Fiscal Year 2019 Energy Innovation Investment Priorities for the U.S. Department of Energy

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The U.S. Department of Energy (DOE) is the largest funder of clean energy innovation in the United States. Each spring, DOE proposes new investments for the following fiscal year as part of the President's Budget Request to Congress. The request includes funding levels for individual offices within DOE along with an in-depth catalogue of specific R&D projects DOE hopes to carry out.

Annually, the world's foremost energy experts and the latest scientific ideas flowing from industry, academia, and DOE's national laboratories inform the ideas in the budget. In essence, until recently, the President's Budget Request for DOE has represented a yearly compendium of which of the nation's clean energy research needs the Federal government intends to address.

Given the rapid transformation occurring in global energy system there is no shortage of research ideas competing for funding. That is why, over the past several years, the prior Administration submitted a list of funding needs that is greater than what Congress was eventually able to appropriate funds for.

But what happens when an Administration proposes deep cuts to energy innovation, even as U.S. economic competitiveness is at stake? Where do the Federal research ideas necessary to sustain U.S. leadership in innovating for the global clean energy future get documented?

To fill that gap, this paper identifies pressing energy innovation research challenges for DOE's Applied Energy programs that could be funded in Fiscal Year (FY) 2019. While we believe that energy innovation funding can and should double over the next several years, the ideas discussed here can be funded with no overall growth from the most recently completed fiscal year (2017).[1]

That said, funding levels for individual efforts are not identified in this document. That is because this document is not a substitute for Presidential Budget Request. No one can develop that except the Administration, and we appeal to them to prepare a robust budget in future years.

We hope that this document represents a conversation starter for those who want to explore how DOE can reasonably and responsibly invest taxpayer funds in order to deepen the United States' longstanding commitment to economic growth through technological innovation.

[1]We would be remiss not to include our strong support for the DOE Office of Science, ARPA-E, the Loan Programs Office, the Office of Technology Transitions, the Policy Office, and International Affairs. These offices are further discussed in Appendix A and we strongly believe these offices should, at minimum, be funded at the FY 2017 level, and preferably, start on a trajectory for significant increases over the next several years.

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Solar Energy R&D

State of the Industry

The rapid growth in solar power in recent years, fueled by ever better technology and significant cost reductions, has settled the debate – solar energy can deliver stable, low cost, domestically produced power in all corners of the country. Over the last decade, the amount of solar power has increased from 0.3 gigawatts (GW) of installed capacity in 2008 to 49 GW by the third quarter of 2017 – enough to power more than 9.5 million average American homes, and representing more than 1.8% of the nation's electric supply. In 2016, solar power ranked as the largest source of new capacity additions (39%) to the electric grid, and employed more than 260,000 Americans in research, manufacturing, installation, and sales. In September 2017, DOE announced that the Nation has met our 2020 utility-scale solar goal of 6 cents per kilowatt-hour (kWh), making it the lowest cost electricity in areas with good solar resources.

The Role of Government and Key Investments Needed

In 2016, DOE's National Laboratories published *On the Path to SunShot* – a series of reports that examines future challenges and opportunities for the solar industry. The reports highlight the key roles DOE-sponsored research has played in achieving cost reduction goals to date. On the Path to SunShot also identifies the next R&D opportunities needed to help cut solar energy costs in half by 2030 and increase solar penetration levels on the grid to 25%. DOE investments in both early stage R&D as well as field validation of new technologies have supported rapid scaling and integration of widespread and increasing penetrations of solar technologies. FY19 budget plans should support the development of a 3-year national laboratory call for proposals.

Key DOE Activity Highlights & Contributions

Photovoltaics (PV)

- R&D on solar PV cell technologies that improve efficiency, lifetime and reliability, lower manufacturing costs, and drive down the cost of solar electricity.

  FY 19 Investment Priorities: Breakthrough, new or improved high performance cell materials and architectures (including perovskites) to achieve >40% efficiencies and module packaging materials (including backsheets, conducting elements and encapsulants); advanced low-cost manufacturing process technologies including thickness reduction, faster processing with fewer steps, especially in collaboration with innovative approaches for accelerating commercialization, while reducing administrative burden; Improved PV module and system-level performance prediction and degradation science for existing and new cell and module technologies; Improvements in long term optimized energy delivery; Updated performance codes and standards that streamline deployment while improving safety and security.

Grid Integration

- Research on the technical challenges associated with increased solar penetration on the grid, including grid reliability, dispatchability, power electronics and communications.

  FY 19 Investment Priorities: Development and demonstration of multi-technology Distributed Energy Resources (DER) integration and coordination of solar "plus": storage, buildings technologies, controllable loads (including EVs), and demand response in collaboration with the Office of Electricity, the Building Technologies Office and the Vehicle Technologies Office (Include high resolution time and location-based value analysis and techno-economic model development); Development of load shifting and shaping technologies, architectures and coordination mechanisms at distribution and transmission level (e.g. peak load reduction); Longer lifetime, high functionality power electronics (including wide bandgap, high temperatur and high voltage materials); DER enablers such as DC, hybrid AC/DC systems, sensors and components; Demonstrations of resilient, flexible systems and protections capable of being interconnected with the grid and/or operated as an energy island; New and expanded user groups for grid data collection and aggregation, advanced analytic method development (including machine learning and artificial intelligence(AI)), and creating interoperability of communication and control standards; Advanced distributed grid modeling, computation, planning tools and analysis, including valuation.

Soft Costs

- Efforts to reduce the non-hardware costs of solar and remove market barriers to solar adoption. Soft costs can account for up to two-thirds of the total cost of a new solar system.

  FY 19 Investment Priorities: Data standards for collecting, aggregating, and sharing grid and solar data; New techno-economic analysis tools and methodologies for DERs; Market and regulatory analysis targeting planning, valuation, and rate design for distribution and transmission coordination of distributed assets (including tools for state and local agencies); Assessment of block-chain technology opportunities; Analytical and institutional support to expand solar access to low and moderate income consumers, new market segments (municipal, community, and shared solar) and multi-technology integration opportunities (e.g. joint infrastructure planning) through Solar Energy Innovators Network and Grid Modernization Lab Call projects.

Technology to Market (T2M)

- Support for innovative commercial manufacturing technologies for solar components.

  FY 19 Investment Priorities: Use of prize authority to build on Catalyst and "innovative

pathways" projects to scale rapid/open innovation programs that utilize crowdsourcing combined with joint business, financing and technology development mechanisms; Development and scaling of advanced silicon manufacturing technologies like epitaxial and direct wafer production that can reduce capital expenditure and eliminate process steps (in collaboration with PV program).

Concentrating Solar Power (CSP)

- R&D on CSP technologies that improve efficiency and reliability, lower manufacturing costs, and drive down the cost of solar electricity.

  FY 19 Investment Priorities: Concepts beyond Gen3 CSP systems; Increased CSP system operating temperature and efficiency, including advanced power cycles (e.g. supercritical CO2) and advanced materials; Advanced collectors and operations that reduce losses (through improved trackers etc.); New CSP thermal systems and components including heat transfer media and materials compatible with those media; R&D on new CSP applications including peaker plant applications, process heat, thermochemical systems, and advanced storage technologies.

Wind Power R&D

State of the Industry

The U.S. has abundant land-based and offshore wind resources across the Nation, and wind power has confirmed its credibility as a scalable, reliable, and environmentally sound domestic energy technology. Over the last decade, wind has rapidly become a mainstream power source in the U.S. electricity portfolio, with 89 gigawatts (GW) of installed capacity across 41 states as of December 2017, supplying 6.1% of the Nation's electricity end-use demand in 2016, and representing 30% of all newly installed U.S. generation capacity from 2012-2016. Strong market demand, coupled with the increasing size of wind turbine components, has spurred the growth of a robust domestic manufacturing sector. The U.S. wind industry supports over 100,000 U.S. jobs in installation, manufacturing, and operations, with more than 500 U.S. wind-manufacturing facilities in 41 states.

The Role of Government & Key Investments Needed

In collaboration with the wind industry, DOE published the *WindVision* report in 2016. The report showed the feasibility, viability and cumulative benefits of wind providing up to 35% of the U.S. electricity by 2050, with interim goals of 10% by 2020 and 20% by 2030. The report created a roadmap identifying the key activities and innovations, by stakeholder type, needed to maximize a robust future for the wind industry and a path for unsubsidized cost competitiveness.

Today, land-based wind, in high wind resource areas with access to transmission capacity, is cost competitive with other electricity generation technologies. DOE's Wind Energy Program activities therefore target innovations applicable to the remaining balance of land, offshore, and distributed wind opportunities to expand the geographic potential for directly cost-competitive wind power (without subsidy) to complement traditional electricity sources and enable a diverse energy portfolio across the Nation. Core challenges for wind power include improvement to wind turbine design, reliability, wind plant optimization, cost reduction, and grid integration.

Key DOE Activity Highlights & Contributions

System Optimization: Atmosphere to electrons (A2e)

- Improve the performance, reliability, and economics of next-generation "smart wind" plants by investigating systems-level interactions influenced by atmospheric conditions, variable terrain, and machine-to-machine wake interactions. Strong leverage of DOE high performance computing (HPC) assets.

  Recent Accomplishments: Commissioning of the turbine-to-turbine (SWiFT) testing facility, Petascale HPC physics codes for wake interaction; High fidelity complex terrain

data campaign; Demonstrated ancillary services through Active Power Control at wind sites.
FY19 Investment Priorities: Development and testing of advanced control systems (flow monitoring and active wake control); Optimizing efficiency and lowering O&M (>20%); Exascale HPC physics codes with DOE Office of Science; High fidelity offshore wind data sets; Advanced LIDAR based feedforward sensor networks for turbine control.

