Energy Innovation Policy: Priorities for the Trump Administration and Congress

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By investing in energy innovation and infrastructure, the United States could wrest back clean-energy markets, creating thousands of jobs in advanced manufacturing and improving its trade balance.

Energy is an enormous and vital economic sector, and clean energy in particular is growing rapidly in much of the world. Countries that have seized this market opportunity, valued at over $300 billion globally in 2015, are fueling economic growth at home and expanding exports abroad.[1] Asian countries have vaulted to the forefront of global trade in clean-energy technology. In particular, China is the world leader in the production of solar panels, batteries, and wind turbines, and it is quickly taking the lead in next-generation nuclear power and technologies to capture carbon. The United States is losing this race because Asian countries are out-investing the United States and dictating the terms of competition, often flooding the market with low-cost, unimaginative products.[2]

But the race is not yet lost. By investing in energy innovation and infrastructure, the United States can wrest back clean-energy markets, creating thousands of advanced manufacturing jobs and improving its trade balance.[3] Moreover, it will take innovation to make cleaner energy truly cost competitive—sans subsidies—enabling widespread adoption that enhances U.S. energy security, improves the environment, and protects public health. The United States has a strong foundation for rapid progress. U.S. universities and national laboratories have developed many of the most promising new technological options on the horizon, and American companies such as Tesla, General Electric, and First Solar have successfully commercialized innovative products.

However, the United States is not doing enough to seize the energy-innovation opportunity and capitalize on its progress to date. Federal funding for energy research and development (R&D) lags well behind funding for space, health, and defense R&D.[4] Eleven other countries around the world spend more on energy R&D as a percentage of GDP than the United States. China spends three times as much.[5]

Private investment in energy innovation has been weak as well. Venture capital and private-equity investment in American renewable-energy companies, for instance, peaked in 2008 at $5.4 billion and slipped to $2.2 billion in 2015.[6] Only a handful of U.S. companies developing advanced nuclear reactors and carbon-capture technologies have raised enough private investment to scale up their innovations; meanwhile, China is sponsoring an all-out push on all of these technology fronts.[7] As a result, researchers, entrepreneurs, and companies lack sufficient funding to invent new technologies; investors are wary of funding technology scale-up; and slow-moving incumbents continue to dominate energy markets.

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There is a second reason for the next administration to focus on spurring energy innovation. Climate change is extremely unlikely to go away. As its observable effects, such as "king tides" that regularly flood streets in Miami Beach, make the scientific consensus on climate change more salient to the general public, the pressure on the United States to do something, both domestically and internationally, will increase. But trying to combat climate change with only existing energy technologies would be expensive, complicated, and unpopular.[8] Instead, by investing in affordable and effective low-carbon energy innovations, America will be able to lead the world in the fight against global warming without imposing onerous regulations that limit consumer choice or alter our way of life.

President-elect Donald Trump and the 115th Congress should make energy innovation a high priority and address the obstacles to developing and deploying new technologies. To do so, they will need to reform a sprawling set of institutions to increase the commercial impact of federal energy R&D and maximize taxpayer return on investment. These reforms should draw inspiration from experiences in other sectors, including life sciences, semiconductors, electronics, and agriculture, where breakthrough technologies have been successfully commercialized.[9]

We distill these lessons into five principles for institutional change that should be applied to key federal agencies, especially the U.S. Department of Energy (DOE):

- Connect basic science with technology priorities,
- Reorient the national labs to pursue commercially relevant RD&D,
- Encourage more private investment in energy innovation,
- Support demonstration projects, and
- Complement "supply-push" policies with "demand-pull" policies.

These reforms will help focus federal energy-innovation resources on urgent and coherent needs. We put forward six candidates for these "Technology Missions":

- Nuclear power;

- Solar energy;
- Energy storage;
- Carbon capture, utilization, and storage;
- Advanced cooling and thermal energy storage; and
- Smart energy management and connected vehicles.

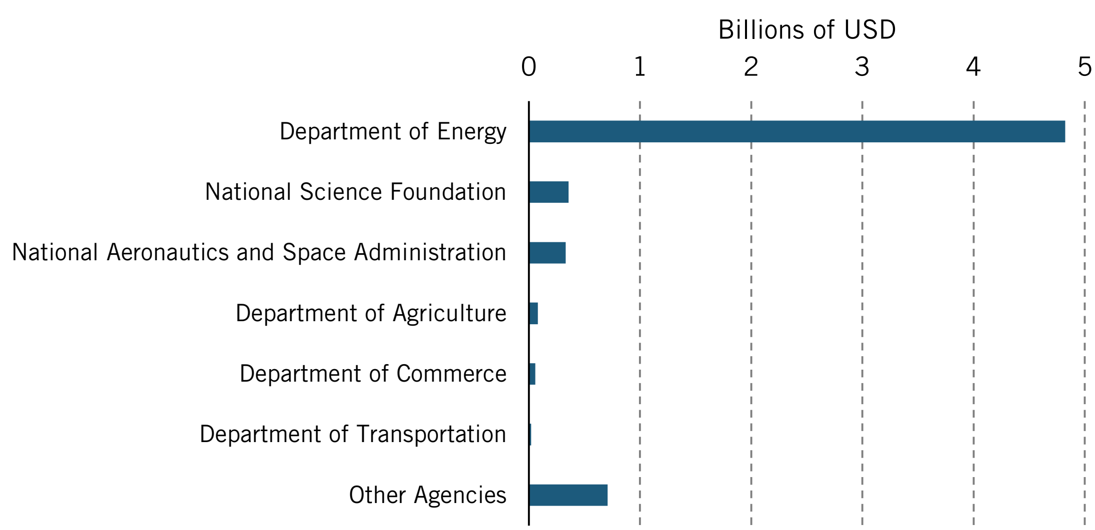
Accelerating energy innovation to accomplish these missions will require significant new funding as well as more effective use of existing resources. Recognizing this fact, 20 countries around the world—representing the vast majority of energy R&D investment and led by the United States—recently committed to a "Mission Innovation" pledge to double public-energy R&D funding over a five-year period.[10] Anticipating this increase, a group of large investors led by Bill Gates has announced a new effort called Breakthrough Energy Ventures that will invest more than a billion dollars in innovative energy technologies.

The Trump administration, in partnership with Congress, should seek to meet the United States' Mission Innovation commitment. Dedicated revenue sources for federal energy-innovation investments would provide private investors with confidence that these investments will be sustained and avoid the stop-and-start pattern that has plagued energy-innovation policy in the past. We close the paper with a set of funding options that merit more careful exploration.

INSTITUTIONAL REFORM: GETTING MORE BANG FOR THE BUCK

The federal government's $6.4 billion clean-energy RD&D investment was spread across a dozen agencies in fiscal year 2016 (Figure 1). About three-quarters of this funding was channeled through the Department of Energy (DOE).[11] Continued federal investment in such programs is essential for improving American energy security and making energy production and use less harmful to public health and the environment.

Figure 1: Federal funding for clean energy R&D in fiscal year 2016[12]



But U.S. federal investment can produce more bang for the buck. Too much of it is spent today on a plethora of disconnected projects that lack focus. Reforming the sprawling federal energy-innovation infrastructure should be an important priority for the Trump administration and the 115th Congress. In doing so, they can build on initiatives conceived and piloted under the Bush and Obama administrations that currently represent only a small fraction of federal investment. The following five principles should guide the reform effort.

1. Connect basic science with technology priorities

DOE has historically emphasized basic scientific research that is excessively insular, uninspired by end uses, and disconnected from applied research, development, demonstration, and commercialization.[13] Explicitly linking basic energy-science funding to broader technology initiatives can more efficiently guide science without stifling it.

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Experience in health, defense, and other sectors suggests that it is possible to tread a middle path between focusing on applications and supporting breakthrough science and technology. The life sciences, for example, have benefited from steady federal support for basic research, which accounts for over half of the National Institutes of Health's (NIH) $30 billion research budget.[14] Yet, NIH requires every proposed research project to be linked to a practical purpose.[15] This approach has helped bring about a broad array of application-relevant discoveries and the development of powerful enabling technologies, such as rapid genetic-sequencing methods, which have sped up the pace of technology commercialization.[16]

DOE might draw on NIH's experience by requiring most basic energy-science programs to identify a Technology Mission or another applied initiative to which they expect to contribute. However, another lesson from NIH is that steady funding (in contrast to historically volatile energy investments) nurtures vital communities and institutions, so this transition should occur gradually. DOE should refrain from abruptly cutting off funding to current projects. The Trump administration should work with Congress over several years to increase the proportion of new appropriations for basic energy science that are explicitly tied to broader initiatives to develop commercially relevant advanced-energy technology.

