wind generation and a broad array of energy efficiency technologies. They have provided innovative financing mechanisms for clean energy adoption, and they have encouraged the application of smart technologies to energy systems. Such programs have created a substantial market for clean energy technologies, enabling those technologies to achieve scale economies and prices that are competitive in some areas with traditional technologies and systems.

Tribal governments, in addition to deploying clean energy in their communities, provide testbeds for distributed forms of energy generation and energy-efficient equipment, as they respond to the challenges of serving communities in remote areas with low population density, where energy costs are high relative to household income.

The Role of States in Creating Clean Energy Markets

Twenty-two states and the largest cities in 11 other states have announced their intention to continue to meet the goals of the Paris Climate Agreement. These communities represent a substantial market for clean energy innovations.¹⁵⁰

Several states have committed to specific goals and actions to mitigate climate change. These vary widely in their dates of adoption, target dates, and levels of commitment. Examples include the following:

- **Maryland:** Maryland has set a goal to reduce GHG emissions statewide by 25 percent by 2020. Legislation in 2016 further extended the goal to a 40 percent reduction by 2030, requiring long-term cuts in pollution.
- **New York:** New York will reduce GHG emissions by 40 percent (from 1990 levels) by 2030 and by 80 percent by 2050. The actions under the plan — which includes increased maintenance and testing for oil and gas infrastructure, reductions in organic waste, and methane collection at landfills — are expected to be implemented by 2020.
- **New Mexico:** Issued in 2005, Executive Order 05-033 sets statewide GHG emission reduction targets of 2000 emission levels by 2012, 10 percent below 2000 levels by 2020, and 75 percent below 2000 emission levels by 2050.
- **Maine:** In 2003, Maine established statewide GHG emission reduction targets of 1990 levels by 2010, 10 percent below 1990 levels by 2020, and 75 to 80 percent below 2003 levels in the long term.
- **California:** By executive order, the state must cut GHGs to 40 percent below 1990 levels by the year 2030. That is an interim target, intended to help California lower emissions to 80 percent below 1990 levels by the year 2050, a goal set by Governor Arnold Schwarzenegger.

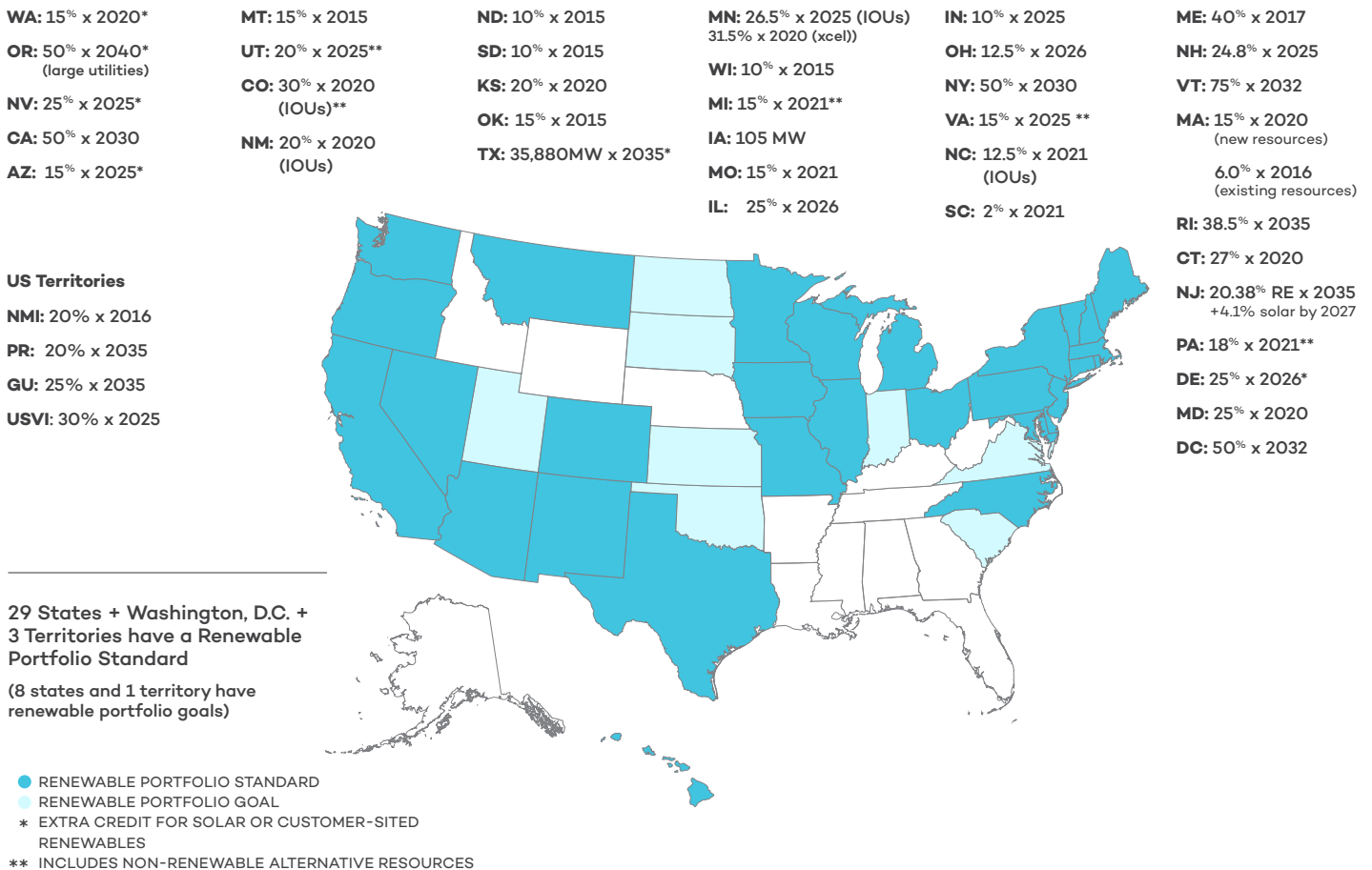
Such clean energy programs fall into two basic categories:

- **Policies that create markets.** States have adopted policies addressing climate change and limiting GHG emissions, and have also created renewable portfolio standard (RPS) or energy efficiency resource standard (EERS) programs. Additionally, they've adopted or strengthened building codes and standards, and standardized and accelerated permitting for clean energy. These measures have created or increased market demand for clean energy innovations.

150. America's Pledge, America's Pledge Phase 1 Report: States, Cities, and Businesses in the United States Are Stepping Up on Climate Action (New York: Bloomberg Philanthropies, 2017), 9, <http://www.bbhub.io/dotorg/sites/28/2017/11/AmericasPledgePhaseOneReportWeb.pdf>

FIG. 5-1

Renewable Portfolio Standard Policies



The majority of states and territories have RPS policies. Those that do not have RPS policies are primarily in the South and Midwest.

Source: North Carolina Clean Energy Technology Center, "Renewable Portfolio Standards," Detailed Summary Maps

151. "State Energy Financing Programs," Financing Committee, National Association of State Energy Officials, accessed March 11, 2018, <https://www.naseo.org/state-energy-financing-programs>

152. Council of Development Finance Agencies, Energy Investment Partnerships: What They Are & How to Get Started (Washington, D.C.: Department of Energy, 2016), 2, <https://www.energy.gov/sites/prod/files/2016/04/f30/February%2023%2C%202016%20Energy%20Investment%20Partnerships%20Webinar%20Series%20What%20Is%20It%20and%20How%20to%20Get%20Started%20Fact%20Sheet.pdf>

- **Policies that overcome economic barriers to clean energy.** States have created a variety of mechanisms to address the economic barriers to deploying clean energy technologies. According to the National Association of State Energy Officials, nearly every state energy office is involved in clean energy financing. Clean energy financing tools include state clean energy funds; green banks; energy efficiency loans; qualified energy conservation bonds; property assessed clean energy (PACE); energy technology-based economic development, commercialization, and investment programs; and alternative fuel vehicle and infrastructure financing programs.¹⁵¹ Table 5-1 shows examples of the use of these mechanisms across eight states.¹⁵² To generate funds for these efforts, some states have used public benefits charges. In addition to these economic incentives, states are encouraging new business models supporting clean energy to emerge in the utility sector and are using innovative ratemaking as a tool to encourage the early deployment of new technologies.

TABLE 5-1

Volatility in Funding for Select DOE Programs (Annual Percent Change)

State	Entity	Programs	Legal Structure	Capitalization	Market Sectors
CA	CA Alternative energy & Advanced Transportation	PACE Loss Reserve; CA Hub for Energy Efficiency Financing	State agency	State allocation + CA PUC allocation	Residential & commercial; efficiency & renewables
CA	CA Infrastructure and Economic Development Bank	CA Lending for Energy and Environmental Needs Center	State agency	Self-capitalized	State & local govt; efficiency; renewables; water conservation; distribution
CT	CT Green Bank	CT solar lease; Energize Connecticut Smart E-Loan; C-PACE; CT solar loan	State agency	System benefits charges + RGGI funds + U.S. DOE grant + private investments + fees	Residential & commercial; efficiency & renewables
FL	Solar & Energy Loan Fund	Clean Energy Loan Fund	Non-profit, CDFI	U.S. DOE grant + private investments	Residential & commercial; efficiency & renewables
HI	Hawaii Green Infrastructure Authority	Green Energy Market Securitization	State agency	Bonds + utility fees	Residential & commercial; efficiency & renewables
NJ	NJ Board of Public Utilities	NJ Clean Energy	State agency	Self-capitalized	Residential & commercial; efficiency & renewables
NJ	NJ Energy Resilience Bank	Wastewater and water treatment plant funding	State agency	U.S. Dept. of Housing and Urban Development grant	Utilities; renewables
NY	NY State Energy Research & Development Authority	Green jobs-Green NY	State agency	System benefits charges + RGGI funds + U.S. DOE grant + Qualified Energy Conservation Bonds	Residential & commercial; efficiency
NY	NY Green Bank	Clean energy financial products and advisory services	Division of a state agency, NYSERDA	Allocation of uncommitted Efficiency & RPS & system benefits charges funds	Residential & commercial; efficiency & renewables
OH	Toledo-Lucas County Port Authority	Better Buildings NW Ohio	Local agency	Fees + U.S. DOE grants + tax levy	Residential & commercial; efficiency & renewables
OH	Greater Cincinnati Energy Alliance	Greater Cincinnati Home Energy Loan; Building Communities Loan	Non-profit	U.S. DOE grant + private impact investment + fees	Residential & non-profit; efficiency & renewables
OH	Port of Greater Cincinnati Development Authority	Greater Cincinnati PACE	Local agency	Fees + county and city allocation	Commercial; efficiency & renewables
OR	Energy Trust of OR	General efficiency incentives	Non-profit	System benefits charge	Residential & commercial; efficiency

There are many clean energy financing tools available across the United States.

Source: Council of Development Finance Agencies, Energy Investment Partnerships, 2

State Renewable Portfolio Standards

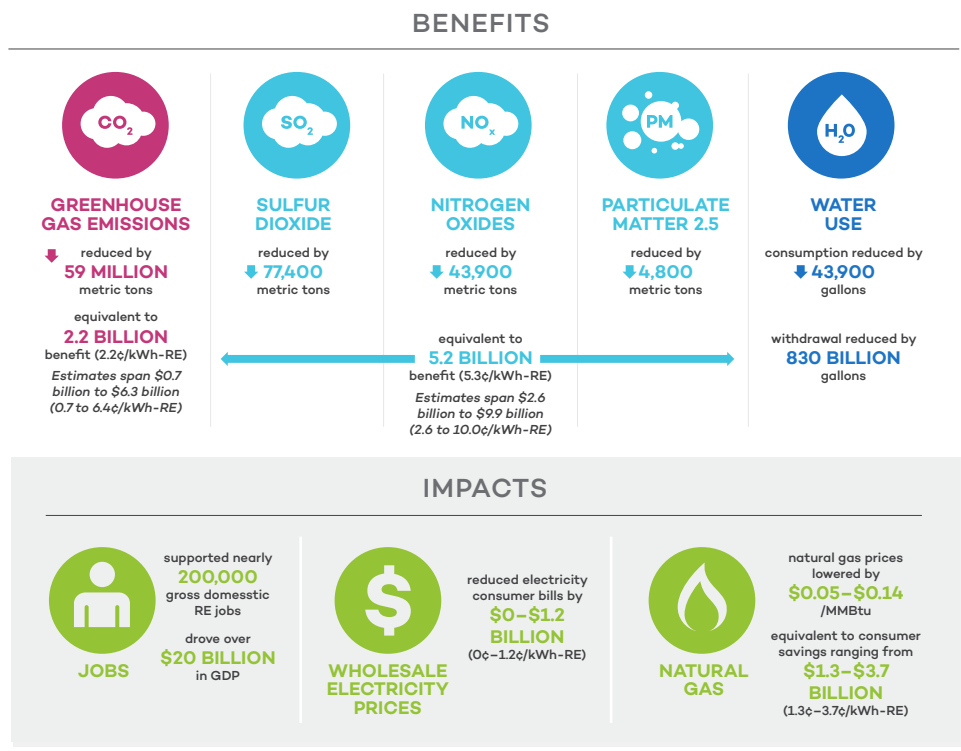
Twenty-nine states and Washington, D.C., collectively covering 56 percent of total U.S. retail electricity sales, have established renewable portfolio standards (RPS) (Figure 5-1).¹⁵³ Voluntary renewable standards exist in eight other states, and mandatory or voluntary RPS policies exist in four U.S. territories.¹⁵⁴ These policies have achieved 95 percent of their goals. Between 2000 and 2015, 60 percent of all growth in U.S. renewable energy generation and 57 percent of new U.S. generation capacity was tied to state RPS requirements. To appreciate the impact, if all states with RPS policies met their goals, renewable generation would see a 50 percent increase over 2016 levels by 2030.¹⁵⁵

A 2016 report by the National Renewable Energy Laboratory, working with Lawrence Berkeley National Laboratory, estimated substantial benefits from state RPS mandates (Figure 5-2), including health benefits from reduced pollutants, lower natural gas and wholesale electricity prices, and jobs and economic development. The report estimates—30,000 jobs were created in operations and maintenance (mostly in solar), while 170,000 were created in construction (mostly in wind), as a result of the RPS.¹⁵⁶

The two maps in Figure 5-3 show total solar jobs, solar jobs per capita, total wind jobs, and the number of wind manufacturing facilities. A comparison between these maps and the map in Figure 5-1 shows the association between states with RPS policies and solar and wind jobs.

FIG. 5-2

Impact & Benefits of State Policies



State RPS policies can produce a myriad of benefits.

Source: Wiser et al., *Retrospective Analysis of the Benefits and Impacts of U.S. Renewable Portfolio Standards*, 2016

153. Galen Barbose, "U.S. Renewables Portfolio Standards: 2017 Annual Status Report" (slides), July 2017, slide 6, <http://eta-publications.lbl.gov/sites/default/files/2017-annual-rps-summary-report.pdf>

154. Jocelyn Durkay, "State Renewable Portfolio Standards and Goals," Energy, Research, National Conference of State Legislatures, August 1, 2017, <http://www.ncsl.org/research/energy/renewable-portfolio-standards.aspx>

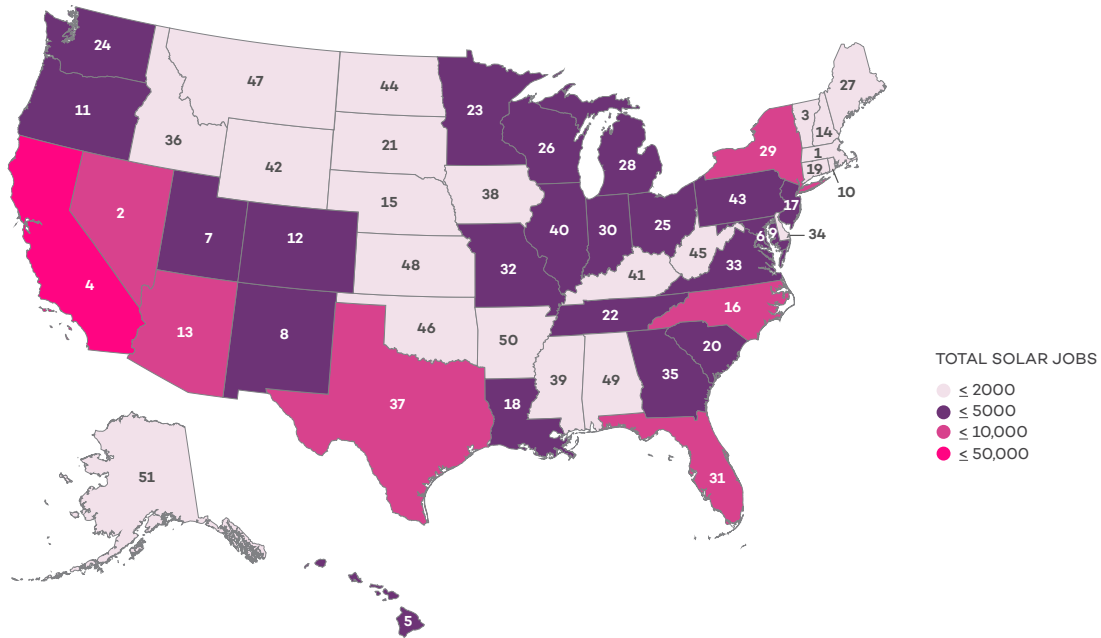
155. Barbose, "U.S. Renewables Portfolio Standards," slide 22. 158. Wiser et al., *Retrospective Analysis*, viii.

156. Wiser et al., *Retrospective Analysis*, viii.

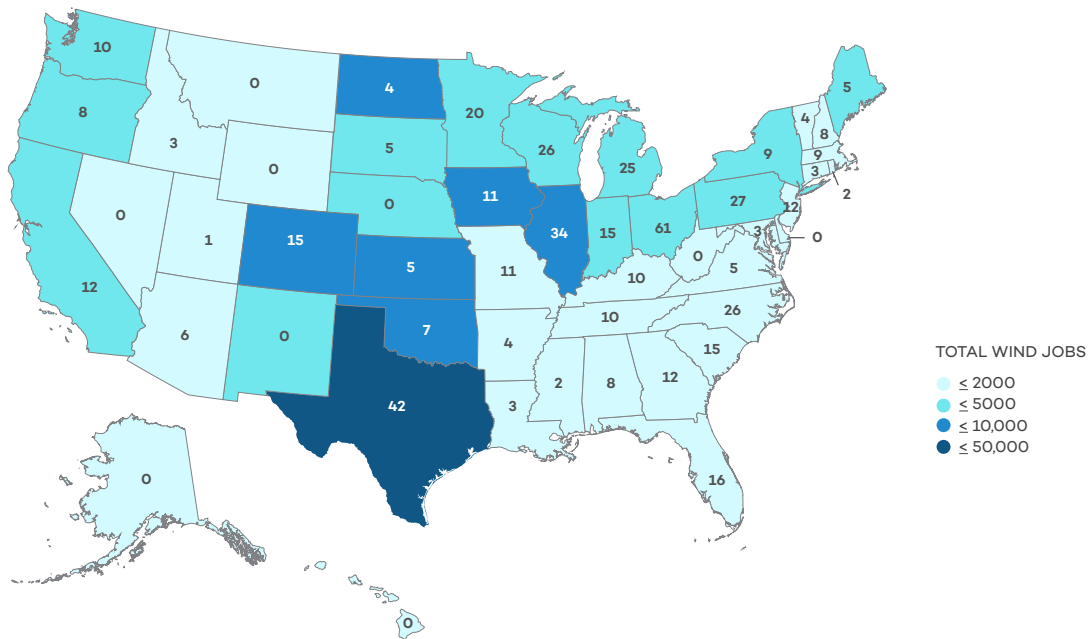
FIG. 5-3

Solar Industry Data by State 2016 and Wind Industry Data by State, 2017

Total Solar Jobs and Solar Jobs Per Capita Rankings by U.S. State, 2016



Total Wind Jobs and Wind Manufacturing Facilities by U.S. State, 2017



The maps reveal the scope and geographic concentration of solar jobs and wind jobs and facilities.

Source: Energy Futures Initiative (EFI), 2018; compiled using data from The Solar Foundation and American Wind Energy Association

Clean Energy Standards

A Clean Energy Standard (CES) is similar to an RPS except that requirements may be met by sources other than renewables such as fuel cells, energy storage and nuclear generation. This is attractive from a regional perspective, where energy mixes for power generation and technologies to mitigate CO₂ emissions may vary widely. CES requirements vary widely by state as to whether they are mandatory or voluntary, how stringent they are, and what types of non-renewable options they include.¹⁵⁷ Text Box 5-1 summarizes some of these activities and programs.

State Energy Efficiency Resource Standards

Energy efficiency resource standards (EERS)¹⁵⁸ are policies that require utilities or other entities to achieve a specified amount of energy savings through energy efficiency programs within a specific timeframe.¹⁵⁹ Twenty-four states and Washington, D.C., have an EERS and six states have energy efficiency goals or pilot programs.¹⁶⁰ An EERS sets a minimum amount of savings to be achieved and allows utilities to develop and implement the strategy to attain those savings. Tools include demand-side management incentives, building codes, peak demand reductions, and consumer-driven actions. States have generally achieved compliance with EERS targets and many have increased the stringency of their targets.¹⁶¹

Savings associated with state energy efficiency deployment are significant. Utilities manage EERS programs and report the costs of those programs annually, as well as the reduction in power sales attributable to them. Assuming that most of the reductions reported in a given year persist into future years, the average cost across the U.S. of achieving a reduction of one MWh of consumption through EERS has been approximately \$20. This cost compares favorably with the retail cost of consuming a MWh, which is in the range of \$90 to \$100.

157. For purposes of this discussion, a clean energy standard is defined as, "...a type of electricity portfolio standard that would set aggregate targets for the level of clean energy that electric utilities would need to sell while giving electric utilities flexibility by: (1) defining clean energy more broadly than just renewables, and (2) allowing for market-based credit trading to facilitate lower-cost compliance. As a concept, a CES builds on the successful experience of the majority of states that have implemented renewable and alternative energy portfolio standards and draws on a history of federal policy deliberation regarding national electricity portfolio standards." Clean Energy Standards: State and Federal Policy Options and Implications, C2ES/RAP, 2011.

158. For purposes of this discussion, the American Council for an Energy-Efficient Economy definition of an EERS is used: "Energy Efficiency Resource Standard (EERS) establishes specific, long-term targets for energy savings that utilities or non-utility program administrators must meet through customer energy efficiency programs. An EERS can apply to either electricity or natural gas utilities, or both, depending.

159. Daniel C. Steinberg and Owen Zinaman, State Energy Efficiency Resource Standards: Design, Status, and Impacts, NREL/TP-6A20-61023 (Golden, CO: National Renewable Energy Laboratory, 2014), vi, <https://www.nrel.gov/docs/fy14osti/61023.pdf>

160. <https://www.eia.gov/todayinenergy/detail.php?id=32332>

161. Steinberg and Zinaman, State Energy Efficiency Resource Standards, 3.

"Savings associated with state energy efficiency deployment are significant. Utilities manage EERS programs and report the costs of those programs annually, as well as the reduction in power sales attributable to them."

TEXT BOX 5-1

State Activities on Clean Energy Standards

- The **New York** CES requires fifty percent of electricity to be derived from renewable energy sources by 2030 and requires load serving entities to procure zero-emissions credits from three existing nuclear plants.
- The **Massachusetts** Clean Energy Standard sets a minimum percentage of electricity sales that must be derived from clean energy sources, beginning at 16 percent in 2018 and rising to 80 percent in 2050.
- **Indiana** has a voluntary CES, with a target of four percent from 2013 to 2018, increasing to seven percent in 2019, and 10 percent post 2019. Twenty-one clean energy technologies qualify for compliance including wind, solar, hydropower, fuel cells, hydrogen, energy storage systems, nuclear energy, and electricity from natural gas that displaces an existing coal-fired plant.
- **New Jersey** recently increased its RPS targets and includes 2 GW of energy storage by 2030. At the same time, New Jersey also became the third state, after New York and Illinois, to pass a nuclear plant credit, through a zero-emission credit program, although it wasn't part of the RPS.
- **New Mexico** has begun considering a Clean Energy Standard with a goal of lowering carbon pollution by electric utilities by four percent per year from 2012 levels, resulting in an 80 percent reduction by 2040. The program, as proposed, would be market-based, and the requirement can be met by increasing generation at low carbon plants, energy efficiency, and renewables.
- The national think tank, **Third Way**, acknowledging that "renewable sources alone cannot support the transition to clean energy fast enough or across all regions," proposed a national clean energy standard in 2011 and recently reiterated its support for the CES as well as a carbon tax. The Third Way proposal would require each state to meet a CES standard of at least 25 percent by 2025 and 50 percent by 2050. Clean energy would include renewables, energy efficiency, natural gas that displaces coal, coal with CCS, waste-to-energy, biomass, and nuclear power.