Advanced Components/Manufacturing

- Pursue "Tall Wind" (hub heights of 140m or greater) to access higher altitude wind resources, lower the cost of energy, and address U.S. transportation and logistics constraints. Topics include: large rotors, modular towers and lightweight generators (superconducting)

  Recent Accomplishments: Completed 110m and 140m wind resource maps; funded research on 100m long blades to address installation and transportation constraints; 3D printed blade mold
  FY19 Investment Priorities: Demonstration at scale (>1MW) of high efficiency/ light weight drivetrain topologies; Development, testing, and demonstration of tall hybrid towers; Development, testing, and demonstration of highly flexible rotors; 3D printing manufacturing component optimization; Wind blade thermoplastic material optimization and recycling program.

Offshore Wind R&D

- Focus on cost reduction for deep-water floating foundations and moorings, and design standard development for the extreme marine conditions unique to U.S. waters. Key focus on reducing cost and improved operations and maintenance through manufacturing, resource assessment, and system optimization.

  Recent Accomplishments: Fully funded offshore demonstration program; fully coupled hydrodynamic engineering tools; meso-scale offshore wind resource maps.
  FY19 Investment Priorities: Offshore wind specific anchor and mooring program for floating structures; Demonstration of low-cost floating platforms; Low-cost high-reliability high fidelity resource characterization sensors, controls and technologies for hurricane survivability; Offshore grid designs and optimization; Offshore specific wind interconnection issues.

Market Acceleration and Barrier Reduction

- Enable effective co-existence of wind energy and wildlife through the development of impact minimization technologies and techniques, including eagle risk assessment, safe

deterrents, other mitigation technologies, offshore wind monitoring, and refinement of curtailment approaches for significant reductions in bat mortality.

- Pursue large scale grid integration efforts and focus on activities including improved forecasting, coupled storage systems for enhanced energy services, and specific cyber threat assessment and vulnerabilities.

Recent Accomplishments: Large-scale regional grid studies, first of a kind offshore wind biological studies and sensored approaches; bat studies and technology for curtailment mitigation; Wind/radar mitigation evaluations.
FY19 Investment Priorities: Demonstration at scale of concurrent cooling transmission technology to minimize transmission congestion; Detection and deterrent environmental research and algorithms; Below water offshore wind biological sensors for low-visibility conditions; Joint agency (DOD, DHS, DOT, DOC) wind/radar pilot program and advanced radar algorithms.

Water Power R&D

State of the Industry

Water power technologies represent a significant portion of U.S. electricity generation infrastructure, with relatively low operating costs (e.g. no refueling costs), but are not currently an optimized resource. Today, hydropower represents 6.5% of U.S. electricity generation, supporting 87,000 U.S. jobs. The current challenges of the electric grid, with the growing number of distributed energy sources and associated intermittency, make energy storage and grid services even more essential for grid balancing and reliability. Enhanced research into water technologies can help enable grid flexibility benefits to utilities and their customers.

The Role of Government & Key Investments Needed

DOE's *Hydropower Vision* study, developed with industry in 2016, determined that an additional 50-65 GW of new hydropower and pumped storage could be added by 2050 by utilizing new sites, adding low impact generation to existing unpowered dams, and taking advantage of pumped storage capacity. Optimization of water power will require both better management of current resources through improved technologies and capture of untapped resources through cutting edge advancements. However, it is expensive to test and evaluate new hydropower and marine hydrokinetics (MHK) technologies and control strategies. DOE's research capacity and convening power help draw down risks and costs by bringing the research community and hydro industry together to strategically address the opportunities. Support for testing and evaluating promising technologies and software solutions is essential to avoid slow adoption by the market, or worse, lack of interest by the market due to the uncertainty of new innovations and the low risk tolerance for utilities.

Key DOE Activity Highlights & Contributions

Hydropower

- Test and evaluate advanced turbine and pumped storage designs (with low environmental impact), and work with industry to increase future market opportunity and uptake.

  Recent Accomplishments: Released Hydropower Vision Study; HydroNEXT awards for pumped storage and non-powered dams; Launched HydroWISE portal.
  FY19 Investment Priorities: Development and testing advanced controls for generation and pumped storage facilities; Modular hydropower structures development; Additive drivetrain component manufacturing; Closed-loop pumped storage hydropower (PSH) component cost reduction and demonstration.

Wave, Current, and Tidal Technologies (MHK)

- Design, develop, test, and deploy MHK devices and components in the lab and in open

water, using the relevant tools, models, and analyses.

Recent Accomplishments: MHK Test Facility Commissioned, Wave Energy Prize Awarded.
FY19 Investment Priorities: Standardized testing of advanced MHK devices and systems; Development and testing of controls to optimize the performance of the MHK components and systems, with a view toward additional value in providing enhanced functionality to the grid.

Geothermal R&D

State of the Industry

Geothermal energy — a relatively untapped resource from the heat of the earth — represents a clean, efficient, versatile, and nearly inexhaustible baseload energy source. While geothermal energy is currently a small source of electricity in the U.S., near-term technology developments have the potential to vastly increase utilization of this renewable resource. Over the last decade, U.S. geothermal electricity generation has grown nearly 20%, with 3.8 gigawatts (GW) of installed capacity in six western states and a mean estimated 30 GW of new undiscovered hydrothermal resources and 100+ GW of new geothermal energy accessible through Enhanced Geothermal Systems (EGS). Deployment of the full spectrum of geothermal technologies (hydrothermal, EGS, and direct use for heating and cooling) can create a new, clean, domestic geothermal industrial ecosystem facilitating the growth of more than 200,000 full-time, high-paying electric sector jobs and 36,000 heat pump installation jobs by 2050, based on recent analysis.

In 2016, a significant spike in geothermal investment began internationally to meet the growing global demand for clean energy with international development interest focused on EGS and direct use applications. With 25% of global installed geothermal capacity and world-leading public and private sector expertise, the U.S. is well positioned to lead this market through exports of technology and intellectual capital if investments in game-changing research and development continue.

The Role of Government & Key Investments Needed

In collaboration with the geothermal community, the DOE developed the *GeoVision* report to outline a vision for growth of the domestic geothermal industry through 2050 across the full range of geothermal applications. The report also includes a roadmap of technical needs to achieve a robust future for the geothermal industry.
DOE's Geothermal Technologies Office accelerates the deployment of domestic electricity generation from conventional hydrothermal in the near-term, and high-potential EGS resources in the long-term through transformative research, development, and demonstration-scale projects that will catalyze commercial adoption.

Together, these near- and long-term investments will expand the geographic reach of geothermal energy to create a cost-competitive, versatile energy and heating/cooling solution across the country. Specific investments in integrated geophysical techniques, innovative drilling, EGS stimulation technologies, advanced reservoir modeling, big data analytics, high temperature corrosion resistant materials, and rare-earth separation technologies are critical to finding the remaining conventional hydrothermal resources, enabling access to the vast, domestic EGS resource, and maintaining the U.S. lead in geothermal intellectual capital and energy production.

Key DOE Activity Highlights & Contributions

Enhanced Geothermal Systems (EGS)

- R&D characterization of fractures and local stress, innovative drilling (crosscutting with conventional subprogram), EGS stimulation methodologies, high temperature tools, tracers, and well completion technologies to access and work in the harsh subsurface; demonstration work through five EGS field projects; an intermediate-scale in situ laboratory in a mine, and a large-scale EGS field laboratory - Frontier Observatory for Research in Geothermal Energy (FORGE) -where EGS technology and methodologies will be developed and tested at scale.

  Recent Accomplishments: improved accuracy of Thermal-Hydrological-Mechanical-Chemical (THMC) models; 300°C capable downhole data transmission capabilities; 300°C directional drilling motor; 6 wells drilled at Collab site; first FORGE characterization well drilled; new geophysical methods for tracking fracture growth.
  FY19 Investment Priorities: EGS Collab initiative – the path to FORGE - focused on understanding fracture creation and modeling; improve multi- zone stimulation technologies; prize competition for proppants in EGS systems; and continued funding for FORGE (Potentially to include full funding of both phase 2 FORGE sites).

Hydrothermal (Conventional Geothermal)

- Support R&D necessary to effectively find and access the estimated 30GW of blind resources (resources without surface expression) at lower cost, enabling private sector development, with a goal of reducing the cost of electricity generated from currently undiscovered hydrothermal resources to 10 cents/kWh by 2020. Also focus on subsurface technology enhancement.

  Recent Accomplishments: Phase III Play Fairway drilling confirmation phase underway; real-time fracture imaging technique using seismic and electrical methods; integration of geophysical and remote sensing techniques for hydrothermal resource confirmation.
  FY19 Investment Priorities: Low risk, high efficiency drilling (crosscutting with EGS); characterization of regional stress; machine learning for hydrothermal resource identification.

Low-Temperature and Co-Production

- Focus on extending the reach of geothermal across the U.S. by increasing revenue streams through mineral recovery from geothermal brines; Support desalination, hybridization, and the utilization of low-temperature geothermal resources beyond the western U.S. for industrial processes, agriculture, and heating and cooling.