DOE's Energy Frontier Research Centers (EFRCs), which were designed during the George W. Bush administration and funded initially in 2009, took a step in the right direction. These 36 centers address interdisciplinary scientific questions that emerged from gatherings of academic, government, and industry researchers.[17] More of the federal government's basic energy-science research should be conducted at EFRCs, which should be linked institutionally to downstream technology activities, such as Technology Missions. Similar linkages should be encouraged to drive energy R&D at other federal agencies, such as the National Science Foundation (NSF), which provides nearly $400 million in funding.[18]

The Obama administration also experimented with new institutions that create greater connectivity along the energy-innovation chain. The Advanced Research Projects Agency-

Energy (ARPA-E), which is modeled on the extraordinarily successful Defense Advanced Research Project Agency (DARPA), funds end-use driven research programs. Entrepreneurs supported by ARPA-E have raised more than $1.25 billion in follow-on funding from private investors.[19] The Manufacturing USA innovation institutes, which were authorized by a bipartisan congressional majority in 2014, link government laboratories and academic researchers with regional industrial clusters. Lightweight Innovations for Tomorrow (LIFT) in Detroit, which works with the aerospace and automotive industries, and PowerAmerica in Raleigh, North Carolina, which advances semiconductor materials, are among several energy-focused manufacturing innovation institutes.[20] Such experiments warrant further refinement and expansion.

Greater autonomy, stronger incentives to collaborate, and better connections to external partners, especially geographically proximate industrial clusters, could amplify the national labs' impact on energy technology.

At the administrative level, DOE has linked science with technology priorities through the creation of the Office of the Under Secretary for Science and Energy (S4) and the Office of Technology Transitions (OTT) within it. These organizational innovations, along with Tech-to-Market Offices that have been established within some of DOE's major program offices, advance the reform agenda articulated jointly by the Information Technology and Innovation Foundation (ITIF), the Center for American Progress, and the Heritage Foundation in 2010.[21] President Trump, in partnership with Congress, should further elevate and fund S4 and OTT, and advance budget requests that continue to integrate the department's narrow technology stovepipes and atomized funding streams.

There will be legislators and interest groups that oppose strengthening the link between basic energy science and energy-technology priorities. Basic science research can and should produce unexpected results with unanticipated applications. In fact, DOE and other federal research agencies can do more to encourage researchers to take risks and pursue longer-term projects, following the example of the Howard Hughes Medical Institute, which funds people rather than projects.[22] But the administration has a strong case to make to its partners in Congress that this middle path is the best one to advance innovation and meet U.S. economic, security, and environmental objectives.

2. Reorient the national laboratories to pursue commercially relevant RD&D

DOE oversees 17 national laboratories, with a collective annual budget of $12.3 billion. [23] These labs are extraordinary repositories of scientific and technical capabilities that have made great contributions to the nation since World War II. Many of these contributions have been in the fields of defense and pure science; surprisingly few have been in energy. One key reason is that the labs' energy activities are too often disconnected from mission-driven, industry-relevant technology development, demonstration, and deployment. Moreover, DOE delegates the labs' limited autonomy to marshal their considerable resources as coherent technology centers. Greater autonomy, stronger incentives to collaborate, and better connections to external partners, especially geographically proximate industrial clusters, could amplify the national labs' impact on energy technology.
The president and Congress should empower them to prioritize this objective.

The most impactful formula for lab-industry relationships centers on well-resourced, long-term RD&D collaborations that tackle commercially relevant problems. Many national labs already possess a critical mass of relevant capabilities, such as Argonne National Laboratory for energy storage and Lawrence Berkeley National Laboratory for solar fuels, and others could develop comparably focused capabilities. Such locations are natural homes for collaborations targeted at specific Technology Missions. These labs can also make important but hard-to-quantify contributions by providing analysis, sharing information, and convening relevant science and technology communities.

In order to build these partnerships, the private sector must have access to clear and comprehensive information about the assets that each national lab can bring to bear on technical challenges, such as research results, intellectual property, facilities and equipment, modeling resources, and technical expertise. DOE has improved its reporting on these assets in recent years by creating an Innovation Portal and Facilities Database, but there is much more left to do. Likewise, the labs must work harder to solicit industry input to better understand market needs and prioritize R&D activities for downstream impact.

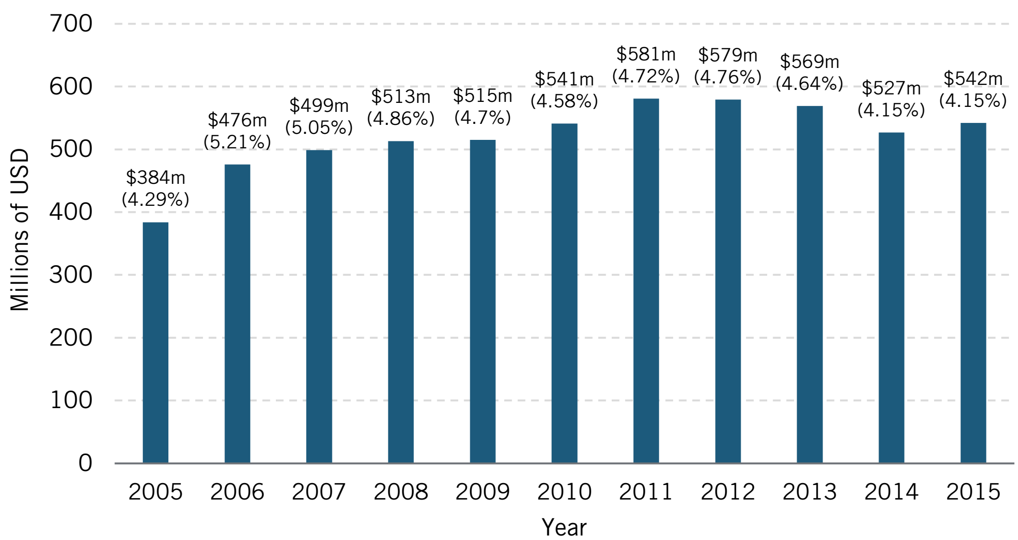
It is vital that the national labs engage with small businesses and start-ups as well as large energy-sector firms.

These information flows must be backed up by incentives for collaboration. Lab-to-market programs that support the translation of R&D results into practical applications help to provide such incentives. For example, Oak Ridge National Laboratory, Sandia National Laboratory, and the National Renewable Energy Laboratory (NREL) have established demonstration facilities that allow companies to try out innovative technologies at low risk in highly applied settings. Lab Bridge and the Technology Commercialization Fund provide financial and legal resources for collaborative RD&D.[24] The Trump administration should substantially expand these efforts. Moreover, there is a pressing need for R&D into manufacturing processes to rapidly scale up discoveries made at the labs. Limited efforts have been made (e.g., the Materials Engineering Research Facility at Argonne) to address this gap to date.

It is vital that the national labs engage with small businesses and start-ups as well as large energy-sector firms. Entrepreneurial firms are key sources of innovation, taking risks that big firms eschew and thinking outside the proverbial box.[25] Regional industrial clusters, such as Silicon Valley's semiconductor industry, thrive when they have a mix of firms of different sizes and vintages.[26] Recent lab initiatives have taken promising steps in the right direction. Cyclotron Road at Lawrence Berkeley Lab hosts external entrepreneurs who can draw on its resources, and Lab Corps encourages internal entrepreneurs to develop their ideas. Small businesses may now apply for vouchers that support work on the labs' premises.[27] These exciting initiatives should be replicated, scaled up across the system, and integrated into the broader regional energy-innovation partnership program.

For the national labs to become more innovative and thus more effective at contributing to industries that produce and use energy, they will need more autonomy than they are currently delegated. Under the Trump administration, DOE should increase the scale of Laboratory-Directed Research and Development (LDRD)—which represents less-restricted funds that lab directors can allocate toward priorities of their choosing—from 4 percent to 6 percent or more of total spending on national labs (Figure 2).[28] And more of the oversight over research projects should reside within the labs rather than in DOE headquarters, so that the labs can determine the best ways to mobilize their resources toward commercializing new technologies.[29]

Figure 2: DOE Laboratory-Directed Research and Development (LDRD) budgets[30]



