Domestic Implementation Framework for *Mission Innovation*

Accelerating the Pace of American Clean Energy Research, Development, and Demonstration through Proven and Powerful Approaches

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Executive Summary

In November 2015, the United States and 19 other nations came together to make a landmark commitment to dramatically accelerate global clean energy innovation, called Mission Innovation. This charter group of Mission Innovation countries—as well as others that have joined since—are seeking to double their public investment in clean energy research and development over five years. Accordingly, Mission Innovation will result in nearly $30 billion of public investment in 2021.

This Framework for Mission Innovation outlines examples of proven and powerful approaches to research, development, and demonstration that will be critical elements to the U.S. domestic implementation of Mission Innovation. Robust implementation must pursue multiple linear and non-linear approaches, not just in terms of technologies, but also in terms of how to get there. This means funding programs that leverage some or all of the following mechanisms:

- Foundational mechanisms to increase breadth of knowledge within a scientific discipline.
- Translational mechanisms to target incremental improvements along defined tech-roadmaps.
- Disruptive mechanisms to validate high-risk, high reward, off-roadmap ideas.
- Integrational mechanisms to facilitate collaboration across disciplines and stakeholders.

This Framework is deliberately outlined in a way that promotes openness to new technologies, paths, and program designs as well as the reality that Mission Innovation may also present an opportunity to fill white spaces where little-to-no research has currently been funded.

The sampling of existing programs highlighted in this Framework, many at the Department of Energy—which plays a uniquely critical role in Mission Innovation—have successfully accelerated clean energy technology development by incorporating the mechanisms above. Building on these successes, the Framework illustrates potential opportunities to scale up and replicate a variety of program designs and apply them to specific energy challenges or areas of focus.

The Framework uses five specific areas of focus to illuminate these opportunities: generation (i.e., harnessing electricity from clean sources); mobility (i.e., moving people and goods using clean energy); connections (i.e., delivering clean energy from supply to demand); structures (i.e., innovating better buildings); processes (i.e., using clean energy to create products and grow food). This document does not attempt to provide comprehensive lists of existing successful efforts or potential future opportunities. Through examples it attempts to shed light on ways in which effective research, development, and demonstration mechanisms could be utilized to accelerate clean energy innovation.

Successful domestic implementation of Mission Innovation can spur job creation and economic growth, boost energy reliability and security, curb adverse environmental and public-health effects, and enhance energy access and equity. In large part, domestic implementation of Mission Innovation will require substantial resources at the U.S. Department of Energy, which makes up three-quarters of the current energy innovation portfolio and has supported—over decades and across Administrations—successful efforts at delivering these benefits for the country.

Contours of the Commitment

Over several decades, the United States has positioned itself as a global energy leader focused on using its resources and know-how to accelerate clean energy innovation. This leadership has required sustained and increasing investment in science and technology that has spurred job creation and economic growth, and has generated powerful solutions in the fight against global threats—like poverty and climate change—faced in the 21st century. Recent Administrations have leveraged this innovation playbook to support progress. Both the Clinton Administration's Climate Change Technology Initiative and the Bush Administration's Advanced Energy Initiative marshaled resources to increase clean energy research and development. Building on that foundation, the Obama Administration began with a historic $90 billion investment designed to accelerate the pace of progress, as part of the American Recovery and Reinvestment Act of 2009 (ARRA) and put Americans to work in the clean energy economy. ARRA funding supported a wide array of programs oriented toward clean energy deployment and some research, development, and demonstration activities, which together helped hasten the energy transformation that defines the current energy landscape.

Yet, despite progress made, there remains underinvestment in clean energy research and development.[1,2] The United States and other leading nations recognize that the scale of the world's energy challenges—such as providing access to electricity for the more than one billion people who currently lack it and achieving the magnitude of emissions reductions needed to avert the worst impacts of climate change—requires significantly increased efforts to accelerate development of energy technologies, especially those with the potential to rapidly scale.

In November 2015, this recognition brought the United States and 19 other nations together to announce a landmark commitment to dramatically accelerate global clean energy innovation by investing in new technologies that will define a clean, affordable, and reliable global power mix. This charter group of Mission Innovation members—as well as others that have joined since—are seeking to double their public clean energy research and development investment over five years. When this goal is achieved, Mission Innovation will result in nearly $30 billion (per year) of public clean energy research and development investment in 2021. In parallel, far-sighted private sector investors—the Breakthrough Energy Coalition—pledged to develop large new investment vehicles to help move outcomes from the government-funded efforts into commercial applications.

<u>Mission Innovation Mission Statement</u>

"In support of economic growth, energy access and security, and an urgent and lasting global response to climate change, our mission is to accelerate the pace of clean energy innovation to achieve performance breakthroughs and cost reductions to provide widely affordable and reliable clean energy solutions that will revolutionize energy system throughout the world over the next two decades and beyond."

http://mission-innovation.net/about/

[1] http://www.pewtrusts.org/~/media/assets/2012/02/energy-innovation-fact-sheet-022712-final.pdf

[2] http://bipartisanpolicy.org/wp-content/uploads/2016/03/BPC-AEIC-Energy-RD-Architecture.pdf

For the United States, this commitment will drive clear and compelling domestic benefits. After all, energy not only powers generation, mobility, structures, and processes, but clean energy innovation also holds the potential to drive job creation and economic growth. The domestic implementation of Mission Innovation can:

- *Drive down energy costs:* Clean energy technologies have the potential to dramatically reduce long-term energy expenditures.[3] This could increase the competitiveness of U.S. businesses and put thousands of dollars in the pocketbooks of American families.

- *Enhance system reliability:* Energy services are deeply embedded into all critical infrastructures and services, including the electric grid, transportation, and telecommunications. Advanced energy technology can improve system reliability.

- *Improve energy security:* Using more diverse energy sources and technologies can increase the resiliency and flexibility of the domestic energy supply chain, helping to protect energy consumers from high-cost market disruptions and reducing exposure to markets with high price volatility, like oil.

- *Curb adverse environmental and public health effects:* Energy-related greenhouse gas emissions are the dominant cause of climate change. Clean energy technology is the largest —and most essential—component of mitigation. The shift to clean energy will also reduce the other harmful pollutants associated with energy use, improving health outcomes.

- *Build economic opportunities:* Maintaining our technological edge will enable opportunities to export our clean technologies, products, and services to other countries.[4] Clean energy can be a major opportunity to create new jobs, enable domestic manufacturing, and catalyze industries.[5,6]

- *Improve energy access and equity:* In many rural and remote places in the United States, communities lack access to reliable and affordable energy services. Advanced energy technologies can support universal energy access, helping boost quality of life and economic development.

This Mission Innovation Framework—and the commitment it seeks to implement—is focused on enabling the clean energy technology advancements needed to unlock benefits in all of these areas. This Framework is not intended to be a roadmap laying out the full span of technology challenges and opportunities—many existing documents accomplish that, such as the Quadrennial Technology Review. Instead it draws attention to the need to be deliberate and strategic about how research, development, and demonstration are conducted to maximize success.

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[3] http://aceee.org/press/2014/03/new-report-finds-energy-efficiency-a
[4] http://info.aee.net/aen-2016-market-report
[5] http://www.irena.org/DocumentDownloads/Publications/IRENA_RE_Jobs_Annual_Review_2016.pdf
[6] http://www.eesi.org/papers/view/fact-sheet-jobs-in-renewable-energy-and-energy-efficiency-2015

Domestic Implementation

The United States is the world's largest funding source of clean energy research and development (R&D), and its investment portfolio spans a broad array of activities from use-inspired basic research to demonstration. It includes funding across multiple Federal agencies and covers the spectrum of clean energy technologies, encompassing R&D[7] on energy-related hardware, software, and systems that avoid, reduce, or sequester greenhouse gas emissions or other air pollutants, including technologies that convert, convey, or store energy resources; improve energy efficiency; or reduce energy consumption. Almost three-quarters of the current energy innovation portfolio is funded at the Department of Energy, where such R&D represents a primary mission of the agency.

This multi-faceted, government-wide approach is both essential to and reflective of how significantly energy is connected to the missions of multiple Federal agencies. Successful U.S. implementation of Mission Innovation requires each agency to bring its individual perspective and its unique capabilities to facilitate targeted and creative solutions. A compelling Framework for Mission Innovation cannot seek to simply provide additional resources to existing activities or over-amplify the path-dependence incentivized by our current investment portfolio. In this context, path-dependence refers to a linear R&D process that is grounded in defined technology roadmaps and focused on incremental progress that moves a technology along the path from research into development and through demonstration. These tactics may not result in the advancements needed to address the breadth of energy challenges at the required pace.

Instead, a compelling Framework must pursue multiple linear and non-linear approaches to innovation, not just in terms of *what* technology challenges to address, but also in terms of *how* to get there. This Framework, therefore, is deliberately and definitively outlined in a way that promotes openness to new technologies, approaches, and program designs as well as to the reality that *Mission Innovation* may also be an opportunity to identify and fill gaps where little-to-no research has currently been funded.

Part of that openness is a recognition that any portfolio must retain flexibility and be iterative—taking into account the swift advancement in the clean energy innovation ecosystem and distributed nature of, and creativity required for, breakthrough-technology advancement. Weighting of resources within a successful Mission Innovation portfolio cannot and should not be hard-wired *a priori*.

Finally, this Framework recognizes that the role of the private sector is considerable and complementary. To bring a new clean energy technology to market at scale, America's entrepreneurs, investors, and large firms must invest at levels that are orders of magnitude greater than the government's catalytic "technology push." These public and private interactions are described in greater detail in the "Accelerating Context" section of this Framework, including the role of new investment vehicles under the Breakthrough Energy Coalition, the Clean Energy Investment Initiative, and related efforts.

[7] The term "R&D" is defined to include technology demonstration activities.

First-Year Proposal and Five-Year Trajectory

The Mission Innovation baseline for the United States is set to fiscal year (FY) 2016, when the total government-wide funding for clean energy R&D was $6.4 billion. Doubling the U.S. federal investment within five years means reaching $12.8 billion in FY 2021 or roughly a 15 percent year-over-year increase in clean energy R&D funding.