Recent Accomplishments: Successful geothermal/ solar hybridization; new methods for reducing heat pump installation timelines; magnetic partitioning technique for mineral extraction; new membranes for geothermal desalination.
FY19 Investment Priorities: Continue Deep Direct Use Field Work feasibility FOA; rare earth and strategic material extraction technologies.

Systems Analysis

- Conduct analyses in the following areas: the environmental impacts of geothermal; the policy and regulatory barriers to development and deployment; economic modeling and validation of geothermal technologies; and collecting and disseminating data for public use to spur geothermal development.

  Recent Accomplishments: Completed GeoVision study addressing geothermal potential within the electric and non-electric sectors to 2050; updated all market, financial and environmental impact models; developed new regulatory roadmapping guidance for developers; continuous improvements to the National Geothermal Data System and Geothermal Data Repository, which houses all GTO project data for public consumption.
  FY19 Investment Priorities: Improve data sharing mechanisms; continue economic modeling of new technologies; address market barriers; support workforce development.

Building Technologies R&D

State of the Industry

Americans spend nearly $400 billion each year to power our homes and commercial buildings, consuming 74% of all electricity used in the U.S., accounting for about 40% of the Nation's total energy bill (more than industry or transportation), and contributing to almost 40% of the Nation's CO2 emissions. On average, families spend about $2,000 per year on energy for their homes, particularly for heating and cooling, lighting, water heating, and refrigeration. For American businesses it reducing energy costs can add to growth and improve competitiveness. Some 2.2 million Americans owe their livelihood to energy efficiency, mostly in the construction, buildings, and equipment industries; most of these jobs cannot be outsourced.

The Role of Government & Key Investments Needed

U.S. building-related industries significantly under invest in R&D, 0.3%—a mere one-tenth of the U.S. industry average of 3%, so government investment is very important for U.S. competitiveness and associated jobs. Federal investment in buildings R&D works for consumers by lowering energy bills and for industry by increasing American competitiveness. A *retrospective analysis* by the National Academies of Sciences, Engineering, and Medicine found a 20 to 1 return (in direct economic benefits) on public investment in energy efficiency R&D for the portfolio they examined from 1978 to 2000. Changes in the marketplace, from LED lights to highly efficient air conditioning, refrigerators, water heaters, windows and more, reflect the success of DOE's R&D investments. Given the long lives of building stock, which lock in their energy use at construction, more work is needed on technologies that can cost-effectively retrofit existing buildings, sharply reduce the energy use of appliances, and for new, radically more efficient buildings.

Key DOE Activity Highlights & Contributions

System Optimization: Emerging Technology R&D

- Catalyze innovation for the largest building energy consumers, including air conditioning & heating, refrigeration, lighting, water heating, appliances, a myriad of miscellaneous electrical loads, and the building "envelope".

  FY19 Investment Priorities: Expand DOE's important work on innovative and high-efficiency heat pump technologies – gas and electric, air source and water source – including for use in colder climates. Further innovative solid-state refrigeration concepts including magneto-caloric and other climate-friendly technologies that don't use traditional refrigerants. Support development of ultrasonic clothes drying technologies, which could transform the market with consumer products that are safer, better for fabrics, and more energy efficient. Perform early stage research needed to optimize the full promise of OLED lighting technology and continue to

advance LED lighting into commercial buildings and other applications. R&D for the building "envelope", notably new insulation technologies such as those using advanced foams that can be used to seal existing buildings and innovative window technologies that can adapt to local weather and sunlight for advanced efficiency and comfort. Across all building technologies, continue to develop and help integrate smart building technologies including the sensors and advanced controls, data analytics, and machine learning necessary to optimize building performance and allow "buildings-to-grid" functionality in a cyber secure environment. Research to integrate building loads with on-site PV and other types of distributed grid-connected generation to optimize overall system performance, while lowering costs, increasing energy reliability and helping integrate distributed renewables.

Demonstration and Market Transformation

- Building owners are often reluctant to try new energy-related technologies, solutions, and decision tools – even when they're highly cost-effective in lowering utility bills – due to the risk and uncertainty involved. Work across the building sector to validate solutions and otherwise educate decision makers about the opportunities for and value of energy efficiency can help all building owners, operators, and occupants to reduce energy waste and increase energy performance.

  FY19 Investment Priorities: Enhance DOE's programs that demonstrate the effectiveness of new technologies and products, particularly regarding HVAC (heating, ventilation and air conditioning) systems, advanced LED lighting systems, building-wide wireless sensor & control systems, and whole-building approaches. Demonstrate to architects and builders the innovative technologies and practices that build zero-net-energy homes and commercial buildings. Develop and deploy advanced tools that help building professionals and end users alike to assess the energy performance of their homes and/or offices and provide recommendations on energy-saving measures. Work with utility companies and others to help them – and their customers – evaluate and capture energy efficiency opportunities.

Efficiency Standards, Building Codes, and Test Procedures

- Continue to meet statutory requirements for appliance, lighting, and equipment efficiency standards to ensure new models continue to make progress on efficiency as technology matures; update test procedures to reflect product improvements, particularly Internet connectivity. Develop building codes for new residential and commercial construction that reflect developments in building energy efficiency – and "lock them in" for the life of the building.

  FY19 Investment Priorities: Ensure DOE has the financial resources to develop new efficiency standards that take into account technological developments – including Internet connectivity, "machine learning" and other control algorithms, and new

materials and manufacturing techniques – while maintaining cost effectiveness. Provide technical assistance requested by state and local building code agencies, and to the extent funding is available to members of the building and construction community, so that building energy codes reflect the best technical and market data for each climate, so the agencies have the wherewithal to adopt and enforce strong codes, and builders—particularly small operations—have the technical expertise to implement the most efficient solutions.

Advanced Manufacturing R&D

State of the Industry

As a foundation of the U.S. economy, manufacturing accounts for a third of the Nation's primary energy use. The effective and efficient use of energy in manufacturing is essential to U.S. competitiveness, economic growth, and job creation. Over the past two decades, energy use in U.S. manufacturing has remained flat, while economic output has doubled. Despite notable structural realignment in manufacturing, the steady increase in energy productivity and efficiency overall has helped drive growth in the U.S. economy. Energy productivity growth has resulted in large part from technology innovation in new products, processes, fuels, and feedstocks for manufacturing. For example, low-cost natural gas, in part due to Federal investments in precision drilling, advanced sensors, and subsurface modeling, have been a boost for manufacturing. Similarly, information technologies, including Internet-of-Things (IoT), artificial intelligence, machine learning, high-performance computing, wide-bandgap power electronics, materials sciences, and additive manufacturing, are poised to grow energy efficiency and productivity in the coming years, particularly in energy-intensive manufacturing sectors.

U.S. manufacturing faces stiff global competition. International competitors have proactive strategies to leverage advances in science and technology for economic advantage (e.g. Germany's 'Industrie4.0' and China's 'Made in China 2025'). For continued and long-term economic growth, U.S. manufacturers must continually innovate by effectively and proactively connecting new science and technology from national labs, small businesses, major research centers, and universities.

Over several decades, the U.S. manufacturing sector has become fractured within supply chains. Supply-chain structuring has the benefit of technological specialization for firms, with capital focused on highest value-add activities. But the absence of vertically-integrated manufacturing firms is an economic challenge to adopting new technologies as the value-add of innovation is often spread across organizations in a supply chain. This leaves U.S. manufacturers vulnerable to innovation displacement by an inability to efficiently adopt many new technologies. Manufacturing consortia and public-private partnerships have the potential to overcome supply chain fragmentation and are essential to U.S. manufacturing technology competitiveness.

The Role of Government & Key Investments Needed

The manufacturing sector (and the agriculture sector) is a foundation of the U.S. economy, national security, and job growth. Against this backdrop, there is broad public agreement on the need for long-term national competitiveness in manufacturing, and, particularly at the state and local level there is agreement on the need for public-sector support for domestic manufacturing. There is a unique opportunity for DOE to connect the scientific assets under their stewardship, such as supercomputers, major scientific tools (e.g. synchrotrons), and basic

materials research capabilities, with the private sector to together address manufacturing-relevant challenges.

DOE's Advanced Manufacturing Office Multi-year Program Plan (MYPP) identified essential cross-cutting energy technologies related to processes, materials, and information that if advanced would further U.S. manufacturing scientific and technical leadership. Cross-cutting topics include sensors and controls, chemical and process intensification, new materials, sustainable and critical materials for energy, power electronics, clean water, nanoscale semiconductors, additive and roll-to-roll processes, and energy systems integration of manufacturing.

To ensure a proper role of government, the DOE Advanced Manufacturing Office addresses these issues through three mechanisms: broadly competed individual R&D projects targeting the creation of new knowledge; public-private partnerships as R&D consortia intended to both advance the state of knowledge as well as connect U.S. supply chains; and technical partnerships intended to transfer knowledge from laboratories and universities to the private sector to advance best practice sharing within the U.S. manufacturing sector in areas related to the most efficient and productive use of energy. Federal R&D support in areas of energy productivity and manufacturing has a track record of boosting U.S. economic competitiveness in the global marketplace.

Key DOE Activity Highlights & Contributions

R&D Projects

- **Recent Accomplishments:** Established High Performance Computing for Manufacturing (HPC4MFG) as a Coordinated Multiple National Lab Program to use and focus DOE supercomputer assets on manufacturing relevant R&D issues; Established Lab-Embedded Entrepreneurial Post-Doc (LEEP) program to increase use of unique national lab resources with scientifically oriented entrepreneurs. (Cyclotron Road, Chain Reaction Innovations, Innovation Crossroads); Established University-based Traineeship Programs in power electronics and advanced manufacturing topics with an identifiable technical workforce gap.