3. Encourage more private investment in energy innovation

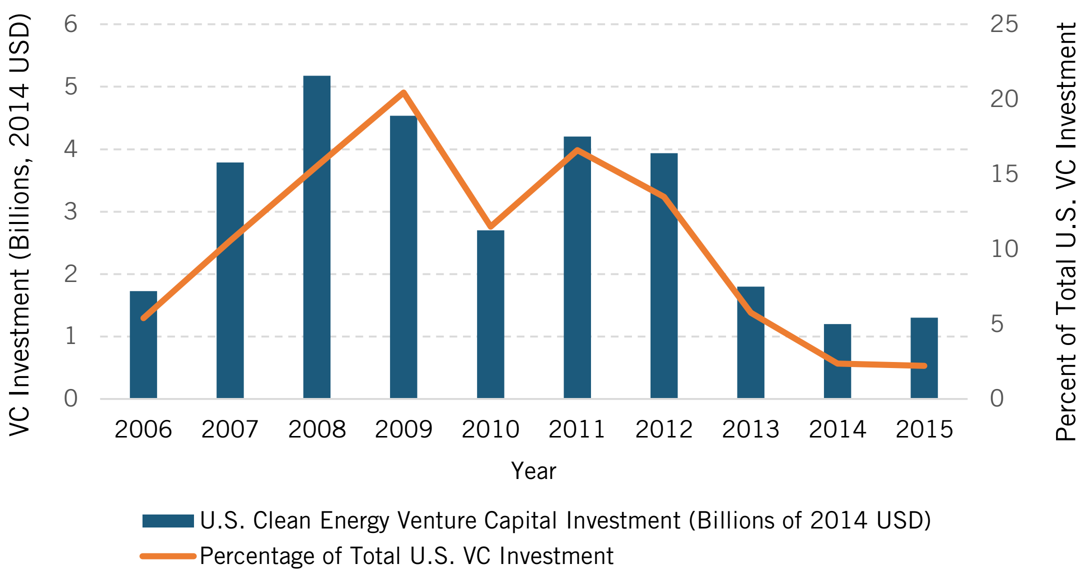
Private investment in energy innovation has hit a rough patch over the past decade. The rate of new company formation has slowed. Venture capital investment has receded (Figure 3). Corporate expenditure on both in-house and external R&D has stagnated.[31] A top priority for the new Congress and administration should be to reverse these trends.

DOE initiatives that provide seed-stage support for advanced-energy start-ups, such as EERE's National Incubator Initiative for Clean Energy and the Cleantech University Prize, are not enough to enable entrepreneurs to acquire follow-on funding from venture capitalists or corporate partners. A more effective Small Business Innovation Research (SBIR) program, which provides federal funds to support commercially-relevant R&D at firms with 500 employees or fewer, could help fill the gap. Research suggests that SBIR funding doubles the chance that a recipient will receive follow-on venture investment.[32] But DOE program offices have not integrated SBIR into their broader strategies for technology development. Limited funding constrains its impact as well—especially for SBIR Phase II and III grants. A review of SBIR could generate options to scale it up, enabling better integration with RD&D funding, or guide DOE to concentrate on alternative solutions.[33]

Although advanced-energy venture investing has slumped recently, considerable latent interest remains, which the federal government can seek to draw out. Investors such as the

Breakthrough Energy Coalition, a 28-member group led by Bill Gates, will put substantial capital into attractive opportunities. Recently, several of them announced the Breakthrough Energy Ventures—with an initial capitalization of over $1 billion and plans to grow—that will invest in refining and scaling technologies emerging from federally funded research. To make it easier to do so, DOE should continue to build out its Clean Energy Investment Center (CEIC), which seeks to simplify the confusing array of federal resources for prospective investors, and could focus their attention on the department's technology priorities.[34] In addition, DOE should expand its Annual Merit Review process, in which all recipients of applied R&D funds must present their results, to include energy-oriented investors. Such gatherings could foster matchmaking between researchers and investors and accelerate initial due diligence.

Figure 3: U.S. venture-capital investment in clean-energy companies[35]



Agencies other than DOE should also explore opportunities to support early-stage advanced-energy companies. For example, SBA's Small Business Investment Company (SBIC) program should support private funds committed to investing in advanced-energy technology start-ups.[36] And on the regulatory side, the Treasury Department should issue additional guidance to institutional investors and charitable foundations, clarifying for example that program-related investments in innovative energy companies qualify for favorable tax treatment.[37] DOE should better support the Treasury Department in developing guidance for energy technologies that qualify for tax incentives, linking those to Technology Mission goals wherever possible.

4. Support demonstration projects to de-risk private-sector investment

Demonstration is a vital phase in the innovation process for many advanced-energy technologies. Demonstration projects seek to establish the safety, reliability, and affordability of technologies under real-world conditions, thereby reducing the risk facing later investors. Unfortunately, such projects have been woefully underfunded in recent years. President Trump and the new Congress should explore new models for judiciously filling this gap with federal resources to unlock private investment.

One model for financing large-scale energy-technology demonstration projects is an independent, federally chartered corporation. This corporation would fund projects that are unattractive to private investors but have the potential to stimulate massive follow-on investment. Because it would be outside government, it would be able to employ flexible hiring practices and provide project assistance on a commercial basis.[38]

A second approach would organize demonstration projects regionally, taking advantage of the diversity of natural resources and public attitudes across the country. A set of new hybrid institutions would have to be created to oversee the selection and management of such projects. This approach would combine state funding linked to energy use with federal support.[39]

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A third mechanism to incentivize private investment in demonstration projects would rely on prizes. Many federal agencies have the authority to offer prizes. NASA has used this authority quite effectively, for instance, to induce private space-launch companies such as SpaceX to meet its demanding standards.[40] Prizes limit the government's risk by providing payment only after proven performance, although the length and cost of some energy-demonstration projects may require a set of payments for hitting carefully designed intermediate milestones. Public prizes in this field would complement philanthropic efforts, such as the Carbon X Prize.[41]

Finally, a recent proposal calls on DOE to create and help fund 10 public-private consortia. Each of these entities would commit $10 million per year for 10 years ("10-10-10") to commercialize a technology.[42] The consortium approach has proven successful in other sectors, most notably in semiconductors, in which SEMATECH, a partnership between the Department of Defense (DOD) and American semiconductor firms, helped the United States retake leadership in the industry in the 1980s.[43]

Each of these models presents institutional and administrative challenges, and the past record of large-scale energy-demonstration projects in the United States is mixed at best. Further analysis will be required to refine them. Whichever model is chosen, it is essential that the demonstration phase is well integrated with applied R&D programs such as ARPA-E and covers a variety of scales, from small pilot plants to large commercial-scale facilities.

5. Complement "supply-push" policies with "demand-pull" policies

The success of energy innovation depends ultimately on meeting the test of markets. Subsidies of indefinite duration are not acceptable. The creation of temporary protected market niches, however, may be vital in bringing costs down while production ramps up, and in providing working capital to early-stage firms. Such "demand-pull" policies have been shown to be vital complements to the "supply-push" provided by federal RD&D for many transformative innovations in the past.[44]

DOD has long experience pairing supply-push and demand-pull. It virtually created the computing industry, midwifing the discipline of computer science even as it bought early computers for uses such as air defense in the 1950s and 1960s. Similar stories can be told about other major high-tech industries, including aircraft, software, and semiconductors. Once the markets for these products took off, federal procurement fell to a small fraction of total sales.[45]

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DOD has already begun to play a similar role for energy innovations that meet its operational needs and provide the military with reliable and secure energy services.[46] The General Services Administration, which serves as the acquisition agent for federal civilian agencies, has also provided demand-pull for energy innovations in areas such as green buildings and alternative-fuel vehicles. Such efforts sometimes bump up against legal and regulatory barriers that should be dismantled. However, it is also essential that policymakers are vigilant about preventing such procurement preferences from being captured by non-innovative incumbents.

DOE is not in the business of procuring energy on a large scale, so the demand-pull that complements its RD&D investments will have to arise from other sources. Tax incentives are one such source. They can help drive innovation by encouraging early adoption by end users. Like procurement, however, such incentives must be regularly reviewed, so that they don't become subsidies for mature technologies. Environmental and energy-efficiency regulations may also drive demand for energy innovation. At its best, the regulatory process engages technically savvy regulatory staff with industrial experts in order to set aggressive but feasible targets on a time frame that allows industry to plan ahead to meet them.

Although DOE's own regulatory role is relatively small, it should play a larger role in providing technical support to other agencies that regulate energy production and use. For example, DOE could increase funding for technical experts at national labs to provide impartial technical input to rulemaking processes conducted by the Federal Energy Regulatory Commission, the Department of the Interior, state utility and transportation regulators, and others.

State, local, and private-sector initiatives may well be more important in providing demand-pull for energy innovation than federal policies. State renewable portfolio standards, for instance, have helped to drive down costs for wind and solar power in recent years. Many large corporations have added momentum to this trend by voluntarily committing to purchase renewable energy.

In fact, in large part because of the growth of renewables, the electric power market is in the midst of an historic transition from a centralized, one-way system to an interactive, dynamic one. State regulators, and regional planning organizations under the purview of the Federal Energy Regulatory Commission (FERC), are on the front lines of this complex process. DOE, drawing on the national labs, should be engaged to provide technical advice and support to these bodies as they navigate this uncharted territory. A combination of bottom-up experimentation and federal information-sharing and coordination is more likely to yield a 21st-century grid that enables innovation than either level acting alone.

PRIORITY SETTING AND "TECHNOLOGY MISSIONS"

Improved priority-setting must go hand-in-hand with institutional reform. A more efficient system is no more valuable than an inefficient one if it is not focused on the right goals. The federal government, led by DOE, has recently adopted new priority-setting processes for energy innovation, but a gap remains between short-term goals and very long-term ones. New "Technology Missions" should be adopted to fill this gap and focus the department's efforts in the medium-term.