As part of domestic implementation of Mission Innovation, the FY 2017 Budget does two things: (1) it provides $7.7 billion in discretionary funding government-wide in FY 2017 for clean energy R&D as the first installment toward the FY 2021 $12.8 billion target; and (2) it embeds increases for Mission Innovation into the budget projections for FY 2018–2021—the “outyears” of the pledge. Although U.S. budgetary decisions are generally made year-by-year for activities like R&D, the Administration has specified outyear levels for a limited number of individual efforts, such as Mission Innovation, to demonstrate its commitment to and acknowledgement of the long-term implications of that pledge. The government-wide trajectory imbedded in the FY 2017 Budget is shown in Table 1.

Table 1: U.S. Mission Innovation // FY 2017 Initial Trajectory
(budget authority in billions of U.S. dollars)

	FY16 Enacted	FY17 Budget	FY18	FY19	FY20	FY21
Gov’t-wide total clean energy R&D	**6.4**	**7.7**	**8.8**	**9.9**	**11.3**	**12.8**

To be sure, however, neither the initial trajectory nor the annual allocations shown represent pre-approved future funding levels for any particular Federal agency or program. The trajectory and allocations will be revisited annually through the President’s Budget formulation process and revised as necessary.

As shown in Figures 1 and 2, the U.S. clean energy R&D portfolio is diverse, spanning 12 Federal agencies in FY 2017: the Departments of Agriculture (USDA), Commerce (DOC), Defense (DOD), Energy (DOE), Housing and Urban Development (HUD), and Transportation (DOT), and the Environmental Protection Agency (EPA), Nuclear Regulatory Commission (NRC), Tennessee Valley Authority (TVA), National Aeronautics and Space Administration (NASA), National Science Foundation (NSF), and U.S. Agency for International Development (USAID).

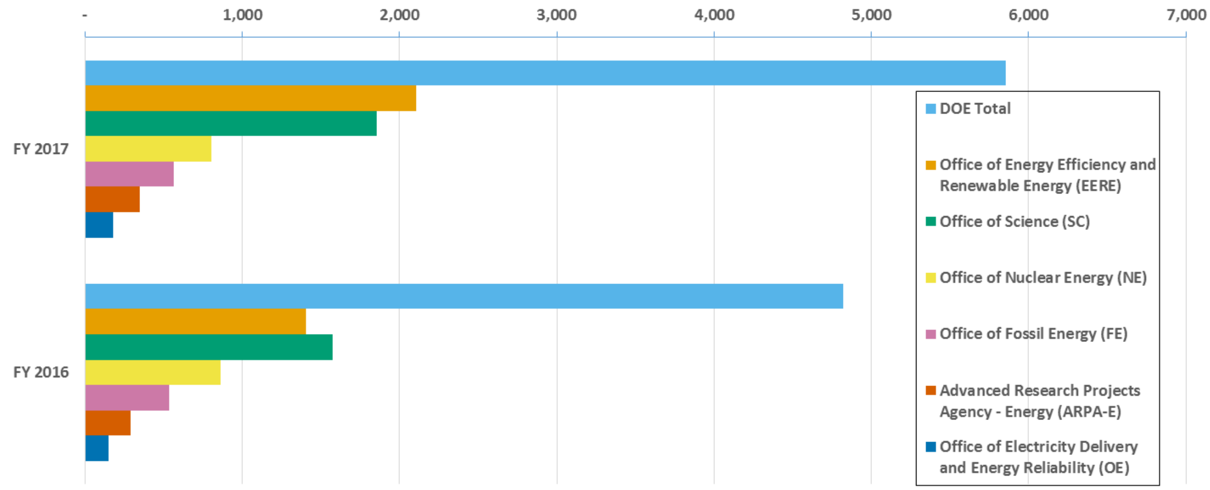
DOE executes the majority of Mission Innovation R&D domestically and maintains significant capabilities and expertise. About 76 percent of the government-wide Mission Innovation investment in FY 2016 and FY 2017 is DOE funding. As shown in Figure 1, the agency’s $4.8 billion in FY 2016 and $5.9 billion in FY 2017 spans multiple offices. DOE was instrumental in designing and building the Mission Innovation initiative and will continue to have a central role in its international and domestic implementation.

Figure 1

Clean Energy R&D Appropriations in Support of Mission Innovation Pledge

Department of Energy Only, by Office

(U.S. Dollars in Millions)



Source: FY 2017 Department of Energy Budget Request to Congress

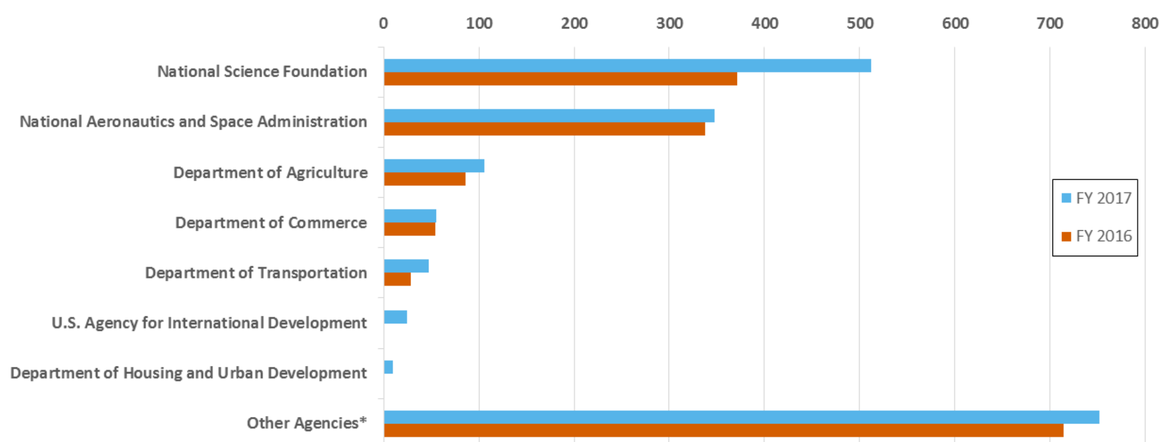
*The decrease in nuclear energy funding is due to an increased focus on SMR licensing and technical support, which is outside the scope of Mission Innovation.

Figure 2

Clean Energy R&D Appropriations in Support of Mission Innovation Pledge

Federal Agencies other than the Department of Energy

(U.S. Dollars in Millions)



Source: Office of Management and Budget FY 2017 Budget

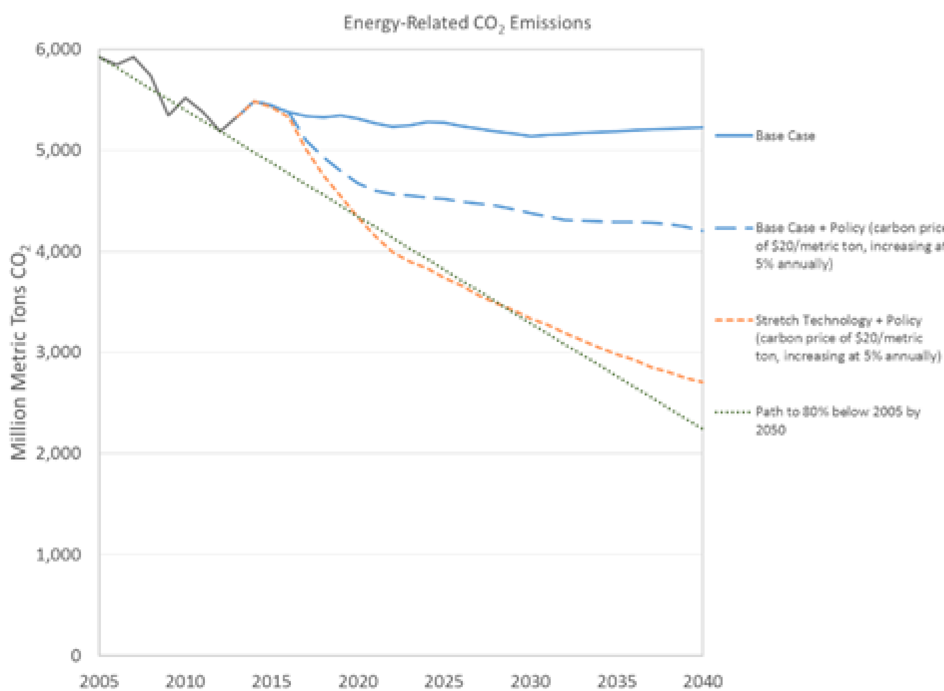
Climate Challenge and Opportunity

Energy services are absolutely essential to modern life, but negative externalities from the provision of these services, such as pollution, impart a significant cost on society. Based on existing technologies and policies, the United States is well on its way to meeting its emission reduction goals of 26 to 28 percent below 2005 levels by 2025. New technology can support lower-cost, more significant decarbonization in the long term, including ambitious emissions reductions of 80 percent or more by 2050.

Analysis performed by the Department of Energy (DOE) shows how innovation is a particularly powerful complement to climate policy. Recently, the agency explored several different energy-sector greenhouse-gas-emissions-reduction scenarios, two of which are highlighted here.

Figure 3

Energy Related CO_2 Emissions Scenarios



The first scenario considered climate policy only, using a carbon price of $20 per metric ton of carbon, increasing 5 percent annually, as a proxy for an economy-wide policy that reduces CO_2 emissions.[8] In this scenario, the model sees a carbon price throughout the economy but technology costs and performance input assumptions do not change from the business as usual baseline.[9] The results of this pathway indicate

[8] The actual carbon prices required to achieve these emissions reductions could be higher or lower, depending on the rate of technological progress, the strength of complementary policies, and many other factors.
[9] A carbon price could motivate the private sector to invest in additional R&D to advance clean energy technologies.

that policy can effectively lower CO_2 emissions, reducing energy-related CO_2 emissions by approximately 29 percent below 2005 levels by 2040.

In the second scenario, DOE examined a future that pairs economy-wide climate policy with significantly accelerated clean energy technology cost reductions and performance improvement. This scenario includes climate policy (same carbon price proxy in scenario one) plus achievement of stretch technology goals that go beyond accomplishing DOE's existing research, development, demonstration, and deployment goals. These stretch technology goals could be realized by expanding federally-funded clean energy research, development, and demonstration through domestic implementation of Mission Innovation and by increasing deployment and technology-transfer activities. Under this second scenario, energy sector emissions would be reduced by approximately 54 percent below 2005 levels by 2040, demonstrating that a combination of technology advances and climate policies are necessary to drive greater emission reductions. This impact represents the mutually reinforcing aspects of policy and technology innovation.