Building Energy Codes and Standards

The residential end-use sector (i.e., homes and apartments) and the commercial end-use sector (i.e., offices, malls, stores, schools, hospitals, hotels, warehouses, restaurants, and places of worship and public assembly) together account for 40 percent of energy end use in the United States.¹⁶²

The direct GHG emissions from these two sectors, together known as the buildings sector, account for 12 percent of total U.S. GHG emissions.¹⁶³ States and many local governments¹⁶⁴ set and enforce building codes and standards, tools that have been effective in addressing these emissions and in deploying clean energy technology, particularly for energy efficiency (Figure 5-4).¹⁶⁵

Homeowners typically spend about \$2,300 a year on energy — more than on property taxes or insurance. Savings associated with energy efficiency can be significant. According to the National Association of Homebuilders, “Nine out of ten buyers would rather buy a home with energy-efficient features and permanently lower utility bills than one without those features that costs 2 percent to 3 percent less.”¹⁶⁶

While more stringent building codes can reduce total energy use of new buildings, building codes vary significantly by state, and the lack of uniformity in updating building energy codes potentially costs U.S. consumers billions of dollars. According to estimates by the Alliance to Save Energy, nationwide compliance with the 2012 International Energy Conservation Code would save U.S. consumers \$40 billion by 2030, from a 2013 baseline. In Peoria, Illinois, for example, building a house under the 2012 International Energy Conservation Code would save the average homeowner between \$9,870 and \$10,080 over the course of a 30-year mortgage, compared to a house built under the 2006 code.¹⁶⁷

162. “Use of Energy in the United States Explained,” Energy Information Administration, last modified June 1, 2017, https://www.eia.gov/energyexplained/index.cfm?page=us_energy_use

163. “Sources of Greenhouse Gas Emissions: Overview,” Environmental Protection Agency, accessed March 11, 2018, <https://www.epa.gov/ghgemissions/sources-greenhouse-gas-emissions>.

164. In states known as home rule states, the state constitution grants local governments authority to make a legislative decision not addressed by the states.

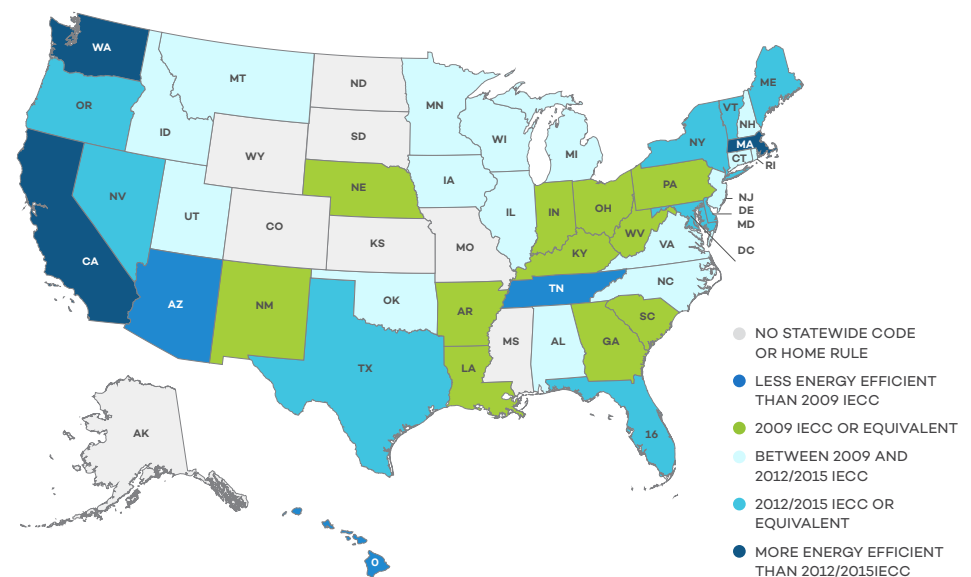
165. “Status of State Energy Code Adoption,” Building Energy Codes Program, Energy Efficiency and Renewable Energy, Department of Energy, last modified December 15, 2017, <https://www.energycodes.gov/status-state-energy-code-adoption>

166. Diana Olick, “What Home Buyers Want,” Realty Check, CNBC, February 25, 2013, <https://www.cnbc.com/id/100491599>

167. “Who Benefits from More Efficient Energy Codes?,” Codes, Energy Efficient Codes Coalition, accessed March 11, 2018, <http://energyefficientcodes.com/codes/>

FIG. 5-4

Building Energy Codes by State & Year — Residential Buildings

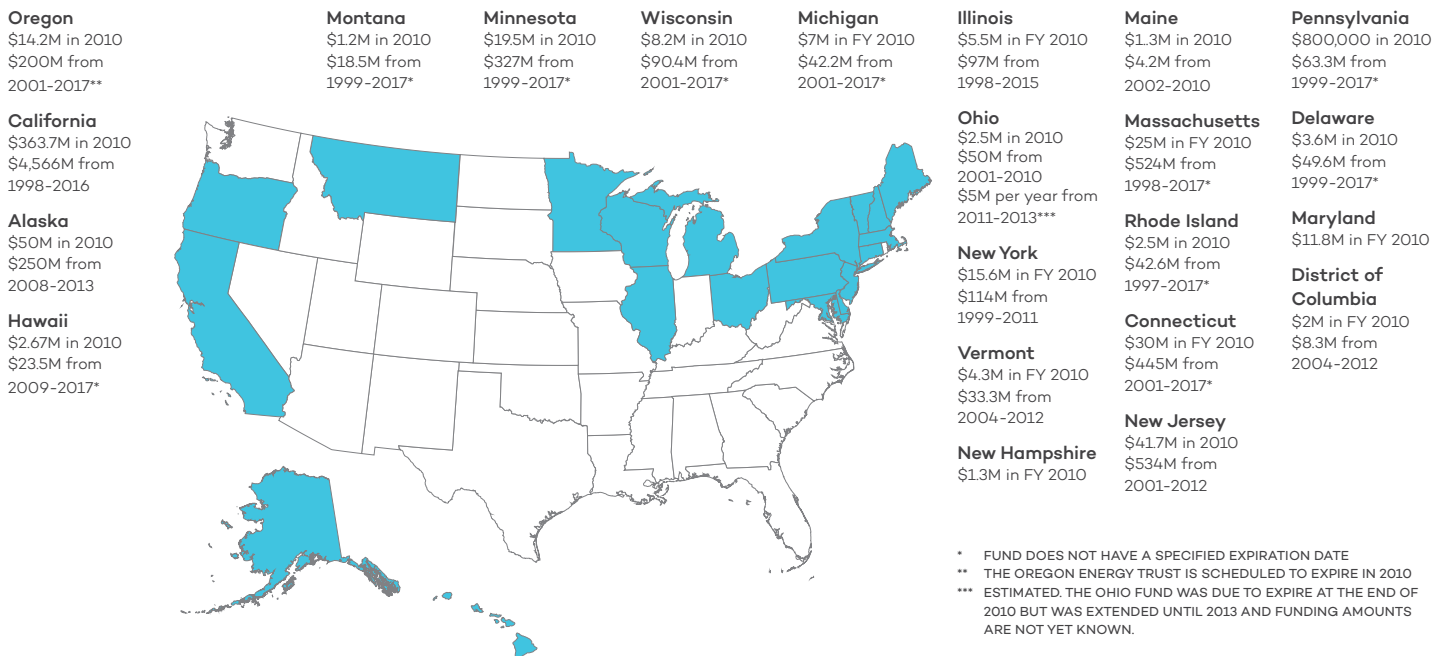


The map suggests considerable variation but limited progress in state building energy codes.

Source: DOE

FIG. 5-5

State Clean Energy Funds Investment in Renewable Energy



Investment figures include only funding in designated state CEFs supported by utility ratepayer surcharges, with the exception of Alaska's legislatively appropriated fund. Otherwise, figures do not include ARRA funds, funds that support RPS efforts, or funds that are raised through bonds or legislative appropriations. As such, the figures presented here represent a lower bound on total state investment in renewable energy.

Source: DSIRE 2011 and CESA 2011

Permitting Processes

Substantial savings could result from accelerated and standardized permitting processes for key clean energy technologies. Streamlining procedures and enhancing process consistency across jurisdictions can help lower costs for developers, governments, and consumers.¹⁶⁸ Delays associated with permitting are not trivial: DOE analysis suggests that 40 percent of the cost of a rooftop solar PV system is associated with permitting process, interconnection, and inspection (PII) requirements, and concludes that standardization of permitting processes is essential for increasing consumer savings.¹⁶⁹ In the United States, permitting for rooftop solar takes almost 23 hours at a cost of \$0.24 per watt; compared to Germany where permitting takes five hours and costs \$0.03 per watt.¹⁷⁰

State Clean Energy Funds

Over 20 states and Washington, D.C., have established Clean Energy Funds to support energy innovation deployment (Figure 5-5). Such initiatives include support for clean technology innovation, clean technology companies, and business incubator programs. These funds receive about \$500 million per year in dedicated support from a variety of sources, including state government budget allocations, loan authorizations, surcharges on electric bills, or climate change-related revenue such as revenue from auction of carbon allowances by the Regional Greenhouse Gas Initiative of nine northeast states.¹⁷¹

168. "Permitting," Regulatory Reform, Interstate Renewable Energy Council, accessed March 11, 2018, <https://irecusa.org/regulatory-reform/permitting/>

169. Minh Le, "Finding Solutions to Solar's Soft Cost Dilemma," Department of Energy, January 8, 2013, <https://www.energy.gov/articles/finding-solutions-solars-soft-cost-dilemma>

170. Joachim Seel, Galen Barbose, and Ryan Wiser, "Why Are Residential PV Prices in Germany So Much Lower Than in the United States? A Scoping Analysis: February 2013 Revision," (slides), Lawrence Berkeley National Laboratory, February 2013, slide 31, <https://emp.lbl.gov/sites/all/files/german-us-pv-price-ppt.pdf>

171. Lewis Milford et al., Leveraging State Clean Energy Funds for Economic Development (Washington, D.C.: Brookings Institution, 2012), 2-3, <https://www.brookings.edu/research/leveraging-state-clean-energy-funds-for-economic-development/>

State clean energy funds generally utilize a project finance model that can directly promote clean energy project installation through rebates, grants, loans, and performance-based incentives.¹⁷² Clean energy funds can incentivize projects and mitigate significant upfront capital costs.¹⁷³ States may consider developing dedicated clean energy revenue streams to develop project finance and engage smart industry support. A viable revenue stream, according to a Brookings-Rockefeller Project report, may be electricity surcharges set on electricity consumption, since this model is generally a stable and reliable revenue source.¹⁷⁴ This idea is a form of a public benefit charge, discussed below.

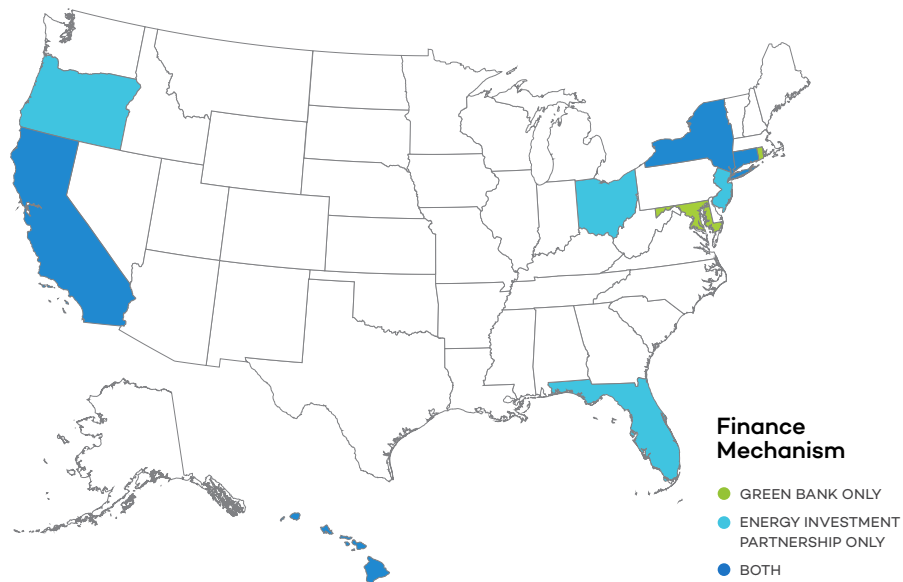
State Green Banks

Green banks are publicly capitalized, domestically focused, financial institutions specifically established to stimulate private investment in clean energy and other green infrastructure. Green banks connect clean energy projects with capital markets and unlock new pools of capital such as institutional investors and the bond market. They are funded through various means, including direct appropriations by the state government (as in New York), application of public benefits charges to electric bills, and issuing bonds to underwrite projects.

Funds from green banks are made available as loans, not grants, with the expectation of recouping all overhead and loan costs and recycling the funding for more projects in the future. Six states have green banks (Figure 5-6)¹⁷⁵; some lend only to municipalities or public organizations such as school systems, universities, or housing authorities. Eight states including California, Connecticut, Florida, Hawaii, New Jersey, New York, Ohio, and Oregon have Energy Investment Partnerships that provide similar financing support.¹⁷⁶

FIG. 5-6

States with Green Banks or Energy Investment Partnerships



Six states currently have green banks (CA, CT, HI, MD, NY, RI), and eight states have energy investment partnerships (CA, CT, FL, HI, NJ, NY, OH, OR).

Source: Energy Futures Initiative (EFI) 2018, compiled using data from U.S. Department of Energy

172. Milford et al., Leveraging State Clean Energy Funds, 3.

173. Milford et al., Leveraging State Clean Energy Funds, 4.

174. Milford et al., Leveraging State Clean Energy Funds, 8.

175. <https://www.nrel.gov/state-local-tribal/basics-green-banks.html>

176. <https://www.energy.gov/sites/prod/files/2016/01/f28/Energy%20Investment%20Partnerships.pdf>

Each green bank's commitment to local market transformation must be translated into unique regional and local strategies, policies and strengths. The New York Green Bank uses an open solicitation process to generate financing strategies from the market that have the potential to scale, while the Connecticut Green Bank has taken a programmatic path to scale by developing distribution channels for standardized solar loans and leases to decrease risks and transaction cost.

Property Assessed Clean Energy Financing (PACE)

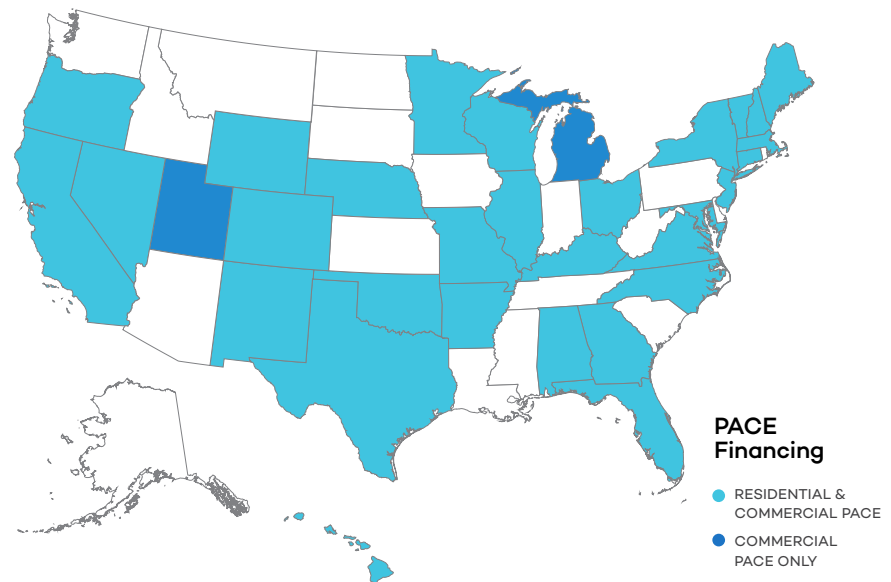
PACE, a major state loan program, is an innovative mechanism for financing energy efficiency and renewable energy improvements on private property. PACE programs offer loans for residential and commercial renewable energy and efficiency improvements.

PACE programs allow state governments, or local governments or other inter-jurisdictional authorities (when authorized by state law), to fund the upfront cost of energy improvements on commercial (C-PACE) and residential (R-PACE) properties, which are paid back over time by the property owners. Thirty-one states, plus Washington, D.C., have both C-PACE and R-PACE programs, while two states maintain only commercial programs (Figure 5-7).¹⁷⁷

Both C-PACE and R-PACE financing have expanded substantially from the program's early years (see Figure 5-8),¹⁷⁸ indicating a high level of interest in PACE programs across the country.

FIG. 5-7

States with PACE Programs



177. "Property Assessed Clean Energy (PACE) Programs" (map), Library, Center for Climate and Energy Solutions, last modified July 2017, <https://www.c2es.org/document/property-assessed-clean-energy-pace-programs/>

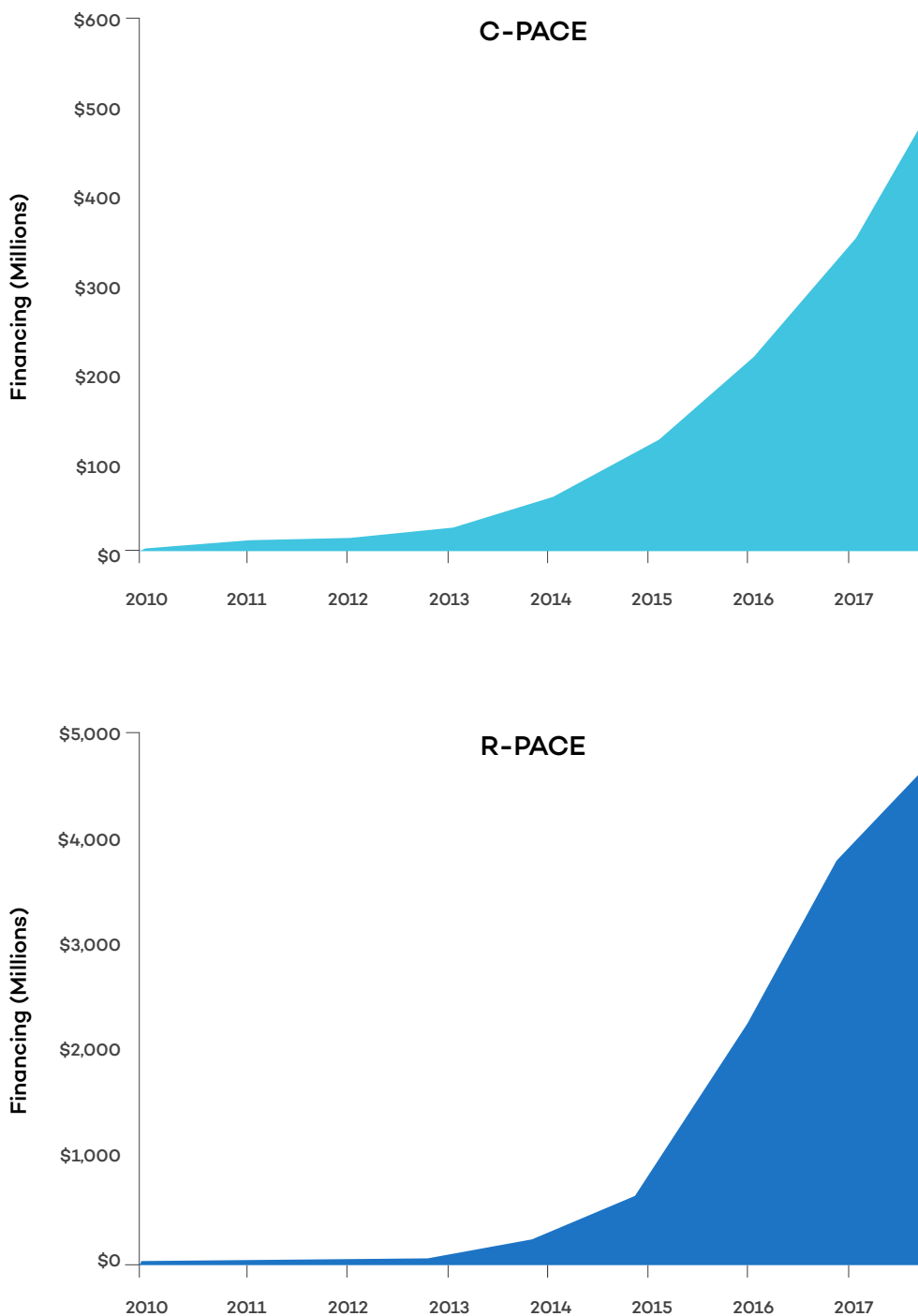
178. "PACE Market Data," PaceNation, accessed March 11, 2018, <http://pacenation.us/pace-market-data/>

The majority of states have authorized a PACE Program; however, Texas and many states in the Midwest have not.

Source: EFI 2018, compiled using data from Center for Climate and Energy Solutions, 2017

FIG. 5-8

Commercial and Residential PACE Program Financing, 2010-2016



Figures indicate the strong upward trajectory of PACE financing, especially residential.

Source: "Pace Market Data," PaceNation, <http://pacenation.us/pace-market-data/>

A PACE program serves to finance efficiency improvements without large up-front cash payments. Under PACE, repayment is spread over multiple years and the cost of financing may be lower, as well. In addition, PACE programs may enable some property owners to deduct interest payments on their PACE loan.^{179,180} Homeowners in jurisdictions that have established PACE programming may fund upgrades such as solar panel installation, duct replacement, new insulation, and in hurricane-prone areas, impact-resistant windows. Commercial PACE programs are broader and may enable financing air circulation projects, heating and cooling, and generation from alternative energy sources.¹⁸¹ In addition to supporting residential and commercial property owners, the PACE program enables municipalities to encourage energy efficiency and renewable energy without placing general funds at risk (Text Box 5-2). It also represents significant engagement with private capital, such as the municipal bond markets.¹⁸²

Despite the many benefits of the PACE program, there are notable challenges to its efficacy and employment. While well-designed PACE programs save energy, money, or both for higher-income households, several consumer protection organizations have advised DOE that PACE programs are not appropriate for low-income homeowners. This is because low-income homeowners are eligible for free or lower-cost energy efficiency programs such as the Weatherization Assistance Program and because they may not be able to afford the addition of a PACE loan to their mortgage. These organizations also found that a number of PACE programs have few consumer protections.¹⁸³

In addition, since a government assessment is placed on the property under the PACE program, it automatically becomes the first lien for any property, which suggests that in the case of foreclosure or default, all missed payments on the property assessment must be paid before the mortgage is paid back. Thus,

179. Mike Centore, "IRS Says PACE Interest Falls Under Mortgage Deductibility Guidelines," PACE News, PACENation, July 11, 2016, <http://pacenation.us/irs-says-pace-interest-falls-mortgage-deductibility-guidelines/>

180. "Property Assessed Clean Energy Programs," State and Local Solution Center, Office of Energy Efficiency and Renewable Energy, Department of Energy, accessed March 11, 2018, <https://www.energy.gov/eere/slsc/property-assessed-clean-energy-programs>

181. Devon Thorsby, "Why You May Want to Rethink a PACE Loan for Energy-Efficient Home Improvements," U.S. News, December 14, 2016, <https://realestate.usnews.com/real-estate/articles/why-you-may-want-to-rethink-a-pace-loan-for-energy-efficient-home-improvements>

182. "Property Assessed Clean Energy Programs," Department of Energy.

183. "PACE Energy Efficiency Mortgages Still Risky Despite New Department of Energy Guidelines," news release, National Consumer Law Center, November 18, 2016, <https://www.nclc.org/media-center/pace-energy-efficiency-still-risky.html>

TEXT BOX 5-2

The Value of PACE Programs

The following project excerpt is from the PACE Houston website:

"The City of Houston adds another project to its TX-PACE portfolio with the closing of a \$135,000 project at the Regency Inn & Suites. This is the first hotel to utilize the TX-PACE program and the first solar project for the City of Houston's TX-PACE program. According to the Texas PACE Authority, 'The project will add a 45kW solar power system that will offset a portion of the hotel's electric usage and help insulate the business from volatility in the power market. The availability of incentives and tax deductions are further motivating hotels around the country to invest in solar, providing a mechanism to strategically allocate resources while decreasing their carbon footprint. The Regency Inn Hotel...will benefit from utility savings and tax incentives of more than \$250,000 over the project's useful life. The project will be financed over an 18-year term.'"

Source: *The Power of Innovation: Inventing the Future*, AEIC, 2017

mortgage lenders are unable to recover a portion of their losses if there is a foreclosure. Fannie Mae and Freddie Mac will not back mortgages with existing PACE assessments unless the FHA loan is given first-lien status over the property assessment. Since not all PACE states have defined the lien and the sequence of payments, lenders are at risk.

Public Benefits Charges

Many of the foregoing modes of clean energy financing can be funded through public benefits charges.¹⁸⁴ Public benefits charges have been used to fund clean energy RD&D, energy efficiency, renewable energy, demand-side management, low-income energy assistance and state green banks.^{185, 186, 187} Originating primarily as a way to invest in energy efficiency and renewable energy programs, and also to provide assistance for low-income customers, public benefits charges were developed to address the barrier to deploying clean energy solutions created by upfront costs, most commonly capital costs. Even though savings over the lifespan of a deployed clean energy technology may offset the capital costs, the initial investment often represents a significant barrier to deployment. In comparison, the impact of the surcharge on the ratepayer is relatively minor. A customer surcharge typically ranges by state from 2.5 percent to 5 percent per month of a customer's total energy bill.¹⁸⁸ For example, in Connecticut, it has been estimated that for an average residential customer (using 700 kilowatt-hours per month), Connecticut's Combined Public Benefits charge of approximately five percent would amount to only \$7.25 in a monthly bill of \$154.82.¹⁸⁹ Thus, public benefits charges can be a key enabler for energy innovation projects.

184. Public benefits charges are not exclusively used for clean energy as they can benefit low-income consumers, but this discussion focuses on their clean energy role.