DOE's Sunshot Initiative lies at the incremental end of the spectrum. It seeks technological, financial, and regulatory tweaks to make solar power cost-competitive by 2020 without fundamentally changing the product.[47] "Grand Challenges," with which the Energy Frontier Research Centers are aligned, occupy the other end of the spectrum. They involve fundamental questions about matter, energy, and information that will be answered over a period of decades.[48]

The Quadrennial Energy Review (QER) and the Quadrennial Technology Review (QTR), both of which were established pursuant to the advice of the President's Council of Advisers on Science and Technology, have the potential to set medium-term priorities.[49] The QER, which was run for the first time in 2015, is a government-wide process that yields recommendations for RD&D investments to support energy innovation. The QTR, created in 2011, requires DOE to identify important advanced-energy technology opportunities across energy supply and end use.

These priority-setting processes have helped to orient federal energy-innovation activities and policies, but they could go further by identifying a set of "Technology Missions." Such missions would build on promising next-generation breakthroughs that have emerged from academic and public laboratories, but require policy support and collaboration with the private sector to successfully bring to market. The missions would leverage existing basic and applied-science initiatives, direct new sources of public RD&D funding toward innovation goals, and support private-sector efforts to develop and demonstrate new products and services.

We put forward six proposed Technology Missions for consideration in the remainder of this section. They represent urgent priorities that have the potential to advance very rapidly and would have big payoffs if they did. The Technology Missions are not meant to monopolize federal energy-innovation investment. In particular, it is vital to sustain enabling technologies, such as new materials and supercomputing, and crosscutting priorities, such as grid modernization and the energy-water nexus, that do not fit neatly into Technology Missions. But establishing such missions, whether those on this list or others, would bring much-needed focus to an effort that has lacked it.

Nuclear Power

Nuclear power plants are by far the largest sources of zero-carbon energy in the United States, supplying about 20% of the nation's electricity. That is about three times as much power as hydroelectric sources provide.

But the U.S. nuclear-power industry faces significant challenges. Although new plants are under construction for the first time in decades, several older plants have shut down or are scheduled to do so in the near future. These aging plants are expensive to maintain and run compared with natural-gas plants in a period of very low gas prices and to wind and solar plants that have received capital subsidies and have no fuel costs at all. A significant number of nuclear operators argue that they can no longer cover their costs in current wholesale electricity markets. Moreover, the costs of new plants have not fallen over time and may have even increased, rendering them less competitive.[50]

Generation IV nuclear reactors would have safety, cost, and fuel cycle advantages over the dominant current-generation technology, light-water reactors.

Innovation in nuclear power is needed to address these challenges. Next-generation, or Generation IV, nuclear reactors can play a pivotal role in stabilizing and decarbonizing the power grid by serving as "flexible baseload." These plants would be able to vary their power output to compensate for variable generation from renewable sources, a vital system function provided mainly by natural-gas plants today.[51] Moreover, these reactors would have safety, cost, and fuel-cycle advantages over light-water reactors, the dominant current-generation technology.

The Generation IV International Forum has selected several designs for development and demonstration, each of which has both promising features and technical challenges.[52] Molten-salt thermal reactors appear to strike a good balance between delivery of benefits and feasibility of commercialization—they could be cheaper, more efficient, and much safer than existing reactors. They may also provide a pathway to develop fast reactors, which bring fuel-cycle advantages.[53]

A Nuclear Energy Technology Mission focused on next-generation nuclear reactors should advance gas-cooled and salt-cooled thermal-reactor technology and investigate other technological options, taking into account private-sector activities already underway to commercialize various designs. It should also investigate designs that operate at high enough temperatures to enable hydrogen coproduction, which would supply fuel for uses that cannot be electrified.[54] Finally, it should support efforts to develop small modular reactors, a crucial step toward making private-sector investment in nuclear generation more viable.

Solar Energy

Solar energy is the most abundant renewable energy source on the planet by multiple orders of magnitude. By the second half of the 21st century, it should serve most of the world's energy demand.

Solar photovoltaic (PV) technology is by far the fastest-growing method for harvesting solar energy today. But for solar PV to grow quickly enough to outcompete fossil fuels without subsidies, allowing the United States to meet its stated goal of reducing greenhouse gas emissions by 80 percent by mid-century, the fully installed average cost will need to fall to 25 cents per watt (1–2 cents per kilowatt-hour).[55] This low target is a result of the falling value that solar can deliver to the power grid as its penetration increases. Current-generation silicon PV technology is very unlikely to hit this cost target, even assuming aggressive cost declines as greater production yields learning benefits for manufacturing and deployment.

Innovative new solar technologies have the potential to surpass the performance and functionality of today's PV technology. They may cost less than the 25 cents per watt target well before mid-century and open up new applications, such as building-integrated systems, solar-coated windows, and portable generators. In particular, over the past five years, researchers around the world have discovered that perovskite PV coatings have the potential to be lightweight, flexible, colorful, and more efficient than silicon PV technology, while using earth-abundant materials and cheap printing processes.[56] Other approaches, such as organic and quantum-dot devices, are also promising.

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The Solar Energy Technology Mission should also encompass approaches that can address the roughly 40 percent of primary energy usage that cannot easily be electrified with today's technological options.[57] These uses include aviation, heavy shipping, and heavy trucking, which primarily rely on liquid fuels derived from petroleum. Decarbonizing these uses will likely require clean drop-in replacement fuels. Researchers have made substantial progress harnessing sunlight to split water and generate hydrogen, which can then be combusted to produce heat, power a fuel cell to generate electricity, or serve as an input for synthetic fuels.[58] Like more conventional forms of energy storage, which are discussed below, solar fuels avoid the intermittency of solar PV, even as they provide flexibility in end use.

A Solar Energy Technology Mission should aim to commercialize (a) highly efficient, versatile, and cost-effective solar PV technologies such as perovskite, organic, or quantum-dot devices; and (b) a robust, efficient, safe, and cost-effective solar-fuel generator that uses earth-abundant materials for electrodes to harness sunlight and catalysts to produce hydrogen.

Energy Storage

Energy storage is an increasingly vital function for electricity systems in the 21st century. Variable renewable generation and increasingly flexible demand are already raising the value of storage, and it may rise further as baseload-power generation declines and transportation end uses expand.

Pumped hydroelectric systems dominate large-scale energy storage in the United States at the moment, but no new capacity has been added to the system in the past decade, and there are relatively few suitable sites for future additions. Most new storage capacity has used lithium-ion batteries.[59] This technology is an extraordinary success story, powering the mobile electronics that we have come to rely on as well as today's electric vehicles.

But it also has important limits. Lithium-ion batteries are not optimal for long duration grid-scale services, for instance. They are also heavier than one would like for powering vehicles. Moreover, this family of battery chemistries appears to be approaching its theoretical limits on performance metrics such as energy density.[60]

New materials for battery components, coupled with careful system integration and attention to manufacturability, could yield superior batteries for grid and vehicle applications. Combinations of innovative components such as sulfur cathodes, lithium-metal anodes, solid electrolytes, and ceramic separators could exhibit higher energy density, better safety, longer lifetimes, and faster power discharge.[61] For electric vehicles, such technologies could yield performance and functionality superior to those of existing internal combustion engines. For long-duration grid-scale applications that are currently served by pumped hydro, an alternative architecture, the flow battery, could be ideal if researchers can successfully manufacture it with earth-abundant materials.[62]

Ultimately, there will not be one silver bullet for energy storage; rather, transformative advances in energy storage would make it considerably easier to decarbonize both the electricity and transportation sectors.

Ultimately, there will not be one silver bullet for energy storage. Rather, a range of different batteries should be devised that offer a menu of different attributes from which to select the appropriate solution for energy-storage services in the electricity and transportation sectors. Moreover, batteries are only a subset of energy-storage technologies; alternative approaches such as fast-charging supercapacitors made of advanced materials such as graphene could complement batteries and further broaden the menu.

Transformative advances in energy storage would make it considerably easier to decarbonize both the electricity and transportation sectors. An Energy Storage Technology Mission should produce next-generation storage technologies that improve on various aspects of lithium-ion battery performance as well as drive costs down even further.

Carbon Capture, Utilization, and Storage (CCUS)

Fossil fuels are cheap and abundant. Even if the costs of their health and environmental externalities are fully factored in, it will be important to continue to make use of them. The cost of mitigating climate change could more than double this century if carbon-dioxide emissions from fossil-fuel use are not captured, utilized, and stored.[63] And turning fossil fuels into stranded assets on a monumental scale, as the "keep it in the ground" movement calls for, would surely provoke massive resistance from the countries and communities where they are found.