  FY19 Investment Priorities: Application of High Performance Computing in Manufacturing; Support for Entrepreneurial Post-Doctoral Researchers at National Labs; Advanced Manufacturing Technology Traineeships; Individual Manufacturing R&D Partnerships with National Labs; R&D Projects Focused on Innovative Small and Medium Businesses; Broad Manufacturing R&D Projects by Universities, Labs & Private Sector.

R&D Consortia

- **Recent Accomplishments:** Established Critical Materials Institute as a National Laboratory

& University based consortium addressing manufacturing challenges related to rare-earths materials; Established Manufacturing Institute Public-Private Partnerships addressing R&D challenges for power electronics, advanced composites, sensors & controls, sustainable materials and process intensification; Established national laboratory based open public-private partnerships to unlock innovation potential in national labs related to additive and carbon fiber processes.

FY19 Investment Priorities: National Lab & University R&D Consortium on Rare Earths and Critical Materials; National Lab & University R&D Consortium on Clean Water; Manufacturing Public-Private Partnership Consortia (ManufacturingUSA Institutes) on Power Electronics, Advanced Composites, Sensors & Controls, Sustainable Materials, Manufacturing Process Intensification and Nanoscale Semiconductors (new); National Lab based Manufacturing Demonstration Consortia on Additive Processes, and Lightweight Carbon Fiber Materials Manufacturing.

Technical Partnerships

- **Recent Accomplishments:** Better Plants partners have cumulatively improved their energy productivity by over $1B; Combined Heat and Power has reliably achieved 8% of US electric generation capacity.

  FY19 Investment Priorities: Better Plants partnership for US manufacturing; Combined Heat and Power Technical Assistance Partnership (CHP-TAP) program; Industrial Assessment Center Partnership program; Energy Productivity Methods (50001) technical best practice partnerships.

Vehicles R&D

State of the Industry

The average American spends most of their household energy expenses on transportation fuel–$4,000 per year. Improvements to vehicle efficiency and electric vehicle (EV) technology save drivers money, reduce oil dependence, and cut pollution. EVs are becoming an important player in the light-duty vehicle (LDV) industry; cost reductions, range increases, and performance improvements have driven widespread growth in EV adoption. Americans purchased 160,000 EVs in 2016, a 37% increase from 2015 sales. As of November 2017, more than 700,000 EVs were on the road in the U.S., supported by 45,000 publicly available EV charging outlets. Bloomberg's Electric Vehicle Outlook 2017 predicts that EVs will account for 54% of new car sales and 33% of the global car fleet in 2040. Even so, vehicles with combustion engines will likely make up the majority of new car sales for the next few decades. While automakers have announced plans to bring a fully-electric semi truck to market by 2019, EV technology has not yet met the needs of long-haul trucks, which carry 80% of goods in the U.S. and use 20% of the transportation fuel.

The Role of Government & Key Investments Needed

DOE's Vehicle Technologies Program leverages public-private research partnerships to strategically address early stage innovation challenges that industry does not undertake on its own. For example, DOE invested $1 billion in EV battery research between 1992 and 2012, creating $3.5 billion in economic value. As a result, battery costs decreased by 70% from 2008 to 2016, making EVs affordable and marketable. DOE has also begun researching efficient futures for tomorrow's connected and autonomous vehicles (CAVS). DOE's Systems and Modeling for Accelerated Research in Transportation (SMART) laboratory consortium supports the development of energy-efficient urban transportation systems. Core vehicle research challenges include combustion engine efficiency, battery cost reduction, range and lifetime increases, improvements to charging infrastructure, energy efficient mobility systems, as well as efficiency improvements and viable electric options for long-haul trucking.

Key DOE Activity Highlights & Contributions

Battery and Electrification Technologies

- Improve the performance, reliability, cost-effectiveness, and lifetime of lithium-ion vehicle batteries and investigation of beyond-lithium-ion batteries. Improve the weight, size, efficiency, and cost of electric drives.

  Recent Accomplishments: Reduced cost of lithium-ion batteries by 70% to $245 kWh in 2017; technologies identified to reduce cost to $70-120/kWhr; Demonstrated >200Wh/kg energy density; Capacitor and inverter improvements; Demonstrated plug-in vehicle integration with the electrical grid; developed SAE J2953 interoperability

standard; developed charging technologies (vehicle to grid, workplace charging metering and communication, and AC/DC charging).
FY19 Investment Priorities: Continue advanced lithium-ion based chemistries, densification, and cost reduction; Support Battery500 Consortium beyond-lithium-ion materials research; Extreme-fast charging R&D including materials, infrastructure, and grid resilience; medium/heavy duty electrification; R&D and a consortium on cyber security for CAVs.

Energy Efficient Mobility Systems

- Improve efficiency of the overall mobility system through CAVS, mobility decision science, and system-level modeling, simulation, and analysis.

  Recent Accomplishments: Established SMART Mobility Lab Consortium, Completed foundational studies of autonomous vehicle energy impacts (Control of CAVs, Regional CAV Energy Use, Car Sharing Demand, Platooning Potential).
  FY19 Investment Priorities: Support SMART lab consortium, Continue high performance computing application development for energy efficient mobility (regional simulations and impacts modeling of CAVS, ride-sharing, etc). Develop communications and control technologies for efficient mobility; Conduct on-road CAVS energy performance demonstrations to integrate data into planning models.

Advanced Engine and Fuel Technologies

- Improve understanding of combustion processes to develop more efficient and better-performing engines and fuels.

  Recent Accomplishments: Completed SuperTruck I; Demonstrated light-duty engine with a 25% fuel economy improvement. Demonstrated Direct Injection Propane engine in a medium-duty truck, established multi-lab lubricants partnership, U.S. DRIVE Fuels Working Group evaluating the properties of lower carbon fuels for future, high efficiency engines.
  FY19 Investment Priorities: Fourth year of SuperTruck II Funding; Vehicle/Fuels Co-optimization; Drivetrain efficiency modeling, fluid power systems R&D.

Materials Technology

- R&D in lightweight materials, multi-material solutions, and manufacturing processes to improve vehicle efficiency through drivetrain and structural weight reductions.

  Recent Accomplishments: New generation of advanced high strength steels that enable 29% lighter automotive structures, developed welding technology for joining different lightweight aluminum alloys, developed new high-temperature cast-aluminum alloys. Developed new carbon fiber technology to reduce energy

consumption by 75% and lower production costs by 20%.
FY19 Investment Priorities: Continue/complete carbon fiber materials development work; dissimilar materials joining; Durable advanced alloys for engines and drivetrains; Increased investment in advanced low-cost, weldable high-strength steel; Virtual crash-testing of lightweight materials through predictive computational tools.

Outreach, Deployment, and Analysis

- Catalyze the adoption of advanced vehicle technologies through public-private partnerships, advanced vehicle competitions, and alternative fueling infrastructure data.

  Recent Accomplishments: Developed industry leading analysis products and delivered reports to the public, including the Transportation Data Book, the Market Report, Benefits Analysis, Smart Mobility Reports, and over 50 other publications. Clean Cities saved over 8.5 Billion gallons of fuel through 2015, published annual fuel economy guide, launched alt-fuel aggregated purchasing capability, greatly expanded consumer-based tools and information resources (such as the alt-fuel station locator). Advanced Vehicle Competition has had more than 16,500 participants, with 83% entering the automotive industry.
  FY19 Investment Priorities: Continue Clean Cities support, Alternative Fuels Data Center, Fueleconomy.gov, EV infrastructure information, and continue the Advanced Vehicle Competition series.

Bioenergy R&D

State of the Industry

Between 2006 and 2016, renewable fuels production doubled in the United States, in large part due to the Renewable Fuels Standard (RFS), to nearly 17B gallons today. Today, production of conventional corn ethanol fuel has plateaued, reflecting the E10 blend wall. Starting from a much smaller base, capacity continues to grow for biodiesel and other advanced biofuels, including cellulosic ethanol. Recent reports confirm that the U.S. has the capacity to produce one billion tons of biomass per year, more than double the current volume. Given the challenging reality of the commodity transportation fuels market, producers have begun to identify new markets for bioproducts while research continues on next generation biofuels. Over the long term, domestically produced biofuels will be necessary in sectors that cannot be cost-effectively electrified (i.e. aircraft, ships, and heavy trucks) and for fossil fuel derived products like plastics.

The Role of Government & Key Investments Needed

In collaboration with the biofuels industry, the U. S. Department of Agriculture, and the research community, DOE published the *Strategic Plan for a Thriving and Sustainable Bioeconomy* in 2016. The plan identifies near, mid, and long term technical needs for bioenergy research, development, and demonstration. The strategy continues to primarily focus on reducing the costs and increasing the reliability of cellulosic biofuel production. It also identifies a new focus on high value added bioproducts including bioplastics, biobased chemicals, lubricants, solvents, and food ingredients from both cellulosic and algal feedstocks.

As shown through experience with the Nation's first advanced biofuel refineries, scale up and integration of new technologies into commercial-scale biorefineries is a challenging and high-risk undertaking. DOE, as part of a coordinated cross-government effort, targets specific technology gaps, including at the pilot and demonstration scale, where the private sector is unable to make necessary investments due to risk, scale, or the time frame required for commercialization.

Key DOE Activity Highlights & Contributions

Feedstock R&D

- In coordination with USDA, develop new biomass feedstocks (herbaceous, woody, waste materials) that can be collected, transported, and converted into transportation fuels and bio-products.