185. "Public Benefits Funds for Renewables and Efficiency," Tax Credits, Rebates, and Saving, Department of Energy, accessed March 11, 2018, <https://energy.gov/savings/public-benefits-funds-renewables-and-efficiency>

186. "Public Benefits Funds," Library, Center for Clean Energy Solutions, last modified May 2017, <https://www.c2es.org/document/public-benefit-funds/>

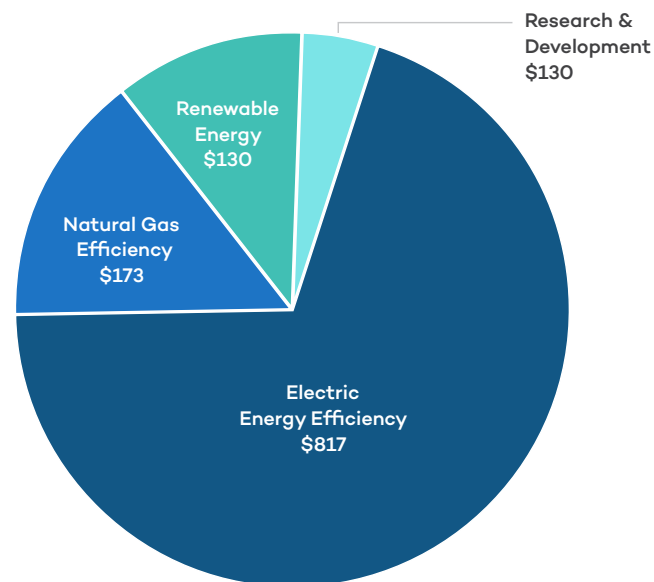
187. Hallie Kennan, Working Paper: State Green Banks for Clean Energy (San Francisco, CA: Energy Innovation: Policy and Technology, 2014), 1, http://energyinnovation.org/wp-content/uploads/2014/06/WorkingPaper_StateGreenBanks.pdf

188. Energy Dictionary, s.v. "public benefits charge," accessed March 11, 2018, https://www.energyvortex.com/energydictionary/public_benefits_charge.html

189. Mary Fitzpatrick, Allocation of Revenues from the Combined Public Benefits Charge, Research Report 2015-R-0047 (Hartford, CT: Office of Legislative Research, Connecticut General Assembly, 2015), 1, <https://www.cga.ct.gov/2015/rpt/pdf/2015-R-0047.pdf>

FIG. 5-9

California Public Benefits Funds for Renewables & Efficiency Funding Levels, 2015 (in millions)



The allocation of public benefits funds suggests the importance of electric energy efficiency programs in relation to California's broader clean energy objectives.

Source: Energy Futures Initiative (EFI), 2018; compiled using data from NC Clean Energy Technology Center, Database of State Incentives for Renewables and Efficiency

Over 30 states have public benefits charges.¹⁹⁰ Two states that have utilized public benefits charges to advance deployment of clean energy technologies are California and New York. In California, public benefits funds for renewables and efficiency reached nearly \$1.2 billion in total funding across four major application areas in 2015 (Figure 5-9). For renewables, these levels were extended annually to 2020.¹⁹¹ New York State adopted a system benefit charge (SBC) in 1996 to support efforts involving R&D, education and outreach, energy efficiency, and low-income energy assistance. New York's program has been re-authorized several times and total SBC funding from 1998 to 2016 amounted to \$2.48 billion.¹⁹²

New Business Models and Innovative Ratemaking

A major challenge to the deployment of new clean energy technologies is reliance by state regulators on traditional ratemaking policies. State utility regulation aims traditionally at finding an optimal balance between low electricity prices and reliable electricity service. This aim creates an inherent bias favoring existing technologies over new and more innovative technologies, which lack long-term track records and often present near-term risks and cost uncertainties. An enhanced role for states earlier in the innovation process could be especially important for the testing and adoption of new technologies.

Several states are promoting and recognizing new business models and innovative approaches to ratemaking that enable utilities to support early-stage technology and deploy innovative clean energy technologies (Text Box 5-3). States are also exploring new ways for utilities to collect revenues, for example, by shifting revenue collection from energy sales to energy savings. The New York Reforming the Energy Vision (REV) was launched in 2014 as a public utility commission initiative that seeks to bring major changes to the electricity system as well as to its regulation, including ratemaking reform. Specifically, REV is working to align utility profits with demand reduction, "infrastructure avoidance" of high-cost projects, and investment in distributed generation, essentially creating a new utility business model.

TEXT BOX 5-3

Innovative Ratemaking for Non-Traditional Costs

Non-traditional tools for innovation in the clean energy ecosystem can stimulate adoption of new technologies and development of new systems, and ratemaking plays a major role in their adoption. The wide-scale deployment of smart meters has enabled companies like Opower and Chai Energy to provide utilities with the tools to manage demand and costs through detailed analyses of customer energy use. This capability empowers utilities to target their customer programs with greater accuracy and thus success, including smoothing energy use over time. It also empowers customers with greater awareness and control of energy choices, thereby facilitating the opportunity for more interaction and collaboration between customers and their respective utilities.

Source: The Power of Innovation: Inventing the Future, AEIC, 2017.

190. U.S. Environmental Protection Agency, Clean Energy Financing Programs: A Decision Guide for States and Communities (Washington, D.C., 2011), 12, <https://www.epa.gov/sites/production/files/2015-08/documents/financingprogramsresourceguide.pdf>

191. "Public Benefit Funds for Renewables and Efficiency" (California, Regulatory Policy), Programs, Database of State Incentives for Renewables and Efficiency, North Carolina Clean Energy Technology Center, last modified September 24, 2015, <http://programs.dsireusa.org/system/program/detail/407>

192. "System Benefits Charge" (New York, Regulatory Policy), Programs, Database of State Incentives for Renewables and Efficiency, North Carolina Clean Energy Technology Center, last modified September 28, 2014, <http://programs.dsireusa.org/system/program/detail/699>

States are also recognizing the role and value of new clean energy technologies for addressing specific energy system challenges. California, Oregon, Massachusetts, and New York have established either requirements or aspirational goals to encourage initial deployment of energy storage technologies (Table 5-4). These initiatives are significant because many energy storage technologies are in later-stage innovation, and these new policies could exert significant “demand pull” on commercialization.

Another important aspect of these initiatives is that they signal a willingness by some states to play a larger role in an earlier stage of development of new technologies and also to adopt alternatives to traditional ratemaking that support new energy technologies.

TABLE 5-4

State Policy Actions to Encourage Deployment of Energy Storage

State	Law	PUC	Terms
California	AB 2514 (2010)	CPUC 92013)	Requires 3 major IOUs to add 1.3 GW of energy storage by 2020
Oregon	HB 2193 (2015)	OPUC (2017)	Requires 2 major IOUs to have a minimum of 5 MWh of energy storage by 2020
Massachusetts	H 4568 (2016)	Dept of Energy Resources (2017)	200 MWh energy storage aspirational target for distribution utilities to be achieved by January 1, 2020
New York	AB 6571 (2017)	NYPUC (TBD)	AB 6571 directs the NYPUC to develop an Energy Storage Deployment Program, including a storage procurement target for 2030

New policies can help bring energy storage technologies to market.

Source: Energy Futures Initiative (EFI), 2017

While state and local programs need to be tailored to regional and local characteristics and capabilities, development of best practices could leverage learning from other programs, accelerate successful implementation, and engender trust through accessibility, transparency, and consumer protections. Several organizations already provide services and tools for advancing best practices for energy programs, such as the National Governors Association Center for Best Practices and the National Association of State Energy Officials; however, there is room for increased work in this area.

State Initiated Regional Carbon Initiatives

Several states have grouped together to devise their own regional carbon pricing systems. In 2005, seven northeastern states developed the first U.S. mandatory market-based effort to reduce greenhouse gases — the Regional Greenhouse Gas Initiative (RGGI) cap-and-trade program. Two other states later joined this cooperative policy effort; the group now comprises Connecticut, Delaware, Maine, Maryland, Massachusetts, New Hampshire, New York, Rhode Island, and Vermont.

RGGI is a cap and trade program that establishes annual limits on CO₂ emissions from fossil fueled power plants in the Northeast and Mid-Atlantic. The primary compliance instrument is a CO₂ allowance made available in auctions four times per year, the price of which increases the cost of fossil generation relative to other technologies.

These allowances have affected emissions in RGGI states two ways, (1) by causing a change in system dispatch due to a higher price for fossil fuels and (2) by decreasing regional electric demand through application of RGGI proceeds to energy efficiency and related measures. Emissions in the RGGI region in 2016 were 15 percent below 2012 levels. California launched a similar cap-and-trade program beginning in 2013. In both programs states sell nearly all emission allowances through auctions. The revenue from those auctions is invested in energy efficiency, renewable energy, and other consumer benefit programs.

These programs have imposed material costs on CO₂ and have affected power costs in ways that favor low-carbon generation dispatch, although with associated increases in overall power costs. In California the program's CO₂ auctions have yielded almost \$3.4 billion by the end of 2016, funds that have been allocated to energy efficiency measures.

The Role of Cities, Tribal, and Rural Communities in Clean Energy Innovation

Cities, tribes, and rural communities also play important roles in responding to climate change and driving innovation in clean energy. Cities set goals and policies that affect GHG emissions and energy use, and cities are emerging as unique platforms for spurring new types of technology innovations. Meanwhile, tens of thousands of rural communities and tribal communities across the country face the challenge of responding to a changing climate and have needs to further their own economic development. Advances in digitalization and other key platform technologies offer opportunities to provide clean energy in a distributed fashion, at lower costs than ever before.

Cities, Tribes, Rural Communities, and Climate Policies

Like many states, a number of cities have embraced goals to reduce their contribution to climate change. Examples of such climate mitigation goals include:

- **Atlanta:** A goal to reduce GHG emissions by 20 percent below 2009 levels by 2020 and 40 percent below 2009 levels by 2030.
- **Berkeley:** A goal to reduce the entire community's GHG emissions by 80 percent below 2000 levels by 2050.
- **Houston and Denver:** Goals for an 80 percent reduction in GHGs by 2050 from a 2005 baseline.
- **Cleveland:** A goal to reduce GHG emissions by 80 percent by 2050 from a 2010 baseline.

The severe impacts that climate change is expected to have on Native Americans are a key factor in their support for climate mitigation measures. In June 2017, the National Congress of American Indians passed a resolution declaring its continued support of the Paris Climate Agreement and resolving to continue to advocate and support for initiatives to reduce GHG emissions, such as increased investment in, and use of, renewable power and energy efficiency.¹⁹³ Commitments of continued support for the Paris Agreement have also been made by several individual tribes.¹⁹⁴

Cities as Innovation Ecosystems

Cities can serve as platforms for powerful innovation ecosystems, particularly in the clean energy space. Between 2005 and 2050, the U.S. population is projected to increase 42 percent, from 296 million to 438 million, and 87 percent of the population is projected to live in cities. Adoption and advancement of new energy technologies and their integration with other platform technologies will be essential to ensure sustainability, safety and economic growth in urban areas.

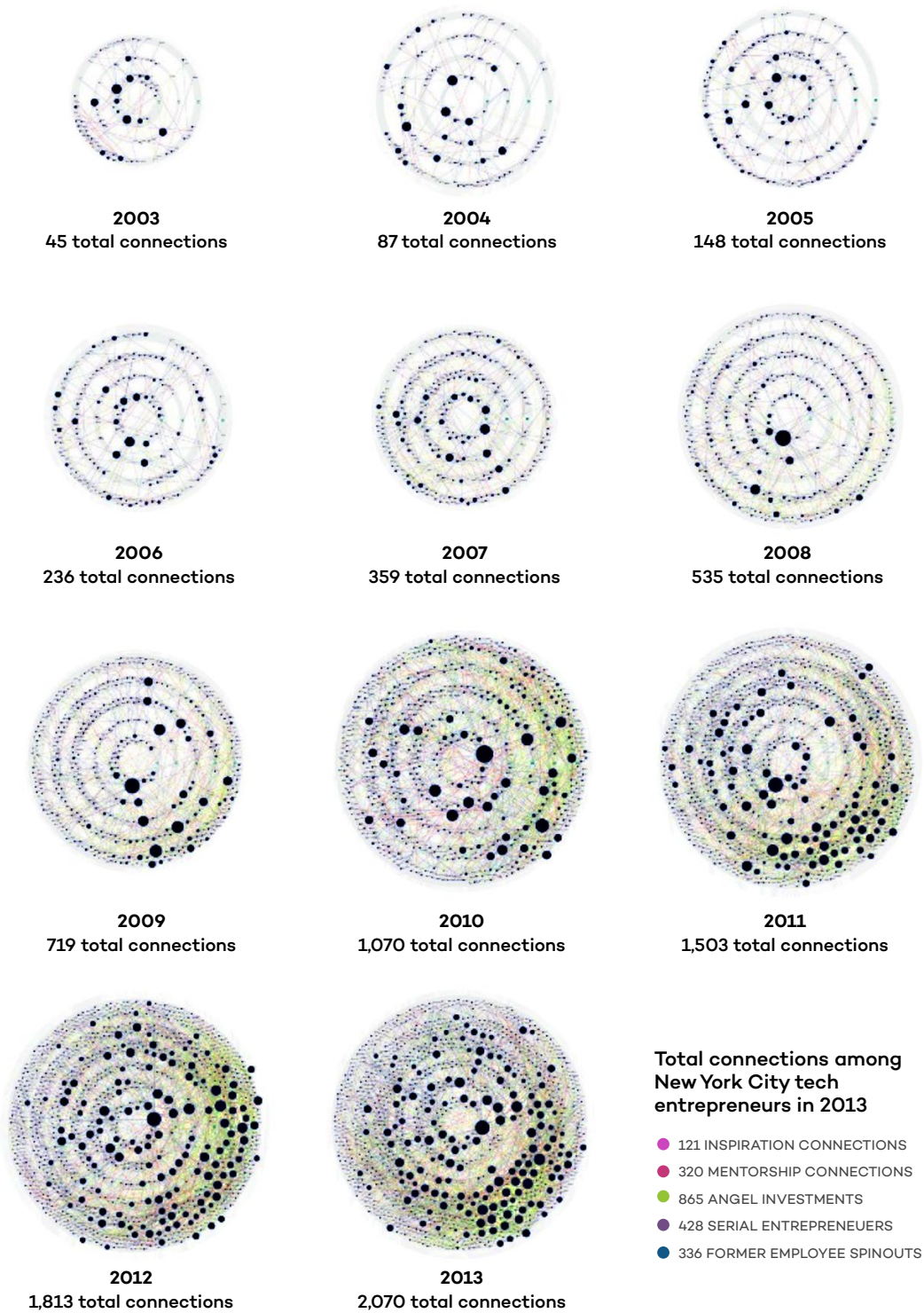
Cities can fill this key niche in innovation because they naturally have the networking assets that are essential for the ecosystem: the people who comprise the pool of employees that innovate and network; infrastructures that support innovation, networks, tacit knowledge sharing and facilitation of interactions between people and economic assets; a supportive policy and regulatory environment; and support for networking activities (e.g., workshops, and conferences). Figure 5-10 highlights the value of these features in the development of New York City's overall technology sector between 2003 and 2013.

193. National Congress of American Indians, Continued Support for the Paris Climate Agreement and Action to Address Climate Change: Resolution No. MOH-17-053 (Washington, D.C., 2017), <http://www.ncai.org/attachments/Resolution>

194. "Tribal Nations Are Still In: Eight Northwest Tribes Sign the We Are Still In Declaration," News, We Are Still In, accessed March 11, 2018, <https://www.wearestillin.com/news/tribal-nations-are-still>

FIG. 5-10

The Growth of New York City's Tech Sector from 2003-2013



The progression of New York City's innovation ecosystem

Source: Endeavor Insight, *The Power of Entrepreneur Networks: How New York City Became the Role Model for Other Urban Tech Hubs* (New York, 2014), 19

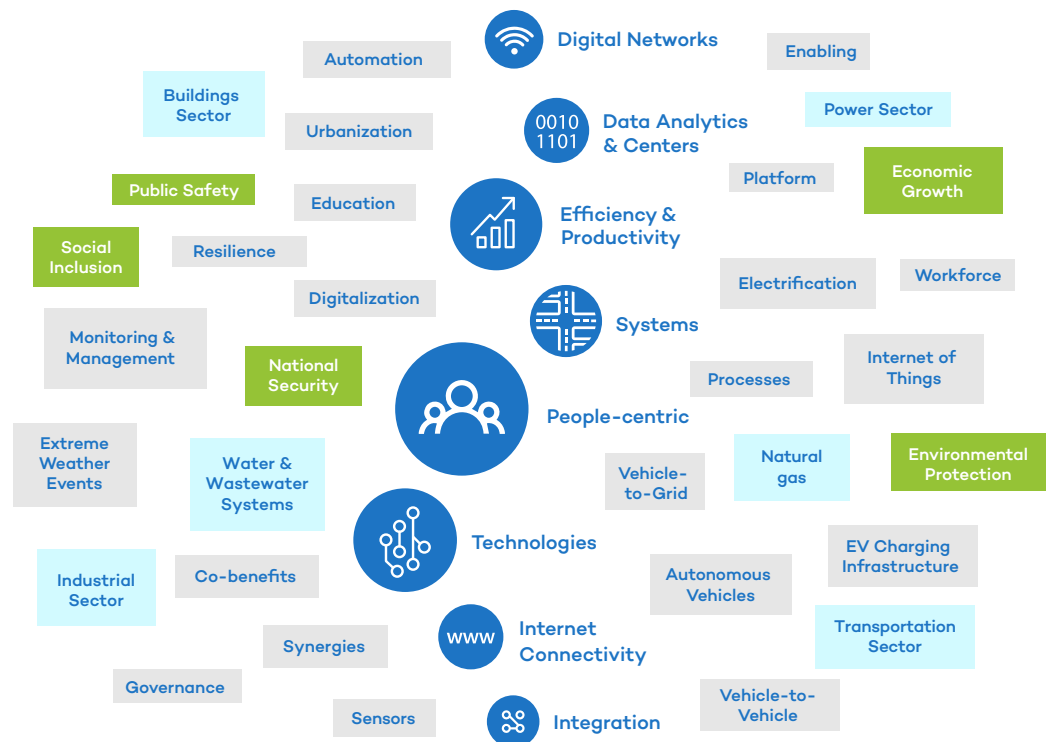
Smart city solutions offer significant opportunities to support clean energy innovation. A smart city could be described as a system that houses and enables the interconnection of many other platform technologies (Figure 5-11). In this way it leverages advances in platform technologies to better serve its population, infrastructure, and economy.

Smart cities serve as platforms of innovation for governments and industries. Global markets for smart city solutions are large and growing. Estimates suggest that in the coming years, the market size could be in the range of \$300 billion to \$700 billion.¹⁹⁵ In the United States, interest in these burgeoning markets and the concept of smart cities has been increasing.

In December 2015, the U.S. Department of Transportation (DOT) launched the Smart City Challenge to solicit proposals for integrating state-of-the-art smart transportation systems into midsize U.S. cities.¹⁹⁶ The Challenge garnered

FIG. 5-11

Conceptual Framework for Smart Cities



195. Rodger Lea, *Smart Cities: An Overview of the Technology Trends Driving Smart Cities* (New York: IEEE, 2017), 13, <https://www.ieee.org/content/dam/ieee-org/ieee-web/pdf/ieee-smart-cities-trend-paper-2017.pdf>

196. "Smart City Challenge," U.S. Department of Transportation, last modified June 29, 2017, <https://www.transportation.gov/smartcity>

The concept of smart cities describes a dynamic process that leverages synergies among a diverse set of people, technologies, processes, systems, and institutions to enhance urban efficiency and citizen well-being through the breakdown of traditional silos, achievement of co-benefits, and creation of integrated urban ecosystems. Smart cities transcend multiple economic sectors (denoted in light blue), involve many dynamic and interactive attributes (light gray), and aim to achieve a host of economic, social, and environmental goals (green). The blue elements in the center describe some examples of the major defining characteristics that are foundational to smart cities.

Source: Energy Futures Initiative (EFI), 2017

significant interest from cities across the country; in total, 78 cities submitted an application, which amounted to roughly one application for each midsize city in the country.¹⁹⁷ In 2016, Columbus, Ohio was announced as the winner and rewarded with \$40 million in public funds to implement its vision of a smart city. Follow-on funding included up to \$10 million from the philanthropic sector and \$90 million from the private sector,¹⁹⁸ which illustrates the potential for smart cities to draw widespread institutional interest and create opportunities for public-private partnerships.

Smart cities are potentially large markets for energy technologies as well as centers for diffusing those technologies. Fostering smart cities is yet another way to foster clean energy innovation. Smart cities not only serve as test beds for modern-day technologies and systems (see Text Box 5-4) but may also assume a critical role as innovation hubs of the future. Municipal utilities also represent an interesting laboratory for energy innovation because they are not subject to traditional state-based regulation. This institutional alignment offers the potential for greater flexibility in pursuing energy innovation initiatives in close coordination with other smart city initiatives. Targeted public policies will be crucial to aid in the future success and growth potential of smart cities. Such policies will need to address emerging related issues such as privacy, cybersecurity, and public access to data.¹⁹⁹

TEXT BOX 5-4

Smart Cities and Electric Utilities as Energy Innovation Laboratories

CPS Energy is the municipally-owned utility for the City of San Antonio, serving 804,000 electricity customers and 343,000 natural gas customers. CPS has pursued an aggressive agenda for both clean electricity generation as well as application of innovative energy concepts to enhance customer services, which helps satisfy the need for smart cities to be provided with affordable, reliable, and clean electricity. As the CPS Energy CEO put it: “We don’t own the smart city...we’re an enabler of the smart city.”

In January 2018, the city of San Antonio announced the formation of a new committee tasked to develop smart city initiatives. The Innovation and Technology Committee, which is composed of public and private citizens, will help craft San Antonio’s smart city vision through a comprehensive inventory of community needs, tailored smart city solutions, and a more focused policy agenda. Several initial themes to be addressed by the committee will include cybersecurity, expanding municipal broadband, digital equity, better mobility, and inclusive economic opportunity.

Source: The Power of Innovation: Inventing the Future, AEIC, 2017.

197. U.S. Department of Transportation [DOT], “U.S. Department of Transportation Announces Columbus as Winner of Unprecedented \$40 Million Smart City Challenge,” press release no. 73-16, June 23, 2016, <https://www.transportation.gov/briefing-room/us-department-transportation-announces-columbus-winner-unprecedented-40-million-smart>

198. DOT, “U.S. Department of Transportation Announces Columbus as Winner.”

199. Lea, Smart Cities, 8, 10.

Smart cities are potentially large markets for energy technologies as well as centers for diffusing those technologies. Fostering smart cities is yet another way to foster clean energy innovation. Smart cities not only serve as testbeds for modern-day technologies and systems (see Text Box 5-4) but may also assume a critical role as innovation hubs of the future. Municipal utilities also represent an interesting laboratory for energy innovation because they are not subject to traditional state-based regulation. This institutional alignment offers the potential for greater flexibility in pursuing energy innovation initiatives in close coordination with other smart city initiatives. Targeted public policies will be crucial to aid in the future success and growth potential of smart cities. Such policies will need to address emerging related issues such as privacy, cybersecurity, and public access to data.²⁰⁰

Energy Innovation in Rural Areas and Tribal Lands

Rural areas and tribal lands provide critical testbeds for adoption and diffusion of clean energy technologies because they can provide solutions to the significant challenges associated with remote areas with low population density.