Current-generation technology for capturing and storing emissions from fossil-fuel power plants is expensive. Researchers have been exploring several methods for capturing carbon dioxide from advanced coal plants, including pre-combustion, post-combustion, and oxy-combustion. To date, none of these technological pathways has emerged as optimal. In fact, the cost of capture may actually have increased over the last decade.[64] DOE forecasts only modest cost decreases of 20 to 30 percent in the near future.[65]

Utilization has the potential to dramatically change these economics if the carbon that is captured can be monetized. Enhanced oil recovery is the only viable use at the moment, but new technologies are emerging that would provide additional options. Near-term opportunities include cement curing and building-material manufacturing. In the longer term, manufacturing of industrial chemicals, plastics, biofuels, and carbon fiber could all use captured carbon dioxide.[66] Although these uses may not account for a very large fraction of carbon emissions, they could provide a vital economic incentive for increased private investment and early adoption of carbon-capture technology.

Carbon storage on a large scale presents a variety of technological and societal challenges. The long-term security of sequestration in specific geological formations must be demonstrated, for example. Once that has been done, an equally secure pipeline system for transporting captured carbon dioxide from power plants and industrial facilities to appropriate formations must be constructed.

Thus, a CCUS Technology Mission should not only focus on upstream capture technologies but also on downstream industrial process technologies that could use carbon dioxide and on systems for transporting and storing it securely. Additionally, the mission should encompass investigation of power-plant designs that promise dramatically lower CCUS costs, such as integrated gasification fuel-cell plants and generators that use supercritical carbon dioxide as a working fluid.[67] As a long-term goal, this mission might extend to processes to harness sunlight to convert carbon dioxide into clean fuels (in partnership with the Solar Energy Technology Mission described above).[68]

A CCUS Technology Mission should not only focus on upstream capture technologies but also on downstream industrial process technologies that could use carbon dioxide and systems for transporting and storing it securely.

Advanced Cooling and Thermal Energy Storage

Energy efficiency complements low-carbon electricity generation and fuel production, reducing emissions and providing economic savings. Even though energy-efficiency opportunities may be more cost-effective than fuel-switching, they are often overlooked in technology assessments.[69] Cooling is a particularly promising end use on which to focus, since more than 90 percent of the world's primary energy generation is either consumed or wasted thermally, and enormous latent demand for this service exists in emerging markets.[70]

Cooling applications consume energy directly through air-conditioning and refrigeration and indirectly through the need to provide heat rejection in power plants, engines, and industrial processes. Rapid growth in global demand for these end uses, particularly air-conditioning and refrigeration in industrializing countries, is adding to the problem. A further complication is that HFCs, the primary refrigerant in use today, have a global warming potential that is thousands of times greater than carbon dioxide.

Although treaty negotiations to phase out HFCs globally were concluded successfully this year, next-generation technological alternatives are needed to execute this agreement.[71] Possible options include HFOs (a related family of chemicals), ammonia, carbon dioxide, hydrocarbons, and non-vapor-compression-based systems, such as magnetic, thermo-elastic and membrane-based technologies, and passive radiant cooling from nanostructured surfaces.[72]

Thermal energy storage allows the heat energy rejected from cooling to be used for valuable purposes such as desalination and water heating. The current lack of robust systems for this function means that an enormous amount of energy is simply lost.[73] Advanced materials and systems that could be used for thermal storage could also improve the efficiency of nuclear, fossil, solar thermal, and geothermal power generation and extend the range of electric vehicles by reducing cooling and heating demand on traction batteries.

An Advanced Cooling and Thermal Energy Storage Technology Mission should focus on developing drop-in alternatives to HFCs, new cooling and refrigeration technologies that do not rely on working fluids, and thermal energy-storage materials.

Smart Energy Management and Connected Vehicles

Cooling is a particularly promising end use on which to focus, since more than 90 percent of the world's primary energy generation is either consumed or wasted thermally, and enormous latent demand exists for this service in emerging markets.

Information technology has revolutionized many sectors of the economy, yet it still has much further to go.[74] Energy management across all the major carbon-emitting sectors is ripe for IT applications. IT can raise the energy efficiency of buildings and industrial facilities and facilitate the use of renewable and storage technologies. The "smart grid" must ultimately interconnect transportation and electric power if the nation is to transition to a low-carbon energy system at a reasonable cost.

Most buildings "use ten times the amount of energy theoretically needed to deliver services," such as lighting and space heating.[75] Many building components, such as windows, appliances, and insulation, contribute to energy waste. IT systems can provide insights into the specific sources of waste and help identify potential solutions. "Smart buildings" can be networked into "smart districts" that optimize energy use collectively.[76]

The expanded application of IT to energy management in buildings and districts will add momentum to the ongoing shift toward decentralized and flexible electricity production and use. Variable wind and solar generation, increasingly diverse storage technologies, and novel demand-response capabilities are placing extraordinary new demands on utilities to balance their systems at multiple levels of aggregation and on multiple time scales. In order to do so, utilities will need the technologies and skills to be able to handle massive amounts of information and act on it in real time.

The transformation of transportation is yet another driver for applying IT to energy management. The transportation sector is currently undergoing three interlinked technology revolutions: the electrification of power trains, the shift to ridesharing and pooling, and the introduction of autonomous driving.[77] The uncontrolled rise of these trends could have harmful effects: Electric vehicle charging could overburden the power grid, and the falling costs of transportation could increase congestion and emissions.[78] But public and private actors, working in close coordination and with the aid of powerful IT tools, could harness these trends for public good. Utilities could compensate electric vehicles for providing storage and other energy services for the grid. And cities could partner with private companies such as Uber to intelligently dispatch, route, and pool connected and autonomous vehicles to reduce wasteful idling and congestion while improving safety.

A Technology Mission for Smart Energy Management and Connected Vehicles should embrace innovations in hardware, software, institutions, and behavior. It should facilitate large-scale demonstration and experimentation to create "smarter and smarter grids" at the district, metropolitan, and regional levels.

FUNDING ENERGY INNOVATION

The Trump administration should work with Congress to increase appropriations for energy RD&D to roughly $13 billion, consistent with the U.S. Mission Innovation pledge.

Institutional reform and priority-setting will make federal energy-innovation investments at current spending levels more productive. Increasing the scale of this investment is nonetheless important, as a wide variety of authoritative reports have argued.[79] The Trump administration should work with Congress to double appropriations for energy RD&D to roughly $13 billion, consistent with the U.S. Mission Innovation pledge.

This funding should support an extended pipeline from basic research through deployment of new technologies, focusing particularly on Technology Missions. Table 1 provides an illustrative breakdown. It allocates roughly two-thirds of RD&D resources to projects related to Technology Missions, including large-scale demonstration projects. The remaining third of funding is divided evenly among other technology applications, enabling technologies, and ARPA-E and other institutions that fund crosscutting priorities.

Table 1: U.S. Federal Energy RD&D - Illustrative Allocation

	$Billions	$Billions	%Total
Technology Missions	4.0		30%
Other Road-Mapped R&D **[1]**	1.5		11%
Off-Road Map R&D **[2]**	1.5		11%
Mission-Related Demonstrations	5.0		37%
Advanced Nuclear		*2.0*	
CCUS		*2.0*	
Other		*1.0*	
Other Enabling Technology	1.5		11%
Total	13.5		

[1] *Including geo geothermal, building technologies, offshore wind, power electronics, fuel cells, hydro-tidal, etc.*

[2] *"Off-road map" here refers to technologies and tech development pathways beyond DOE's multi-year program plans, including opportunistic, high-risk/high-reward initiatives such as ARPA-E's programs.*

Although expanded federal funding for energy innovation, especially in tandem with institutional reforms that improve the return on public investment, should be a bipartisan priority capable of securing congressional support, annual appropriations have proven to be unstable in the past. Innovation is best supported with steady public investments that provide confidence to entrepreneurs, researchers, and established firms that their own investments will yield results. A source of federal revenue that is dedicated to energy-innovation funding would provide this much-needed stability. Below we lay out several potential revenue streams, ordered in descending magnitude, that are worthy of further exploration.[80]

Innovation is best supported with steady public investments that provide confidence to entrepreneurs, researchers, and established firms that their own investments will yield results. A source of federal revenue that is dedicated to energy-innovation funding would provide this much-needed stability.

1. Carbon tax

A carbon tax has been widely recognized on both sides of the aisle and by key energy-industry players such as ExxonMobil as a prudent and efficient mechanism to account for the externalities of greenhouse gases.[81] A small carbon tax would be sufficient to fully fund expanded energy-innovation efforts. For example, a $5.00 per ton of carbon-dioxide tax on the U.S. electric power sector would raise approximately $9.4 billion annually. A tax of $7.00 per ton would raise $13.0 billion annually, enough to fully fund a doubled federal energy RD&D budget.

2. Electricity wires fee

Congress could enact a small, nationwide surcharge on U.S. electricity sales that pass through the electrical power grid, known as a "wires fee." A wires fee of just $0.001 (one tenth of a cent) per kilowatt-hour on U.S. electricity generation available to the grid would generate approximately $4 billion annually.