  Recent Accomplishments: Continued operation of the Feedstock Process Development Unit at INL.
  FY19 Investment Priorities: Establish a Regional Feedstock Partnership Initiative to

test new and existing feedstocks in field trials in order to improve crop strains, develop best management practices, and novel harvesting/pre-processing equipment methods.

Conversion R&D

- Develop innovative conversion technologies (biochemical, thermochemical, catalytic, hybrid) that can convert biomass and waste materials into fuels and products at lower cost and higher yield.

  Recent Accomplishments: Reduction in cost of production for ethanol from lignocellulosic biomass feedstocks, continued operation of pilot plants at NREL and PNNL and the Advanced Biofuels Process Development Unit at LBNL.
  FY19 Investment Priorities: Support new industry/academic/National Lab consortia (2-4) on innovative conversion topics including catalysts, micro-organisms, and novel process concepts (such as super-critical water extraction); R&D on production of ethanol from lignocellulosic biomass and other feedstocks for alcohol-to-jet pathways; Utilization of CO2, CH4, and CO from waste flue gases and liquids to produce fuels, chemicals and bio-products.

Advanced Development and Optimization

- Scale up of innovative new conversion process concepts from the laboratory to pilot and demonstration scales with techno-economic analysis and life cycle analysis. These efforts help to reduce costs and risks, and catalyze the private sector to raise capital and build commercial scale facilities.

  Recent Accomplishments: Production of cellulosic ethanol from corn stover at Poet facility in Emmetsburg, Iowa and achievement of financial close for Fulcrum biorefinery that will produce renewable jet and renewable diesel from municipal solid waste in Reno, Nevada.
  FY19 Investment Priorities: Fund 3-5 pilot facilities at sufficient scale to generate accurate cost/emissions data; Focus on drop-in (hydrocarbon-like) fuels which are used in the difficult-to-decarbonize aviation, medium/heavy duty vehicle, and marine sectors is recommended; Support synthesis gas upgrading equipment innovations, including size/cost reductions.

Analysis

- Studies and analytical activities focusing on three areas: resource assessment, techno-economic analysis, and life-cycle analysis.

  Recent Accomplishments: "Billion Ton 2016" resource assessment publication, Publication of eight design reports showing techno-economic analysis of a variety of pathways, public release of the Biomass Scenario Model.

FY19 Investment Priorities: Resource assessment, techno-economic analysis, and life-cycle analysis of new pathways that utilize CO2, CH4, and CO. Fund updated 2019 "Billion Ton" resource assessment report, which should include a first-ever in-depth assessment of waste fats, oils, and greases, and oil seed crops.

Algae R&D

- Discovery of new algal species that have high productivity and high lipid content in order to reduce the cost of production of fuels and products and cost reduction for existing species/systems.

  Recent Accomplishments: Awarded 7 projects totaling $16 million aimed at reducing the cost of algal biofuels and bio-products.
  FY19 Investment Priorities: Saline/brackish/grey water tolerant algae, Photo-bioreactor systems, macro-algae cultivation, product development, including low-carbon animal feed to displace higher carbon grain.

Hydrogen and Fuel Cell R&D

State of the Industry

Hydrogen can be produced from domestic fossil resources, or from renewable or nuclear sources, increasing U.S. energy independence. Fuel cell vehicles have much higher efficiencies than conventional vehicles, but do not themselves emit pollution—substantially benefiting public health. Fuel cell systems can provide back-up power, improving grid reliability and resiliency. Hydrogen fuel cell vehicles are now available to U.S. consumers (Toyota, Honda, Hyundai), hydrogen refueling infrastructure continues to grow, and the fuel cell forklift market grew by 40% in 2016. Today's fuel cell vehicle sector provides over 16,000 U.S. jobs and has the potential to grow dramatically. New applications for fuel cells are being explored, including in trains, long-haul trucking, at ports, at data centers, and for carbon capture. Hydrogen can also be used for grid storage and the production of fuels, fertilizers, and chemicals, These developments are being spurred by the low cost of natural gas, the primary feedstock for hydrogen production today, and advances in fuel cell technologies. For example, federally supported innovation has facilitated a nearly 50% reduction in the cost of fuel cells over the past decade and a quadrupling of fuel cell life. Further R&D is required, however, to advance fuel cell vehicles to match the cost and durability of conventional vehicles. R&D investments by DOE have enabled some 650 hydrogen and fuel cell-related patents and contributed to industry commercializing over 30 technologies .

The Role of Government & Key Investments Needed

The hydrogen and fuel cell industry is at a very early stage, and lacks the capabilities and critical mass to address the high risk and long timeframe R&D challenges that must be overcome to realize its potentially very high return. Federal support addresses these needs and enables new possibilities to efficiently utilize our abundant domestic energy resources, which can expand our economy while protecting our environment.

More work is needed to further cut costs and improve the durability of fuel cells. Even as hydrogen is produced from natural gas at scale today, innovative R&D is needed on low-cost hydrogen produced from wind, solar, biomass, nuclear power, or other sources that minimize carbon emissions. Further development of low-cost, high performance hydrogen storage is also needed, as are advances in manufacturing and infrastructure technologies.

Key DOE Activity Highlights & Contributions

Fuel Cell R&D

- Advance fuel cell systems to match the cost of conventional engines by reducing their cost and increasing their durability, with particular attention to eliminating the use of platinum group metals in catalysts and electrodes, improving electrode and membrane electrode assembly durability, reducing balance-of-plant costs, and improving system integration.

Recent Accomplishments: R&D support reduced platinum use in fuel cells by 5X and cut automotive fuel cell costs in half since 2006, to roughly $60/kW, while quadrupling fuel cell durability to 120,000 miles. An R&D100 award was won in 2017 for platinum group metal-free catalysts.
FY19 Investment Priorities: Fuel cell costs need to be further reduced to $40/kW and their durability increased to 150,000 miles through reductions in the use of platinum group metals, improvements in electrodes and membranes, and improved balance-of-plant components and systems.

Hydrogen R&D

- Hydrogen is primarily generated today by reforming natural gas; in the future, hydrogen needs to be produced from renewable energy or nuclear sources through electrolysis or by direct production. Advances are also needed to improve hydrogen storage capacities and costs, and to improve hydrogen compressors and other system components.

  Recent Accomplishments: Hydrogen electrolyzer stack costs have been reduced by 80% since 2006.
  FY19 Investment Priorities: Achieve hydrogen costs of $4/gge (gallon of gasoline equivalent) delivered to the consumer, with the cost of delivery and dispensing reduced to less than $2/gge. Reduce the production cost of hydrogen from renewable or nuclear energy towards the long-term goal of less than $2/gge with a balanced program including electro, thermal, and hybrid processes. Develop on-board hydrogen storage systems for automobiles that provide a range of more than 300 miles, at a cost of less than $8/kW.

Manufacturing R&D

- Production of hydrogen fuel cells, hydrogen generation systems, compressors, and other components at low cost poses new challenges such as: quality-control tools for the manufacture of hydrogen system components and systems; fabrication processes for low-cost high volume production of fuel cells and hydrogen storage systems; and other key technologies.

  Recent Accomplishments: Won an R&D 100 award in 2017 for metal joining technology.
  FY19 Investment Priorities: Develop real-time in situ metrology for process control systems for manufacturing, such as for roll-to-roll production lines for membranes, anode and cathode materials, and other key hydrogen system components.

Systems Analysis

- Systems analysis provides core guidance on technology and system R&D needs and

progress, lifecycle material and environmental impacts, crosscutting impacts across energy sources and end-uses, market and financial issues, and overall program performance and impacts.

Accomplishments to Date: Evaluated: impacts of R&D on advancing fuel cell and hydrogen technologies; life cycle analyses of water use in hydrogen production pathways; and infrastructure needs
FY19 Investment Priorities: Quantify cost and emissions impacts of hydrogen production pathways; evaluate infrastructure requirements and limitations; and evaluate technology R&D needs.

Safety, Codes and Standards

- To ensure the highest possible safety, extensive work has been done to develop improved materials and sensors for safety, to develop codes and standards throughout the hydrogen production, transport, dispensing, and use system, and to train first responders.

  Recent Accomplishments: Developed training materials and trained more than 36,000 first responders and code officials. Launched H2Tools as a free, online best practices and national hydrogen safety training resource for emergency responders.
  FY19 Investment Priorities: Further research is needed on hydrogen compatibility with metallic and non-metallic materials in a high pressure environment, advanced sensor development, and to expand training for code officials.

Electric Grid R&D

State of the Industry

Today's electric grid is being asked to perform in ways for which it was not originally designed. For example, in 2016, variable wind and solar accounted for nearly two thirds of new generation capacity on the electric grid, much of it being deployed closer to its end use, disrupting the central station generation model of the past. This is occurring even as electricity sales have held steady in absolute terms and declined per-capita – a trend that current projections forecast to continue in the future.

At the same time, utilities are in the midst of a huge, multi-billion dollar grid upgrade. Along with nearly 70M recently installed smart meters, thousands of new automated switches and sensors are helping avoid and manage outages on the grid. The real-time data these devices provide, along with improved load and renewable output forecasts and the ability to selectively control loads from smart devices like connected thermostats and appliances (demand-side management), has transformed grid operators' ability to reliably and economically manage the grid. Grid-scale energy storage is taking on increasing importance as the amount of wind and solar power on the grid is projected to grow. Since 2008, the capacity of batteries on the grid has grown by 10x but the total capacity remains low. As more devices begin to interact with the grid, 'two-way flows' of electricity and information will provide new services and opportunities for profit on the electric system. Given the proliferation of computing devices monitoring and managing the grid, cyber threats are a serious and growing security, safety, and economic challenge for the electricity sector. In addition, climate change-linked weather events have led to an observable increase in the frequency and duration of power outages in the U.S.