Rural electric cooperatives have successfully leveraged their smaller size and strong relationships with their members, who are also customers, to become clean energy laboratories. An example is “Upgrade to \$ave” — an energy efficiency initiative by the Roanoke Electric Cooperative funded by the Rural Utility Services program of the U.S. Department of Agriculture (USDA). This initiative allows members to opt into energy efficiency improvements and to pay back the cost over time through their energy bill. The Dakota Electric Association, in partnership with Great River Energy (a generation and transmission electric cooperative), is conducting a pilot project using smart water heaters that can interact with the grid to function as storage, thereby balancing supply and demand. In Alaska, where energy costs are very high, populations are widely dispersed, and many rely on diesel fuel for heat and power generation. The Alaska Native Tribal Health Consortium’s Rural Energy Initiative has efficiency projects in 44 communities, and renewable energy projects in another 35 communities, demonstrating the effectiveness of these technologies for rural communities (Figure 5-12).²⁰¹

There are, however, major challenges to developing innovation systems on tribal lands in the United States that rely heavily on federal, state and local government actions. Many of these areas lack access to sufficient energy services, which hinders all forms of development. The 2010 U.S. Census determined that 1.1 million Native Americans live on tribal lands. A 2000 Energy Information Administration study suggested that 14.2 percent of tribal households lack access to electricity and the Navajo Nation accounts for 75 percent of all households without electricity. Across all tribes, one in seven households are without electricity, which equates to approximately 160,000 people.²⁰² While there are piecemeal efforts, Federal funding for tribal electrification continues to be insufficient. Between 2002 and 2017, DOE invested \$78 million in 250 tribal energy projects.²⁰³

Many challenges hinder the infrastructure development of tribes, further exacerbating economic development. Basic challenges include issues related to remote locations, widely dispersed homes, and the prohibitive cost of utility distribution lines. These issues are compounded by the challenges of poverty. As a result, Indian households on reservations spend a higher proportion of their income on energy, whether electricity or natural gas, than U.S. households do, in general.²⁰⁴ Federal tax exemptions for federally recognized tribes negate their ability to employ the Federal Production Tax Credit or Investment Tax Credit

200. Lea, Smart Cities, 8, 10.

201. https://comm.ncsl.org/productfiles/94723904/NTES_David_Beveridge.pdf

202. Energy Information Administration [EIA], Energy Consumption and Renewable Energy Development Potential on Indian Lands (Washington, D.C., 2000), ix, <https://www.eia.gov/renewable/archive/neaf0001.pdf>

203. “DOE Announces Intent to Issue New Funding Opportunity for Tribal Energy Infrastructure Development,” Office of Indian Energy Policy and Programs, Department of Energy, November 13, 2017, <https://energy.gov/indianenergy/articles/doe-announces-intent-issue-new-funding-opportunity-tribal-energy>

204. EIA, Energy on Indian Lands, 4-5.

FIG. 5-12

Current and Identified Clean Energy Projects in Alaska's Rural Energy Initiative

Current and Identified Projects Through 2019

Current Energy Efficiency Projects

● 44 COMMUNITIES

Identified Energy Efficiency Projects

● 82 COMMUNITIES

Current Renewable Energy Projects

◆ 25 HEAT RECOVERY PROJECTS

5 BIOMASS PROJECTS

4 WIND-TO-HEAT PROJECTS

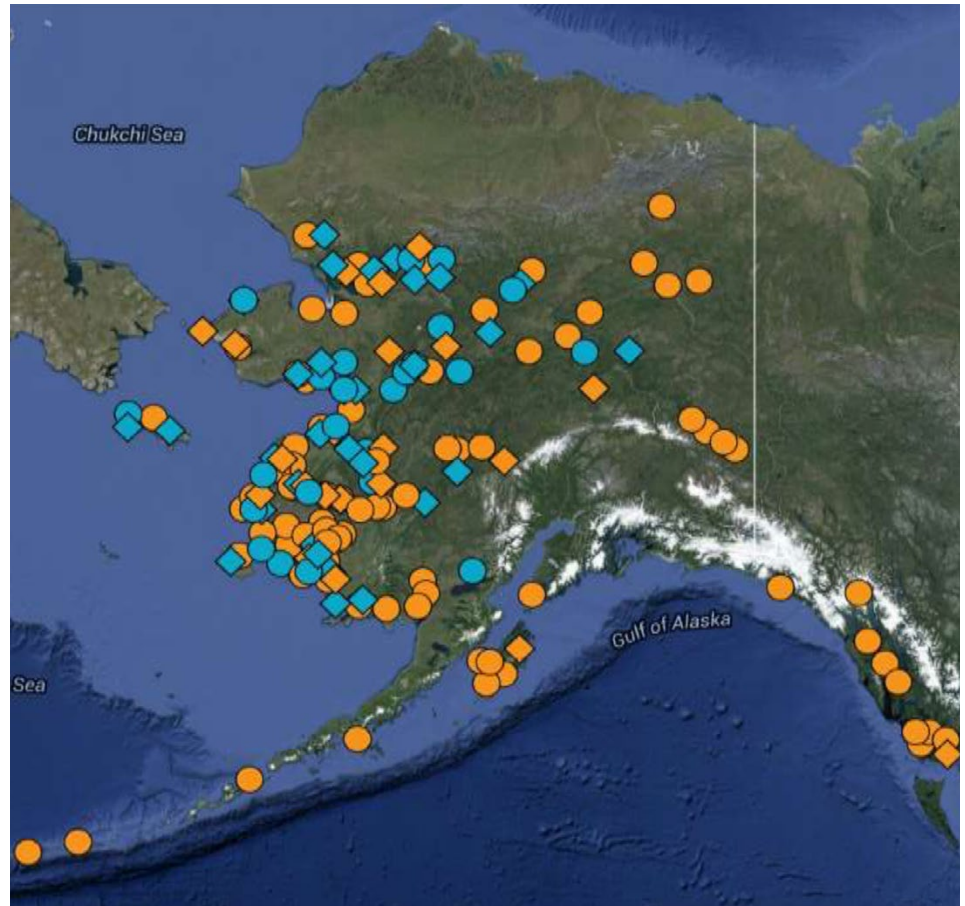
Identified Renewable Energy Projects

◆ 16 HEAT RECOVERY PROJECTS

5 BIOMASS PROJECTS

1 GROUND SOURCE HEAT PUMP PROJECT

1 HYDROELECTRIC PROJECT



Many clean energy projects are being undertaken across rural Alaska.

Source: Alaska Native Tribal Health Consortium, Rural Energy Initiative

205. U.S. Department of Energy [DOE], Developing Clean Energy Projects on Tribal Lands: Data and Resources for Tribes (Washington, D.C., 2012), 3, <https://www.nrel.gov/docs/fy13osti/57048.pdf>

206. DOE, Quadrennial Energy Review: Transforming the Nation's Electricity System: The Second Installment of the QER (Washington, D.C., 2017), 2-24, <https://energy.gov/sites/prod/files/2017/02/f34/Quadrennial%20Energy%20Review--Second%20Installment%20%28Full%20Report%29.pdf>

without expensive and complicated corporate structures. Most tribes also do not meet eligibility requirements for existing loan guarantee programs. In addition, lack of access to broadband translates to a lack of access to distributed energy resource technology and limits options for technologies such as microgrids that could address some key issues on tribal lands.

Yet, tribal lands possess considerable energy potential. DOE notes that Native American land occupies 2 percent of U.S. land but may contain approximately 5 percent of all national renewable energy resources.²⁰⁵ There are over 9 million megawatts (MW) of renewable energy potential on reservations, but only 125 to 130 MW have been installed thus far because of a lack of capital.²⁰⁶ Thus, despite the declining costs of wind and solar projects, tribes have not largely employed such technologies because of limited access to private capital for projects on reservations as well as geographic dispersion.

Government agencies and states have developed or improved upon many of their programs to aid in tribal electrification and energy infrastructure development. The Department of Interior has programs that provide technical assistance to tribes for energy development. The DOE Office of Indian Energy Policy and Programs has modernized its technical assistance strategy (Text Box 5-5). The USDA Rural Utilities Service provides low-cost loans to rural utilities, including tribal initiatives for increasing grid access. State finance programs, such as New Mexico's Tribal Infrastructure Fund, have acknowledged the importance of ensuring that greater financial support is available to tribes. Siting and permitting rules for transmission rights-of-way on tribal lands were clarified in 2015, which may ease the bureaucratic burden for tribes seeking greater energy infrastructure development. Additionally, the Energy Policy Act of 2005 authorized the Tribal Indian Energy Loan Guarantee Program, which provides loan guarantees for renewable energy on reservations.

Some tribes have stated an interest in establishing tribal energy offices for energy efficiency and energy security programs. To help enable such programs, the federal government could make renewable energy tax credits refundable and provide loan guarantees. In addition, there could be support for advanced technology acceleration and economic development opportunities, such as through new incentives and financial support, workforce development resources, and enhanced consultation.

TEXT BOX 5-5

Recent DOE Activities on Tribal Energy Access

On January 6, 2017, in the Second Installment of the Quadrennial Energy Review, DOE called for full tribal electrification including through grants and technical assistance. On November 13, 2017, DOE's Office of Indian Energy Policy and Programs announced a notice of intent to issue a funding opportunity announcement (FOA) for "Energy Infrastructure Deployment on Tribal Lands" later in 2017 to promote energy efficiency and energy generation for tribal buildings, community-scale energy generation on tribal lands, and energy systems for emergency situations or long-term resilience. The Tribal Energy Loan Guarantee Program was funded by Congress in FY 2017 and FY 2018, and an initial solicitation was issued in July 2018.

Source: "DOE Announces Intent to Issue New Funding Opportunity for Tribal Energy Infrastructure Development," Office of Indian Energy Policy and Programs, Department of Energy, November 13, 2017

Federal Initiatives that Support State, Local, Tribal and Government Leadership in Clean Energy Innovation

Independent of the federal government's activities directly associated with clean energy innovation development and deployment (see Chapter 4), several federal agencies provide support to states, local governments and tribal governments. Below are selected examples:

Department of Agriculture

The USDA Rural Energy for America Program offers loan guarantees and grants to rural communities of less than 50,000 people for clean energy and energy efficiency projects. Eligible applicants include small businesses, agricultural producers, institutions of higher learning, and state, tribal, and local governments. Qualifying projects include the purchase, installation, and construction of renewable energy systems, energy efficiency improvements to non-residential buildings, renewable technologies that reduce energy consumption, and energy audits.²⁰⁷

The High Energy Cost Grant Program, administered through the USDA Rural Utilities Service, provides grants to rural communities for the purchase, construction, installation, repair, or replacement of energy infrastructure and equipment (e.g., electricity, natural gas, home heating fuels) throughout generation, transmission, and distribution operations. Projects are eligible regardless of on-grid or off-grid circumstances, and include those related to energy conservation, energy efficiency, and renewable energy. The major criterion for eligibility is that projects must serve rural communities whose residential household energy expenditure is more than 275 percent of the national average. States, businesses, cooperatives, associations, organizations, and tribal entities are all eligible for grants under this program.²⁰⁸

The Rural Utilities Service Rural Energy Savings Program provides zero-interest loans to qualified entities who can then offer loans of no more than 3 percent interest rate to qualified customers for the purposes of implementing energy efficiency projects. These loans generally go toward technologies that help customers reduce their energy usage and costs through efficiency measures. The loans can be repaid through a surcharge on the customer's energy bill for the properties in which the energy efficiency measures have been implemented.²⁰⁹

Department of Transportation

The Transportation Infrastructure Finance and Innovation Act Program, administered through DOT, is a credit assistance program for surface transportation projects of regional or national significance including highways, passenger rail, bus service, port facilities, and rural infrastructure. The program authorizes DOT to provide three forms of credit assistance: secured loans, loan guarantees, and standby lines of credit. Eligible applicants include state transportation departments, transit operators, local governments, and private entities. The aim of the program is to leverage private capital to improve surface transportation systems.²¹⁰

207. Partnership for Sustainable Communities, Federal Resources for Sustainable Rural Communities (Washington, D.C.: Department of Transportation, 2012), 33, 43, https://www.sustainablecommunities.gov/sites/sustainablecommunities.gov/files/docs/federal_resources_rural.pdf

208. DOE, Federal Financing Programs for Clean Energy – 2016 (Washington, D.C., 2016), 61, <https://www.energy.gov/sites/prod/files/2016/05/f32/Federal%20Financing%20Programs%20for%20Clean%20Energy.pdf>

209. DOE, Federal Financing Programs for Clean Energy – 2016, 63.

210. DOE, Federal Financing Programs for Clean Energy – 2016, 91.

Department of Housing and Urban Development

Public Housing Energy Performance Contracts, administered through the Department of Housing and Urban Development, is a financing technique that allows entities to repay the installation costs of energy conservation and efficiency projects through the cost savings achieved by the reduced energy consumption. This technique helps avoid upfront capital expenditures associated with installation that may be too burdensome for some entities. In place of upfront capital expenditures by the entity, a third-party pays for the energy conservation and efficiency improvements and then is repaid out of the energy savings.²¹¹

Department of the Treasury

Qualified Energy Conservation Bonds, administered through the Department of the Treasury, allow state, local, and tribal government issuers to borrow money at favorable rates to help fund energy efficiency projects. Congress has already authorized \$3.2 billion of these bonds to qualified issuers, but many of these bonds have not yet been issued for relevant projects. As an added incentive, the Treasury also offers a tax benefit to help offset the issuer's borrowing costs, making these types of bonds among the lowest-cost public financing options available.²¹²

Department of Energy

DOE also currently provides technical assistance to state, local, and tribal entities on a range of energy issues, including assistance to state energy offices and state public utility regulatory commissions. Technical assistance can cover a variety of issues, including assisting these state commissions in addressing challenges presented by new technologies, and tools including analysis support, convened discussions with stakeholders, education and training through workshops and webinars, and consultations with technical experts. For example, DOE's Office of Energy Efficiency and Renewable Energy provides assistance to states and local governments to enable them to upgrade their building codes by analyzing energy savings and cost impacts associated with code adoption, providing comparative analysis of future code options, and advising on potential modification of the model code language. Increasing funding for DOE technical assistance and targeting modernization of state programs to include a focus on clean energy technologies could significantly advance the states' role in clean energy innovation.

Clean energy incubators and accelerators have been providing support to regional and local entrepreneurs by providing lab space, business expertise, mentors, access to investors, and testing and demonstration opportunities (Text Box 5-6). Recognizing the value of these incubators, in 2014 DOE launched the National Incubator Initiative for Clean Energy to create a national support network for clean energy entrepreneurs.²¹³ The network, Incubatenergy, is the first nationwide network for incubators and accelerators dedicated to stimulating more efficient and accessible resources for clean energy entrepreneurs. The result was over \$1.6 billion in follow-on funding for supported companies, the issuance of 190 patents, and the addition of more than 3,000 new jobs associated with clean energy.²¹⁴ DOE has sought to stimulate further expansion of state green bank programs by proposing to utilize a portion of its Title XVII Loan Guarantee Program resources to support state green bank financing.

211. DOE, Federal Financing Programs for Clean Energy – 2016, 75.

212. DOE, Federal Financing Programs for Clean Energy – 2016, 97.

213. DOE, "Energy Department Invests \$3.2 Million to Support Clean Energy Small Businesses and Entrepreneurs," news release, June 20, 2014, <https://energy.gov/articles/energy-department-invests-32-million-support-clean-energy-small-businesses-and>

214. Alice Wang, "Incubators and Accelerators: What Every Cleantech Startup Should Know," Office of Energy Efficiency and Renewable Energy, Department of Energy, February 22, 2017, <https://energy.gov/eere/articles/incubators-and-accelerators-what-every-cleantech-startup-should-know>

TEXT BOX 5-6

Clean Energy Incubators and Accelerators

Clean energy incubators and accelerators are created and funded by a variety of stakeholders ranging from corporate-funded incubators, such as the Wells Fargo Innovation Incubator (IN2) to publicly-funded incubators such as the Los Angeles Cleantech Incubator (LACI).

IN2 started with \$10 million from Wells Fargo and provides grants to startups to reduce energy consumption of commercial buildings. Projects are vetted by DOE's National Renewable Energy Laboratory. IN2 has funded 20 early-stage startups and in 2017 Wells Fargo added another \$20 million to expand into transportation, microgrids, energy storage, and sustainable agriculture.

Founded as a cluster-driven economic development initiative by the City of Los Angeles and its Department of Water & Power, LACI is recognized as one of the most innovative business incubators in the world by UBI Global. In the past six years, LACI has helped 72 portfolio companies raise \$159 million in funding, earn \$220 million in revenue, create 1,695 jobs, and deliver more than \$379 million in long-term economic value.

215. Ken Costello and Rajnish Barua, Evaluation of Public Regulation Commission Staffing and Budget Allocation: A Report to the New Mexico Legislative Council Service (Silver Spring, MD: National Regulatory Research Institute, 2017), iv, https://www.nmlegis.gov/Publications/Studies_Research_Reports/Evaluation%20of%20Public%20Regulation%20Commission%20Staffing%20and%20Budget%20Allocation%20-%20May%202017.pdf

216. Section 111 of the Public Utility Regulatory Policies Act of 1978 (PURPA) requires that each state public utility commission "must consider" for their regulated electric utilities whether to adopt verbatim specific statutory standards as requirements on those electric utilities. By "must-consider," PURPA stipulates that states must start regulatory proceedings by a specified deadline and make a yes or no decision by another specified date on adoption of the standard, verbatim. For non-state jurisdictional utilities -- publicly- and cooperative- owned electric utilities -- PURPA requires the same "must consider" steps for their utility governing boards (which are either locally elected or appointed). The Tennessee Valley Authority is deemed to be the state regulatory authority for those electric utilities over which it has ratemaking authority.

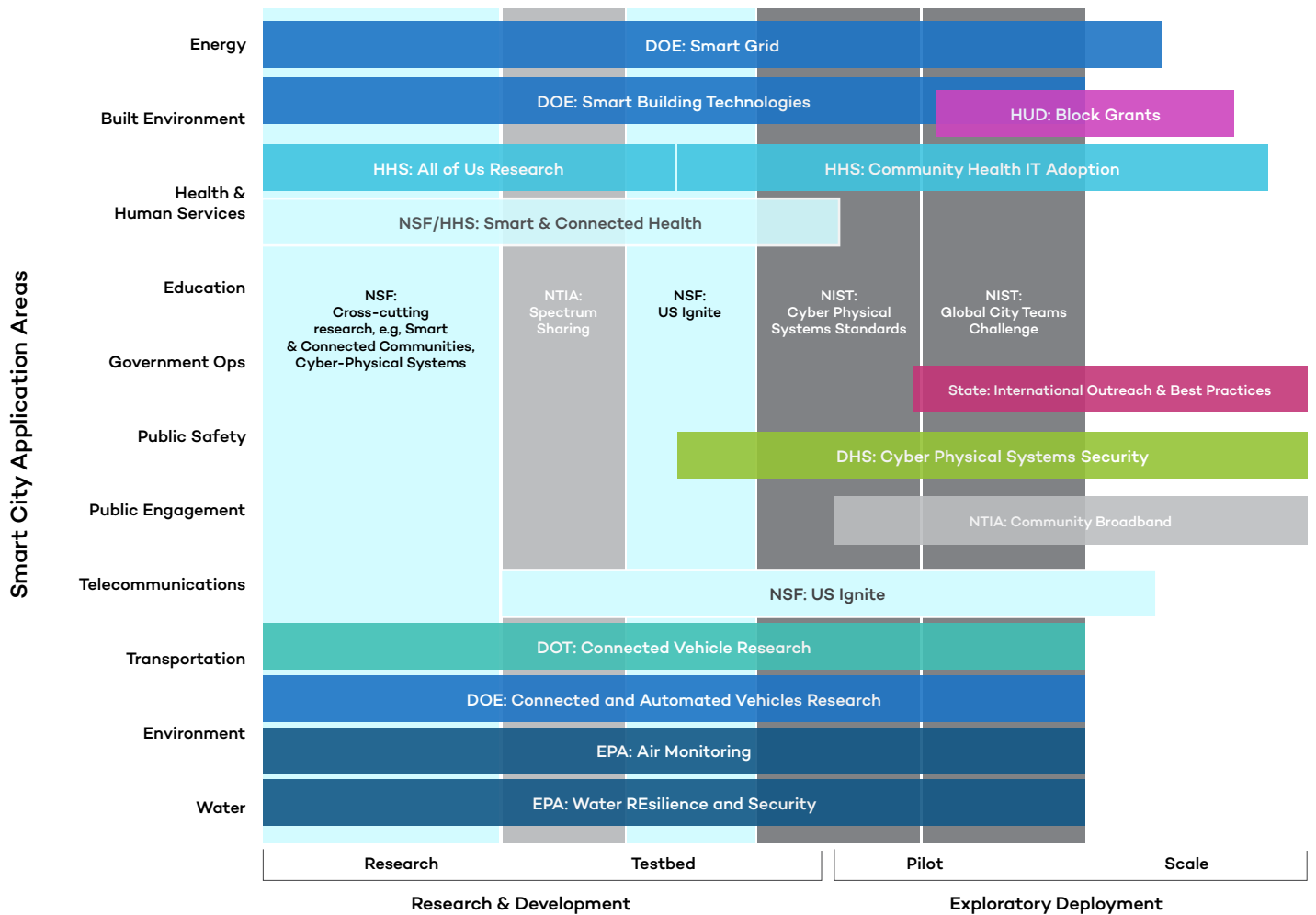
217. <https://cdn.americanprogress.org/wp-content/uploads/2015/05/PURPA-report-final.pdf>

The importance of DOE's technical assistance is underscored by the disconnect often found between the jurisdiction and responsibilities of a state public utility commission and the resources needed to effectively address issues under the commission's purview. A May 2017 report by the National Regulatory Research Institute provided a stark view of commission resource needs. In evaluating the New Mexico Public Regulation Commission, the report pointed out that "frequently, a state utility commission has to undertake more tasks with less money, a situation that can spiral into a situation where the commission is unable to adequately address the issues brought before it."²¹⁵

Another federal tool for advancing state clean energy deployment is the Public Utility Regulatory Policies Act (PURPA). Under PURPA, state electric utility regulators must consider whether to adopt standards as requirements on electric utilities.²¹⁶ Previous standards have significantly advanced clean energy policies. For example, state adoption of PURPA standards for integrated resource and demand-management programs resulted in the doubling of energy efficiency investments, from \$1.2 billion in 1990 to \$2.8 billion in 1993.²¹⁷

FIG. 5-13

Federal Role in the Promotion of Smart Cities



Examples of smart cities programs supported by the federal government.

Source: National Science and Technology Council, Smart Cities and Communities Task Force

218. Smart Cities and Communities Task Force, Networking and Information Technology Research and Development Subcommittee, Smart Cities and Communities Federal Strategic Plan: Exploring Innovation Together (Draft for Public Comment) (Washington, D.C.: National Science and Technology Council, 3, https://www.nitrd.gov/drafts/SCC_StrategicPlan_Draft.pdf)

219. Smart Cities and Communities Task Force, Smart Cities and Communities Federal Strategic Plan, 5.

The federal government has a Smart Cities and Communities Task Force to guide interagency programs in funding in this area. The scope of the Federal government's efforts in clean energy innovation for smart cities is illustrated by the membership of this Task Force, which consists of members from eight federal departments, three independent federal agencies, and two offices in the Executive Office of the President.²¹⁸ Figure 5-13 depicts the interrelated roles of these Federal departments and independent agencies in application areas key to smart cities.

According to this task force, addressing Smart City opportunities requires “new forms of cross-sector and cross-government collaboration, experimentation, knowledge-sharing, and alignment.”²¹⁹ A high-level framework is needed to guide and coordinate smart city Federal initiatives and recommended next steps, including accelerating fundamental R&D; facilitating secure and resilient infrastructure, systems, and services; and fostering data sharing, knowledge sharing, best practices, and collaboration.

RECOMMENDATIONS

The Role of State, Local, and Tribal Governments in Clean Energy Innovation

- States should consider adopting clean energy portfolio standards and zero-emissions credits in order to strengthen markets for clean energy innovation to include renewables and other forms of zero- or low-carbon energy.
- States should collaborate to identify best practices for clean energy programs, including consumer protections, standardization to reduce administrative costs, and financing mechanisms.
- State and local regulatory agencies should consider ways in which existing ratemaking principles could be adapted to incentivize utilities to deploy established clean energy technologies, test emerging energy technologies, and realize value from behind the meter technologies.
- The Federal government should increase technical assistance, capacity building, and funding for state, local, and tribal government clean energy initiatives and infrastructure.
- DOE should modify its current loan program regulations under Title XVII Loan Guarantee Program authority to stimulate increased state and tribal clean energy financing. Examples include providing a share of its credit authority to backstop state energy financing programs such as Green Banks, and implementing the Tribal Energy Loan Guarantee Program to reflect tribal energy opportunities and challenges.
- City, state, and Federal governments should improve coordination and planning across their agencies to facilitate development of smart cities and smart communities. In addition, the Federal government should continue support for the smart cities and communities, including accelerating fundamental R&D and fostering data and knowledge sharing, best practices and collaboration.

Chapter 6. Fostering Regional Clean Energy Innovation Ecosystems

Energy resources, infrastructure, and employment profiles vary significantly by region of the country. This chapter reviews the key features of regional innovation ecosystems, examines their impact, and discusses where incentives might encourage their broader distribution.

FINDINGS

Fostering Regional Clean Energy Innovation Ecosystems

- Many of the issues faced by the energy sector are also highly regional in nature and would be better managed by strategies tailored to each region's specific needs. Significant regional variation also exists in energy-use market applications. For example, more than half of the manufacturing industry subsector is concentrated in eight states.
- Regional energy innovation ecosystems can be strengthened by increasing the connectivity of existing financial resources and research capabilities at the regional level.
- Many energy innovation clusters in the United States are evolving into fully-integrated innovation ecosystems. There are also many areas of the country where energy innovation is nascent or non-existent, requiring special efforts to establish the underpinnings for regional innovation ecosystems.
- Investments that increase the connectivity among regional innovation participants can foster significant additional innovation potential. While federally-funded research and development (R&D) historically has not been well connected to state and regional economic development, activating these regional clusters to break down the barriers among Federal, state, and local resources will create new synergies.
- There are strong relationships among innovation, job creation, and technology deployment in the solar and wind energy industries.
- State and local governments, the private sector, universities, and philanthropies can all play key roles in supporting the establishment of incubator space to enable small companies to develop and prototype new technologies and ideas.
- The DOE national laboratory system can play a major role in regional clean energy innovation ecosystems. Lawrence Berkeley National Laboratory has initiated an innovative program, Cyclotron Road, to make available unique laboratory capabilities, as well as technical assistance from laboratory scientists and engineers. Argonne National Laboratory and Oak Ridge National Laboratory have since initiated similar programs.
- The deployment of platform technologies, such as advanced additive manufacturing, data analytics and robotics, offer the potential to expand innovation into areas of the country that currently do not have significant innovation resources. However, many of these regions also lack broadband internet access, a key enabler of platform technologies and other aspects of the modern economy that businesses and researchers rely on for data, graphics, and video capabilities.

TEXT BOX 6-1

What is a Regional Innovation Ecosystem?

“An innovation ecosystem consists of a group of local actors and dynamic processes, which together produce solutions to different challenges. The main features of the ecosystem include top-level universities and research institutions, sufficient financing for new companies and research plans, a symbiotic combination of large established companies and new startups, specialization of and cooperation among companies, service companies specialized in the needs of local companies, a sufficient local market for new innovative products, and global networking. In addition, successful ecosystems have a ‘community of fate,’ meaning that the actors of the region see that their success is linked to the success of the whole region.”