3. Proceeds from sale of petroleum reserves

The U.S. Strategic Petroleum Reserve (SPR) holds a vast store of value that could be unlocked through the creation of a public-private partnership to operate the SPR, which would generate a one-time windfall to fund energy innovation. Congress could require oil companies to purchase the oil in the SPR and hold it in reserve, as other countries do, for use in emergencies to counteract a shock to the oil market. Given oil prices of approximately $50 per barrel, this strategy could raise over three-quarters of the additional funding required to meet the U.S. Mission Innovation commitment over the next five years.[82]

4. Oil and gas extraction royalties

By harmonizing the rate at which the federal government charges onshore and offshore oil and gas production, the Trump administration could raise substantial funding to support energy innovation. According to the Department of the Interior, total federal revenue from oil and gas extraction on federal lands in 2013 was $10.9 billion (onshore and offshore), dominated by the roughly $7.5 billion coming from production in the Gulf of Mexico, where the royalty rate is 18.75 percent.[83] By contrast, the federal government charges a royalty of just 12.5 percent for oil and gas extraction from onshore public lands, a rate that has not been updated since 1920.[84] Over $1 billion could be raised annually for federal energy-innovation investments by harmonizing these rates. Raising the federal royalty rate is an executive action that does not require congressional approval. Current law states that the rate should be "not less than" 12.5 percent, but it does not set an upper limit.

5. Fossil-fuel export fee

Congress could levy a small fee on U.S. fossil fuels that would apply only to exports. This fee would neither raise prices for American consumers nor materially impact the viability of U.S. exports.[85] An export fee of $1 per short ton of coal, $1 per barrel of crude oil, and $0.10 per thousand cubic feet of liquefied natural gas (LNG) would have raised approximately $250 million in 2015. With the projected growth in LNG exports, the LNG fee alone could raise $250 million by 2020.

CONCLUSION

President-elect Trump has an opportunity to make good on his campaign promises to create well-paid advanced-manufacturing jobs, protect the environment, embrace a diverse energy mix that includes fossil fuels, and boost the flagging U.S. trade balance. Seizing that opportunity, in cooperation with the 115th Congress, will require investing in energy innovation, a priority that both sides of the aisle can get behind. But the obstacles to bringing advanced-energy technologies to market are formidable. Institutional reforms are sorely needed that focus federal energy-innovation institutions such as DOE on technology commercialization and on supporting innovation through all stages of the extended innovation pipeline. By organizing the energy-innovation effort around overarching Technology Missions, the administration and Congress will be able to demonstrate to taxpayers a superior rate of return on the public's investment. Dedicated and expanded federal funding will help to induce private investment, so that the United States not only has clean, affordable, reliable, and safe energy for its own needs, but also becomes a much more effective player in the burgeoning global advanced-energy market. To be sure, this agenda is a substantial undertaking, but the prize is easily worth the effort.

ENDNOTES

1. Bloomberg New Energy Finance, "Clean Energy Defies Fossil Fuel Price Crash to Attract Record $329BN Global Investment in 2015," news release, January 14, 2016, https://about.bnef.com/press-releases/clean-energy-defies-fossil-fuel-price-crash-to-attract-record-329bn-global-investment-in-2015/.
2. Ben Miller and Robert D. Atkinson, "Rising Tigers, Sleeping Giant II" (Information Technology and Innovation Foundation, July 27, 2015), https://itif.org/publications/2015/07/27/rising-tigers-sleeping-giant-ii.
3. Board on Science, Technology, and Economic Policy, Committee on Comparative National Innovation Policies, National Research Council, *Rising to the Challenge: U.S. Innovation Policy for the Global Economy* (Washington, DC: National Academies Press, 2012), 89.
4. John F. Sargent et al., "Federal Research and Development Funding: FY 2017" (Washington, DC: Congressional Research Service, June 24, 2016), https://www.fas.org/sgp/crs/misc/R44516.pdf.
5. American Energy Innovation Council, "Restoring American Energy Innovation Leadership: Report Card, Challenges, and Opportunities" (Bipartisan Policy Center, February 2015), http://americanenergyinnovation.org/wp-content/uploads/2015/02/AEIC-Restoring-American-Energy-Innovation-Leadership-2015.pdf.
6. Joseph Byrne et al., *Global Trends in Renewable Energy Investment 2016* (Frankfurt School-UNEP Centre and Bloomberg New Energy Finance, 2016), http://fs-unep-centre.org/sites/default/files/publications/globaltrendsinrenewableenergyinvestment2016lowres_0.pdf.
7. Richard Martin, "Fail-Safe Nuclear Power," *Technology Review*, August 2, 2016, https://www.technologyreview.com/s/602051/fail-safe-nuclear-power/; Naomi Mapstone, "China's Interest in Carbon Capture and Storage Scheme Grows," *Financial Times*, April 19, 2015, https://www.ft.com/content/da9a6dd6-d927-11e4-b907-00144feab7de.
8. Varun Sivaram and Teryn Norris, "The Clean Energy Revolution: Fighting Climate Change With Innovation," *Foreign Affairs*, March/April 2016.
9. Rebecca M. Henderson and Richard G. Newell, eds., *Accelerating Energy Innovation: Insights from Multiple Sectors* (Chicago and London: The University of Chicago Press, 2011).
10. "Mission Innovation: Accelerating the Clean Energy Revolution," accessed December 9, 2016, http://mission-innovation.net/.
11. Office of Management and Budget, "Advancing Clean Energy Domestically and Abroad and Taking Action on Climate Change" (The White House, February 2017), https://www.whitehouse.gov/sites/default/files/omb/budget/fy2017/assets/fact_sheets/Advancing%20Clean%20Energy%20Domestically%20and%20Abroad%20and%20Taking%20Action%20on%20Climate%20Change.pdf.
12. Abdullah Hasan, "FACT SHEET: Advancing Clean Energy Research and Development in the President's FY 2017 Budget" *The White House Blog*, October 13, 2016, https://www.whitehouse.gov/blog/2016/10/12/factsheet-advancing-clean-energy-research-and-development-presidents-fy-2017-budget.
13. Daniel Sarewitz, "Saving Science," *The New Atlantis 49* (Spring/Summer 2016): 4–40, http://www.thenewatlantis.com/docLib/20160816_TNA49Sarewitz.pdf.
14. National Institutes of Health, "About NIH: What We Do: Budget," last modified April 4, 2016, https://www.nih.gov/about-nih/what-we-do/budget.
15. Ferric C. Fang and Arturo Casadevall, "Lost in Translation—Basic Science in the Era of Translational Research," *Infection and Immunity 78*, no. 2 (February 2010): 563–566, http://iai.asm.org/content/78/2/563.full.

16. Iain M. Cockburn and Scott Stern, "Finding the Endless Frontier: Lessons From the Life Sciences Innovation System for Technology Policy," *Capitalism and Society 5*, no. 1 (2010): 1–6, https://papers.ssrn.com/sol3/papers.cfm?abstract_id=2208693.

17. Office of Science, "Energy Frontier Research Centers," U.S. Department of Energy, August 31, 2015, http://science.energy.gov/bes/efrc/centers/.

18. National Science Foundation (NSF), *FY 2016 Budget Request to Congress* (Arlington, VA: NSF, February 2, 2015), https://www.nsf.gov/about/budget/fy2016/.

19. Mike Orcutt, "Why ARPA-E Needs to Grow Up," *MIT Technology Review*, March 1, 2016 https://www.technologyreview.com/s/600896/why-arpa-e-needs-to-grow-up/.

20. National Economic Council, "Revitalizing American Manufacturing" (Washington, DC: The White House, October 2016), https://www.whitehouse.gov/sites/whitehouse.gov/files/images/NEC_Manufacturing_Report_October_2016.pdf.

21. Matthew Stepp et al. "Turning the Page: Reimagining the National Labs in the 21st Century Innovation Economy" (Information Technology and Innovation Foundation, Center for American Progress, and Heritage Foundation, June 20, 2013), http://www2.itif.org/2013-turning-page-national-lab-innovation-economy.pdf.

22. Pierre Azoulay, Joshua S. Graff Zivin, and Gustavo Manso, "Incentives and Creativity: Evidence From the Academic Life Sciences," *RAND Journal of Economics 42*, no. 3 (September 2011): 527–554, http://pazoulay.scripts.mit.edu/docs/hhmi.pdf.

23. Office of Chief Financial Officer, *Department of Energy FY 2017 Congressional Budget Request: Laboratory Tables Preliminary* (Washington, DC: U.S. Department of Energy, February 2017), http://energy.gov/sites/prod/files/2016/02/f29/FY2017BudgetLaboratoryTable_0.pdf.

24. Ali Zaidi and Lynn Orr, "Advancing the Frontiers of Clean Energy Innovation" *The White House Blog*, October 13, 2016, https://www.whitehouse.gov/blog/2016/10/12/advancing-frontiers-clean-energy-innovation; U.S. Department of Energy, "Technology Transfer Execution Plan, 2016–2018" (Washington, DC: U.S. Department of Energy, October 2016), http://energy.gov/sites/prod/files/2016/10/f33/TTEP%20Final.pdf.