The Role of Government

In collaboration with the utility industry, DOE established the Grid Modernization Initiative in 2015 – an annual $300M coordinated R&D program. The GMI includes a *multi-year R&D roadmap* that describes six technical areas that industry and government should develop to jointly establish a cost-effective path to a resilient, secure, sustainable, and reliable grid.

DOE, including its National Labs, supports grid modernization by advancing fundamental knowledge in material science, computational sciences, and mathematics for grid-related software and hardware. In addition, DOE serves as a convening authority, developing common approaches to test and validate new technologies, interoperability and interconnection standards, developing technologies and best practices for grid security and resilience, and informing stakeholders of emerging threats – and responding where appropriate.

Key DOE Activity Highlights & Contributions

Resilient Distribution Systems

- Advanced microgrid RDD&D; Transactive energy development and deployment; Open-source, open-standards based distribution system application software development platform.

  Recent Accomplishments: Deployed microgrids through Industry, state, and military partnerships; microgrid design and operational analysis tools; Published Transactive Energy Framework, established a transactive energy valuation framework; supported field validation projects for transactive energy; Developed a conceptual design for GridApps-D - a future advanced distribution system management software platform.
  FY19 Investment Priorities: Networked microgrid system design; laboratory and field microgrid controller demonstrations; New transactive energy distributor operating models; Valuation of energy services including dispatch flexibility, resilience, ancillary services, storage, and low carbon amount others; Evaluate mechanisms to deliver and share market signals to a variety of energy management systems; Study and evaluate customer energy usage behaviors in response to price signals; Continue to develop and test GridApps-D; Research into new control and operational theories for distributed devices; integration of sensors into distribution management systems for true end-to-end grid visibility.

Transmission Reliability

- Supports the nation's capacity to analyze the electricity delivery system using big data, advanced mathematical theory, and high-performance computing and develops tools that utilize high fidelity synchrophasor data to maintain grid reliability and resilience and prevent catastrophic failures.

  Recent Accomplishments: Near 100% visibility of the behavior of the entire U.S. high-voltage transmission network using nearly 2,000 Phasor Measurement Units (PMUs); Improved utility modeling capabilities.
  FY19 Investment Priorities: Improved synchrophaser timing (using GPS and Loran); Distribution system PMU network; Improved synchrophaser-based modeling technologies for grid operators; Future grid modeling uncertainty definition;

Transformer Resilience and Advanced Components

- Next-gen grid hardware to withstand natural and man-made threats, facilitate rapid recovery and restoration, and provide new capabilities that meet future grid requirements.

  Recent Accomplishments: Published R&D framework: Materials Innovation for Grid T&D Components and Next-Generation Grid Component R&D; Five large power transformer design awards; Six Lab projects on materials, designs, and models for grid components.
  FY19 Investment Priorities: Flexible and adaptable power transformers; Substation

power electronics; Hybrid AC and DC microgrid and DER architectures; All hazards (including EMP) component design; Low cost sensors for grid component monitoring.

Energy Storage

- Developing new grid scale electrical energy storage technologies for both the transmission and distribution systems, with system costs, increased performance, lifetime, and safety, ; Defining the value and benefits storage can provide across the grid infrastructure.

  Recent Accomplishments: Breakthrough flow battery research to reduce the cost by half; Ten R&D 100 Awards; over 170 peer reviewed publications; 120 patents and patent applications; 14 commercial technology licenses; Supported energy storage developments in nine states; established industry-wide Energy Storage Safety Working Group
  FY19 Investment Priorities: Next generation materials and chemistries and new approaches to accelerating energy storage innovation for concept to proof of concept; Aqueous soluble organic flow battery chemistries that utilize domestically sourced earth-abundant materials; Expanding its Safety Forum to include codes and standard adoption; Expand regional workshops to engage utility regulatory commissions; Continue technical assistance to state energy storage demonstrations.

Electric Grid Cyber Security R&D

State of the Industry

Government agencies and private sector cyber security firms have determined that the U.S. energy sector is being targeted by waves of cyber attacks, which could provide foes with the means to significantly impact parts of the electric grid and endanger the wellbeing of millions of Americans.

Previous rounds of threats have targeted information technology - or IT - systems (email and business applications) at energy companies. While disruptive, it is difficult for attacks on IT systems to have a direct impact on energy delivery systems. However, starting in late 2015, hackers tied to the Russian government demonstrated a sophisticated new attack vector. By targeting Operating Technologies or "OT" (software and hardware directly controlling to equipment on the grid) at a Ukrainian energy company, the attackers caused the first-ever cyber-linked blackout. A year later, cyber attackers struck in Ukraine again, knocking out power to parts of Kiev.

U.S. officials have warned that hackers from Russia, Iran, and China are mapping U.S. electric grids to detect similar vulnerabilities and prepare for future attacks. While the largest U.S. utilities can afford industry-leading tools to detect and prevent all but the most sophisticated attacks (termed 'advanced persistent threats'), smaller utilities are often vulnerable to the most basic IT and OT attacks.

The Role of Government & Key Investments Needed

While it is the primary responsibility of the owners and operators of energy infrastructure to protect their IT and OT assets from cyber threats, the security of energy infrastructure requires government investments because energy underpins every other type of critical infrastructure and emergency response.

Cyber threats to IT systems affect every sector of the economy, including the energy sector. Because these IT systems are ubiquitous, cyber attacks can be identified and patched quickly. However, OT systems, which, if compromised, can cause power outages, are often older, more complex, and proprietary, making detection and repair of cyber attacks more difficult. For these reasons, DOE should continue to develop advanced tools and techniques to identify and defeat advanced-persistent threats to OT systems.

In collaboration with the electric industry, DOE will publish the Electric Grid Cyber Multi Year Program Plan in winter 2018. The report creates a roadmap to enhance cybersecurity preparedness, coordinate response and recovery, and accelerate R&D of game-changing and resilience-building cyber protections for energy systems. R&D innovations identified in the report include new tools and technologies to identify and protect energy delivery equipment from cyber threats, and are discussed below.

Key DOE Activity Highlights & Contributions

Situational Awareness

- Develop a sensor network to protect energy industry operating technologies.

  Recent Accomplishments: Developed a sensor network (CRISP) that detects malware and potentially anomalous activity on energy industry IT systems and transitioned it to private partners to run and manage.
  FY19 Investment Priorities: In partnership with utilities and the National Labs, expand CRISP to operating technologies by developing sensors and computing platforms that have the ability to see commands issued to control systems and - in real time - determine if those commands would have a destabilizing or dangerous impact on grid operations; Identify critical generators nationwide and engage with the private sector to assure assets can operate without cyber capabilities.

Next Generation Cyber Defenses

- Develop a dynamic moving target cyber defense capability.

  Recent Accomplishments: Published the Cybersecurity Capability Maturity Model (C2M2); Developed dozens of innovative technologies, tools, and techniques to reduce cyber risks.
  FY19 Investment Priorities: Continue to fund innovative cyber defense tool development, including tools, technologies and analytics necessary to identify critical vulnerabilities at the intersection of natural gas and electricity systems under a range of scenarios; Lab-led energy sector cyber training program; New capability to deploy lab experts in order to respond to cyber incidents.

Fossil Power and Combustion Systems R&D

State of the Industry

The aging coal power fleet is operating in a radically different market environment than just a decade ago, and the rapid pace of change in power markets is expected to continue. Much of this change is due to increased availability of low-cost natural gas and a new generation of combined cycle natural gas power plants which operate more efficiently and at lower cost than legacy coal plants. These gas plants also emit about 70% less CO2 per kWh generated.

In particular, coal plants are now often being asked to cycle more rapidly, in a manner different from original design and in response to changing market dynamics, putting stress on structural and operating components. With further research and development, retrofit or replacement technologies can improve plant performance and help some of these plants remain viable in the future. In the U.S., the first (and only) ultra supercritical (USC) coal plant was deployed in 2012 and the first modern integrated coal gasification combined cycle (IGCC) plant came online in 2013. Challenges for future advanced fossil plants including reducing construction and operating costs, achieving dramatic efficiency gains, and integrating carbon capture technologies, all of which can be addressed through technology innovation.

The Role of Government & Key Investments Needed

R&D in areas such as materials, fluid dynamics, fuel properties and preparation characteristics, and a new generation of plant controls can lead to new components and systems and can help improve the efficiency and reliability of coal-fired power plants significantly. While other countries have taken the lead in USC plant deployment, the U.S. is well positioned to leverage critical expertise in materials, modeling, design and systems-scale engineering. The early stage nature of such research, along with the high cost and risk of demonstrating and deploying these technologies, necessitates cost-shared federal investment in this space.

Key DOE Activity Highlights & Contributions

Advanced Turbines

Recent Accomplishments: Advances include single crystal turbine blades; new thermal barrier coatings; high operating temperature capabilities with attendant increases in efficiency and lower emissions; advanced seal technologies.