Source: Kaisa Oksanen and Antti Hautamäki, “Transforming Regions into Innovation Ecosystems: A Model for Renewing Local Industrial Structures,” *Innovation Journal: The Public Sector Innovation Journal*, 19, no. 2, article 5 (2014)

The Growth of Regional Innovation Ecosystems

Many energy innovation clusters in the United States are evolving into fully-integrated innovation ecosystems. The growth of regional innovation ecosystems can provide a richer distribution of innovation capacities around the United States. This can help meet key national goals by breaking down barriers among the key players, creating new synergies, maximizing the value of regional resources, and utilizing existing infrastructures as much as possible.

The regional innovation cluster in the Chicago metropolitan area offers an example of a robust innovation ecosystem. The Chicago Metropolitan Agency for Planning (CMAP) was created in 2005 to enhance partnerships between stakeholders in the innovation process across multiple economic sectors (Figure 6-1). This region is also home to leading research Universities, two DOE National Labs, a DOE Energy Innovation Hub, multiple lead and partner organizations in Energy Frontier Research Centers (EFRCs), and many leading private sector innovators.

There are also many areas of the country where energy ecosystems are nascent, requiring a special focus on broadening access to, and benefits from, clean energy innovation. Working together, the federal government, states, cities, the private sector, universities, labs, and philanthropies can collaborate to foster effective ecosystems on a regional scale.

Regional Variations in Energy Supply

The energy sector is inherently regional with variations in energy resources and their associated infrastructure. The significant regional variation in energy resources such as coal, oil, natural gas, and wind is shown in Figure 6-2.

Energy supply and job creation tend to track the location of energy resources. Forty percent of U.S. solar jobs are in California, with another seven percent of total solar jobs in nearby Nevada, Arizona, Utah, and Colorado. Eleven percent of solar jobs are on the east coast in Massachusetts, New York, and New Jersey. Texas (four percent) and Florida (three percent) also have significant shares of the U.S. solar workforce.

FIG. 6-1

From CMAP, “Benefits of Clustering”



Input-Output

Industries tend to purchase and consume one another's products in the process of transforming goods and services from raw materials to final products.



Labor Pooling

Many of the industries require workers with related skills, which can result in a strong labor pool for employers and good job prospects for workers



Knowledge Spillover

Because of labor pooling, supportive entities and related industries, ideas and innovation can flourish through formal and informal associations, worker movement and creation or related businesses

Source: Chicago Metropolitan Agency for Planning and U.S. Cluster Mapping Project, included in CMAP Report *Regional Economy and Clusters*, 2016

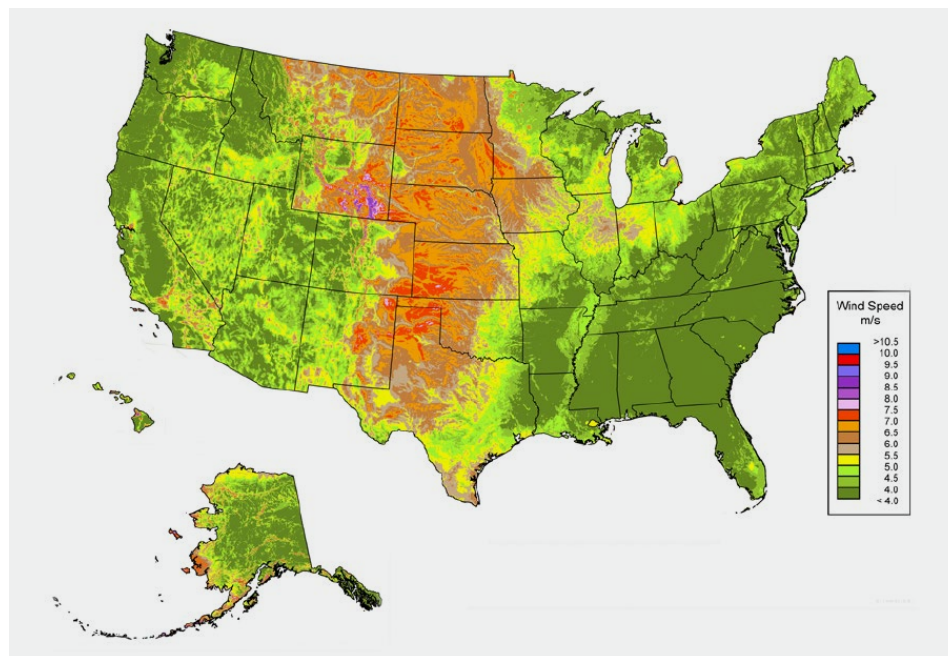
FIG. 6-2

Shale Plays and Wind Speeds: The Regional Nature of Energy Resources

Lower 48 Shale Plays



United States Annual Average Wind Speed at 30m



Energy resources are geographically distributed in the United States.

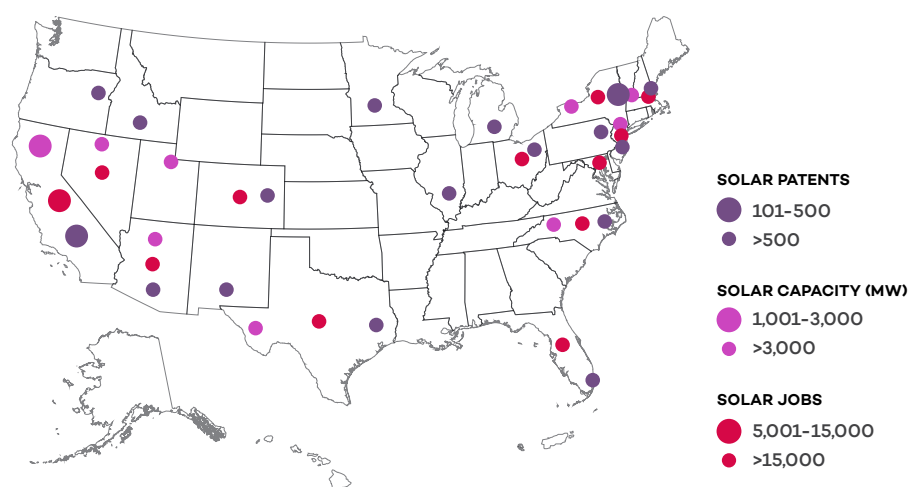
Note: The average wind speeds indicated on this map are model-derived estimates that may not represent the true wind resource at any given location. Small terrain features, vegetation, buildings, and atmospheric effects may cause the wind speed to depart from the map estimates.

Source: Energy Information Administration, AWS Truepower, National Renewable Energy Laboratory

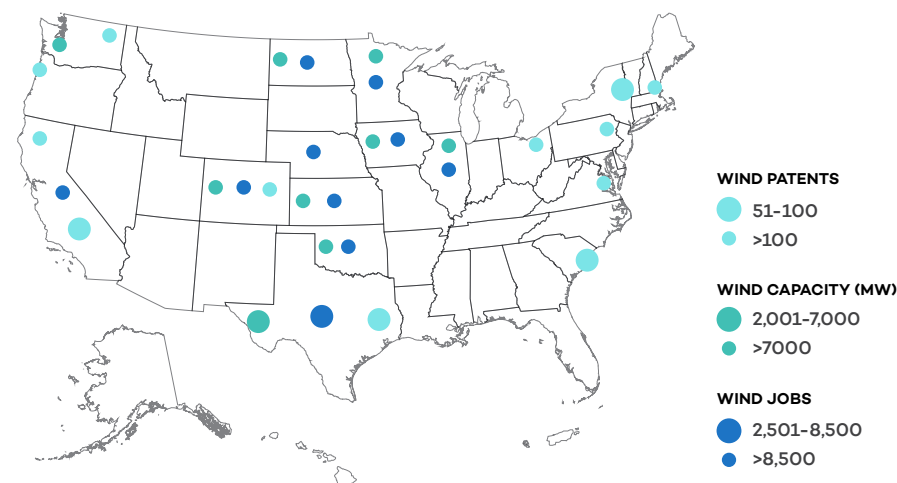
In 2016, the electric power sector added 7.7 gigawatts (GW) of new utility-scale solar power, the largest yearly increase to date, and an amount that was greater than all utility-scale solar added before 2014.²²⁰ Thirty percent of U.S. states saw measurable growth²²¹ in installed solar capacity, with the largest capacity increases in 2016 (i.e., combined capacity from both new utility-scale and rooftop systems) occurring in California (5.1 GW added, for a total of 18.3 GW capacity), Utah (1.2 GW added, for a total of 1.5 GW capacity), and Georgia (1.0 GW added, for a total of 1.4 GW capacity).²²² Supporting this growth were an estimated 260,000 solar jobs, ranging from PV installers to array manufacturers, highly concentrated in a few regions across the country.²²³ This concentration is shown, for solar jobs, in Figure 6-3.

FIG. 6-3

Maps of Solar and Wind Energy Innovation Indicators



Innovation clusters are emerging in the solar sector as solar jobs, installed capacity, and number of solar patents are growing in certain regions. These clusters could drive the formation of regional innovation ecosystems.



Innovation clusters are emerging in the wind sector in certain regions, especially in the Midwest. Other regions, such as the Northeast, have a high number of patents due to strong research centers. These clusters could drive the formation of regional innovation ecosystems.

220. Energy Information Administration [EIA], "U.S. Electric Generating Capacity Increase in 2016 Was Largest Net Change Since 2011," *Today in Energy*, February 27, 2017, <https://www.eia.gov/todayinenergy/detail.php?id=30112>

221. Calculated as states with greater than 1 percent of U.S. total solar capacity growth

222. "Top 10 Solar States," Solar Energy Industries Association, accessed March 12, 2018, <https://www.seia.org/research-resources/top-10-solar-states-0>

223. "Solar Jobs Census 2016," Solar Foundation, accessed March 12, 2018, <https://solarstates.org/#states/solar-jobs/2016>

Source: Energy Futures Initiative (EFI), compiled using data from The Solar Foundation and American Wind Energy Association

A similar concentration can be observed for wind jobs. Although supported by the larger innovation ecosystem of public and private-sector funding and incentives, these concentrations of adoption reflect localized conditions and opportunities.

Regional Variations in Energy Use

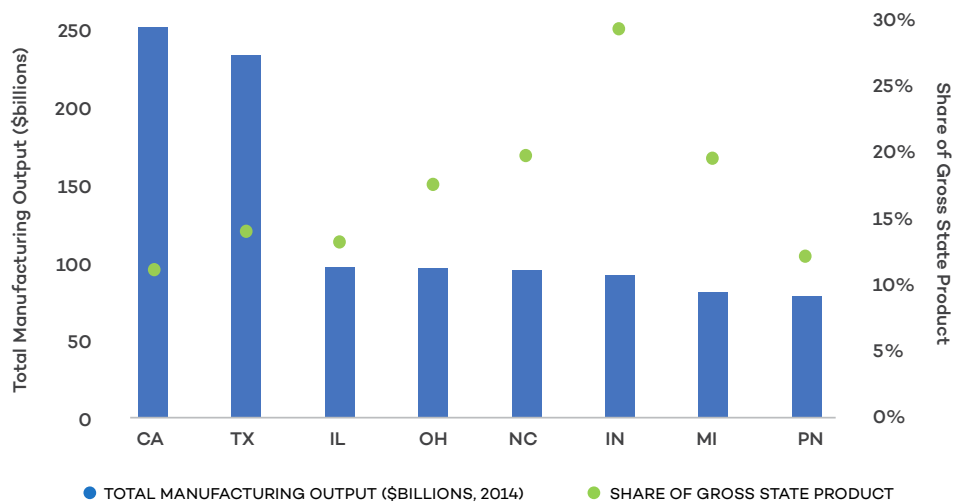
Significant regional variation also exists in energy use. Markets for the distribution of electricity for end uses are governed by different regulatory bodies at the state level, and in organized markets, at a regional level. In the industrial sector, which uses 22 percent of U.S. primary energy and which is the economy's biggest end-use emitter of greenhouse gases (GHGs), activities are highly concentrated by region. More than half of the manufacturing industry subsector is concentrated in eight states as shown in Figure 6-4.

Manufacturing directly supports nearly 12.5 million people (8.5 percent of total U.S. employment) and indirectly supports four jobs for every manufacturing job, the largest economic multiplier of any sector.^{224, 225} This sector provides a significant portion of total economic activity in these regions. The U.S. Gulf Coast maintains 45 percent of the country's oil refining capacity, and a major share of U.S. crude oil production and petroleum-based industries. About one-half of U.S. steel manufacturing is done in the Great Lakes and Southeast regions. The Midwest contains the majority of U.S. ethanol production.

The patterns of innovation follow these regional variations. There are strong relationships among innovation, job creation, and technology deployment in the solar and wind energy industries, as is seen in Figure 6-2. A favorable policy environment, created by state mandates and financial incentives, has also helped to shape this virtuous cycle.

FIG. 6-4

Top Eight States in Terms of Total Manufacturing Output, and Share of Gross State Product, 2014



224. "Top 20 Facts About Manufacturing," Newsroom, National Association of Manufacturers, accessed March 12, 2018, <http://www.nam.org/Newsroom/Top-20-Facts-About-Manufacturing/>

225. U.S. Department of Energy [DOE], Energy Innovation Portfolio Plan FY 2018 - FY 2022 (Washington, D.C., 2017), 32, https://www.energy.gov/sites/prod/files/2017/01/f34/DOE%20Energy%20Innovation%20Portfolio%20Plan%20FY%202018-22_0.pdf

U.S. manufacturing is highly concentrated in certain states and represents a significant portion of the economy in those regions.

Source: Energy Futures Initiative (EFI), 2018; adapted from the National Association of Manufacturers

Energy Innovation Ecosystems: Features, Players, Trends

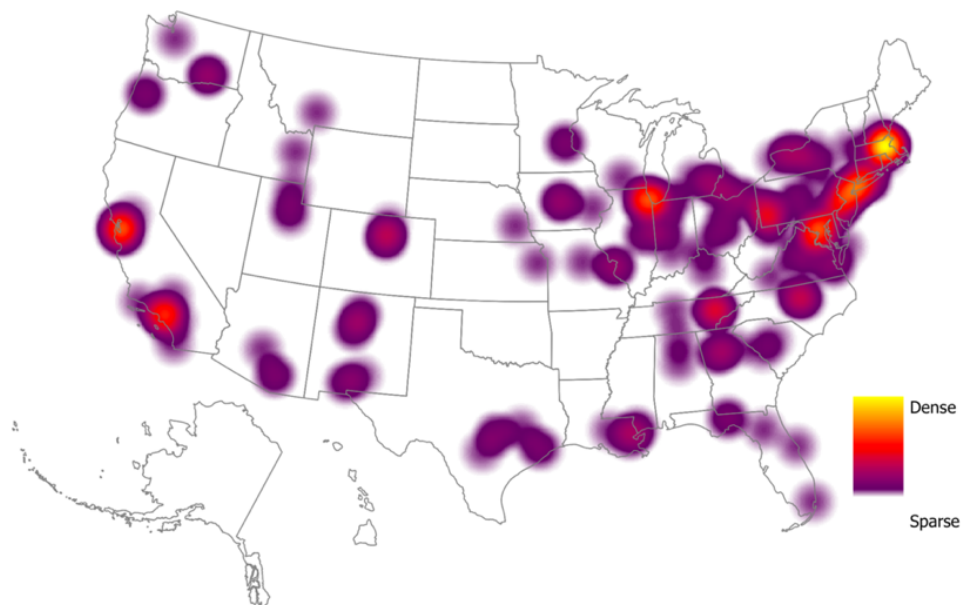
Analysis of national data on energy innovation reveals strong regional clustering. Combining data on the location of Department of Energy (DOE) national laboratories and Energy Innovation Hubs, the DOE-funded Energy Frontier Research Centers, the National Network for Manufacturing Innovation Centers, NASA laboratories and facilities, the top 100 research universities, and the major Federally Funded Research and Development Centers (FFRDCs) into a single heat map shows significant clustering of innovation capabilities (Figure 6-5). What the heat map shows is that there is a robust system of innovation enablers in many, but not all, parts of the United States.

But are innovation clusters also innovation ecosystems? Data analytics work conducted at Oak Ridge National Laboratory suggests that an effective energy innovation ecosystem exists where there is significant and meaningful interaction among five components, as illustrated in Figure 6-6.²²⁶ The innovation base, consisting of a cluster of innovation assets and people, is a necessary but not sufficient condition for achieving a true innovation ecosystem.

The concept of an innovation ecosystem is derived from the cluster theory of competitive advantage, a highly regional strategy of economic development first introduced by Michael Porter.²²⁷ The original theory was based on the idea that concentrated collections of firms, suppliers, and related industries would

FIG. 6-5

Regional Clean Energy Innovation Index



226. Jessica Lin et al., "Ecosystem Discovery: Measuring Clean Energy Innovation Ecosystems through Knowledge Discovery and Mapping Techniques," *Electricity Journal*, 29, no. 8 (October 2016): p. 65, <https://doi.org/10.1016/j.tej.2016.09.012>. <https://www.sciencedirect.com/science/article/pii/S1040619016301518?via%3Dihub>

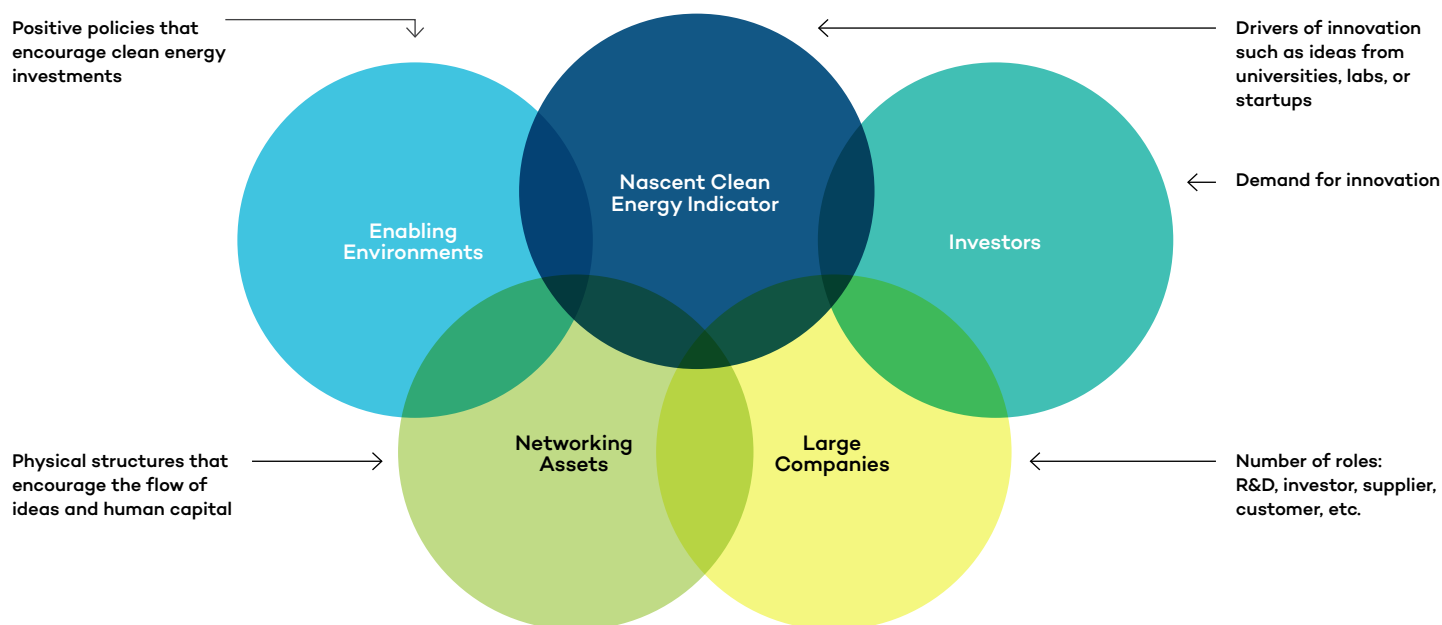
227. "What Are Clusters?," Frameworks and Key Concepts, Competitiveness and Economic Development, Institute for Strategy and Competitiveness, Harvard Business School, accessed March 12, 2018, <https://www.isc.hbs.edu/competitiveness-economic-development/frameworks-and-key-concepts/Pages/clusters.aspx>

EFI's Regional Clean Energy Innovation Index combines locational data for energy RD&D resources across the country to analyze the potential benefits to innovation of regional clustering.

Source: Energy Futures Initiative (EFI), 2017. Compiled using data from Hersch, 2014; Manufacturing USA; National Aeronautics and Space Administration; National Science Foundation; DOE

FIG. 6-6

Principal Elements of a Regional Clean Energy Innovation Ecosystem



The five principal elements of a clean energy innovation ecosystem involve the interaction among investors, large companies, networking assets, enabling environments, and nascent clean energy indicators.

Source: Energy Futures Initiative (EFI), 2018; adapted from Lin, 2016

provide competitive advantage of that region. Work by scholars at the Brookings Institution expanded the concept of an innovation ecosystem to encompass the synergistic interaction among people, firms, and locational assets that facilitates idea generation and accelerates commercialization.²²⁸ Evolving energy innovation ecosystems in the Midwest and California — including the innovation base, the investors, and the adopters — are illustrated in Figure 6-7.²²⁹

Small-scale innovators represent an important new entrant into regional innovation ecosystems. Many are spinoffs from the major research universities in that region; others may be innovators seeking to transfer technologies developed at the DOE national laboratories to commercial application. Some are innovators seeking incubator space to test out new ideas. State and local governments, the private sector, universities, the DOE national laboratories, and philanthropies all can play key roles in supporting the establishment of incubator space to enable small companies to perform the development and prototyping of new technologies and ideas. The DOE national laboratory system can play a major role in this process. Lawrence Berkeley National Laboratory initiated an incubator program, Cyclotron Road, to make available unique laboratory capabilities as well as technical assistance from laboratory scientists and engineers. Argonne National Laboratory and Oak Ridge National Laboratory have since initiated similar programs. These efforts represent a prime example of how regional innovation clusters become true ecosystems.

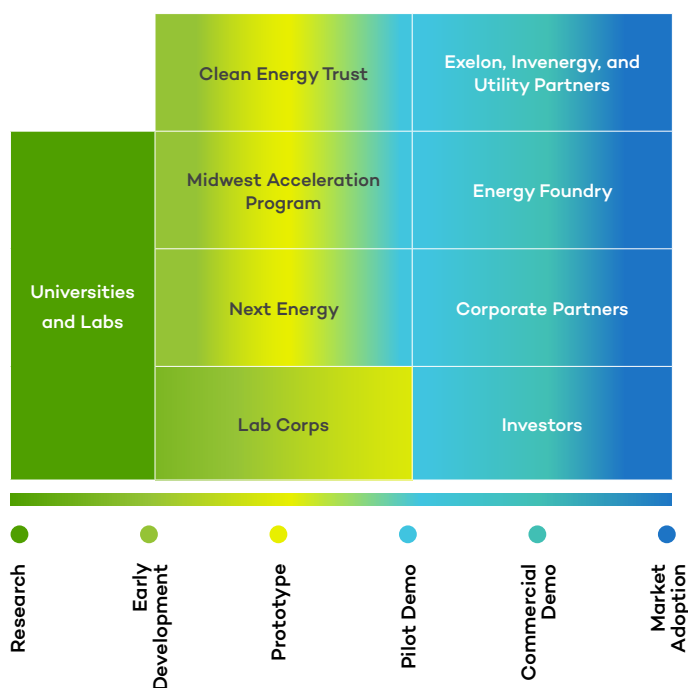
228. Bruce Katz and Julie Wagner, *The Rise of Innovation Districts: A New Geography of Innovation in America* (Washington, D.C.: Brookings Institution, 2014), 2, <https://www.brookings.edu/wp-content/uploads/2016/07/InnovationDistricts1.pdf>

229. Electric Power Research Institute, *Pathways to Success: Clean Energy Innovation Ecosystems: Best Practices Report #3* (Palo Alto, CA, 2016), 8, <https://www.epri.com/#/pages/product/000000003002009410/>

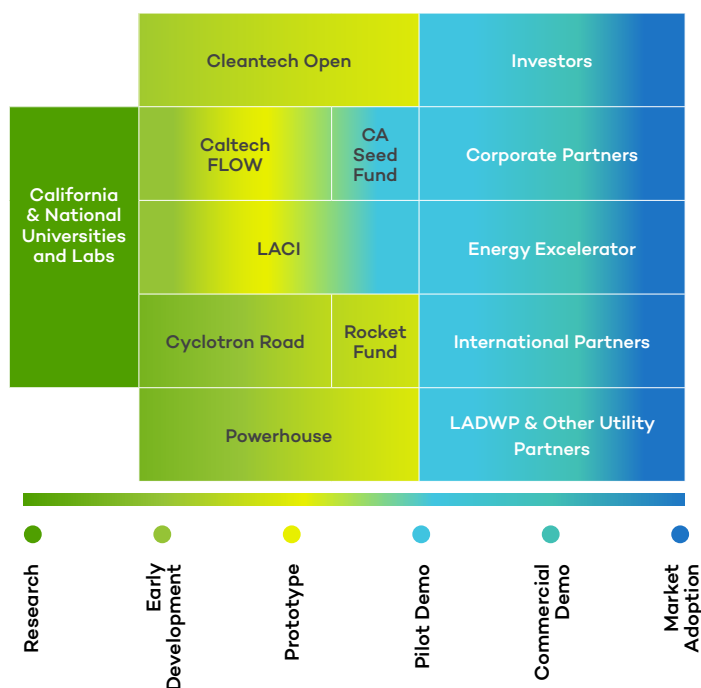
FIG. 6-7

Select Energy Innovation Ecosystem Players by Region and Role in Process

Midwest Entrepreneur Ecosystem



California Entrepreneur Ecosystem



The convergence of people, firms, and locational assets can help seed the formation of energy innovation ecosystems.