25. Richard K. Lester and David M. Hart, *Unlocking Energy Innovation: How America Can Build a Low-Cost, Low-Carbon Energy System* (Cambridge MA: MIT Press, 2012).

26. Mark Muro and Bruce Katz, "The New 'Cluster Moment': How Regional Innovation Clusters Can Foster the Next Economy" (Brookings Institution, September 2010), https://www.brookings.edu/wp-content/uploads/2016/06/0921_clusters_muro_katz.pdf.

27. U.S. Department of Energy, "Small Business Vouchers Pilot," accessed December 9, 2016, https://www.sbv.org/.

28. TJ Glauthier, Jarod L. Cohen, et al., "Securing America's Future: Realizing the Potential of the DOE National Laboratories: Final Report of the Commission to Review the Effectiveness of the National Energy Laboratories" (Washington, DC: Department of Energy, September 4, 2015), http://energy.gov/sites/prod/files/2015/09/f26/DOE%20Lab%20Commission%20draft%20Final%20Report%20Volume%201.pdf.

29. Stepp et al., "Turning the Page"; Laura Diaz Anadon et al., "How to Fix the National Laboratories," *National Interest*, October 25, 2016, http://nationalinterest.org/feature/how-fix-the-national-laboratories-18181.

30. Budgets are expressed in nominal dollars in bold and as a percentage of total spending on national laboratories in parentheses below. U.S. Department of Energy, LDRD reports to Congress, various years, accessed December 9, 2016, http://www.energy.gov/cfo/reports/laboratory-directed-research-and-development-annual-reports .

31. Benjamin Gaddy, Varun Sivaram, Francis O'Sullivan, "Venture Capital and Cleantech: The Wrong Model for Clean Energy Innovation" (working paper, MIT Energy Initiative, Cambridge, MA, July 2016), https://energy.mit.edu/wp-content/uploads/2016/07/MITEI-WP-2016-06.pdf.
32. Sabrina T. Howell, "Financing Constraints as Barriers to Innovation: Evidence From R&D Grants to Energy Startups" (working paper, Harvard University, Cambridge MA, May 5, 2015), http://scholar.harvard.edu/showell/home.
33. Stephen Ezell and Scott Andes, "Localizing the Economic Impact of Research and Development: A Primer for the Trump Administration and Congress" (Information Technology and Innovation Foundation and Brookings Institution, December 2016).
34. "U.S. Department of Energy's Clean Energy Investment Center," U.S. Department of Energy, accessed December 9, 2016, http://energy.gov/technologytransitions/us-department-energys-clean-energy-investment-center.
35. American Energy Innovation Council, "Restoring American Energy Innovation Leadership"; "U.S. Cleantech and Investment Insights" (PriceWaterhouseCoopers, 2015), https://www.pwc.com/us/en/technology/publications/assets/pwc-us-cleantech-investments-and-insights-q4-2015.pdf.
36. National Academies of Sciences, Engineering, and Medicine, *The Power of Change: Innovation for Development and Deployment of Increasingly Clean Electric Power Technologies* (Washington, DC: The National Academies Press, 2016).
37. Sarah Kearney, Alicia Seiger, and Peter Berliner, "Impact Investing in the Energy Sector: How Federal Action Can Galvanize Private Support for Energy Innovation and Deployment" (PRIME Coalition, MIT Sloan School of Management, Steyer-Taylor Center for Energy Policy and Finance, and Mission Investors Exchange, October 2016), http://law.stanford.edu/wp-content/uploads/sites/default/files/publication/753322/doc/slspublic/Impact_Investing_in_Energy.pdf.
38. John M. Deutch, "An Energy Technology Corporation Will Improve the Federal Government's Efforts to Accelerate Energy Innovation" (The Hamilton Project, May 2011), http://www.hamiltonproject.org/assets/legacy/files/downloads_and_links/05_energy_corporation_deutch_paper_1.pdf.
39. Richard K. Lester and David M. Hart, "Closing the Energy-Demonstration Gap," *Issues in Science and Technology 31*, no. 2 (Winter 2015), http://issues.org/31-2/closing-the-energy-demonstration-gap-2/.
40. National Aeronautics and Space Administration (NASA) and Space Exploration Technologies Corporation (SpaceX), "Space Act Agreement Between National Aeronautics and Space Administration and Space Exploration Technologies Corp. for Commercial Orbital Transportation Services Demonstration (COTS)" (Washington, DC: NASA, Summer 2006), https://www.nasa.gov/centers/johnson/pdf/189228main_setc_nnj06ta26a.pdf.
41. "NRG COSIA Carbon Xprize," XPRIZE Foundation, accessed December 9, 2016, http://carbon.xprize.org/.
42. Arun Majumdar et al., "Energy Innovation Needs New Private-Sector Push," *Bloomberg View*, February 11, 2016, https://www.bloomberg.com/view/articles/2016-02-11/energy-innovation-needs-new-private-sector-push.
43. David C. Mowery, "Federal Policy and the Development of Semiconductors, Computer Hardware, and Computer Software: A Policy Model for Climate Change R&D?" in *Accelerating Energy Innovation: Insights from Multiple Sectors*, edited by Rebecca M. Henderson and Richard G. Newell (Chicago: University of Chicago Press, 2011), 15–17.
44. Varun Sivaram, "Pairing Push and Pull Policies: A Heavy-Duty Model for Innovation," *Council on Foreign Relations*, September 27, 2016, http://blogs.cfr.org/sivaram/2016/09/27/pairing-push-and-pull-policies-a-heavy-duty-model-for-innovation/.

45 Mowery, “Development of Semiconductors, Computer Hardware, and Software.”

46. “About ESTCP,” Strategic Environmental Research and Development Program (SERDP) and Environmental Security Technology Certification Program (ESTCP), accessed December 9, 2016, https://www.serdp-estcp.org/About-SERDP-and-ESTCP/About-ESTCP; Secretary of Energy Advisory Board, Task Force on Federal Energy Management, “Final Report,” September 14, 2016, accessed December 9, 2016, http://energy.gov/seab/downloads/draft-report-task-force-federal-energy-management.

47. National Renewable Energy Laboratory, *SunShot Vision Study* (Washington, DC: U.S. Department of Energy, February 2012), http://www.nrel.gov/docs/fy12osti/47927.pdf.

48. Office of Science, “Research: Grand Challenges” (Washington, DC: U.S. Department of Energy, September 29, 2016), http://science.energy.gov/bes/efrc/research/grand-challenges/.

49. President’s Council of Advisors on Science and Technology (PCAST), “Report to the President on Accelerating the Pace of Change in Energy Technologies Through an Integrated Federal Energy Policy” (Washington, DC: Executive Office of the President, November 29, 2010), https://www.whitehouse.gov/sites/default/files/microsites/ostp/pcast-energy-tech-report.pdf.

50. Nathan E. Hultman et al. “What History Can Teach Us About the Future Costs of U.S. Nuclear Power,” *Environmental Science & Technology* (April 1, 2007): 2088–2093.

51. Fernando J. de Sisternes et al., “The Value of Energy Storage in Decarbonizing the Electricity Sector,” *Applied Energy 175* (2016): 368–379.

52. John E. Kelly, “Generation IV International Forum: A Decade of Progress Through International Cooperation,” *Progress in Nuclear Energy 77* (November 2014): 240–246.

53. Ted Nordhaus, Jessica Lovering, and Michael Shellenberger, “How to Make Nuclear Cheap: Safety, Readiness, Modularity, and Efficiency” (Breakthrough Institute, June 2014), http://thebreakthrough.org/images/pdfs/Breakthrough_Institute_How_to_Make_Nuclear_Cheap.pdf.

54. Giorgio Locatelli, Mauro Mancini, and Nicola Todeschini, “Generation IV Nuclear Reactors: Current Status and Future Prospects,” *Energy Policy 61* (2013): 1503–1520.

55. Varun Sivaram and Shayle Kann, “Solar Power Needs a More Ambitious Cost Target,” *Nature Energy 1* (2016).

56. Varun Sivaram et al., “Perovskite Solar Cells Could Beat the Efficiency of Silicon,” *Scientific American*, July 2015, https://www.scientificamerican.com/article/perovskite-solar-cells-could-beat-the-efficiency-of-silicon/.

57. Nathan S. Lewis and George Crabtree*, Basic Research Needs for Solar Energy Utilization: Report of the Basic Energy Sciences Workshop of Solar Energy Utilization* (Washington, DC: Office of Basic Energy Science, U.S. Department of Energy, April 21–25, 2005), http://science.energy.gov/~/media/bes/pdf/reports/files/Basic_Research_Needs_for_Solar_Energy_Utilization_rpt.pdf.