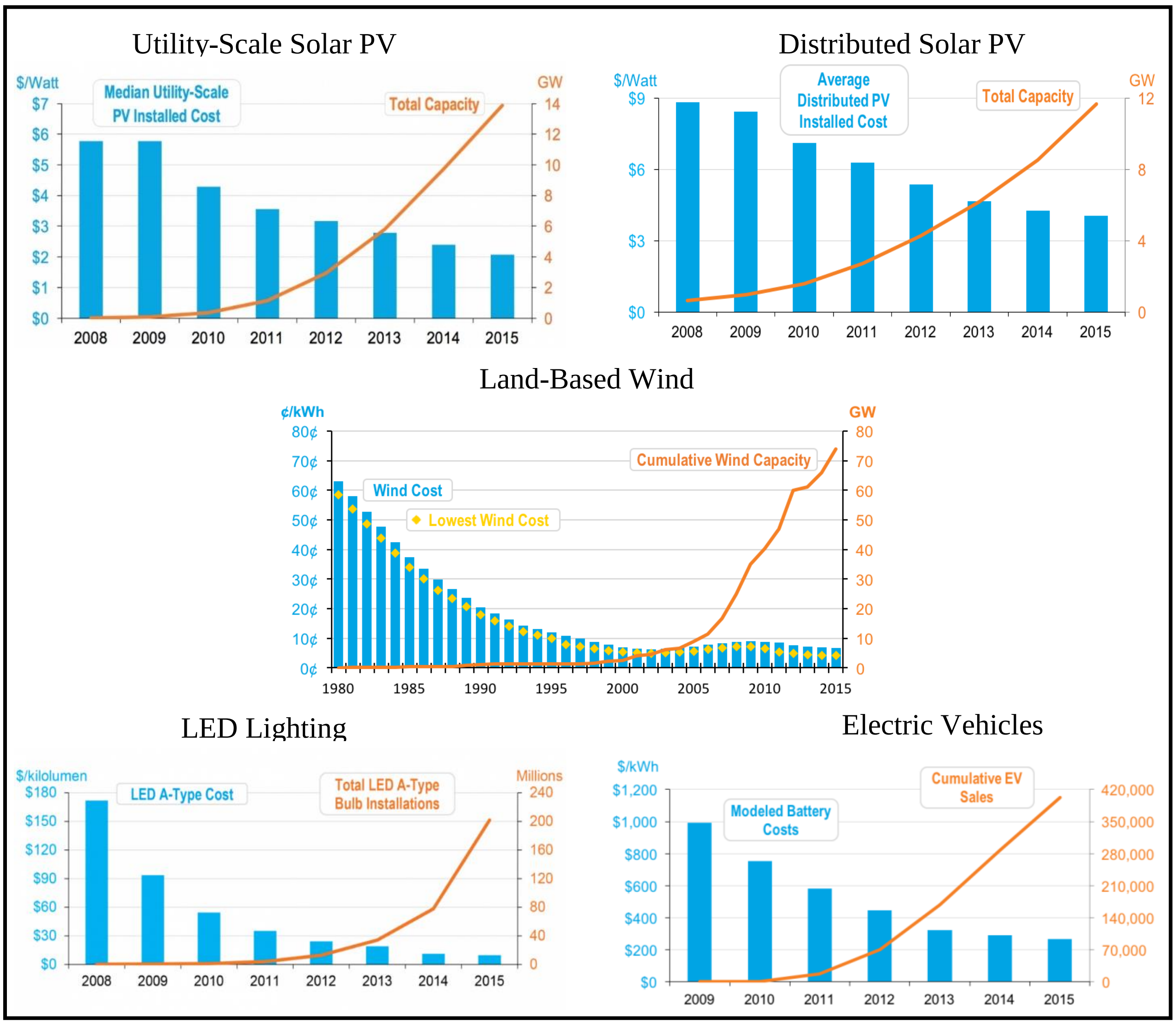
The recently issued Administration Mid-Century Strategy, which incorporates non-energy-sector emissions sources and sinks to achieve emissions reductions of 80 percent or more by 2050, and the analysis discussed above share the same bottom line on this point: combining policy and support for innovation increases the feasibility and can reduce the costs of ambitious climate goals.

Proven and Powerful Approaches

Successfully meeting clean energy and emissions reduction goals requires research, development, and demonstration approaches that build on existing efforts and leverage the successes and lessons learned during this Administration. Notable successes include the technologies shown in Figure 4 that have seen dramatic cost reduction and increases in U.S. adoption, as highlighted in the Energy Department's "Revolution…Now" report: wind, large-scale and distributed solar PV, electric vehicles and LED lighting.

Figure 4

Examples of Clean Energy Cost Reductions and Deployment Increases



To continue to drive similar trends in these and emerging technologies, there is a need to enhance the foundation of knowledge within disciplines, make the translation of technology development from basic research to applied R&D to demonstration more efficient and effective, accelerate the disruption of current pathways and cost curves, and promote the integration of ideas and solutions across disciplines, sectors, and technologies. We need to move beyond a focus on what to research, develop, and demonstrate. We need to think critically and creatively about how best to implement research, development, and demonstration programs to achieve broadly successful outcomes.

R&D Mechanisms

The innovation process traditionally has been viewed as a linear process beginning with basic scientific research and extending through applied research, development, demonstration and commercial deployment. It is becoming increasingly evident, however, that innovation is a complex nonlinear process, with multiple feedback loops, for which there is no single, superior program structure. The Mission Innovation portfolio will be planned and implemented to take maximum advantage of innovation opportunities, recognizing that different program structures are more effective in different contexts. Consequently, an effective clean energy innovation strategy should include a mix of foundational, translational, disruptive, and integrational innovation mechanisms:

- Foundational mechanisms increase breadth of knowledge within a discipline.
- Translational mechanisms target steady improvements on defined technology roadmaps.
- Disruptive mechanisms validate high-risk, high-reward, off-roadmap ideas.
- Integrational mechanisms facilitate collaboration across disciplines and stakeholders.

These mechanisms are not always mutually exclusive, and each encompasses a wide variety of program designs. Often, successful programs have been designed to include elements of some or all of these mechanisms. Program design is an important factor in determining the success of an R&D program, but it is not the only one. Personalities, availability of resources, timing, and other exogenous factors play a significant role. However, program design is a factor the government—appropriators, authorizers, and agency personnel—can control, learning from failures and improving upon past success.

This Administration has enhanced existing or developed new foundational, translational, disruptive, and integrational programs to help make the portfolio more effective, flexible, and able to respond to the rapidly changing clean energy technology landscape.

Foundational

The Federal clean energy R&D portfolio is built upon strong core programs supported by unparalleled R&D facilities that increase the breadth knowledge within relevant disciplines.

Supporting Unique Foundational Capabilities

The USDA Agricultural Research Service's unique collection of more than 100,000 species of microbes helps scientists working on economical bioconversion technologies for cost-competitive fuels and high value chemicals and other coproducts. This collection provides researchers access to microbes that may have desirable traits or the ability to perform certain functions, and could enable new energy conversion pathways and more robust energy crops. The study of these microbes may enhance efforts in synthetic biology by providing scientists with the tools needed to design new organisms that excrete chemical precursors for bioproducts or enable biofuel production.

For example, DOE supports R&D and infrastructure at 17 National Laboratories, research universities, and numerous user facilities that provide access to unique scientific equipment at no cost to the users. The National Labs are a long-term investment in R&D with sustained research in mission critical areas. NSF invests in research primarily through competitive awards to individual investigators and small groups in the U.S. academic community, as well as larger centers with multiple academic researchers, in order to optimize the return on our clean energy research investment. USDA supports the Land Grant Universities through capacity-building grants to leverage their expertise and supports competitive peer-reviewed research, education and extension activities through multiple programs, including the Agriculture and Food Research Initiative. The U.S. commitment to double clean energy R&D funding under Mission Innovation will involve increasing resources for established, effective technology development efforts that are deemed priorities for achieving our goals as well as supporting new efforts that accelerate innovation. Continued investment in our strengths is fundamental to success.

Translational

Translational, path-dependent R&D can be beneficial when the technological goal is well defined; there is a clear framework for moving a complete solution to market, and the timing of the solution is not immediate. This type of R&D will continue to be the bedrock of the innovation ecosystem, but we must strengthen interfaces connecting each phase of development along defined technology roadmaps and enable better on-ramping of breakthrough technologies through more flexible program design to increase utility and rate of path-dependent innovation. The following successful programs could provide effective reference points for designing new programs or improving existing ones.

- The DOE SuperTruck program demonstrates the benefits of strengthened connectivity between stages of R&D mapped to a specific program goal and linked to a market pull mechanism, such as standards or regulations. Project partners have already commercialized over 20 technologies and several more are expected to be commercially available within the next two years and results from the program have been used to inform standards for truck fuel economy. The current success of the program's prototype demonstrations was in part driven by the strong link to the component-level, applied R&D done by the 21st Century Truck Partnership. Other factors also contributed to the success, such as the limited number of private-sector partners in the field.

- DOE's Energy Innovation Hubs, such as the Consortium for Advanced Simulation of Light Water Reactors, uniquely boost translational connectivity from basic to applied R&D and leverage an interdisciplinary approach via large, multi-institution collaborations designed to accelerate the pace of discovery for energy solutions deemed critically important for energy security. These span basic research, engineering development, and hand-off to the private sector for commercialization through collaborations comprised of universities, private industry, non-profits, and government laboratories.

- NASA initiated a translational program to use experimental airplanes (X-planes) to scale, test, and validate cleaner airplane technologies with current and prospective domestic commercial airline manufacturers that supply a large percentage of planes flown by commercial airlines. NASA-funded X-planes will pave the way to adoption because they address key barriers that a commercial airplane manufacturer must address in introducing new technologies: validating technological readiness and benefit, demonstrating the ability to integrate the technologies into an affordable and producible design, and obtaining operational insights on non-functional requirements, such as maintainability. Though a clean aviation technology may be partially validated in a laboratory setting or even as a full-scale subsystem, without the manufacturer having confidence that new technology can be effectively integrated into the airframe and achieve the expected benefit, adoption is widely seen as being too risky. Therefore, experience with the construction, integration, and operation of new clean aviation technologies provides critical risk reduction that cannot be accomplished without large-scale flight testing.