Source: Energy Futures Initiative (EFI), 2018; adapted from Electric Power Research Institute, *Pathways to Success: Clean Energy Innovation Ecosystems*, 8

The combination of trends in platform technologies, combined with decentralization of energy systems, adds further impetus to the strengthening of regional innovation ecosystems. Energy systems are becoming more decentralized and resources more distributed, as they shift from pure energy-delivery businesses to integrated platforms tailored to customer demands. The deployment and use of digital technologies, automation, and artificial intelligence has grown exponentially over the last decade, enabled by rapidly declining costs and improved performance of sensors, computing capabilities, and data transmission systems. Smarter grids, industries, and cities will provide greater situational awareness of system health, performance, and customer needs at the regional, local, and customer levels. These changes will drive the energy sector to become even more regionalized and further democratize the tools necessary to innovate.

Another major trend that will further enable regional clean energy innovation ecosystems is the growth of the sharing economy in which individuals borrow or rent assets when the price of an asset is high or when it is not fully utilized.²³⁰ Uber, Lyft and Airbnb are examples of this form of collaborative consumption. They were enabled by the growth of digital platforms and social networking. The sharing economy will continue to influence the development of energy sector technologies, system designs and operations, as well as demand — each of which may be shaped more efficiently based on local and regional conditions.

230. Investopedia, s.v. "sharing economy," accessed March 12, 2018, <https://www.investopedia.com/terms/s/sharing-economy.asp>

“The combination of trends in platform technologies, combined with decentralization of energy systems, adds further impetus to the strengthening of regional innovation ecosystems. Energy systems are becoming more decentralized and resources more distributed, as they shift from pure energy-delivery businesses to integrated platforms tailored to customer demands.”

For example, although uncertainty exists, the growth of autonomous, electric, and connected vehicles could require changes to energy distribution systems,²³¹ along with possible improvements in grid-edge technologies.²³² Due to the massive size of these distribution systems and the number of companies that will directly and indirectly benefit from these augmentations — vendors, automobile manufacturers, and big data companies, among others — a regional strategy would be ideal. Light-duty vehicles are the largest source of GHG emissions in the transportation sector²³³ and operate in mostly local or regional areas. For this reason, smarter and less polluting light-duty vehicles would benefit greatly from an organized, coordinated support infrastructure.

Many of the risks faced by the energy sector are highly regional in nature and would be better managed by strategies tailored to each region's specific needs. Electric utilities in the Gulf Coast, for example, need resilient infrastructures for withstanding hurricanes and sea-level rise; natural gas producers in the Northeast must accommodate polar vortexes, while drillers in West Texas are dealing with severe drought, competing with other water users and uses. Threats from increasing frequency and sophistication of physical and cyberattacks are also highly regionalized. Both the cause and effect of physical attacks on energy networks tend to be geographically concentrated, while the consequences of cyber events in the energy sector could be more localized due to the tailored nature of vulnerable system architectures.²³⁴

Regional energy innovation ecosystems can be strengthened by increasing the connectivity of existing financial resources and research capabilities at the regional level. Investments that increase the connectivity among regional innovation participants can foster significant additional innovation potential. While Federally-funded R&D historically has not been well connected to state and regional economic development, activating these regional clusters to bridge the gaps among Federal, state, and local resources will create new synergies. It bears repeating: Federal support is key but regional leadership is critical.

A recent National Academy of Sciences study of innovation in clean electric power technologies noted that:

*Public/private partnerships to accelerate new market development and evolve regulations for new entrants are being formed in clusters and regions. The United States has a significant number of emerging increasingly clean energy clusters, as well as regional initiatives designed to connect the region's innovation resources with early-stage ventures. Federal policy for energy innovation can take advantage of the strengths of these regional differences in innovation conditions, capabilities, and priorities.*²³⁵

The report recommended the formation of Regional Energy Innovation and Development Institutes (REIDI) — energy-specific venture development organizations that would add several capabilities specific to the energy innovation system and its needs. The REIDI could be a public or a non-profit entity funded from equal matching of federal and regional funding resources, with the possibility that one source of regional funding would be from electricity system benefits charges. The report suggests that the REIDI program could reach a scale of \$250 million total budget within 5 to 10 years, with individual REIDIs varying in size from \$2 million to \$40 million, depending on their scope. The role of the REIDI would primarily focus on midstage innovation and would include a broad range of innovation activities as indicated in Text Box 6-2.

231. https://www.energy.gov/sites/prod/files/2017/06/f34/Challenges_and_Opportunities_of_Grid_Modernization_and_Electric_Transportation.pdf

232. <http://www.iea.org/publications/freepublications/publication/DigitalizationandEnergy3.pdf> [see comment]

233. “Fast Facts on Transportation Greenhouse Gas Emissions,” Green Vehicles Guide, Environmental Protection Agency, accessed March 12, 2018, <https://www.epa.gov/greenvehicles/fast-facts-transportation-greenhouse-gas-emissions>

234. <https://www.energy.gov/sites/prod/files/2017/01/f34/Cyber%20Threat%20and%20Vulnerability%20Analysis%20of%20the%20U.S.%20Electric%20Sector.pdf>

235. National Academies of Sciences, Engineering, and Medicine, *The Power of Change: Innovation for Development and Deployment of Increasingly Clean Electric Power Technologies* (Washington, D.C.: National Academies Press, 2016), 68, doi: 10.17226/21712.

TEXT BOX 6-2

Roles and Responsibilities of a Regional Energy Innovation and Development Institute

Innovation acceleration: providing support and modest innovation funding and services to promising projects; supporting technology development, but with an additional focus on leveraging local resources of mentors, customers, investors, entrepreneurs, teams, and early-adoption market connections to help new innovations prove their business and economic value.

Market and cluster research: focusing on regional market and cluster potential, and seeking to connect cluster and market needs to innovators and innovation concepts to rapid market feedback.

Access to technical resources: developing and supporting access to a regional network of testbeds and simulation modeling laboratories, and coordinating the leveraging and growth of test resources with recommended national Technology Test Bed and Simulation Network.

Ecosystem development: designing and leveraging programs to develop regional innovation resources (including mentors; experienced entrepreneurs; customers; partners; R&D facilities, including national laboratories; test sites; capital providers; educators; and team members) as well as initiatives to invest in regional assets for incubation, acceleration, R&D, business development, mentoring, and education.

Policy and regulatory alignment: developing initiatives to change the policy and regulatory structures that eliminate obstacles and implement market signals for emerging categories of increasingly clean technologies.

Smart deployment: designing and implementing initiatives to stimulate market demand, siting processes, customer and innovator connections, business development connections, and early-adoption customers for emerging increasingly clean technologies (including the public sector as customer).

Source: National Academy of Sciences, Engineering, and Medicine, The Power of Change: Innovation for Development and Deployment of Increasingly Clean Electric Power Technologies, 71

There is significant evidence that increased cooperative R&D arrangements, such as regional innovation ecosystems, encourage greater private sector R&D investment. One study noted that, “There exists some first evidence that geographic proximity may help to overcome institutional differences between cooperators, which suggests another rationale for facilitating and supporting regional clusters of R&D activity to exploit agglomeration economies.”^{236, 237}

A 2017 study by the Hamilton Project of the Brookings Institution described lessons that the energy sector could learn from drug development in the pharmaceutical industry. One of its proposals noted that:

*There is...room for improvement in energy innovation by importing this valuable practice [contract research] from the pharmaceutical industry. We propose that regional actors — governments, universities, national labs, and companies — work to foster the creation of a robust set of research service providers to supplement existing user facilities. These services should be matched to regional strengths, taking into consideration the local business environment and the local scientific expertise. Nationwide, these efforts would combine to form a diverse research service industry that operates across the varied subsectors of energy technology.*²³⁸

The previous Administration, as part of its Mission Innovation initiative, proposed \$110 million in its Fiscal Year (FY) 2017 budget to establish a national network of up to 10 multistate Regional Clean Energy Innovation Partnerships. The proposal was caught in the crossfire of a statutory discretionary spending cap that essentially froze FY 2017 spending at FY 2016 levels, combined with an end-of-an-Administration election year cycle. Nonetheless, Congress did signal its support for DOE to move forward in encouraging greater regional innovation. In its report on the Energy and Water Development Appropriations Bill, 2017, under a heading of “Regional Partnerships,” the Senate Committee on Appropriations stated:

*The Committee urges the Department to utilize investments through existing regional capabilities that include industry, universities, and State and regional economic development assets. The Committee further encourages the national laboratories to expand their geographic outreach through people and access to specialized equipment and user facilities in order to contribute to the success of these regional initiatives.*²³⁹

This same directive was included in the Senate committee report for the FY 2018 appropriations bill for DOE.²⁴⁰ This congressional directive indicates support for DOE efforts, led through the national laboratories, as the basis for proceeding with next steps in fostering greater regional innovation connectivity through more strategic application of existing funding streams.

236. Bettina Becker, “Public R&D Policies and Private R&D Investment: A Survey of the Empirical Evidence,” *Journal of Economic Surveys*, 29, no. 5 (December 2015): 917–942, <https://dx.doi.org/10.1111/joes.12074>

237. Bettina Becker, “Public R&D Policies and Private R&D Investment: A Survey of the Empirical Evidence,” p. 24, https://research.aston.ac.uk/portal/files/19057068/Public_R_and_D_policies_and_private_R_and_D_investment.pdf

238. Anna Goldstein et al., *Promoting Energy Innovation with Lessons from Drug Development* (Washington, D.C., Brookings, 2017), 10, <https://www.brookings.edu/research/promoting-energy-innovation-with-lessons-from-drug-development/>

239. S. Rep. No. 114-236, 60–61 (2016), <https://www.congress.gov/114/crpt/srpt236/CRPT-114srpt236.pdf>

240. S. Rep. No. 115-132, 61 (2017), <https://www.congress.gov/115/crpt/srpt132/CRPT-115srpt132.pdf>

TABLE 6-1

Counties with Limited Access to the Broadband Internet

Number and Percentage of Counties without Broadband Internet Access for at Least Half of the Population of the County, By State and Region															
Region:	South						West						Midwest		
State	AL	AR	LA	MS	OK	TX	AK	CO	ID	MT	NM	NV	IL	MO	NE
Number of Counties	26	31	30	39	38	106	22	24	18	37	15	10	39	53	49
% of Counties in State	39	41	47	48	49	42	76	38	41	66	45	59	38	46	53

Source: Calculated from data in Federal Communications Commission, 2016 Broadband Access Report, Appendix E: Americans Without Access to Fixed Advanced Telecommunications Capability by County

Creating Regional Innovation Opportunities Where Innovation Clustering Does Not Exist

241. An examination of the map in Figure 6-4, for areas that do not show clustering of regional innovation capabilities, indicates where these regions may be found.

242. Federal Communications Commission [FCC], 2016 Broadband Progress Report (Washington, D.C., 2016), 33-34, https://apps.fcc.gov/edocs_public/attachmatch/FCC-16-6A1.pdf. Broadband access is defined by the FCC as meeting a speed benchmark of 25 Mbps download/3 Mbps upload for fixed telecommunications service.

243. FCC, "Appendix E: Americans Without Access to Fixed Advanced Telecommunications Capability by County," 2016 Broadband Access Report, https://apps.fcc.gov/edocs_public/attachmatch/FCC-16-6A2.xlsx. Appendix E was not published with the report but was posted at the address shown in this footnote on the FCC website. The FCC's statistics define "county" as a county-level jurisdictional or census unit, as some states (e.g., Alaska) do not have counties, but other organizational units at that level, and other states have "incorporated cities" in addition to formal counties.

Certain regions of the country still lack major energy innovation clustering opportunities. These regions tend to be more rural, have fewer major research universities and lower population densities, and tend to be more economically distressed.²⁴¹ Many of the major changes occurring in the energy sector, and across the wider economy, offer unique opportunities for these regions to develop new capabilities to support jobs, industries, and the U.S. energy innovation ecosystem.

The application of platform technologies — such as advanced additive manufacturing, data analytics, and robotics — offer the potential to expand innovation into areas of the country that currently do not have significant innovation resources. However, many of these regions also lack broadband internet access, a key enabler of platform technologies and other aspects of the modern economy. In particular, businesses and researchers pursuing innovation rely on broadband internet access for data, graphics video, and other advanced telecommunications capabilities.

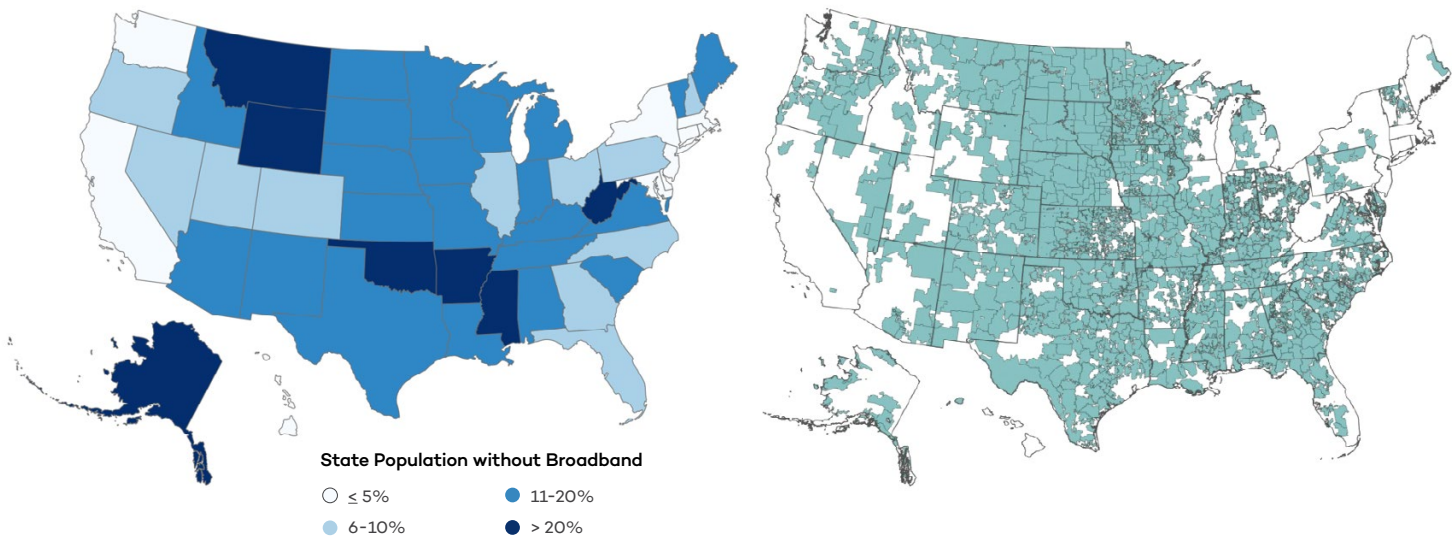
While 90 percent of Americans have access to broadband internet, only 39 percent of Americans living in rural areas have access.²⁴² Of the 902 counties that lack access for half or more of their populations, 537 of them are in just 15 states, concentrated mostly in the southern, western, and midwestern United States, as shown in Table 6-1.²⁴³ These states are also highlighted, based on state population data, in Figure 6-8. The areas of the country covered by these states and counties are typically served by rural electric cooperatives. Cooperatives already provide

FIG. 6-8

Map of Broadband Internet Access and Map of Electric Cooperative Service Territories

Percent of Population Without Broadband Internet

Electric Cooperative Service Territory



Correlation exists between states and regions serviced by electric cooperatives and those with relatively higher populations without broadband Internet access.

Source: EFI, 2018; adapted from the National Student Clearinghouse Research Center and National Rural Electric Cooperative Association

a nexus for regional energy innovation; additional support may enable them to expand their role as vehicles for further clean energy innovation in these areas. The lack of broadband is also a persistent problem on Native American Tribal Lands. On average, 41 percent of Americans living in Tribal Lands lack broadband internet, compared to four percent of Americans in urban areas.²⁴⁴

In January 2017, the Administration announced two executive actions aimed at expanding broadband internet access in rural areas. A presidential memorandum now instructs the Department of the Interior to develop a plan for using the department's towers and other infrastructure assets to facilitate broadband expansion.²⁴⁵ The other action, an Executive Order, streamlines the process for installing antennas on federal property.²⁴⁶

These actions are mainly aimed at making rural broadband expansion more attractive for private investment. The federal government already provides financial support for broadband expansion in the form of grants or loans from various agencies, including the Federal Communications Commission (FCC), the Appalachian Regional Commission, and the Departments of Commerce and Agriculture. The current administration has stated that current programs are insufficient and described the recent executive actions as merely a stopgap measure while a larger funding plan is developed. Additional resources are needed, and budget requests should be scrutinized to ensure that funding is adequate. Overall, it is clear that the first step in creating regional innovation opportunities in these areas is to deploy broadband services.

244. FCC, 2016 Broadband Progress Report, 3.

245. Donald J. Trump, "Memorandum on Supporting Broadband Tower Facilities in Rural America on Federal Properties Managed by the Department of the Interior," January 8, 2018, Daily Comp. Pres. Docs., 2018 DCPD No. 00012, <https://www.govinfo.gov/content/pkg/DCPD-201800012/pdf/DCPD-201800012.pdf>

246. Donald J. Trump, "Executive Order 13821—Streamlining and Expediting Requests to Locate Broadband Facilities in Rural America," January 8, 2018, Daily Comp. Pres. Docs., 2018 DCPD No. 00011, <https://www.federalregister.gov/documents/2018/01/11/2018-00553/streamlining-and-expediting-requests-to-locate-broadband-facilities-in-rural-america>

RECOMMENDATIONS

Fostering Regional Clean Energy Innovation Ecosystems

- Federal energy innovation programs should provide greater flexibility to encourage formation of more regional collaborations among a portfolio of programs and projects. The aim would be to attract increased nonfederal investment from states, the private sector, investors, philanthropies, and other entities, in order to increase prospects for innovation, job creation, and economic growth. Steps could include:
 - incentivizing regional organizations to coordinate individual R&D projects within a region, and
 - establishing regional innovation partnership demonstration programs as a priority cross-cutting program within the restructured DOE innovation portfolio.
- DOE national laboratories and other federal laboratories and FFRDCs can serve as anchors for regional clean energy innovation and should be given sufficient flexibility in the expenditure of discretionary funds to support regional clean energy innovation options. As part of their technology transfer responsibilities, the national laboratories should:
 - have the flexibility to set aside a very small percentage (e.g., less than 1 percent) of the laboratory budget to seed formation of regional innovation ecosystems that also have the potential to enhance technology transfer from and to the laboratories;
 - expand national laboratory innovation incubator programs (e.g., expansion of Cyclotron Road); and
 - be held accountable for improved performance in regional innovation, with DOE incorporating innovation metrics into its award fee determinations for the national laboratories.
- Universities, private industry, philanthropies, state and local governments, and DOE should seek to expand and strengthen incubator capabilities within regions to provide additional tools to enable innovators to conduct R&D and prototyping.
- USDA should focus its rural economic development programs and the Rural Utilities Service grant and loan programs to foster regional innovation ecosystems in rural areas that currently have less developed innovation clusters.
- The Department of the Treasury and DOE should review and revise the guidance for the R&D tax credit to increase flexibility and to encourage greater private-sector support for regional innovation partnerships. Alternatively, DOE and the Department of the Treasury could propose that Congress create a new credit for this purpose.
- USDA, the FCC, and DOE should enhance partnerships through the National Response Framework to enable broadband access in rural areas that would improve energy emergency response and recovery efforts and support future developments in the energy innovation ecosystem. While the FCC has made improvements, both in broadening the definition of broadband in 2015 — as download speeds six times the previous standard — and in improving access for more communities, the “digital divide” continues between urban and rural areas. This would support energy innovation clusters in new regions throughout the country, and help the FCC carry out its mission to provide universal access of broadband internet.

Chapter 7. Mobilizing Increased Private Sector Investment in Energy Innovation

This chapter examines the impact of fiscal policy, budget cuts, and the recently-passed Tax Cuts and Jobs Act of 2017 (TCJA) on funding for, and investment in, clean energy innovation, including opportunities for key providers of investment capital to support the adoption and diffusion of clean energy technologies. It also examines the expanded 45Q credits included in the Balanced Budget Act that provide additional incentives for carbon capture, utilization and sequestration (CCUS).

FINDINGS

Mobilizing Increased Private Sector Investment in Energy Innovation

- Private sector, Federal and academic R&D investments and trends, and how the results of U.S. investments in clean energy innovation compare with other countries and regions, are important indicators for U.S. economic competitiveness and security.
- U.S. patent activity, largely in the private sector, shows the U.S. leading Europe and Japan in bioenergy, cleaner coal and smart grid between 2014-2016.
- For U.S.-based entities, budget caps, reduced discretionary spending, and the TCJA will put downward pressure on federal spending but will provide corporations with \$1 trillion to \$1.5 trillion that could be invested in energy innovation and infrastructure. This increased investment pool will seek the highest return on capital. Additionally, there will be opportunities to target public policies that will make increased private investment in energy innovation part of the investment portfolio.
- The TCJA left unchanged the existing tax credits for renewable energy (wind, solar and geothermal), but did not extend the so-called “orphan” tax credits for fuel cells, combined heat and power projects, geothermal heat pumps, and new nuclear power plants. Most of these credits had expired at the end of 2016. While the TCJA did not modify the existing renewable energy tax credits, the value of these credits is reduced due to the impact of other changes in corporate tax provisions.
- Increased capital investment likely will flow to new plant and capital equipment for both modernization and expansion. Once installed, this new capital stock could easily have a useful life of 20 years or more. Public policy measures could assist in providing better information on energy innovation and climate change implications that could ultimately make this new capital stock more effective and efficient on a life-cycle cost basis.
- There are risks associated with investments in decarbonization technologies, including market design, the uncertainty of mandates, subsidies, approvals, and permitting, in addition to investment and tax issues.
- The new 45Q provisions have the potential to significantly enhance the development and market diffusion of CCUS technologies and processes in both industrial and power applications, creating commercial opportunities both in the U.S. and abroad.

Landscape of Private Sector Investment in Energy Innovation

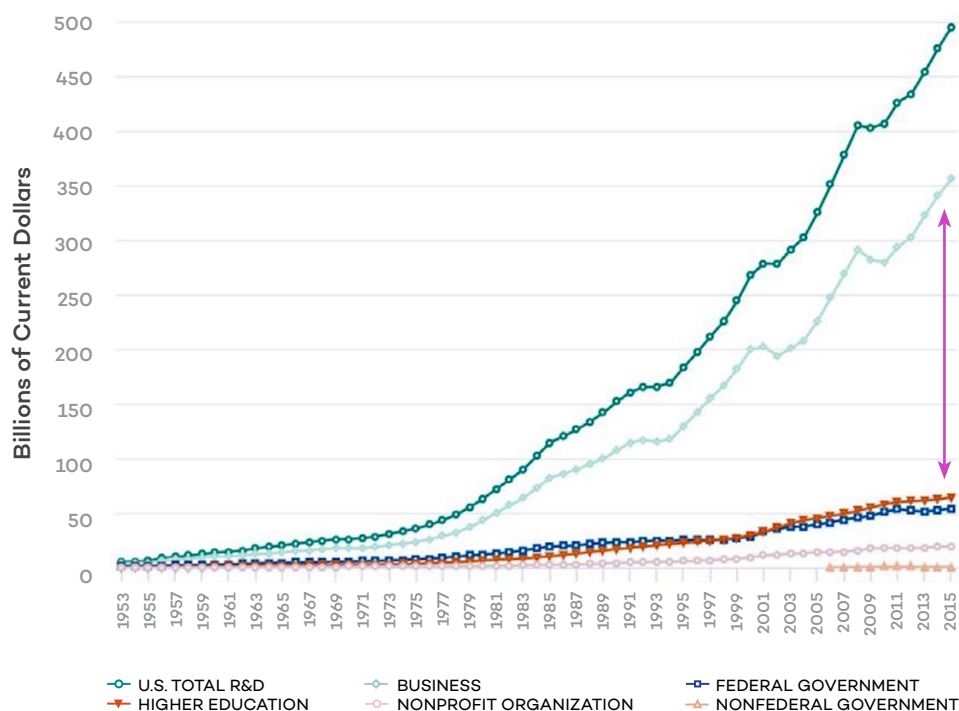
The private sector and investors — small businesses, corporations, angel investors, venture capital firms, investment banks, institutional investors, and sovereign wealth funds — provide the investment capital to support adoption and diffusion of clean energy technologies. Each of these investors plays by a separate set of rules. They support innovation at different stages of the innovation pipeline (but primarily later stage investment); focus on different types of innovation (such as software versus hardware, or energy management versus energy supply); and invest at varying scales (from tens of thousands of dollars to tens of billions).

Private and Public-Sector Innovation Investments

Private sector, Federal and academic R&D investments and trends, and how the results of U.S. investments in clean energy innovation compared to other countries and regions, are important indicators for U.S. economic competitiveness and security. Figure 7-1 shows the R&D investments by the range of players in the U.S. between 1953 and 2015. Of special interest, beyond the dramatic increases in

FIG. 7-1

U.S. R&D Investments by Sector, 1953-2015



Total U.S. R&D investments — both by industry and the Federal government — have dramatically increased since the late 1970s, suggesting their relative importance to U.S. national goals over time. While not specific to energy, this figure provides some idea of the private, public, and academic sectors on R&D. The arrow shows the delta between private and Federal spending. As noted earlier, however, the Federal government supports a significant amount of R&D spending by higher education.