58. National Energy Technology Laboratory, “Liquid Fuels: Fisher-Tropsch Synthesis” (Washington, DC: U.S. Department of Energy), http://www.netl.doe.gov/research/coal/energy-systems/gasification/gasifipedia/ftsynthesis; Nathan S. Lewis, “Research Opportunities to Advance Solar Energy Utilization,” *Science 351*, no. 6271 (January 2016), http://science.sciencemag.org/content/351/6271/aad1920; Matthew R. Shaner et al., “A Comparative Techno-Economic Analysis of Renewable Hydrogen Production Using Solar Energy,” *Energy and Environmental Science 9* (2016): 2354–2371.

59. David M. Hart and Alfred Sarkissian, “Deployment of Grid-Scale Batteries in the United States” (unpublished case study prepared for DOE Office of Energy Policy and Strategic Analysis, Washington, D.C., September 19, 2016), http://davidhart.gmu.edu/wp-content/uploads/2016/11/Grid-Scale-Batteries-GMU-case-study-final-9-19-16.pdf.

60. Jürgen Janek and Wolfgang G. Zeier, “A Solid Future for Battery Development,” *Nature Energy* (September 8, 2016), http://www.nature.com/articles/nenergy2016141.

61. Mukul D. Tikekar et al., “Design Principles for Electrolytes and Interfaces for Stable Lithium-Metal Batteries,” *Nature Energy* (2016), http://www.nature.com/articles/nenergy2016114; Quan Pang et al., “Advances in Lithium-Sulfur Batteries Based on Multifunctional Cathodes and Electrolytes,” *Nature Energy* 1 (2016), http://www.nature.com/articles/nenergy2016132; Yong-Sheng Hu, “Batteries: Getting Solid,” *Nature Energy* (2016), http://www.nature.com/articles/nenergy201642; Hun Lee et al., “A Review of Recent Developments in Membrane Separators for Rechargeable Lithium-Ion Batteries,” *Energy and Environmental Science 7* (2014): 3857–3886.

62. Wei Wang and Vince Sprenkle, “Energy Storage: Redox Flow Batteries Go Organic,” *Nature Chemistry 8* (2016): 204–206.; Tobias Janoschka et al., “An Aqueous, Polymer-Based Redox-Flow Battery Using Non-Corrosive, Safe, and Low-Cost Materials,” *Nature 527* (2015): 78–81.

63. Intergovernmental Panel on Climate Change, “Climate Change 2014 Synthesis Report: Summary for Policymakers” (2014), https://www.ipcc.ch/pdf/assessment-report/ar5/syr/AR5_SYR_FINAL_SPM.pdf .

64. Edward S. Rubin, John E. Davidson, and Howard J. Herzog, “The Cost of CO2 Capture and Storage,” *International Journal of Greenhouse Gas Control 40* (2015): 378–400.

65. Kristin Gerdes et al., “Current and Future Power Generation Technologies: Pathways to Reducing the Cost of Carbon Capture for Coal-Fueled Power Plants,” *Energy Procedia 63* (2014): 7541–7557.

66. XiaoZhi Lim, “How to Make the Most of Carbon Dioxide,” *Nature*, October 28, 2015 http://www.nature.com/news/how-to-make-the-most-of-carbon-dioxide-1.18653; The Global CO_2 Initiative and CO_2 Sciences, “A Roadmap for the Global Implementation of Carbon Utilization Technologies” (November 2016), https://www.globalco2initiative.org/documents/CBPI_Roadmap_Executive_Summary_Nov_2016_web.pdf.

67. Energy Sector Planning and Analysis for SEAP and OPPB, *Techno-Economic Analysis of Integrated Gasification Fuel Cell Systems* (Office of Fossil Energy, National Energy Technology Laboratory, U.S. Department of Energy, November 24, 2014), https://www.netl.doe.gov/energy-analyses/temp/FY15_Techno-EconomicAnalysisofIntegratedGasificationFuelCellSystems_112015.pdf; Yoonhan Ahn et al., “Review of Supercritical CO_2 Power Cycle Technology and Current Status of Research and Development,” *Nuclear Engineer and Technology 47*, no. 6 (October 2015): 647–661.

68. Chong Liu et al., “Water Splitting-Biosynthetic System With CO2 Reduction Efficiencies Exceeding Photosynthesis,” *Science 352* (2016): 1210–1213.

69. Charlie Wilson et al., “Marginalization of End-Use Technologies in Energy Innovation for Climate Protection,” *Nature Climate Change 2* (November 2012): 780–788.

70. Ilan Gur et al., “Searching for a Better Thermal Battery,” *Science 335* (2012): 1454–1455.

71. Stephen Seidel et al., “Not-in-Kind Alternatives to High Global Warming HFCs” (Center for Climate and Energy Solutions, October 7, 2016), http://www.c2es.org/publications/not-kind-alternatives-high-global-warming-hfcs.

72. W. Goetzler et al., “Research & Development Roadmap for Next-Generation Low Global Warming Potential Refrigerants” (Building Technologies Office, Office of Energy Efficiency and Renewable Energy, U.S. Department of Energy, November 2014), http://energy.gov/sites/prod/files/2014/12/f19/Refrigerants%20Roadmap%20Final%20Report%202014.pdf.; William Goetzler et al., “Energy Savings Potential and RD&D Opportunities for Non-Vapor-Compression HVAC Technologies” (Building Technologies Office, Office of Energy Efficiency and Renewable Energy, U.S. Department of Energy, March 2014), http://energy.gov/sites/prod/files/2014/03/f12/Non-Vapor%20Compression%20HVAC%20Report.pdf.; Aaswath P. Raman et al., “Passive Radiative Cooling Below Ambient Air Temperature Under Direct Sunlight,” *Nature 515* (2014): 540–544.

73. Gur et al., "Searching for a Better Thermal Battery."

74. Luke A. Stewart and Robert D. Atkinson, "Looking for Jobs? Look to IT in 2012 and Beyond" (Information Technology and Innovation Foundation, August 2012), http://www2.itif.org/2012-jobs-it.pdf.

75. Henry Kelly, "The Potential of More Efficient Buildings," *Issues in Science and Technology* (Summer 2016): 21.

76. President's Council of Advisors on Science and Technology, "Technology and the Future of Cities" (Washington, DC: Executive Office of the President, March 2016), https://www.whitehouse.gov/sites/default/files/microsites/ostp/PCAST/pcast_cities_report___final_3_2016.pdf.

77. Levi Tillemann and Colin McCormick, "Get Ready for the World of Driverless, Electric, Shared Cars," *Slate*, June 2016, http://www.slate.com/articles/technology/future_tense/2016/06/driverless_electric_shared_cars_will_revolutionize_our_transportation_system.html; Laura Vimmerstedt et al., *Transformative Reduction of Transportation Greenhouse Gas Emissions: Opportunities for Change in Technologies and Systems* (Golden, CO: National Renewable Energy Laboratory, April 2015), http://www.nrel.gov/docs/fy15osti/62943.pdf.

78. Zia Wadud, Don MacKenzie, and Paul Leiby, "Help or Hindrance? The Travel, Energy and Carbon Impacts of Highly Automated Vehicles," *Transportation Research Part A: Policy and Practice 86* (April 2016): 1–18.

79. See, for example, American Energy Innovation Council, "A Business Plan for America's Energy Future" (Bipartisan Policy Center, June 2010), http://cdn.bipartisanpolicy.org/wp-content/uploads/sites/default/files/AEIC_REPORT_Final.pdf; PCAST, "Accelerating."

80. Data for these revenue streams were collected from databases hosted by the Energy Information Administration and the International Energy Agency, unless otherwise cited.

81. Ken Cohen, "ExxonMobil and the Carbon Tax," *Energy Factor by ExxonMobil*, December 12, 2015, https://energyfactor.exxonmobil.com/corporate-citizenship-sustainability/exxonmobil-and-the-carbon-tax/.

82. Heather L. Ross, "Turning Rainy Day Oil Into Clean Energy Gold: Funding Mission Innovation With a Strengthened Strategic Petroleum Reserve" (discussion paper, Resources for the Future, April 2016), http://www.rff.org/files/document/file/RFF-DP-16-14.pdf.

83. United States Extractive Industries Transparency Initiative, Revenue (explore data, revenue; accessed December 9, 2016), https://useiti.doi.gov/explore.

84. Center for Western Priorities, "A Fair Share: The Case for Updating Oil and Gas Royalties on Our Public Lands" (Center for Western Priorities, June 18, 2015), http://www.westernpriorities.org/wp-content/uploads/2015/06/Royalties-Report_update.pdf.

85. For a more detailed proposal, see Melissa Carey and Josh Freed, "How a Fee on Fossil Exports Can Make the U.S. a Clean Energy Super Power" (Third Way, March 11, 2014), http://www.thirdway.org/memo/how-a-fee-on-fossil-exports-can-make-the-us-a-clean-energy-superpower.

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