Disruptive

Programs designed to promote disruptive innovation are needed to leapfrog the traditional path-dependent approach or create a new solution pathway. They can create a space to foster breakthrough solutions, shift the direction of ideation, and allow Federal agencies to invest in higher risk technologies. R&D mechanisms that promote disruptive innovation can be stand-alone, multi-sector programs with sufficient on-ramping opportunities so that technologies they develop can be picked up directly by the private sector, or by other established programs for further development or translational R&D. Encouraging disruptive innovation requires new approaches. The Advanced Research Projects Agency (ARPA-E) has developed a disruptive R&D funding approach that builds on the DARPA model. It is also possible to accelerate innovative problem solving using prize competitions. Both approaches have been championed by this Administration.

- ARPA-E was established with the mission to overcome long-term and high-risk technological barriers in the development of energy technologies, by promoting revolutionary technical advances and accelerating their development in areas that industry by itself is not likely to undertake because of technical and financial uncertainty. ARPA-E's goal for its R&D activities is enhancing the economic and energy security of the United States and sustaining U.S. leadership in advanced energy technology. ARPA-E has operational authorities similar to those of DARPA, which allow it to address new areas of innovation rapidly and flexibly. In its first seven years of funding, the Agency has developed a unique and effective operational model to address its mission and goals. Term limited employees with exceptional technical and/or commercialization experience develop and manage the agency's dynamic portfolio of R&D activities. ARPA-E's personnel actively manage the projects for technical success and commercial potential, with very promising early outcomes. About 30% of the innovative projects move on to further development under translational government programs, and about 20% have attracted substantial private sector support to develop commercial applications. This model of disruptive innovation draws on the results of foundational R&D, provides accelerative inputs to translational R&D, and is a highly effective pathway for moving the outcomes of government-supported R&D to hand-off to private sector investors. The ARPA-E model can also be seen as a hybrid approach—it provides not only an effective disruptive R&D mechanism, but also includes a strong element of integrational R&D through its active use of teams to bring in expertise and perspective from both the academic and commercial sectors.

- Incentive prizes can advance the state-of-the-art in clean energy by defining a problem, setting ambitious but achievable goals, and inviting diverse individuals and teams to develop solutions that are rigorously tested and only awarded if they meet high performance standards. Long-term, complex, capital intensive technology development can be addressed through discrete competitions that are focused on clearly defined problems. The Lighting Prize (L-Prize), Catalyst Energy Prize Competition and the Wave Energy Prize, are examples of the effective use of discrete prizes to develop innovative clean energy solutions. In addition, prizes can leverage federal resources like data, facilities and expertise and can be used in series and as a part of Grand Challenges like the SunShot Initiative and EV Everywhere to create multiple innovations over time.

Integrational

Bringing together parties with different perspectives and different skillsets is essential in developing innovative new technologies. Strong connectivity between R&D and the ultimate users can facilitate more relevant research and development, worthwhile demonstration of technologies at scales useful to inform deployment, and effective standard setting and regulatory rule making. Integrational R&D mechanisms, like consortia and centers, are often used to conduct "precompetitive" research. They provide opportunities to distribute results more cost effectively, pool talent, and share risks. For example, consortia may be useful when there are shared concerns about meeting new safety requirements, when there are entities motivated to solve the same problem to improve their competitiveness, or when a challenge requires multiple disciplines to work together. The following successful programs could provide effective reference points for designing new programs or reinvigorating less effective programs:

- NASA implemented the University Leadership Initiative to bring forward broad, system-level concepts, tools and methods, and revolutionary ideas. The initiative allows university teams to independently define the most critical technical challenges that must be solved to achieve a given strategic thrust of NASA Aeronautics. Multi-disciplinary university teams propose independent, innovative research projects to solve technical challenges and develop their own success criteria and progress indicators.

- NSF's Engineering Research Center (ERC) program aims to integrate engineering research and education with technological innovation. ERCs focus on advancing fundamental engineering knowledge and enabling technologies for engineered systems. Over the last three decades ERCs have produced a wide range of engineered systems and other technologies that have transformed product lines and industrial practices and processes. ERCs conduct both foundational and translational research with a strong innovation component, focusing on education and broad participation. ERCs expose students to the integrative aspects of engineered systems, industrial practice, and innovation.

Supporting Multidisciplinary Innovation

The Energy Frontier Research Centers program today is comprised of 36 centers involving partnerships spanning more than 110 universities, national laboratories, non-profit organizations, and for-profit firms across the U.S. and four foreign countries. EFRC research has resulted in more than 7,500 peer reviewed publications, nearly 500 invention disclosures and more than 650 domestic and international patent applications, leading to 50 issued patents and more than 100 technology licenses. At least 90 companies have benefited from EFRC research, including at least 10 startup companies that originated from EFRC research programs. The new technologies coming out of these companies includes photovoltaic devices with novel physical properties, electrodes for next generation lithium-ion batteries, and materials to efficiently capture carbon dioxide.

Platform Technologies for R&D

"Platform technologies" are tools, techniques, and instruments that fundamentally change how research is conducted across disciplines. For example, tools like the laser and atomic force microscopy have transformed the physical sciences, just as polymerase chain reaction and microarrays have transformed the life sciences. Platform technologies often enable orders of magnitude improvements in fundamental research attributes such as accuracy, precision, resolution, throughput, flexibility, breadth of application, costs of construction or operation, or user-friendliness.

Our path to doubling clean energy R&D investment under Mission Innovation must support targeted investments in the development of platform technologies for two primary reasons.

- First, clean energy innovation needs are inherently cross-cutting and interdisciplinary, so the development of new platform technologies is a high-impact way to drive innovation across many relevant domains.
- Second, the urgency of transitioning to a low-carbon economy requires new tools that reduce the time and cost associated with the "design, build, test, learn" cycle for any given technology.

Platform technologies can fundamentally accelerate the process of innovation by lowering costs and barriers, as tools such as cloud computing and open source software have allowed small teams to rapidly and inexpensively develop IT-based innovations. The following platform technologies are ripe for new developments that could accelerate progress across the clean energy technologies discussed later in this framework.

High-Performance Computing Applications

Exascale computing systems, which will ultimately deliver approximately 100 times the performance of current computing systems across a range of applications, are a key source of clean energy platform technologies because they can sharpen the ability of planners to manage complex systems and shorten the time it takes to test the viability of new technologies. For example, higher performance computing is already improving the planning, operation, and maintenance of the power grid, even as it becomes more complex because of increased use of smart meters and incorporation of intermittent resources energy such as wind and solar. Exascale computing can also support modeling and simulation work that promises to lower the cost and time to design and deploy a wide range of complex products that would have previously required much lengthier real-world testing cycles, such as new reactor technology for nuclear power. DOE is engaged with industry to deploy exascale computers early in the next decade. Through the National Strategic Computing Initiative (NSCI), Federal agencies are also collaborating to invest in a range of promising computing alternatives that reach at this potential and ultimately transcend the physical limitations of current semiconductor technologies.

Engineering Biology

Life-sciences innovation, in particular engineering biology, promise to yield a critical set of clean energy platform technologies that accelerate our ability to achieve breakthroughs in domains such as low-carbon-fuel production, cost-effective carbon sequestration, and efficient resource utilization (*e.g.,* nitrogen fixation in non-legume plants). New platform technologies such as the CRISPR-Cas9 gene editing system are already driving down the time, cost, and complexity of engineering biological systems, and further investments can accelerate this trend. For example, NSF is supporting the BIOFAB production facility to rapidly characterize the thousands of genetic control elements in *E. coli* so that they can be efficiently "mixed and matched" in future synthetic organisms. DOE is supporting the Agile BioFoundry, a consortium of national labs that will work with the private sector to advance biomanufacturing and reduce the time and cost to develop bioproducts.

Advanced Materials

New materials require new platform technologies to accelerate the commercialization of a wide range of clean energy technology priorities, such as lightweight vehicles, low-cost fuel cells, high-performance solar cells, solid-state refrigeration, and thermoelectric devices that convert waste heat to electricity. Through the Materials Genome Initiative, Federal agencies are collaborating to cut in half the time to transition an advanced material from discovery to deployment, which currently takes 20 years on average.

Advanced Manufacturing Process Technologies

Advanced manufacturing processes represent a promising arena for new platform technologies that lower the time and cost of manufacturing, at scale, the many components and devices that comprise a clean energy system. Through a national network of manufacturing innovation institutes, Manufacturing USA supports multi-sector research collaborations in the production of advanced composites, power electronics, smart sensors, and more. Such public-private partnerships serve to accelerate the commercial readiness of new manufacturing-process technologies and improve the efficiency of the industrial sector.

Artificial Intelligence and Machine Learning

Machine learning and other forms of artificial intelligence (AI) promise to yield new platform technologies that will increase the impact of current AI applications in clean energy, such as improved energy efficiency in individual homes and large data centers; novel structural health monitoring and infrastructure asset management; semi-automated electric grid and power plant management; and better routing and autonomous transportation technologies, allowing for reduced overall system energy use and transportation-related emissions. The National Artificial Intelligence Research and Development Strategic Plan calls for specific actions to help advance these and other national priorities, including making long-term investments in AI research; developing effective methods for human-AI collaboration to achieve performance optimization; and focusing on high-potential application areas, such as intelligent transportation.

Application to Specific Areas of Focus

The powerful and proven approaches outlined in the previous section have successfully accelerated clean energy technology development through programs that have incorporated an appropriate mix of foundational, translational, disruptive and integrational attributes along with the flexibility to adapt as technology advances. Building from successes, this section illustrates potential opportunities to scale up and replicate a variety of program designs and apply them to specific clean energy challenge areas.