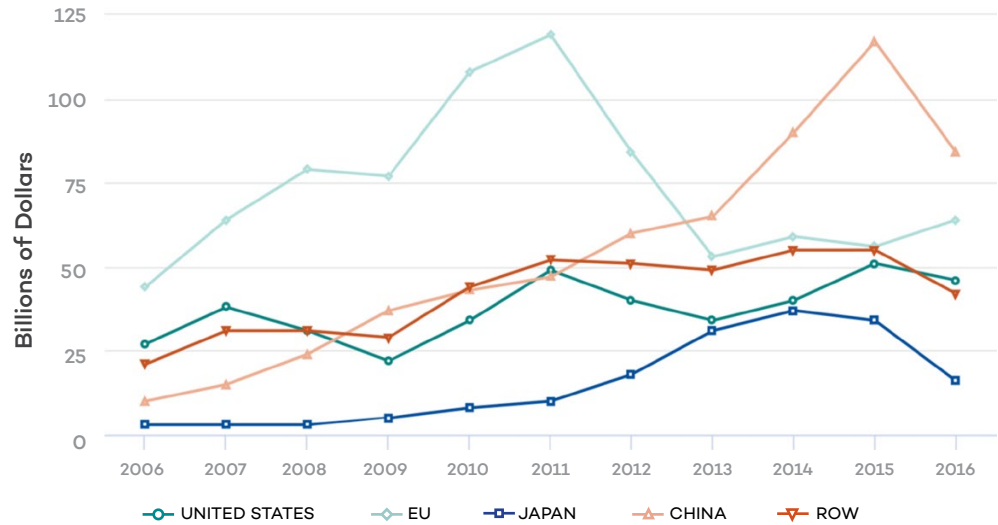
Source: National Science Foundation website, accessed May 26, 2018

overall R&D investments over this time period, is the rise in non-profits and their expenditures on R&D relative to nonfederal government investment.

Specific to energy, Figure 7-2 compares later stage spending in a range of sustainable energy areas by region or country. It is worth noting that U.S. investment in these areas shows an uptick between 2014-15, placing it above the “rest of world” and Japan in this investment category but below China and the EU.

FIG. 7-2

Later-stage Private Investment in Sustainable Energy Technologies by Selected Region or Country, 2006-2016



Data for 2016 are preliminary. Sustainable energy technologies include biomass, geothermal, wind, solar, biofuels, and energy smart and efficiency technologies. Later-stage private investment includes asset financing, small scale distributed capacity, mergers and acquisitions, public equity, and reinvested equity.

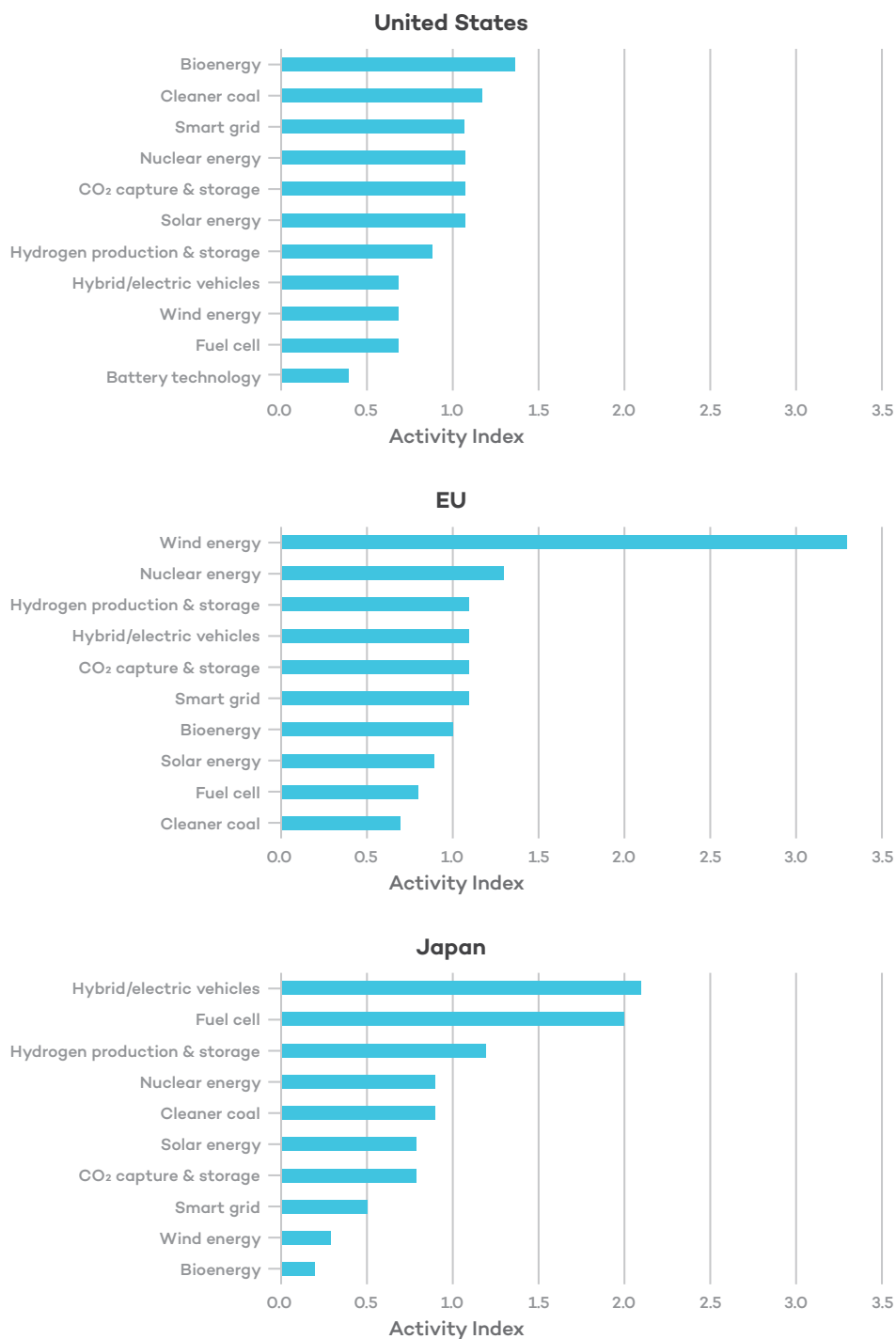
Source: Bloomberg New Energy Finance (2017), <https://about.bnef.com/> accessed 15 February 2017, Science and Engineering Indicators 2018

Another important indicator of opportunities for development and deployment by the private sector is patent activity. Figure 7-3 shows patent level indicators in several countries, including the U.S.; this can serve as proxy for relative innovation focus and activity, and stage of innovation. It is important to note, however, that most patents are never commercialized; these data cannot be viewed as indicators of deployment, although patents do indicate interest and optionality. According to the National Science Board's 2018 *Science and Engineering Indicators*:

“The purpose of patenting is to allow inventors to gain the economic benefits of their inventions in exchange for disclosure of technical information about the invention. Most patenting takes place in the business sector. Motivations differ substantially from the motivation of authors of peer-reviewed literature, where original contributions to publicly available knowledge may benefit reputation and career advancement without a direct financial benefit for the authors. Business researchers are also more likely to be engaged in experimental development activity than their academic and government counterparts, suggesting more opportunities for direct commercial applications of their work.”

FIG. 7-3

Patent Activity/Activity Index for a Range of Sustainable Energy Technologies for the U.S., EU, and Japan



For any given area of technological development, the Patenting Activity Index indicates the extent to which a country specializes in that area. It is an output measure of specialization, assessing the share of a country's patents produced in each technological area. The indicator is computed by comparing a country to the global average.

Source: National Science Foundation website, accessed May 26, 2018

There are several things to note in these country comparisons. The U.S. is the index leader in bioenergy, cleaner coal and smart grid patents; the EU is in front on wind, nuclear and hydrogen; and Japan is leading in hybrid/electric vehicles, fuel cells and hydrogen production. All three countries/regions have patents in CO₂ capture and storage. As noted, most patent activity takes place in the private sector. These indices likely reflect policy, academic activity, as well as the focus of public and private sector investments, often complementary.

Opportunities for Clean Energy Innovation in the Tax Cuts and Job Creation Act

The TCJA presents opportunities in the context of U.S. clean energy innovation investments, and U.S. competitiveness and security goals. For U.S.-based entities, the TCJA will unleash substantial resources for investment purposes that would have otherwise been collected by the federal government. This increased investment pool will seek the highest return on capital. There will be opportunities to target public policies that will make increased private investment in energy innovation part of the investment portfolio. The private sector is, of course, not a monolithic entity in the energy innovation landscape. It consists of many disparate entities, as illustrated in Figure 7-4.

The private sector includes both for-profit and nonprofit entities that have one or more functional capabilities, spanning the roles of innovation investor, research performer, technology and services provider, and innovation user. A complete inventory of total private-sector investment in energy innovation is difficult to compile because there is no common set of criteria to define the scope of energy innovation investment. In addition, much of the data on this investment is proprietary.

Chapter 2 provides an overview of many of the major private-sector players and their roles in energy innovation. Several key data points from chapter 2 and related data are highlighted here to provide a scale for the private-sector investment in energy innovation:

- Total public-market and private-equity investment in clean energy technology deployment totaled \$45.6 billion in 2016.
- Venture capital (VC) in the United States committed about \$1 billion in investments in clean energy in 2014, comprising a little more than 4 percent of total VC investment.
- U.S. corporations spent \$296.7 billion on R&D across the board in 2015²⁴⁷; in the same year, \$4.0 billion was spent by private investors in the United States on clean energy R&D (i.e., early-stage financing of clean energy technologies).²⁴⁸
- Energy-related industries have been major players in the corporate R&D investment pool. The automotive industry spent about \$16.6 billion on R&D in 2015.²⁴⁹ In 2016, the automotive industry made a similar level of investment, of which about \$2 billion was for pre-commercial investment in clean energy technology, including electric vehicles. The U.S. aerospace industry expended about \$11.1 billion on R&D in 2015.²⁵⁰
- Finally, and key to this discussion, the energy industries themselves expended about \$5 billion in 2015, including about \$1.1 billion in upstream petroleum and natural gas exploration and production and about \$250 million by utilities.

The future scope and direction of private sector energy-related innovation, from R&D through deployment, will depend upon several factors, including growth in the

247. Raymond M. Wolfe, Business R&D Performed in the United States Reached \$356 Billion in 2015, NSF 17-320 (Arlington, VA: National Science Foundation, 2017), 2, <https://www.nsf.gov/statistics/2017/nsf17320/nsf17320.pdf>

248. National Science Board, Science and Engineering Indicators 2018 (Arlington, VA: National Science Foundation, 2018), Figure 6-37, <https://www.nsf.gov/statistics/2018/nsb20181/report>

249. Wolfe, Business R&D, 3.

250. Wolfe, Business R&D, 3.

Current Landscape of Private Sector in Clean Energy Innovation



U.S. and global economy, trade flows, changing market dynamics, and government policies (monetary, fiscal, trade, and regulatory). A new and very significant factor in this growth will be the private sector response to the recently enacted TCJA. The potential scale of this impact, as well as the effects of subsequent public policy strategies on the trajectory of private investment in energy innovation, is examined further in the sections that follow.

The central objective of the TCJA is to reduce income tax rates for corporations and individuals. The TCJA included several other notable changes in U.S. tax policy, as well. The changes to corporate tax policy are substantial and include the following:

- a reduction in the corporate tax rate from 35 percent to 21 percent on a permanent basis;
- an increase in bonus depreciation to 100 percent for 5 years (allowing 100 percent expensing of capital investment); regulated public utilities are not eligible for the 100 percent expensing;
- elimination from taxation of dividends received by domestic companies from their foreign subsidiaries; and
- repeal or limitations on deductibility of corporate business expenses, the most significant being a limitation on deductibility of interest costs to 30 percent of adjusted taxable income; regulated public utilities are not subject to the 30 percent cap.

The future scope and direction of private sector energy-related innovation, from R&D through deployment, will depend upon several factors, including growth in the U.S. and global economy, trade flows, changing market dynamics, and government policies (monetary, fiscal, trade, and regulatory). A new and very significant factor in this growth will be the private sector response to the recently enacted TCJA.

The changes to individual taxes, many of which expire after 5 years include the following:

- lowering the top individual income tax rate from 39.6 to 37 percent, with lower rates for most of the other rate brackets as well;
- increasing the standard deduction while eliminating personal exemptions;
- doubling the exemption amount for the estate, gift, and generation-skipping transfer tax;
- capping the deductibility of state and local income and personal property taxes;
- requiring that only 80 percent of pass-through income from partnerships, S-corporations, and other pass-through entities be subject to personal income tax.

Within the energy community, a principal focus during congressional consideration of the TCJA was the fate of the current energy tax incentives. The Act left unchanged the existing tax credits for renewable energy (wind, solar and geothermal), but did not extend the so-called “orphan” tax credits for fuel cells, combined heat and power projects, geothermal heat pumps, and new nuclear power plants. Most of these credits had expired at the end of 2016. The Bipartisan Budget Act of 2018 modified and extended the nuclear power PTC. Other credits were extended for only one year, expiring at the end of 2017; their future fate remains pending in Congress.

While the TCJA did not modify the existing renewable energy tax credits, the value of these credits will change due to the impact of other changes in corporate tax provisions. These effects include the following:

- Existing wind and solar facilities will now become more profitable due to the lower corporate tax rate.
- On the other hand, lower tax rates, combined with an anti-abuse provision (known as the base erosion anti-abuse tax, or BEAT), likely will reduce the supply of tax-equity investment for financing new solar and wind projects. Tax equity currently accounts for 50 to 60 percent of the capital financing for a typical wind project and 40 to 50 percent of the capital financing for a typical solar project. In addition, the structure of BEAT makes it difficult for tax-equity investors to know, when they close a tax-equity deal, if they will receive all the tax credits they were expecting.
- The BEAT provisions require that corporate taxpayers, including tax equity investors, meet certain tests in order to remain eligible to utilize the annual PTC. For example, if a multinational corporation claims large tax deductions other, unrelated cross-border payments to foreign affiliates that reduce taxable income below the BEAT threshold test, that entity is prohibited from taking advantage of the PTC in that taxable year. The uncertainties associated with the application of BEAT in future years may cause energy project developers to rely on the ITC conversion provisions of the PTC and thus diminish prospects for utilization of tax equity investors.²⁵¹
- The full amount of revenue from prepaid power purchase contracts will need to be recorded upfront rather than spread out over the life of the contract. This will make such contracts less attractive.

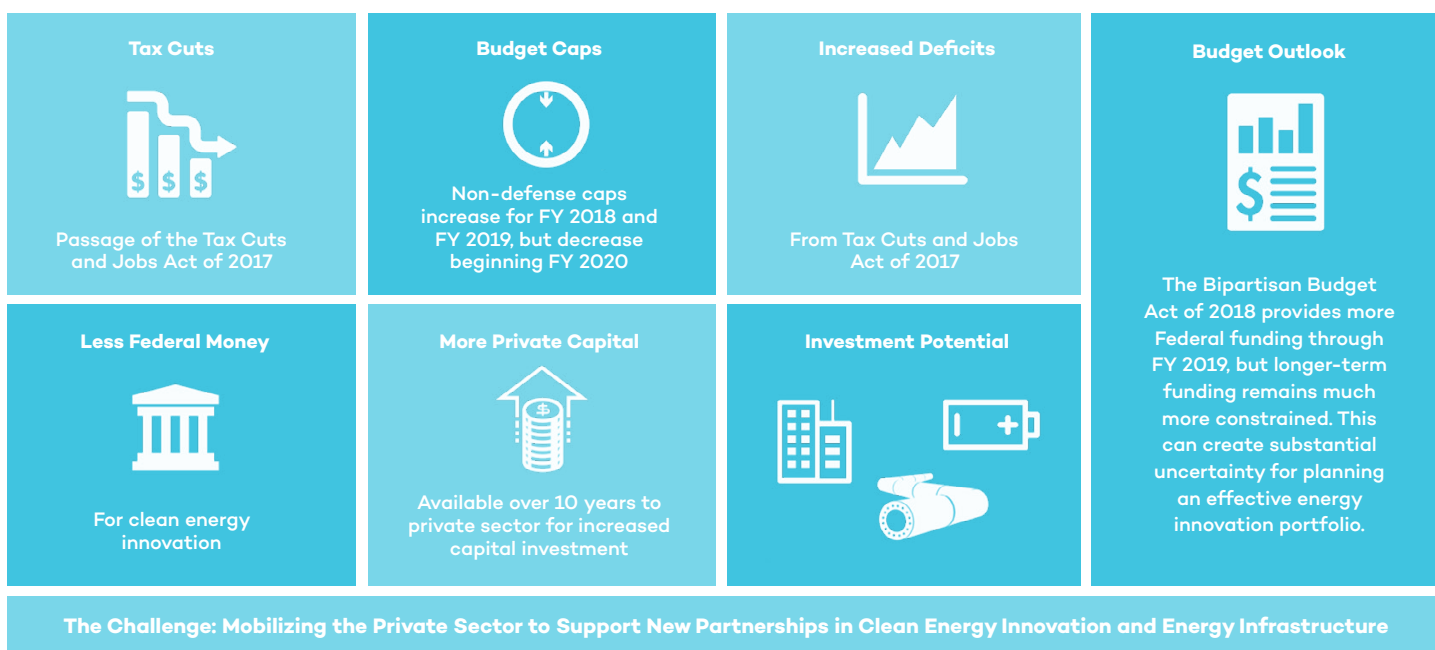
Although the focus of the energy community was on preserving the existing tax incentives for deployment of renewable energy technologies, the larger question for clean energy innovation is how the business community at large will allocate

251. Keith Martin, “Final U.S. Tax Bill: Effect on Project Finance Market,” Norton Rose Fulbright, December 16, 2017, <http://www.nortonrosefulbright.com/knowledge/publications/160375/final-us-tax-bill-effect-on-project-finance-market>

FIG. 7-5

Potential to Mobilize Additional Private Sector Capital for Clean Energy Innovation from Tax Reform

\$1 – 1.5 Trillion In New Private Capital Will Be Unlocked Over The Next 10 Years



Passage of the Tax Cuts and Jobs Act of 2017 could unlock additional private capital for investments in clean energy innovation.

Source: Energy Futures Initiative (EFI), 2017

the increased investment funds likely to become available as a result of the changes in the corporate tax provisions.

The analysis of effects of TCJA on capital stock by the staff of the Joint Committee on Taxation (JCT) concluded that corporate capital investment is likely to increase, leading to a higher level of capital stock. The JCT states that:

During the budget window [from FY 2018 to FY 2027] increased investment primarily due to the reduction in the corporate tax rate, the five-year extension of the bonus depreciation at 100 percent with an additional phase-out period, and the added tax deduction for certain pass-through business income results in a gradual accumulation of capital stock, which is forecast to reach its peak toward the end of the budget period.²⁵²

The 2017 tax cut could have a material impact on clean energy investment. The Congressional Budget Office June 2017 baseline forecast estimates cumulative total nonresidential fixed investment of nearly \$30 trillion over the 10-year budget window.²⁵³ Using these parameters, this report estimates that the potential incremental increase of private capital investment over the next 10 years to be in the range of up to \$1.5 trillion,²⁵⁴ with the effect larger during the first five years and then gradually tapering off as the projected accumulation of capital stock reaches its peak.²⁵⁵ A potentially significant fraction of this increased investment capital could be deployed into energy-related investment, both in energy production and distribution infrastructure, as well as in plant and equipment that consumes energy (Figure 7-5).

252. Joint Committee on Taxation [JCT], Macroeconomic Analysis of the Conference Agreement for H.R. 1, the "Tax Cuts and Jobs Act" (JCX- 69-17) (Washington, D.C., 2017), 5, https://www.jct.gov/publications.html?func=download&id=5055&chk=5055&no_html=1

253. Calculated as the sum of Nonresidential fixed investment, 2018-2027, under Components of GDP (nominal), June 2017 Baseline Forecast—Data Release (Calendar Year), in "10-Year Economic Projections: June 2017," Budget and Economic Data, Products, Congressional Budget Office, last modified October 12, 2017, <https://www.cbo.gov/sites/default/files/recurringdata/51135-2017-06-economicprojections2.xlsx>

254. This estimate was derived by applying the JCT estimate of a 0.9 percent incremental increase in the rate of nonresidential fixed investment across the baseline projection of nonresidential fixed investment over the 10-year projection period.

255. JCT, Macroeconomic Analysis, 3.

Strategies to Influence Increased Private Capital Investment in Energy Innovation

The TCJA, viewed in concert with potential changes in federal budget caps on discretionary spending, has the potential to shift much of the initiative for investment in clean energy innovation from the Federal government to the private sector. As noted in chapter 4, for government spending in general, the Bipartisan Budget Act of 2018 (BBA) increases non-defense discretionary spending caps for FY 2018 and FY 2019, but the caps would revert to lower levels beginning in FY 2020 under the current statutory caps set in the Budget Control Act of 2011 (BCA). The Congressional Budget Resolution for FY 2018 proposed a further reduction in the statutory caps by \$632 billion over the next 10 years, but this proposal ultimately was superseded by the BBA. The Administration FY 2019 budget again proposes substantial reductions to the current statutory non-defense spending cap totaling about \$1.6 trillion over the 10-year period (FY 2019-2028), creating uncertainty over the longer-term funding profile for Federal investment in energy innovation and other domestic programs, and setting the stage for a new round of budget negotiations likely to occur in early 2019.

The reductions to the sequester spending caps proposed in the FY 2018 Congressional Budget Resolution were motivated in large part to offset part of the projected \$1.5 trillion budget deficit increase over 10 years, due to enactment of the TCJA. As noted above, the macroeconomic modeling of TCJA indicates that the combined effects of the Act could increase private sector investment in new plant and capital equipment by up to \$1.5 trillion over the next 10 years, with the likelihood that the effects may be front-loaded in the early years. This suggests that new approaches to public-private partnerships that leverage private investment with relatively scarce federal resources are needed.

Should this increased capital flow to new plant and capital equipment for both modernization and expansion, the associated capital stock could easily have a useful life of 20 years or more. This presents both an opportunity and a challenge for adoption and diffusion of clean energy technologies. The opportunity is the potential for significant market pull and market signals for the deployment of clean energy technologies. The challenge is to provide investors the confidence they need to put capital into projects that may be risky. A recent analysis of ways to address these challenges and create new opportunities has identified a set of risk categories and associated investment risks (Table 7-1). This same analysis suggested a set of follow-on research needs to more broadly address the need to de-risk investments in clean energy technologies for a low-carbon future (Table 7-2).²⁵⁶

Public policy measures could assist in providing better information on energy innovation and climate change implications that could ultimately make this new capital stock more effective and efficient on a life-cycle cost basis. Five strategies, in particular, merit consideration.

1. Expand technical information dissemination and technical assistance activities.

Federally-funded National Network of Manufacturing Institutes and the Manufacturing Extension Partnerships can play an important role in assisting manufacturers, particularly small companies, in making investment decisions by providing information and assistance on deployment of state-of-the-art innovative technologies. DOE national laboratories also could play an increased role in this area. The cost to the federal budget would be relatively small, on the order of tens of millions of dollars, but the potential benefits could be significantly greater.

“The opportunity is the potential for significant market pull and market signals for the deployment of clean energy technologies. The challenge is to provide investors the confidence they need to put capital into projects that may be risky.”

256. Reicher et al., *Derisking Decarbonization*, 65.

TABLE 7-1

Risk Categories and Specific Investment Risks

Risk Category	Specific Investment Risks
Markets	Electricity Market Design
	Fossil Fuel Prices
Policy	Mandates & Carbon Pricing
	Government Subsidies
Project Development	Innovative Technologies
	Government Approvals & Permitting
Investment Framework	Rule of Law
	Tax Issues
	Debt Regulation, Equity Disclosure & Currencies

The large-scale investments needed to address climate change will require the de-risking of clean energy projects to attract major institutional investors.

Source: Dan Reicher, Jeff Brown, and David Fedor, *Derisking Decarbonization: Making Green Energy Investments Blue Chip*, 9

2. De-risk near-commercial innovative clean energy technologies to accelerate commercialization. There may be a significant inventory of near-commercial innovative energy technologies in the innovation pipeline that could be readied for commercial deployment at scale. The first step would be the development of such an inventory. Individual projects would be de-risked through scale-up or demonstration through public-private partnerships. The program could be implemented quickly through a combination of a streamlined competitive selection process and the use of flexible financial vehicles such as Technology Investment Agreements authorized by DOE's Other Transactions Authority. An illustration of how this can be accomplished can be found in DOE's success in placing, quickly and effectively, significant levels of funding from the 2009 American Recovery and Reinvestment Act into programs such as the smart grid demonstration program.