FY19 Investment Priorities: New turbine materials and components which can withstand widely variable operating conditions, including temperature, pressure and chemical (including consideration of other working fluids); analysis which can allow migration to predictive component replacement and maintenance vs current scheduled practices; topping cycle technologies. Includes advanced materials, ceramics and coatings for increasingly aggressive environments, at both the lab and

pilot scale; new turbomachinery design for new operating conditions coupled with valve and castings development for new materials. It is critical to carefully define proper federal investment in turbines vs that which industry will accomplish in an established market.

Gasification Systems

Recent Accomplishments: R&D to date has proven the technical viability of gasification systems at lab and prototype scales; the challenge has continued to be system integration since these plants are essentially combined chemical and power plants. Successful large-scale demonstration of warm gas clean-up technology (Polk County, FL); New approaches to oxygen separation being developed.

FY19 Investment Priorities: Plant optimization, systems approach to coal properties/ utilization/preparation and impact on combustion integrity, mindful that industry currently has less interest in gasification systems as compared to direct fired generation. Priorities also strongly intersect with targeted R&D on materials for harsh environments. Ensure concurrent focus on modular and scalable conversion technologies that could be deployed globally.

Solid Oxide Fuel Cells

Recent Accomplishments: Anode-supported planar SOFC technologies have matured to market acceptance, and demonstrations have been successful at 50 to 200 kWe scale. System integration and operational experience continues to progress. Future tests at 400 KWe to 1 MWe scale will continue progress to full utility-scale adoption and utilization (1 MWe is commonly accepted as the scalable module). Industry will not advance through these stages without federal engagement.

FY19 Investment Priorities: Due to the success of past SOFC R&D and industry uptake, remaining challenges include addressing long term materials/electrode reliability, and improving stack performance and durability by addressing technologies to increase cell area and in-stack fuel reformation. In addition, technologies that improve quality and address variability in feedstock materials are critical to predictable performance. A renewed assessment of industry uptake of new technologies is warranted. Finally, SOFC's can effectively be run in reverse, using CO2 and electricity as feedstocks to produce fuels and chemicals. This is a fertile area of CO2 conversion and use.

Sensors & Controls

Recent Accomplishments: Prior R&D has developed sensors and process controls for operating conditions expected in a variety of settings, including gasification, oxy-combustion and ultrasupercritical conditions, and combustion systems. These advances have led to improvements in plant operating efficiency with lowered

emission across the traditional power plant fleet.

FY19 Investment Priorities: R&D into new sensors which allow more complex and real-time analysis of temperature and pressure conditions throughout fossil energy systems, which reflect the new operating conditions required of these plants due to integration with more complex and variable energy systems. Includes multi-location and system performance vs single point measurements; embedded sensors and wireless systems; densely distributed systems. In addition, artificial intelligence approaches have high promise but have not been widely considered for applications in this sector. A study on AI potentials for sensor and control systems should be undertaken to craft a future R&D program.

Materials

Recent Accomplishments: NETL and DOE have completed a new high-temperature, high temperature INCONEL alloy and brought it to market, providing a pathway for substantial cost reductions and improved performance for new combustion and conversion pathways. In addition, materials development for both sensors and operating components has led to improved efficiency and safer operations, and is cited by industry as being of critical value.

FY19 Investment Priorities: New materials for rapid temp and operating condition swings, and widely variable physico-chemical settings. Technologies for lower water use (since CO2 capture can require increased water use). Requires close cooperation with DOE Advanced Manufacturing Office (AMO), in both material discovery and operational testing. Extreme environment materials, with a long-term target of preventative vs scheduled maintenance of systems. New alloys discovery building on current modeling work. Includes new computational tools for material discovery, design of capture system components,

Supercritical CO2 (STEP)

Recent Accomplishments: Supercritical CO2 provides a means to retrofit existing plants to get much higher efficiency, and to create new systems that use supercritical CO2 as a working fluid (e.g., the Allam Cycle). These approaches are applicable to a variety of energy source applications (renewable, solar thermal, nuclear, and fossil energy systems) and have cross-cutting applications (since the greatest benefits are produced at very high temperatures, the program is seated at FE). The technology has advanced to successful development of a non-condensing closed cycle Brayton cycle which must now be tested at larger scale before commercialization is possible.

FY19 Investment Priorities: A critical future focus needs to be integration of STEP and utilization technologies, with low cost (and frequently intermittent) renewable technologies. Lower input energy requirements coupled with advances in both

direct and indirect supercritical systems offers high potential. Continue funding for the STEP project in Texas to ensure it can be tested over a broad range of operating conditions, ensuring proper application not just to fossil energy sources but also to renewables and nuclear energy. Future research to include turbomachinery design, heat exchanger design, and new materials development for unique super critical CO2 operating conditions.

Carbon Capture R&D

State of the Industry

Carbon capture, use, and sequestration (CCUS) technologies are the only option available to prevent trillions of dollars of coal, industrial and natural gas assets from becoming stranded in a more carbon constrained future. Multiple studies show that the future costs of dealing with atmospheric pollution (health, infrastructure, etc) are much higher if effective CCUS is not available as an option. The good news is that more than 40 years of targeted research have yielded carbon capture technologies that are well-tested, reliable, and in some cases deployed commercially. Globally, over 20 large scale facilities exist, removing nearly 40M tons of CO2 annually. The United States leads the globe, hosting the most and largest of these facilities.

In January 2017, the world's largest post-combustion capture facility came online at a power plant near Houston, and by October, had already captured 1M tons of CO2. In April 2017, the world's first Bioenergy with Carbon Capture (BECCS) facility came online at an ethanol facility in Illinois, demonstrating the viability of 'negative emissions' technology. In addition to power facilities, carbon capture is being investigated in the industrial sector, which cannot be easily decarbonized without CCUS. The U.S. is a global leader in developing and advancing these technologies.

The Role of Government & Key Investments Needed

Through research, the cost of capture dropped by over 40% between 2000 and 2015. Even with this progress, the pace of CCUS innovation must increase to ensure it is widely deployed in time to prevent the worst impacts of climate change. For each of the three carbon capture pathways (pre-combustion, post-combustion, and oxy-combustion) DOE's research efforts are focused on discovering new chemical pathways, making CO2 capture processes more energy efficient, scaling up CO2 capture technologies to the necessary size for full-scale deployment at fossil energy power systems, and improving the cost effectiveness of novel technologies for CO2 capture so that fossil based systems with carbon capture are cost competitive. Given the enormous complexity, capital-intense nature, and long time frames for carbon capture technology, federal funding and operational oversight remains critical to bringing these technologies to market.

Key DOE Activity Highlights & Contributions

Pre-Combustion RDD&D

> **Recent Accomplishments:** Successfully developed viable pre-combustion and CO2 capture at multiple sites throughout the country under different operating and feedstock conditions.
>
> **FY19 Investment Priorities:** Systems integration of multiple new and early TRL

technologies, into complex plant, gasification and CO2 capture systems for power generation and industrial facilities; R&D to improve conversion efficiency to create lower cost hydrogen for power generation (coal and natural gas – additional authorization to allow natural gas) and fuel; Continued support for pre-combustion R&D at the national Carbon Capture Center (NCCC) and participation in the international CCS Test Center Network.

Post-Combustion RDD&D

Recent Accomplishments: Successful demonstrations of 1st generation and amine-based capture systems; successful lab and pilot testing of 2nd generation capture at .5-1 Mw scale. The core technologies for basic post-combustion capture have been established, setting the stage for more advanced R&D into future transformational technologies for CCUS.

FY19 Investment Priorities: Innovative membrane technologies which can function with next generation and non-aqueous solvents and sorbents; advanced chemical system R&D in order to move beyond amine technologies; Continued solvent R&D, especially catalyzed solvents; Retrofit systems integration; chemical sorbents R&D, including metal organic frameworks, and physical solvents R&D including new ionic liquids; and cryogenic capture. Expanded work on carbon dioxide removal from air (direct air capture, or DAC), which only recently began.

Advanced Combustion (Oxy-Combustion and Chemical Looping) RDD&D

Recent Accomplishments: Results to date include successful early stage cryogenic and membrane separation, boiler and component design for increased operating temperatures, and carbon capture technologies tailored to the operating conditions of these systems.

FY19 Investment Priorities: Chemical looping technologies which can operate at lower parasitic energy requirements; R&D into next generation O2 purification including membranes; application of cryogenic processes including high pressure. R&D to move separators and combustors from lab to pilot scale to allow eventual application in coal and natural gas fired systems (additional authorization needed for natural gas), including applications such as pressurized fluidized bed reactors.

Carbon Storage and Utilization R&D

State of the Industry

Based on 20 years of DOE funded applied research, we now know that the United States has enough subsurface capacity to accommodate at least 900 and perhaps up to 7000 years of carbon pollution from stationary sources at 2016 levels. As of September 2017, over 15 million tons of CO2 had been injected below the ground in the U.S. A host of new technologies have been developed to improve the safety and permanence of CO2 injection, and to monitor injected CO2 and verify its containment. In addition, new markets for CO2 have developed or are developing, including for enhanced oil recovery (which can enable CCS) and for plastics, chemicals, fuels and cement manufacturing. Finally, CO2 has a critical existing commercial application in enhanced oil recovery at a number of locations both in the US and globally.

The Role of Government & Key Investments Needed

While efforts to develop CO2 into a more broadly marketable commodity are ongoing, an overall lack of a functioning national CO2 market and related infrastructure means that federal R&D accounts for the vast majority of funding in the space, and will remain critical in order to drive storage and use/application costs down, in preparation for a future market.