Clean Energy Technology innovation programs historically have been organized and funded along the lines of specific energy resources, such as solar energy, natural gas, etc. Planning and prioritization of the Mission Innovation clean energy research, development, and demonstration portfolio can be made more effective and efficient by considering how programs can be designed, or redesigned, to promote accelerated innovation. The following five sub-sections—generation (i.e., harnessing electricity from clean sources); mobility (i.e., moving people and goods using clean energy); connections (i.e., delivering clean energy from supply to demand); structures (i.e., innovating better buildings); processes (i.e., using clean energy to make things and grow food)—highlight a sampling of how program designs are and could be applied in specific technology-oriented areas of focus.

Rather than provide a glossary of current Federal clean energy R&D programs in each of these five areas of focus, the treatment here presents examples of existing programs that illustrate effective application of foundational, translational, disruptive, and integrational R&D mechanisms as well as examples of potential programs extrapolated from existing program designs to illustrate how a given design could help solve a different problem. These are not specific proposals, pursuing any would require additional design detail and budgetary evaluation; nor do they represent an exhaustive list. Instead, the examples below are intended to represent different levels of technical complexity, impact, and application to promote consideration of program design in the development of future clean energy R&D efforts—to create a Framework for Mission Innovation implementation. In particular, the DOE Mission Innovation portfolio, which constitutes approximately three-fourths of the current U.S. Mission Innovation portfolio, is not fully addressed in these examples.

Generation | Harnessing Electricity from Clean Sources

Innovation in technologies that generate power without combusting fossil fuels at central station power plants has taken place at a rapid pace over the past several decades. These technologies, as well as those that serve to curb the carbon footprint of fossil-fuel combustion, have been transformational in providing climate-conscious planners and consumers with cost-effective choices. Increasingly, however, these technologies are also delivering additional, non-climate benefits, including increased resilience and reliability, consumer choice, and air quality. These additional benefits could grow dramatically: For example, further innovation could lower the cost of clean power below the current price point for traditional power; or smooth the pathway for power generation to not just be carbon-neutral, but also carbon-negative. With growing electrification potential in both transportation and industry, generation becomes more central to any decarbonization strategy. Further innovation can expand the production and use of clean electricity across renewable (e.g., wind, photovoltaic and concentrating solar power, geothermal, marine-hydrokinetic), nuclear, bioenergy, hydrogen, and carbon-capture-and-storage technologies.

Examples - Current Application in Generation

CONSORTIUM FOR ADVANCED SIMULATION OF LIGHT WATER REACTORS

Consortium for Advanced Simulation of Light Water Reactor (CASL) was the first of four Energy Innovation Hubs (Hubs) developed by the DOE beginning in 2010. These Hubs uniquely boost translational connectivity from basic to applied R&D and leverage an interdisciplinary approach via large, multi-institutional collaborations designed to accelerate the pace of discovery for energy solutions deemed critically important. Specifically, CASL combines the expertise of the DOE Oak Ridge National Laboratory with industry partners and universities to develop Virtual Environment for Reactor Applications (VERA). During the first five-year stage of CASL, the operation of traditional pressurized-water nuclear reactors was simulated to identify opportunities for efficiency gains in operation and maintenance of the reactor. During the second five-year stage, CASL will work to expand VERA to accommodate other types of nuclear reactors. Learning from the second stage could lead to more efficient reactor designs that improve lifetime operation in a power plant.

SUNSHOT GRAND CHALLENGE

The DOE-led SunShot Initiative is a multi-agency initiative structured around a bold, integrating goal: making solar energy cost-competitive with conventional forms of electricity generation by 2020. This comprehensive approach set a vision and framework for advancing technology and integrating it into the marketplace. SunShot includes technology R&D programs in PV, concentrating solar power (CSP) technologies, grid systems integration, balance-of-system soft costs, deployment barriers, and technology commercialization. Initial benchmarking of both the state of the technology as well as of the market enabled the program to take a comprehensive approach, coordinating with DOE's Office of Science, ARPA-E, NSF, USDA, EPA, and U.S Department of Housing and Urban Development. SunShot developed a number of cutting-edge program models including: next generation technology R&D for PV; component and integrated system developments for CSP; utility grid integration projects and "plug and play" device concepts for rooftop PV; a highly successful small-business program that advances both hardware and software technologies; disruptive innovation prize and challenge programs like the SunShot and Catalyst prizes; and foundational social and decision science research and analysis on data science and standards that improve technology bankability. The integrated portfolio approach across multiple technology paths and stages, coupled with collaboration across Federal agencies has supported rapid growth in all sectors of the U.S. solar value chain.

Examples - Potential Application in Generation

BRAYTON GRAND CHALLENGE

Thermo-electric generation technologies in nuclear, coal, natural gas, and bioenergy plants have traditionally operated on steam-based Rankine power cycles. Brayton cycles combined with supercritical CO2 (sCO2) as a working fluid could improve the efficiency of new (and possibly existing) energy generation plants. An overarching program focused on a unified goal (like the DOE EV Everywhere and SunShot programs) could help to organize and focus a range of stakeholders on making sCO2 Brayton cycles cost competitive with current Rankine cycle technology, increasing efficiency, reducing the cost of capital, and reducing the footprint of conventional power plants.

Natural Gas CCS Demonstration

Natural gas is rapidly transitioning from a secondary fuel to a primary fuel for power generation in many regions. While combusting natural gas has roughly half of the CO2 emissions of coal, emissions from natural gas power plants will ultimately need to be captured and sequestered in order to mitigate climate change. While DOE with industrial partners has robust CCS programs for coal plants and industrial sources, more work is needed to develop CCS technologies specifically for the unique challenges of natural gas power plants including higher oxygen content and lower CO2 content in the flue gas. A translation approach would expedite demonstration of natural gas CCS by adapting carbon capture technologies originally developed for coal systems or for industrial processes. In addition, lessons learned from both the Clean Coal Power Initiative (CCPI) and the Industrial Carbon Capture and Storage (ICCS) Program can be applied to determine the appropriate scale and award structure for successfully demonstrating natural gas CCS. DOE experience has indicated that smaller demonstration projects at the 50 MW scale (still commercially relevant but non-utility-scale) could expedite technology validation while maximizing the value of public funds.

For discussion of additional generation technologies, see Chapter 4, Advancing Clean Electric Power Technologies, of the 2015 DOE Quadrennial Technology Review.

Mobility | Moving People and Goods Using Clean Energy

Moving people and goods—from private vehicles to public transit, bicycles to aircraft, and railway to maritime shipping—consumes 28 percent of domestic energy and produces negative externalities, including incidents, congestion, and one-third of U.S. greenhouse emissions. Through innovation, we can keep the economy moving forward, while rolling back these negative externalities. This means investment in breakthroughs that boost efficiency at the component, vehicle, and transportation system levels; increase electrification and automation; and back out petroleum in favor of renewable liquid fuels. Policy that spurs technology innovation—through both push and pull mechanisms—can also be effective in driving reduction of greenhouse gas emissions from this part of economy. Vigorous implementation of Mission Innovation for mobility must appreciate these high stakes and address all modes of transportation as well as the interactivity between those modes and between mobility and generation, an interaction that will gain prominence as electric vehicle adoption increases.

Examples - Current Application in Mobility

NASA-FAA Research Transition Teams

To address the operational efficiency of the in-service commercial airline fleet, NASA and FAA have established a series of Research Transition Teams (RTTs) that work to align NASA technology development with the FAA's air-traffic-system needs. The RTTs illustrate enhanced connectivity in translational research, development, and demonstration by establishing successful, well-supported, transparent linkages between technology developers and ultimate users. The RTTs have a co-lead from each agency and are overseen by a coordinating committee of senior FAA and NASA executives that adjusts the scope of efforts, ensures adequate resources, monitors progress, and resolves issues. The RTTs feed technology into an Airspace Technology Demonstration program that conducts virtual and live demonstrations of NASA-developed technologies in a small number of aircraft and/or airports to validate the technology and help identify implementation issues. RTTs are not limited to clean energy R&D, but also provide a best-practices model to consider when establishing R&D efforts that need strong connectivity and integration with the user community.

Advanced Engine Technology Development

Versatile Affordable Advanced Turbine Engine Technology (VAATE) is the United States' current planning construct for turbine engine technology development, and Advanced Turbine Technologies for Affordable Mission Capability (ATTAM) is the follow-on effort to continue to improve turbine engine capability. VAATE and ATTAM follow a well-defined technology-development strategy that combines strong interagency teamwork, specialized talent, and leading-edge tools to drive progress. The team is a partnership among DOD, NASA, FAA, DOE, industry, and academia, each bringing its unique competencies and years of experience to the table. VAATE and ATTAM rely on shared hardware and software capabilities to support the technology leaps required to reach goals. These efforts reflect effective multi-agency translational R&D where agencies are working together on common propulsion goals. The component- and system-level technologies transitioning from these efforts will provide revolutionary solutions to reduce fuel burn and specialty fuel demand for turbine engines.

DOT Support of Low Emission Buses in the Nation's Transit Fleets

DOT's Federal Transit Administration (FTA) has a long history of supporting the successful adoption of alternative fuels and clean emission vehicles. Successful translational R&D programs such as FTA's National Fuel Cell Bus Program, which invested in the research, development and testing of fuel cell bus technology helped pave the way for FTA's capital bus program to support the continued acquisition and deployment of low emission transit buses through the FTA's Low or No-Emission (Low-No) Bus Competitive Grant Program. The Low-No Program focuses on assisting transit agencies to acquire the cleanest and most energy-efficient U.S.-made transit buses to support the transition of the nation's transit fleet to the lowest polluting and most energy-efficient transit vehicles.

Examples - Potential Application in Mobility

Smart Mobility Test Center and Network

Technology developers have created or proposed hundreds of smart mobility technologies, ranging from ridesharing apps, to automated traffic management systems, to automated vehicles. Testing these technologies in real cities, however, is expensive and can present policy and regulatory challenges. A combination of translational and integrational research mechanisms could explore energy efficiencies beyond the traditional vehicle-level focus and accelerate sustainable transportation at the system level. A Smart Mobility Test Center could serve as a part physical, part digital test bed to strengthen translational research capabilities to move beyond component research to investigate systems-level implications of intelligent transportation systems such as connectivity and automation and future mobility systems and solutions related to the transport of both people and goods. This would serve a similar role to the Energy Systems Integration Facility at the DOE National Renewable Energy Laboratory, which allows testing of novel electric, fuel, thermal, and water technologies with a simulated infrastructure in the loop. A Smart Mobility System Network combining a laboratory consortium and complementary industry-led teams could leverage the capabilities of the test center with integrational R&D that uses and generates real-world data to support the ramp up to successively larger-scale public-private demonstrations in real-world conditions.