3. Increase investments to expand the availability of open-access testbeds and incubator space to enable more rapid commercialization of innovative technologies. Historically, many large corporations maintained large in-house research facilities (e.g., Bell Labs, Xerox PARC, DuPont Experimental Station) with extensive scientific and technical capabilities to perform research including development of prototypes for market development. Today's innovation

TABLE 7-2

Research Needs for De-Risking Clean Energy Investments

	Taxpayer Investors	Non-Taxpayer Investors
Introduction	Size of Investment Needed	Compare IEA vs. other experts; quantify funds freed up through reduction in high carbon investments
	Institutional Flows	Analyze investor subcategories to eliminate double counting (interviews with OECD, ICI, SWFI, IMF, World Bank); strip out asset valuation in some data (insurance); incorporate appropriate amount of bank lending capacity
	Wealth vs. Climate Spending in Non-OECD	Better data on wealth in BRICs and other non-OECDs since information is poor in OECD and other databases
	Offsetting Factors	Investigate macroeconomic boost from clean-energy spending vs. drag of repaying clean energy investments
Markets	Electricity Market Design	Investigate market design in “competitive markets” expanded to include EU and Australia; compare best practices in fully-regulated states, provinces or nations
	Fossil Fuel Prices	Implementation issues for CfDs involving natural gas and oil; impact on privately-traded commodities markets
Policy	Mandates and Carbon Pricing	Leakage issues in carbon pricing systems for single states, provinces, countries; evaluate carbon abatement cost impacts of high-cost complementary measures interacting with carbon pricing; compare RPS approaches
	Government Subsidies	Evaluate credit aspects of best practices/design in electricity market CfDs for low-carbon; data analysis — grants vs. loans
Project Development	Innovative Technologies	Policy changes to increase government involvement in developing bankable standard design in bulk storage, CCS, nuclear, etc.
	Government Approvals & Permitting	Global environmental benefits vs. local impacts in environmental laws (e.g., NEPA); specific permitting, PPA transmission issues
Investment Framework	Rule of Law	Bilateral vs. multilateral investor protection treaties under auspices of climate agreements; mandatory arbitration
	Tax Issues	Bilateral vs. multilateral investor protection treaties under auspices of climate agreements; mandatory arbitration
	Debt Regulation, Equity Disclosure, and Currencies	<ul style="list-style-type: none"> • Capital adequacy rule changes • Equity valuation impacts of climate disclosures • Frameworks for soft currency hedging

De-risking investments in clean energy technologies will require further quantitative and qualitative research to help address uncertainties and optimize decarbonization pathways for a low-carbon future.

Source: Dan Reicher, Jeff Brown, and David Fedor, Derisking Decarbonization: Making Green Energy Investments Blue Chip, 65

“State and local governments, with philanthropic support, have stepped in to create incubator space (e.g., the Pittsburgh Electricity Center). Universities have also supported partnerships in these types of efforts.”

landscape is very different — with the decline of large corporate in-house capabilities, greater reliance on outsourcing and technology acquisition, and an increasing role for individual and small-scale innovators seeking to develop new energy-related products and processes. The inability to provide incubator space, including testbeds for prototyping, is an impediment to energy innovation involving significant hardware. One reflection of this issue is the trend within the investor community (VC in particular) to favor investments in software-based innovation rather than hardware-based innovation. (Other factors also are at play, including scale of investment, greater regulatory burdens, and potential payback time.) State and local governments, with some philanthropic support, have stepped in to create incubator space (e.g., Pittsburgh Electricity Center). Universities have also supported partnerships with these types of efforts. The DOE National Laboratories have initiated technical support efforts such as the Cyclotron Road initiative at Lawrence Berkeley and similar programs at Argonne National Laboratory and Oak Ridge National Laboratory. Increased industry investment in expanding these capabilities can accelerate the flow of innovation and generate new options on a faster scale for possible commercial deployment.

4. Encourage consideration of weather and climate resilience in capital asset investment decisions. Private businesses will always seek to find the least-cost alternative investment strategy that maximizes return to investors. Public entities also will seek the lowest-cost alternative when allocating public monies to infrastructure projects. These entities, however, do consider risk and contingencies in formulating projects and making investment decisions.

These risks are addressed through a combination of following minimum standards for mitigation of the risk, as well as obtaining insurance. The level of insurance also involves a careful trade-off analysis, considering potential risk exposure versus the cost of insurance. There are, for example, well-established standards for incorporating fire mitigation measures into capital stock (in compliance with standards typically set by state and local governments), as well as investing in insurance to cover remaining risk exposure (with prices set by the insurance industry). The same is true with flood protection and flood insurance, where both the standards and the insurance are largely controlled by the federal government. In recent decades the same pattern has emerged for earthquakes and other natural hazards.

These same concepts can be applied to clean energy innovation investments. The Federal government can work with standards agencies, such as the International Organization for Standardization (known by its international acronym, ISO), to incorporate climate resilience requirements as appropriate into various ISO standards. The standards would provide valuable guidance for both private investment as well as public-private partnerships in infrastructure investment (Text Box 7-1).

5. Encourage greater “pooling” of private sector investments through formation of energy innovation consortia and other collaborative RDD&D arrangements.

Research and Development consortia have shown to be a proven model for encouraging broader private sector investment in technology innovation. Research and development consortia are particularly effective where the areas of research have high-spillover effects benefiting the industry sector and its customers. Consortia arrangements also are effective when they can entice commitment of incremental funding from the participants that would not otherwise be the case. The federal government can play an important role in this

TEXT BOX 7-1

Role of the ISO

The International Organization for Standardization (ISO) is an independent and nongovernmental organization that has members from over 160 national standards bodies. For the United States, the participating standards body is the American National Standards Institute (ANSI). The ISO has issued over 22,000 International Standards for goods and services, which arise from voluntary and consensus-based discussions among experts. The ISO works to achieve practical, actionable solutions to global market challenges, and seeks to be responsive to technology innovation and to changing environmental and market conditions.

The ISO has sought to address standards-setting in the context of climate change and increased climatological variability and volatility. A recent report by the ISO highlights the organization's efforts to consider climate change across an array of categories, such as monitoring climatological events, measuring and reporting greenhouse gas emissions, environmental management and communication, and sustainable communities. For example, there is a wide array of standards that directly address climate change resilience. There are International Standards for mitigation, such as ISO 13.200 for accident and disaster control, and sustainable development, including ISO/TR 19083-1:2016 for intelligent transportation systems.

The internalization of the rapidly evolving effects of climate change is also complemented by a concentration on innovation support. For instance, the ISO has established a committee specifically related to robotics, drones, additive manufacturing, and biomimetics. The ISO is further adapting to the Fourth Industrial Revolution with International Standards that focus on the safety of collaborative industrial robot systems.

These standards will also assess the effectiveness of information security management systems, particularly in the context of increasingly diverse types of cyber-attacks. Furthermore, there is an ISO Smart Manufacturing Coordinating Committee to support an overall goal of enabling greater international trade.

The sheer scope of the ISO International Standards may appear daunting to both investors and companies. This may be especially true for those who are uncertain as to how best to begin the process and the applicable International Standards for which to aim. Additionally, although there is considerable impetus behind sustainable projects, goods, and services, the nuances of the international market and specific regional characteristics — as well as the necessary capital to meet such standards — may deter or frustrate investors. Furthermore, those investors and firms interested in employing such progressive International Standards must have both the technical capacity and the foresight to understand the merit of such investments.

In the United States, Federal agencies employ ISO standards while also collaborating with organizations specifically dedicated to mitigating natural disasters and manmade hazards, such as the National Fire Protection Association and the Alliance for Telecommunications Industry Solutions (ATIS). For instance, in a joint venture with ANSI, ATIS developed the standard ATIS-O600329.2008 Network Equipment Earthquake Resistance to ensure basic functionality of telecommunications infrastructure and systems during and after an earthquake. Standards related to other severe weather events, such as hurricanes, more closely align with stringent building and construction codes and regulations.

Recent climate events have illustrated the prudence of climate-resilient investments and the importance of adhering to high standards (whether they are ISO International Standards, national standards and regulations, or state-specific codes and practices). At the same time, such events reveal the challenges of coordinating the development of such standards, codes, and best practices in the context of climate change, given the complex geographic and sociopolitical factors that must be considered.

regard by providing matching funds, and thus leveraging increased private sector investment. The organization of research and development consortia, and the role of the federal government in such consortia, can take a variety of forms.

For example:

- **The Gas Technology Institute (GTI) and the Electric Power Research Institute (EPRI)** are energy industry-formed research and development organizations supporting a broad agenda within their respective industry sectors. The federal government may cost share individual research projects on a project-by-project basis. The Gas Research Institute, a forerunner organization to GTI, was funded for a number of years through a dedicated surcharge on interstate natural gas shipments, approved by the Federal Energy Regulatory Commission (FERC).
- In 1982, several major computer manufacturers in the U.S. formed the **Microelectronics and Computer Corporation (MCC)**, the first computer industry research and development consortium. The consortium leveraged member company investments in systems architecture and design, microelectronics packaging, distributed information technology and environmental management practices. The federal government did not cost share in the consortium, but Congressional enactment of the National Cooperative Research Act in 1984 helped to facilitate the implementation of the MCC and all U.S. research and development consortia. MCC was a pioneer in artificial intelligence applications and spawned several spin-outs over its lifetime. MCC ceased operation in 2004.
- **Sematech** was formed in 1987 as a consortium of 14 private sector entities to advance technologies for semiconductor manufacturing. To further leverage private sector investment and accelerate the pace of innovation to meet national security requirements, Congress authorized a multi-year \$500 million cost sharing program with Sematech, through the Defense Advanced Research Projects Agency (DARPA). With the consolidation of the chipmaking companies in the 1990s, Sematech evolved into an international R&D collaboration. In 2015, Sematech merged with the State University of New York (SUNY) Polytechnic Institute in Albany NY to broaden its research and development portfolio into clean energy, microelectronics and biotechnology.
- **Research Partnership to Secure Energy for America (RPSEA)** was formed in 2005 as a broad-based consortium of large and small companies, research universities and National Laboratories to advance technologies for environmentally-secure production of natural gas and other petroleum resources from unconventional and ultra-deepwater formations. The federal government provided multi-year funding of \$50 million annually from a set aside of royalty income from the leasing of federal oil and gas resources. RPSEA participants provided matching funding on a project-by-project basis. Federal funding ended in FY 2011.
- **The DOE Energy Innovation Hubs** are broad-based consortia, typically led by DOE National Laboratories, that bring together multi-disciplinary teams from industry and universities as well, that undertake multi-year research and development programs in energy innovation areas of high national significance, such as nuclear power modeling, energy storage, critical materials, sunlight-to-fuels and energy-water issues. DOE cost shares multi-year research programs with each Hub.

These examples illustrate a potentially significant opportunity to encourage the private sector to deploy increased investment capital in energy innovation through consortia arrangements, with leadership and “seed capital” provided by the federal government. Such arrangements could unlock a significant share of increased capital becoming available for private sector investment as a result of the TCJA.

The investment and the insurance industries also can take further efforts to ensure that climate risk is adequately factored into investment decisions. For example, Moody's recently issued a report describing how it will evaluate state and local government bond issues to weigh the impact of climate risks on the investment quality of bond issuances.²⁵⁷ The assessment will take into account not only the potential *exposure* to climate risk but also the *resilience* of the bond issuer in responding to climate events. The assessment will address financial parameters, such as the size of populations and assets potentially affected and the financial capacity of the issuer to absorb costs. Additionally, it will address the effect of governmental policies to mitigate risk. Innovation in energy systems (e.g., distributed grid architectures, on-site generation capabilities, energy-efficient equipment, energy storage back-up, and improved energy monitoring and control systems) and buildings and infrastructure incorporating more climate resilient features can be factors in reducing credit risk and credit pricing. Moody's has adopted similar concepts in its methodology for capturing the effects of physical climate change in its ratings of sovereign credit risk globally, as illustrated in Figure 7-6.²⁵⁸

Opportunities for Clean Energy Innovation in Expanded 45Q Provisions

The Bipartisan Budget Act (BBA) passed by Congress on February 8, 2018 included expanded provisions for carbon dioxide (CO₂) capture, utilization, and storage (CCUS). These provisions, based on Senate Bill S. 1535 (FUTURE Act) and its companion legislation in the House, expand and reform the Section 45Q tax credits originally enacted in 2008. They include an increase in the credit value for qualifying projects, a longer time horizon for developers to claim the credit, a more expansive definition of qualifying utilization projects beyond enhanced oil recovery (EOR), and eligibility of direct air capture. The provisions act like a production tax credit and are designed to encourage innovation in and adoption of low-carbon technologies related to CCUS, including direct air capture (DAC) of CO₂ and conversion of CO₂ into useable products.

The new 45Q provisions have the potential to significantly enhance the development and market diffusion of CCUS technologies and processes in both industrial and power applications, creating commercial opportunities both in the U.S. and abroad. The provisions provide greater market and financing certainty to help attract additional follow-on investment from the private sector. They will also likely help accelerate the pace of innovation in CCUS technologies and processes and could mitigate asset risk for fossil fuel producers by enabling continued use of fossil fuels in a carbon-constrained world. (See figure 7-7.)

It is reasonable to believe that many industrial projects, some natural gas and coal power projects, and some advanced fossil energy projects will begin construction before January 2024 and become eligible to receive the 45Q credits — an estimate as large as 100 million tons per year of CO₂. If so, the U.S. Treasury would provide between \$3.5 and \$5 billion per year of tax credits starting in 2025. Although this may seem large, it is roughly equivalent to the wind production tax credits, which the Joint Committee on Taxation assessed to be \$23.7 billion over 5 years (2016–2020).²⁵⁹ Other estimates suggest that the revamped 45Q credits could lead to \$1 billion in new investments by 2024 and add 10 to 30 million tons of additional CO₂ capture capacity, increasing total global capture by up to two thirds.²⁶⁰

257. “Announcement: Moody's: Climate Change is Forecast to Heighten US Exposure to Economic Loss Placing Short- and Long-Term Credit Pressure on US States and Local Governments,” Moody's Investor Service, November 28, 2017, <https://pscdocs.utah.gov/electric/17docs/1703540/298277ExBDirTest-KellyWRA12-5-2017.pdf>

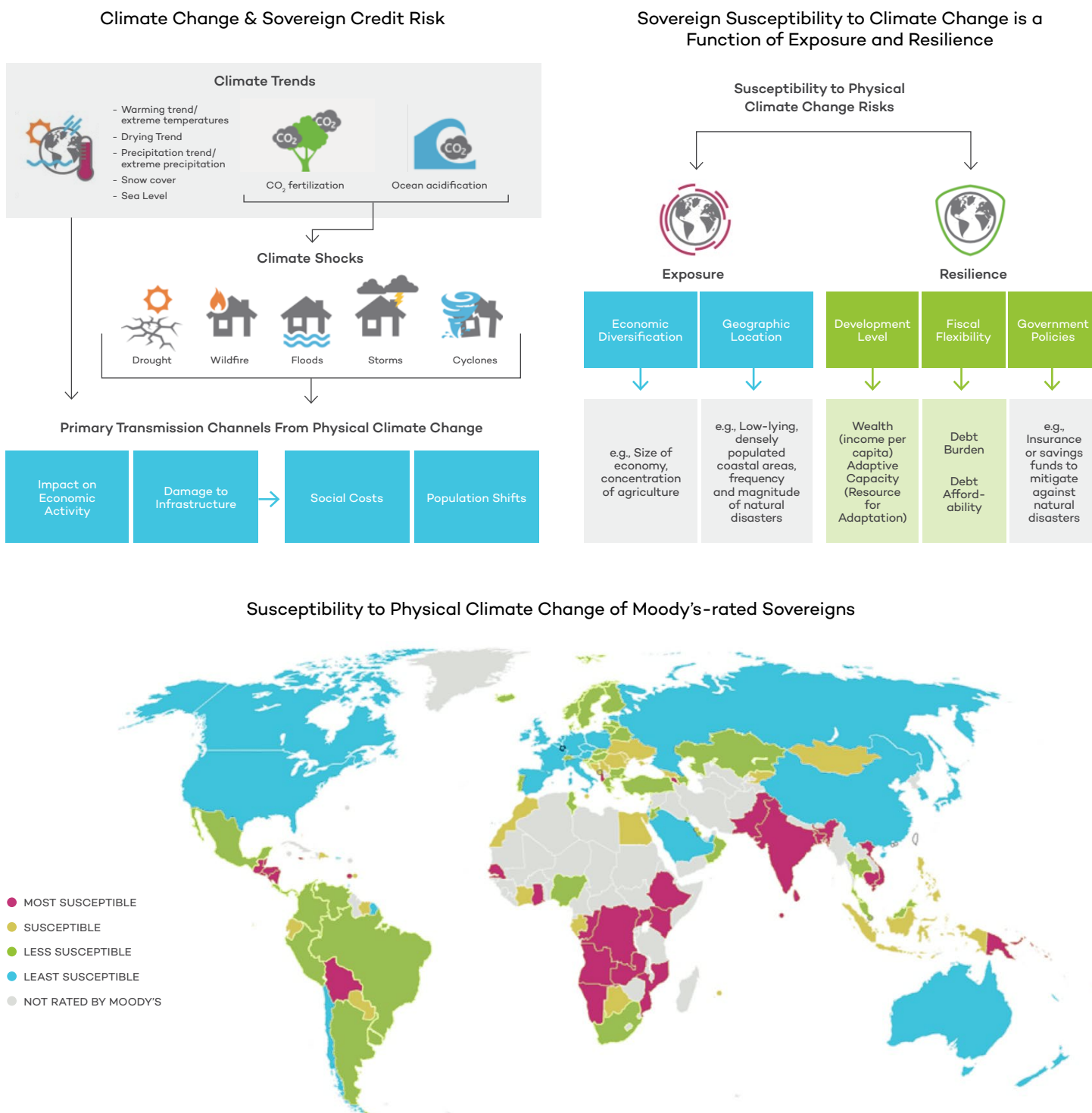
258. Moody's Investor Service, How Moody's Assesses the Physical Effects of Climate Change on Sovereign Issuers, Report No. 1039339 (New York, 2016), <https://www.eticanews.it/wp-content/uploads/2017/01/Moodys-climate-change-and-sovereigns-November-7.pdf>

259. Joint Committee on Taxation, annual tax expenditure tables, <https://www.jct.gov/publications.html?func=select&id=5>

260. <https://www.iea.org/newsroom/news/2018/march/commentary-us-budget-bill-may-help-carbon-capture-get-back-on-track.html>

FIG. 7-6

Moody's Climate Change and Sovereign Credit Risk









Moody's Investors Service methodology for factoring climate change into its ratings of sovereign credit risk.

Source: Moody's Investor Service, *How Moody's Assesses the Physical Effects of Climate Change on Sovereign Issuers*, 4, 8, 11

FIG. 7-7

Tax Credit Available for Different Sources and Uses of CO₂

Minimum Size of Eligible Carbon Capture Plant by Type (ktCO₂/yr) Relevant Level of Tax Credit in a Given Operational Year (\$USD/tCO₂)

														
	Type of CO ₂ Storage/Use	Power Plant	Other Industrial Facility	Direct Air Capture	2018	2019	2020	2021	2022	2023	2024	2025	2026	Beyond 2026
	Dedicated Geological Storage	500	100	100	28	31	34	36	39	42	45	47	50	Indexed to Inflation
	Storage via EOR	500	100	100	17	19	22	24	26	28	31	33	35	
	Other Utilization Processes ¹	25	25	25	17 ²	19	22	24	26	28	31	33	35	

US budget bill may help carbon capture get back on track, International Energy Agency.

1. Each CO₂ source cannot be greater than 500 ktCO₂/yr

2. Any credit will only apply to the portion of the converted CO₂ that can be shown to reduce overall emissions

Source: Closely adapted from Simon Bennett and Tristan Stanley

While the 45Q provisions represent a major step forward for emissions reductions, the size and duration of the credits may be insufficient to incentivize retrofit the variety of facilities that are eligible, including many coal and natural gas power generation facilities. Also, the long-term post-injection monitoring, reporting and verification requirements could become an impediment for some operators, possibly limiting the universe of those that might otherwise take advantage of the credits.

Because of the January 2024 timeline to commence construction, companies, states, and investors should act quickly to determine how to best take advantage of these credits. There's also an urgency to determine what actions to take to maximize the opportunities enabled by the expanded 45Q provisions, thereby kick-starting larger scale deployment of CCUS. The IRS should quickly issue the necessary implementation guidance, including clarification for qualifying projects regarding the commencement of construction. Tax credit exchange markets should begin to incorporate 45Q credit exchange mechanisms into their business plans.

Additional Measures

Congress should consider additional measures to facilitate and accelerate CCUS deployment, including addressing uncertainties regarding long-term post-injection carbon management, monitoring, reporting and verification. Although most studies recognize that the risks are very low (both low probability and low consequence), questions about long-term obligations for long-term post-injection site monitoring could impede CCUS deployment; this could be problematic when operators lease subsurface rights and must make separate arrangements with landowners to conduct post-injection MRV activities.

Long-term post-injection management could be organized through new institutional arrangements ranging from an industry-led voluntary agreement or a statutory risk-sharing initiative. Financial support could be organized in a fund (not unlike the Oil Spill Liability Trust Fund) financed by a small fraction of the 45Q credit value. A backstop mechanism to address long-term post-injection MRV would provide additional assurance that the 45Q credit results in permanent carbon removal from the environment, while providing greater certainty for private sector business models to proceed with CCUS projects.

Stakeholders should consider the adoption of a universal registry specifically designed to facilitate transactions between suppliers and buyers of CO₂, with transparent and verifiable data, possibly through use of blockchain technology. In many cases, accounting for CO₂ emissions avoided by a CCUS project is straightforward. In contrast, exchanges and registries are limited today, and do not have experience with CCUS. Given successful monitoring and successful structuring of tax credit exchanges, some kind of carbon registry is a likely product of the operation of many projects nationwide. The specifics of such a registry are unclear. However, blockchain technology may be a good approach to managing such a registry. Such a platform could help provide value for CCUS projects, whether the CO₂ be captured from point sources or removed from the atmosphere through direct air capture.

Expanded investment in CCUS and largescale carbon removal technologies is needed to accelerate the pace of innovation in this critical area. Given the trajectory of capacity additions in the electric power sector, R&D investments should reflect a larger focus on natural gas generation. DOE-supported R&D on carbon capture technologies has been an important contributing factor to achieving cost reductions in CCS from more than \$100 per tCO₂ in 2005 to approximately \$60 per tCO₂ at present. Further reductions in the cost of carbon capture technology will enable greater participation in the 45Q program, especially if combined with other enhancements discussed in this paper. The time window for further innovation, however, is limited, as qualifying projects must commence construction by January 1, 2024. Deployment of CCS technologies can achieve cost reductions from first-of-a-kind technologies by as much as 25 to 30 percent, with additional operating cost reductions of 20 to 30 percent possible through expanded R&D. An accelerated, time-limited R&D program that is targeted for 3–5 years and funds a suite of projects will help further reduce costs, improve technology performance, and decrease technical risks for CCS project developers.

Conclusion: Enhancing Private Sector Options Can Help Meet National Goals

The private sector in the U.S. plays a role in all stages of the innovation process, particularly in translation and diffusion. It is also the largest funder of R&D in the U.S., at amounts that dwarf all other supporters of research, including the Federal and non-federal governments and private philanthropy.

It is essential to a clean energy future that policies and programs support and align with the key private sector players in the innovation process. There are significant opportunities for the private sector to effectively use new Federal policies — the TCJA and the 45Q expansion in the BBA — to invest in clean energy innovation and deploy and diffuse clean energy technologies. Enhancements of Federal and state policies could further enable or improve these opportunities for the private sector.

KEY RECOMMENDATIONS

Mobilizing Increased Private Sector Investment in Clean Energy Innovation

- The Administration and Congress should support information sharing and technical assistance programs to enable the private sector to expand investment in clean energy innovation, including modernization of energy infrastructures. Continued Federal funding for the Department of Commerce (DOC) Manufacturing Extension Partnership (MEP) program, and the Department of Defense, DOE, and DOC joint program of National Network of Manufacturing Institutes at a scale on the order of \$200 million total annual funding, or roughly \$2 billion over the next 10 years could leverage a significant share of the \$1.5 trillion in increased private-sector capital investment over this same timeframe.
- The private sector, universities, DOE national laboratories, state and regional economic development entities, and the philanthropic community should investigate opportunities to form partnerships to expand regionally-based incubator and test bed facilities to speed the pace of prototyping and accelerate commercial readiness of new energy-related technology and systems innovations.
- Industry and government should expand efforts to work with the ISO to incorporate clean energy innovation and climate resiliency concepts into ISO standards.
- DOE should target federal funding in ways that will incentivize and leverage increased private sector investment in energy innovation. These include:
 - Providing seed funding and matching grants to encourage formation of energy innovation research and development consortia in areas with large potential spillover impacts where cost-shared collaboration could leverage increased private sector investment. DOE should enable a variety of collaborative arrangements, including research consortia, Hubs or other business model structures.
 - DOE should work with the Office of Management and Budget and Congress to seek to set aside a small portion of its existing applied energy R&D funding to support accelerated de-risking of near-commercial innovative energy technologies and systems on an accelerated basis, to make these options more attractive for private capital investment, using the ARPA-E business model as a template.
 - DOE should significantly increase the level of federal R&D investment in CCUS and largescale carbon removal technologies to accelerate the pace of innovation. Given the trajectory of capacity additions in the electric power sector, R&D investments should reflect a larger focus on natural gas generation.

- In addition to funding, Congress should consider other measures to facilitate and accelerate CCUS deployment, including addressing uncertainties regarding long-term post-injection carbon management, monitoring, reporting and verification. A backstop mechanism to address long-term post-injection, MRV would provide additional assurance that the 45Q credit results in permanent carbon removal from the environment, while providing greater certainty for private sector business models to proceed with CCUS projects.
- Stakeholders should consider adoption of a registry specifically designed to facilitate transactions between suppliers and buyers of CO₂, with transparent and verifiable data, possibly through the use of blockchain technology.