Advanced Research Projects Model for Transportation

Federal research in transportation could be made more innovative to match the complexity of the emerging transportation system and its associated infrastructure. A disruptive mechanism such as an advanced research projects model would be one idea to consider, with the goal of prompting leading experts to identify and pursue key challenge areas. Similar to ARPA-E and DARPA, an ARPA model focused on transportation R&D could potentially supplement the scope of existing Federal programs with limited term funding for high-risk research, with flexible mechanisms like "open" funding opportunity announcements intended to promote disruptive technology development.

X-Planes for Aviation Efficiency

Within the aviation sector, large single- and double-aisle commercial aircraft account for a large majority of global emissions. Though clean aviation technologies may be partially validated in a laboratory setting or even as a full-scale subsystem, the ability to integrate technologies onto an advanced airframe, and test them under real operating conditions dramatically increases the likelihood that they will be adopted by manufacturers and airlines. Making this a reality calls for enhanced translational R&D that effectively moves aviation efficiency advancements through to systems-level demonstration while working closely with the commercial aircraft industry and other relevant stakeholders to maximize adoptability. The X-Plane, or experimental plane, can be an effective tool for validating how component technologies perform when integrated into an operating system.

For discussion of additional mobility technologies, see Chapter 7, Advancing Systems and Technologies to Produce Cleaner Fuels, and Chapter 8, Advancing Clean Transportation and Vehicle Systems and Technologies, of the 2015 DOE Quadrennial Technology Review.

Connection | Delivering Clean Energy from Supply to Demand

The complexity of the connecting infrastructure that ties together energy supply and demand across various physical and time-scales cannot be understated. It is a complexity worth taking on: Innovation can accelerate support of the evolution of infrastructure to better incentivize integration of clean energy resources and empowerment of consumer demand preferences – all in a way that is more efficient and secure. This means development of both individual technologies as well as protocols for the use of sensors, controls, communications, automation, and energy storage that can enable a range of stationary and transportation applications. The full utility of these technologies and protocols, however, depends on the development of innovative platforms, networks, and marketplaces – strengthened through advances in information technology, advanced computational capacity, and modeling of complex systems. These lines of effort can benefit from social, behavioral and decision science insights that increase understanding of human-technology-system interactions, support effective design and implementation of systems, and speed the integration of new technologies by helping to align technical and system attributes with desired outcomes.

Examples - Current Application in Connection

ENERGY SYSTEMS INTEGRATION FACILITY

Established in 2013 at the DOE National Renewable Energy Laboratory, the Energy Systems Integration Facility (ESIF) is a testing facility designed to test and model the safe, efficient, and cost-effective integration of clean energy technologies into the grid. The facility was designed with significant stakeholder input on the proposed design and functionality. The resulting capabilities, both human and equipment, provide high-value assets that might otherwise be cost-prohibitive for private-sector organizations to build, maintain, and operate on their own. ESIF supports the translational development, evaluation, and demonstration of innovative clean energy technologies by providing the infrastructure, including high-performance computing and analytics, necessary to evaluate the increasingly complex dynamics of incorporating new technologies into our existing energy infrastructure.

POWERAMERICA, MANUFACTURING USA INSTITUTE FOR MANUFACTURING INNOVATION

PowerAmerica Institute is an example of an integrational program working to make wide bandgap semiconductor technologies cost-competitive with silicon-based power electronics. Power electronics

Grid Modernization Laboratory Consortium

The electricity grid is undergoing a transformation in order to meet the demands of the 21st century and beyond. The Grid Modernization Laboratory Consortium (GMLC) is a strategic National Lab-agency partnership focused on developing the tools and technologies that measure, analyze, predict, protect, and control the grid; and better enable new technology integration. To do this, the GMLC combines the federal government's convening power with the world-leading expertise and research facilities of the DOE national laboratory enterprise to help frame new grid architecture design elements, develop new planning and real-time operations platforms, provide metrics and analytics to improve grid performance and security, and enhance government and industry capabilities for designing the infrastructure and regulatory models needed for successful grid modernization. The GMLC builds on the systems-based analytical foundation of the Quadrennial Technology Review and supports critical R&D in grid architectures, components, distribution management, and security tools. This effort recognizes regional differences and will strengthen regional strategies while defining a diverse and balanced national strategy.

convert and control electrical power in a growing array of grid connected devices. Wide bandgap semiconductor material can improve energy efficiency, reduce cost and system size in the next generation of consumer and retail electronics. The Manufacturing USA Institute model has created shared facilities and brings together manufacturers, end-users, and experts from top research universities and government agencies to accomplish their goals. Institutes can serve as a regional focal point, bridging the gap between applied research and product development with an emphasis on key technology areas that may encourage regional investment. Institutes are examples of adaptable integrational R&D capable of addressing a range of challenges in a manner that ultimately encourages private sector-led solutions while developing regional innovation ecosystems.

SMART POWER INFRASTRUCTURE DEMONSTRATION FOR ENERGY RELIABILITY AND SECURITY

The Smart Power Infrastructure Demonstration for Energy Reliability and Security (SPIDERS) project is an example of an integrational R&D mechanism that was used to develop, install, and validate scalable, cyber-secure, smart-microgrid solutions to enhance continuity of operations on military bases. SPIDERS catalyzed novel integration of renewable energy, energy storage, and backup-diesel generation in a fully islanding and cyber-secure microgrid. This Joint Capability Technology Demonstration was a three-phase, $30 million collaboration between DOD, DOE, and DHS, completed in 2015. Separate military bases hosted each of the three phases and each subsequent phase demonstrated a progressively more complex and larger scope of installation. The third phase microgrid demonstration at Camp H.M. Smith, Hawaii sought to support the complete electric load of the base during an extended electrical outage. The results of these projects are expected to have spillover effects on advanced civilian deployment of microgrids that are secure, capable of independent operation, and able to significantly reduce greenhouse gas emissions.

Examples - Potential Application in Connection

ENGINEERING RESEARCH CENTER ON MULTI-LAYERED, NESTED GRID ENABLING DISTRIBUTED ENERGY RESOURCES

The development of new architectures and market mechanisms to optimize the function of the electric grid in order to accommodate more distributed energy resource like solar PV and responsive loads has led to the development of multi-layered nested grids and similar concepts. These concepts operate the electric transmission and distribution system as a network of microgrids that can be coordinated to allow the sharing of resources when connected, or run independently to improve security in the event of an emergency or outage. An NSF model like the three-plane Engineering Research Center approach could support the advancement of an interdisciplinary and multi-scale engineering and economics problem like this one. This builds on the success of lines of NSF research such as those in cyber-physical systems (including work on the internet of things, adding connectivity to everyday devices) and of game and auction theory research (like the work that led to the design of the successful FCC spectrum auction that has increased access to and generated value from underutilized communications frequencies once reserved exclusively for government purposes). This approach could prove beneficial for advancing grid concepts that better align infrastructure, markets and function with the provision of modern grid services.

NEXT-GENERATION TRANSFORMER PROTOTYPE DEVELOPMENT AND DEMONSTRATION

Approximately 70 percent of large power transformers are 25 years or older, and boosting their resilience to the increasing number of natural and man-made threats is an energy security and grid modernization imperative. Transformers will need to be more resilient to geomagnetic disturbances, electromagnetic pulses, and other physical stresses, as well as better equipped to provide power flow control capabilities. An effective translational research and development program, similar to DOE's SuperTruck program, that is mapped to specific next-generation transformer technology goals could be structured around pairing federal research capabilities with teams of grid asset owners to develop prototypes with flexible and adaptable designs. These prototypes would aim to be interoperable with legacy systems and facilitate expansion of a more secure and efficient supply chain.

CATALYST PRIZE COMPETITION FOR SYSTEM ANALYTICS

The proliferation of data resources (GIS, weather, sensors, etc.) that can be applied for grid or transportation analytics opens the door to improved technology integration, system management and operation, and customer engagement for energy and transportation service providers. "Catalyst Energy Prize" software-challenge-style programs that facilitate data utilization in these areas could provide a platform for identifying relevant problem sets; build a community of solvers with diverse talents; rapidly prototype potential software and automation solutions built on those datasets; and support the ongoing connection between the business, software development, and utility/transport communities. This could provide a low-cost and agile mechanism for identifying and developing multiple new solution pathways using existing data.

REGIONAL ENERGY STORAGE DEMONSTRATION

Energy storage is becoming increasingly important for the grid as the role of variable renewables such as wind and solar grows. At the transmission level, technologies such as pumped hydropower storage serve an important role; at the distribution level, technologies such as batteries can support a number of desirable grid attributes. An effective translational approach to scale-up and validate innovative storage technologies could be strengthened by a targeted portfolio of regional storage demonstrations to enable evaluation of performance and other factors under real world conditions. State and Federal regulatory decisions hinge on such information. To best support informed decision-making, integrated demonstrations should include a regional focus and incorporate features from the variety of technology, policy, regulatory, and business realities faced by stakeholders.

For discussion of additional connecting technologies, see Chapter 3, Enabling Modernization of the Electric Power System, of the 2015 DOE Quadrennial Technology Review.

Structures | Innovating Better Buildings

The places we live, work, and gather consume most of electricity in the United States. Innovation in clean energy can make those places better—stronger, safer, more functional, and more sustainable both environmentally and economically. Implementation of Mission Innovation must focus on both the specific technologies and the crosscutting breakthroughs that reach at this potential. From a portfolio perspective, this could include investments in improved (high efficiency) electric space heating and water heating technology; efficient lighting; building envelope including roofs, walls, floors, and windows, both to reduce thermal loads and to develop products that can control the flow of moisture in and out of a building; building systems; and power electronics. An effective portfolio should not underweight the types of research needed to tie these breakthroughs together with the grid and generation—putting to use the potential of peak-usage-time demand reduction, facilitating the integration of variable generation, and decreasing the pace of new electricity capacity requirements. Optimization of structures also requires that research pay attention to the people living, working, or coming together in these places—meaning research on user interfaces, design thinking, and testing for usability.

Examples - Current Application in Structures

L-PRIZE

The Department of Energy launched the L-Prize competition in 2008 to challenge industry to develop high-quality, high-efficiency solid state lighting (SSL) products. SSL products existed and had the potential to save significant energy but provided inadequate lighting when compared to less expensive incumbent technologies. Cost pressures, performance trade-offs, and component availability discouraged manufacturers from attempting to achieve more aggressive performance targets on their own. By challenging lighting manufacturers and partnering with utilities, energy efficiency programs, and large-volume end users, the L-Prize represents an effective use of the prize competition model to incentivize disruptive innovation at a relatively low cost to the government. While the prize resulted in one winner, the challenge catalyzed market competition and pushed lighting manufacturers toward a clear target. Since 2008, LED A-type bulb costs have dropped by 94 percent.

NSF I-LAB

An example of foundational R&D that is helping to increase the breadth of knowledge in the buildings sector is the NSF-sponsored work at the Innovation in Integrated Informatics Lab (i-Lab) at the University of Southern California. This research will advance knowledge of the impact of human-building interactions on energy use thereby enabling accelerated increases in the energy efficiency of buildings and structures. I-Lab researchers are exploring intelligent, collaborative, and personalized ways to connect built environments with their users to transform built environments into attentive and self-learning entities that adapt to user preferences for energy conservation.

Examples - Potential Application in Structures

ENERGY EFFICIENT MANUFACTURED HOUSING PROTOTYPE DEVELOPMENT AND DEMONSTRATION

Prefabricated housing presents an opportunity to deliver low-cost, energy-efficient homes that incorporate manufacturing innovations that may be difficult to replicate in an on-site building environment. Integrating human-centered design (both for construction and occupancy), energy efficiency, and improved economics could benefit from a translational research, development, and demonstration model like the DOE Vehicle Technologies Office SuperTruck program which leveraged component R&D led by an industry consortium (21st Century Truck Partnership) to demonstrate Class 8 tractor trailers with improved fuel and freight efficiency. Similar to Class 8 trucks, manufactured homes are long-lived assets involving multiple energy consuming component technologies, manufactured by a relatively small number of companies, and operating under regulatory standards for performance. Applying a similar model to the manufactured housing space could bring together multiple manufacturers to demonstrate both improved individual components (windows, heating and cooling, insulation) as well as improved complete building system designs.

Platform Technologies to Enable Energy Science for Cities

The rapid emergence of new sensing, communication, and computation capabilities provide an opportunity to dramatically improve the efficiency, sustainability, and resilience of cities as well as rural communities by examining them as integrated, multi-scale, complex systems rather than as loosely coupled components or sectors. Advances in platform technologies such as high-performance computing and artificial intelligence can create a new capability for modeling cities and informing decision-makers and others about programs, policies, and practices that can meet community environmental, economic, and energy objectives.

Energy Prize Challenge for Home Automation and Grid Connectivity

New home-automation devices are beginning to proliferate and the open-source platforms and protocols they use present an opportunity to demonstrate significant reductions in energy use and improvements in system operation by providing users with feedback and information; encouraging new habits; enabling control of lighting, heating, cooling, appliances and miscellaneous electric loads; and linking controls with the distribution grid. So far, few combined software-hardware applications have been developed that address energy specifically or are targeted at providing smart grid services such as demand response. With a fast-growing marketplace of competitors already in existence and new devices entering the market, it is a good time to develop and integrate energy efficiency or energy consumption reduction modes into these platforms, apps, and devices. There is also an opportunity to enhance communication and data sharing between the automated home and the distribution grid. Using prizes and competitions to develop energy-focused, home-automation software and applications could tap into a broad community of solvers to create a range of disruptive solutions. This approach may also be suitable for other data-intensive technology applications such as distribution system management.

For discussion of additional structures technologies, see Chapter 5, Increasing Efficiency of Building Systems and Technologies, of the 2015 DOE Quadrennial Technology Review.

Processes | Using Clean Energy for Manufacturing, Agriculture, and Water

Large and important parts of our economy use energy to turn one thing into another—from agriculture to chemicals processing to water management. Process-energy use and associated emissions arise from an enormous variety of individual applications, which has made these areas challenging to address. Even so, analysis by the Energy Department and others has identified many opportunities for technology improvement to processes that could have a wide-ranging effect. Investment in processes innovation seeks to minimize the energy required, shift away from high-carbon energy sources, and develop next-generation processes. More specifically, this requires investment in technology areas like: efficient or electrified process heating, motor efficiency and controls, sensors and process optimization, additive and other novel manufacturing approaches, industrial carbon capture, improved energy-crop yields, methane-leak detection and removal, lower-energy water purification, and direct CO_2 removal. However, the context within which these technology solutions will be deployed is also primed for research on expanding modeling capabilities; leveraging insights from decision science and market design; and putting to use the potential of increased sensing, computing, and automation.

Examples - Current Application in Processes

Materials Genome Initiative

President Obama announced the Materials Genome Initiative (MGI) on June 24, 2011 with the aim of doubling the speed and reducing the cost of discovering, developing, and deploying new advanced materials. Recognizing that foundational knowledge in materials development can serve as a platform for technological innovations, the MGI leveraged existing R&D policies, programs, resources, and infrastructure with new strategic investments in computational tools, software, new methods for material characterization, and the development of open standards and databases to galvanize a multi-agency effort around a common goal to make the process of discovery and development of advanced materials faster, less expensive, and more predictable. The MGI exemplifies the confluence of foundational and integrational approaches to efficiently spur innovation not through the creation of a new program, but by capturing the additive benefits of enhancing the interconnection of disparate R&D programs.

DOE's Advanced Manufacturing Office (AMO)

The unique mix of R&D project work and facility support within AMO makes it a useful example of combining foundational, translational, disruptive, and integrational R&D mechanisms. AMO uses multiple R&D mechanisms to improve the overall efficiency of innovation in clean energy manufacturing and employ the assets and capabilities of both the public and private sectors. Through traditional R&D projects, AMO enables exploration of novel, energy-efficient, next-generation materials and innovative-process technologies for both specific industry sectors and a wider range of manufacturing industries, and pursues foundational energy technologies for multiple industry sectors. Through consortia, like Institutes and Hubs, AMO creates shared facilities and brings together manufacturers and end-users from U.S. industry, with researchers from universities and national labs to accomplish their goals. Institutes can also serve as a regional focal point, with emphasis on key technology areas that may encourage regional investment. The breadth of mechanisms provides for adaptable, integrational R&D capable of addressing a range of challenges in a manner that ultimately encourages private sector-led solutions while developing regional innovation ecosystems.

Examples - Potential Application in Processes

Clean Water-Energy Innovation Hub for Pipe Parity

High-efficiency, low-cost removal of salt and other impurities from water could be transformative for the world's water challenges. Significant research investments and progress has been made, but major engineering and technical challenges remain to achieve clean water processing and production at the same economic, energy, and emissions cost as existing water supplies. As an integral component of a multi-agency pipe-parity strategy, a Hub would bring together a range of R&D disciplines to pursue breakthrough advances spanning from basic to applied research in filtration, pre-treatment, membrane, operation, and energy inputs for clean water processing and production. As a hybrid approach of translational and integrational R&D mechanism, the ultimate goal of the Hub would be to develop technologies for low-cost, low-energy water production for municipal, industrial, and agricultural use, with the feedwater potentially coming from a diversity of sources—including seawater, surface and lake waters, brackish water, and produced waters.

Consortium for Low Carbon Cement Production

Cement production is critical for the modern building industry but is energy intensive and produces significant process-related emissions from the calcination of limestone. Cement production was responsible for about 829 million metric tons of CO2 globally in 2001, more than three percent of the total from fossil-fuel use. Approximately half of cement emissions are from energy use and half from process-related emissions. The industry is also relatively concentrated, with approximately half of U.S. production coming from five companies. A competitive, Federally-funded R&D consortium with industry leaders could provide new incentives for development and testing of lower-carbon, cement-production technology with reduced use and reduced or captured process emissions.

Prize Model for Methane Detection and Monitoring

Methane emissions and leaks from diverse sectors and sources are a major climate challenge. Detection, measurement, and monitoring of emissions is a key limiting factor for reducing emissions. Technologies exist to measure methane at a variety of scales but have been limited in sensitivity, cost, and deployability to a variety of sectors and applications. In 2013, ARPA-E initiated its $30M MONITOR program to develop advanced technologies for addressing this problem. Building off the MONITOR outcomes, a new methane-detection prize similar to the L-Prize could be used to incentivize creation of business models and applications approaches to apply these new approaches all across the Natural Gas system, including production, processing sites, pipelines and distribution in urban areas.

Capturing CO2 from Dilute Sources

Technology to capture CO2 from dilute source could play a critical role in long-term, low-emission futures, but no major Federal program currently exists to develop these technologies. A new white-space R&D program could evaluate possible applications for capture from more dilute sources, establish goals for efficiency and cost of a demonstrated system and fund competitive applied R&D to adapt technology that has been developed for power plant carbon capture, drive down costs, improve energy efficiency, and demonstrate complete systems along a defined multi-year program plan. This is a new area of research and would first require exploratory work to determine which research mechanisms could be most useful and to perform techno-economic analysis of candidate technologies. It is likely a hybrid of approaches would be needed, such as foundational R&D plus translational, path-dependent work that connects to integrational efforts like EFRCs or Hubs.

For discussion of additional process technologies, see Chapter 6, Innovating Clean Energy Technologies in Advanced Manufacturing and Chapter 7, Advancing Systems and Technologies to Produce Cleaner Fuels, of the 2015 DOE Quadrennial Technology Review.

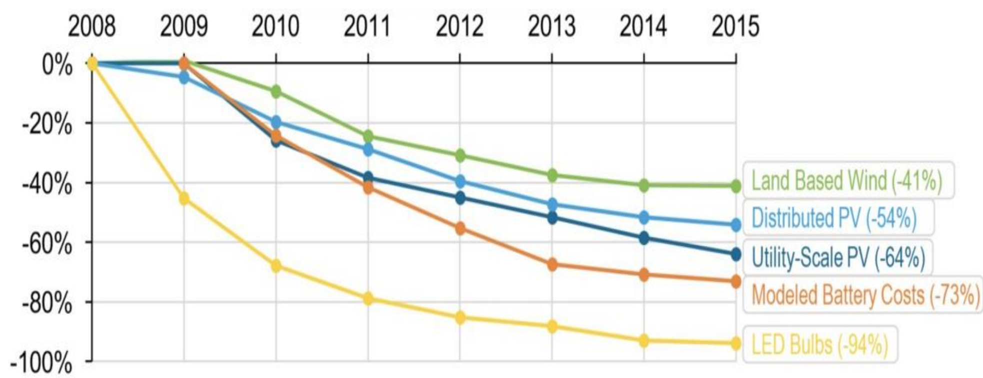
Accelerating Context

Progress on Clean Energy Innovation

The recent pace of clean energy technological change has been breathtaking: wind and solar provided two-thirds of all new U.S. electricity generation capacity last year, with more than a million solar power systems now on rooftops across the country; nearly half a million electric vehicles are on the road, with battery costs falling 73 percent since 2009; and energy-efficient LED bulb costs plummeted 94 percent over the same period, with sales more than doubling last year alone (Fig. 5.[10])

Figure 5

Clean Energy Cost Reductions



These technologies are being deployed at scale today thanks in large measure to public R&D investments in decades past, just as the R&D investments outlined in this framework will drive future market transformations.

Importance of Complementary Policy and Private Sector Action

That leap from the laboratory to the marketplace does not happen effortlessly, however. Clean energy innovations tend to be "hard technologies"—that is, technologies based on physical hardware and process science that face technical challenges between invention and large-scale adoption (though complementary software and soft-cost reduction innovations are also needed). Unlike software innovations, clean energy technologies typically cannot generate millions of customers at low cost in just a few years. Unlike biomedical innovations, clean energy technologies typically cannot proceed predictably through a well-established set of regulatory milestones and distribution channels. Indeed, clean energy technologies do not reside in one particular sector, rather they span applications in energy generation, the built environment, transportation, industrial processes, and land use—all of which rely on

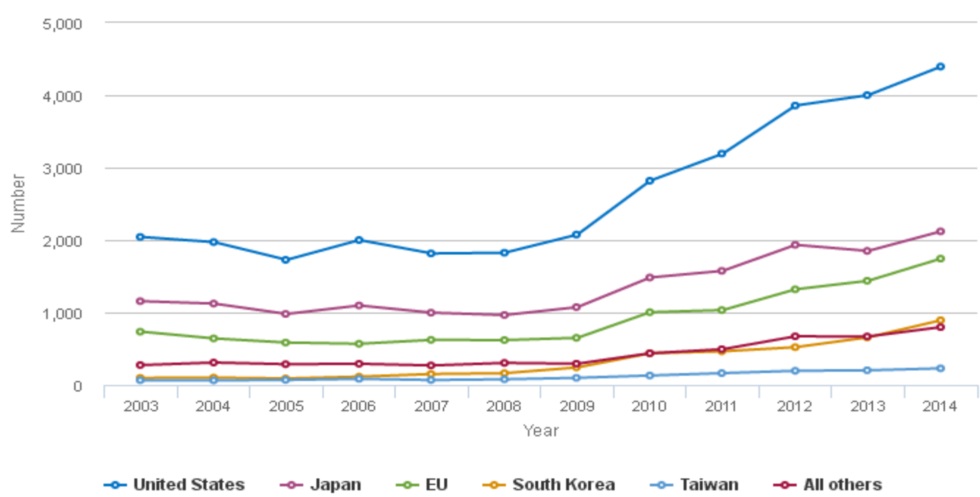
[10] http://energy.gov/eere/downloads/revolutionnow-2016-update

long-lived incumbent infrastructure. Energy technologies also often compete in commodity markets with razor-thin margins—new technologies may therefore face high market risk with relatively low or unpredictable returns for investors.

For all of these reasons, clean energy technologies can take a significant amount of time, capital, and multisector collaboration to achieve widespread adoption in the marketplace. The volume of potentially commercializable innovations is increasing rapidly, as evidenced by the surge in U.S. clean energy patents[11] since 2009 (Fig. 6).

Figure 6

USPTO Alternative Energy and Pollution Control Patents



Yet, traditional venture capital investment in early-stage clean energy technology companies has not recovered from its global pre-recession peak. A number of promising Federal programs are addressing this challenge by providing entrepreneurial researchers with the time, resources, and training needed to increase the likelihood of successful follow-on investment within capital-intensive industries. For example, DOE's Lab-Embedded Entrepreneurship Programs are recruiting world-class entrepreneurial researchers to work within the DOE National Labs and advance their cutting-edge energy technologies toward product launch, leveraging unique facilities and research collaborations within Berkeley Lab in northern California (Cyclotron Road), Argonne National Laboratory near Chicago (Chain Reaction Innovations), and Oak Ridge National Laboratory in Tennessee (Innovation Crossroads). DOE's Lab-Corps program works in the other direction, empowering National Lab researchers to achieve their entrepreneurial potential through an intensive customer-focused training program, modeled on the National Science Foundation's Innovation Corps (I-Corps) curriculum.

[11] https://www.nsf.gov/statistics/2016/nsb20161/uploads/1/9/fig06-50_1449775749968.png

The R&D investments described in this Framework are just the beginning of a long-term commercialization pathway that requires sustained public- and private-sector investment, alongside program and policy support:

- **Private-sector R&D** complements government-funded R&D by focusing on technologies with more immediate commercial potential. Although private-sector R&D comprises around two-thirds of total U.S. R&D, a relatively low fraction has been historically devoted to clean energy innovation. An important incentive to boost U.S. private-sector R&D, the Research and Experimentation tax credit, was made permanent last year for the first time since its enactment in the early 1980s—and was expanded to allow pre-revenue startups and small businesses to take advantage for the first time.

- **Early-stage equity investment** often represents the first "handoff" between government-funded R&D and private-sector investors seeking market returns, while a new technology is still being validated. This stage is increasingly attracting investors with a longer time horizon than a traditional venture capital fund—for example, the Breakthrough Energy Coalition, a group of over 28 private investors from 10 countries that has pledged to invest significant levels of private capital in clean energy innovations as a direct complement to the increased government R&D funding under Mission Innovation.

- **Industrial-scale facilities** are typically required to address the final stages of technology risk before full commercial deployment. Large long-term investors such as pension funds and university endowments have an increasingly important role to play at this stage, as evidenced by over $1 billion committed by such investors through a new "Aligned Intermediary" for clean energy projects, part of the $4 billion committed in response to the Administration's Clean Energy Investment Initiative. The DOE Loan Programs Office also catalyzes private investment in industrial-scale facilities to prove out novel clean energy technologies.

- **Human capital development** is needed to ensure that a diverse, well-trained, and innovative workforce is available to support deployment, operations, and future R&D efforts in clean energy. To sustain a clean energy economy, pipelines of talent need to be developed and maintained for professions including engineering, entrepreneurship, and the skilled trades, as well as in supporting fields such as finance and information technology. Leveraging public and private investments in R&D at the state and local level can create opportunities to bolster economic development and create new institutions and infrastructure that support this kind of human capital development, while meeting changing market demands and growing jobs.

- **Commercial market demand** is the "pull" on new technologies that complements the "push" of government R&D. The recent extension of tax credits for U.S. solar and wind energy facilities will continue to incentivize market growth for these technologies until they can be deployed in every part of the country on a cost-competitive basis. Strong demand signals that reduce market risk for new technologies would help accelerate the commercialization and deployment of other clean energy technologies as well, particularly those in commodity markets. Promising approaches include advance market commitments (binding commitments to purchase a certain volume of a new product at a fixed price, once the product meets pre-defined performance characteristics) and other ways to create price floors for high priority technologies in risky, volatile, or highly competitive markets; government as "early adopter" of new technologies (*e.g.,* military installation microgrid solutions vetted through the DOD's Environmental Security Technology Certification Program); and public-private efforts to spur private-sector adoption (*e.g.,* the DOE Rooftop Chiller Challenge defining commercial specifications and mobilizing industry demand for energy-efficient, cost-effective commercial air conditioners).

Federally funded R&D is the "seed corn" that ultimately yields clean energy technology adoption at scale. The U.S. strategy for Mission Innovation is not only to double essential R&D investments, but also to optimize their readiness for private sector investment and ultimate economic impact. That is why this framework document articulates a playbook of R&D modalities that can be adopted for particular technology scenarios—enhancing the *foundation* of knowledge within disciplines, making the *translation* of technology development from basic research to applied R&D to demonstration more efficient and effective, accelerating the *disruption* of current pathways and cost curves, and promoting the *integration* of ideas and solutions across disciplines, sectors, and technologies—all to deliver impact at the scale of the energy sector. At the same time that these modalities can be applied to major sectoral energy challenges (mobility, connection, structures, generation, and processes), this framework recognizes the need to make new investments in cross-cutting platform technologies with the potential to accelerate the design-build-test cycle of clean energy research itself.

Through a half-century of American leadership and ingenuity in clean energy innovation, we have already enjoyed the benefits of improved public health, significant new job creation, and enhanced national security. Mission Innovation investments will build on these core American strengths and deliver even greater economic impact in the decades to come.

Conclusion

Accelerated innovation in clean energy R&D that can lead to real impact in the energy sector requires a strong, multi-faceted, multi-agency approach that provides additional resources to successful, effective, existing core activities; expands the foundation of knowledge in all sectors; supports accelerated translation of technology through the phases of R&D; shakes up path-dependencies to better enable breakthrough solutions, and builds strong linkages across disciplines and users to enhance the relevance and utility of results. There are many ways to conduct R&D, and many paths to using R&D outcomes to achieve our energy goals, both in terms of *what* we chose to invest in and *how* we choose to get there. This document lays out just a few illustrative opportunities and attempts to shed light on ways in which effective R&D mechanisms could be utilized to accelerate clean energy innovation and impact. We need to be strategic and deliberate when developing new programs and enhancing existing ones to ensure the best R&D mechanisms, or more likely, combination of mechanisms, are employed. Smart application of the significant funding increases under Mission Innovation will be needed to maximize the likelihood of rapid success.