While the size of many subsurface storage reservoirs has been initially characterized, detailed site-specific work is required to confirm onshore and offshore storage geometries and boundaries, prove that CO2 can be pumped in at an adequate rate, and demonstrate that the CO2 will remain stored permanently. In addition, research is needed to develop tools to map and simulate below ground fractures and faults with high degrees of resolution and fidelity, develop wellbore materials that can better resist corrosion by CO2-saturated brine and to increase the ability to monitor and mitigate risk of induced seismicity. Carbon use and reuse research needs include low-cost catalysts and processes that can reduce the cost of CO2 conversion to value added products.

In addition there is need for further R&D into what would effectively be next-generation enhanced oil recovery, or EOR. While industry uses existing naturally occurring CO2 to improve fluid flow and recovery factors in a number of oil reservoirs, there is the opportunity to dramatically increase CO2 injection (which means a portion of the CO2 permanently remains in the ground) via more advanced R&D into rock-liquid-gas systems and subsurface engineering. Done effectively, advanced EOR offers the potential for a lower CO2 footprint than many other sources due to the residual CO2, which remains in the ground or in converted to mineral phase.

Key DOE Activity Highlights & Contributions

Storage Infrastructure RDD&D

Recent Accomplishments: Following the successes of the large and sustained efforts for the Regional Carbon Sequestration Partnerships, new federal investment to date has allowed site-specific characterization and validation for CO2 storage, and has established baseline knowledge of subsurface fluid flow, pressure mitigation and long term storage. It has also provided cost effective monitoring technologies at a large to regional scale and helped address risks and concerns about site integrity and the effectiveness of long-term storage. These are both essential for a functioning CO2 storage market.

FY19 Investment Priorities: Advanced research into materials integrity and durability. Continued need for R&D in data infrastructure and analysis; R&D on both onshore and offshore sites to include stress state characterization.

Advanced Storage R&D

Recent Accomplishments: Highly successful efforts in prior years include the national Risk Assessment Partnerships (NRAP), which developed science-based prediction for engineered geologic systems; the regional carbon sequestration partnerships (RCSPs) which determined the best geologic storage approaches and technologies for 7 sites/ regions in the country; and the carbon storage and facility enterprise (Carbonsafe) which is a more recent effort to design and develop integrated subsurface storage complexes.

FY19 Investment Priorities: Developing storage monitoring, risk assessment and reservoir monitoring technologies suitable for very long-term subsurface storage; Continue and expand funding for Carbonsafe projects.; Next-generation enhanced oil recovery use of CO2, which could provide early commercial storage applications; advanced sensors for monitoring pressure wave conditions in the subsurface.

Carbon Use and Re-use RDD&D

Recent Accomplishments: The program began in earnest only recently. As such, key accomplishments include assessments of viable technology pathways and early support for promising technology companies and research labs.

FY19 Investment Priorities: Focus on catalytic conversion of CO2 (including electrical, thermal, and biological pathways), alone and in combination with other materials such as methane; focus on conversion to durable carbon products such as carbon fiber, carbon black, polycarbonate glass, and cement. mineralization conversion at increasingly material and larger scales; and utilization in conjunction with biologic processes.

Program Support

Recent Accomplishments:

FY19 Investment Priorities: Continued support is needed to complete ongoing NRAP tasks; EDX has evolved to be a world-class online system for energy system data management, and requires continued support. Continued support for international collaborations in order to leverage U.S. technologies faster and at lower cost.

Nuclear Energy R&D

State of the Industry

Nuclear energy currently represents nearly 20% of U.S. electricity production, as well as 60% of all zero-carbon electricity. It represents a highly reliable source of carbon–free electricity that also provides a significant economic benefit of hundreds of high paying jobs to their adjacent communities. In total, there are over 100,000 jobs in nuclear energy. Over the last five years conventional nuclear power generators have faced significant economic challenges competing against low marginal cost resources in wholesale power markets, leading to the early retirement of several reactors. New York, Illinois and Connecticut have enacted policies to compensate nuclear for its low-carbon attributes and keep plants online.

Outside of the existing fleet of nuclear power plants, there is also a growing interest in developing advanced reactor designs with new competitive attributes such as the flexibility to integrate with renewables, to provide high temperature process heat for industrial applications, to operate with reduced or negligible waste yields, and to provide hardened low carbon power for off-grid use. In total, there are over 50 advanced nuclear concepts being developed across the United States, and five of these companies are engaged in pre-application activities with the Nuclear Regulatory Commission (NRC).

The Role of Government & Key Investments Needed

Nuclear energy has unique regulatory challenges that limit the ability of the private sector to conduct full-scale research and development independently, and many of the facilities necessary to complete nuclear R&D are highly capital intensive. Therefore, DOE has a unique role in supporting nuclear energy research and development. A recent report identified that many of the early stage nuclear energy designs being pursed in the United States have economic advantages, but still face technical challenges that must be solved before licensing can begin.

The primary focus of DOE's nuclear energy R&D program is on the infrastructure and technology development needed to enable the next generation of advanced nuclear concepts. The research should focus on those private-public partnerships, currently being driven by a new class of commercial entrepreneurs, that will make new reactor designs both economic and licensable, while enabling fuel cycle security and sustainability.

The DOE investments in nuclear energy innovation include: maintaining critical unique national R&D infrastructure, funding early innovation work that could revolutionize future generation nuclear concepts, and providing research support through private-public partnerships to progress advanced reactor and advanced nuclear fuel concepts. Some specific key activities include developing a fast-spectrum test reactor for accelerated advanced reactor licensing, developing advanced technology fuels (ATF) for use in both conventional and advanced reactors, and supporting the demonstration of small modular reactors.

Key DOE Activity Highlights & Contributions

Nuclear Science User Facilities and Fast-Spectrum Test Reactor Development

- The Nuclear Science User Facilities program provides access to unique world-class nuclear research facilities, technical expertise from experienced scientists and engineers, and assistance with experiment design, assembly, safety analysis and examination and is a critical component of the U.S.'s national infrastructure. A critical missing piece of national infrastructure is a fast spectrum test reactor that can provide a variety of research and development functions. Startup of the facility should commence by 2025

  Recent Accomplishments: Collected significant feedback from industry stakeholders on necessary performance requirements for the fast test reactor (FTR). In FY18, DOE will finalize an assessment of necessary FTR capabilities, components, and preconceptual design work and begin specifying technical attributes.
  FY19 Investment Priorities: Increase Nuclear Science User Facility access and begin initial conceptual design and engineering work for the fast test reactor. Both should target programs that provide the greatest value to the new set of commercial entrepreneurs.

Supporting Early Stage Innovation through Nuclear Energy Enabling Technologies (NEET)

- Competitiveness in modern markets requires a variety of nuclear energy products beyond large gigawatt-scale electricity production. This opens the opportunity to incorporate innovation into many additional aspects of nuclear energy.

  Recent Accomplishments: R&D awards to support modular steel manufacturing techniques and direct metal laser melting techniques and funded 4 new additive manufacturing projects. Provided a modeling & simulation "test stand" that allows commercial users to verify modern simulation approaches. Supporting research and demonstration of advanced monitoring and communication technology for the harsh environments of nuclear system.
  FY19 Investment Priorities: Expanded support for early innovation into product design, manufacturing, materials, sensing, computation, and data analytics establishing a clear pathway for advanced reactor developers to continue with later stage work.

Advanced Reactors

- DOE supports, through national laboratory and university programs, a significant source of expertise that can provide value towards developing new advanced commercial nuclear energy concepts. Since each commercial company may have different research needs, a flexible partnership model for private-public research programs is needed. DOE NE

developed that in the recently released FOA that supports designs in multiple stages of readiness including demonstration; development, and regulatory readiness. This program needs continued support and growth.

Recent Accomplishments: DOE currently supports two five-year advanced reactor development cost-shares, one with X-Energy and one with Southern Company–TerraPower. In December 2017 DOE released the framework for a new FOA that would be funded under this priority.
FY19 Investment Priorities: Provide funding for the advanced nuclear FOA released in December 2017. Focus should be placed technologies and companies bringing significant private cost-share and expertise to the table.

Advanced Fuels Development and Demonstration

- R&D for accident tolerant fuels (ATF) developed for water reactors, TRISO fuels for gas reactors, fast reactor fuels, and molten salt-fueled systems.

Recent Accomplishments: Completion of Phase 1 of ATF program, including multiple feasibility studies and initial irradiation of multiple ATF rods in the ATR; Completion of a large fraction of the TRISO fuel development program.
FY19 Investment Priorities: Continue Phase 2 development of advanced technology fuels (ATF) concepts including ATR irradiations of multiple ATF concepts; beginning transient irradiations in TREAT;, initiating lead test rod demonstration in two commercial reactors and continue post-irradiation examination of previous irradiation campaigns; Continue utilizing CASL code development to further ATF licensing through the development of NRC topical reports that greatly increase plant safety and cost-effectiveness - consider down selection to two concepts for further development; Finish the TRISO fuel testing program; Continued support for fast reactor fuels; Initiate fundamental studies on salt-fuel compositions to support commercial salt reactor development.

Appendix A: Other DOE Offices

Advanced Research Projects Agency for Energy (ARPA-E)

ARPA-E has built its reputation as an innovative model for research activities at the Department of Energy (DOE) since it was first funded in 2009. Modeled after the successful Defense Advanced Research Projects Agency (DARPA) – which is credited with the creation of GPS and the Internet – ARPA-E was created as one of the key recommendations of the National Academy's 2007 Rising Above the Gathering Storm report to ensure the United States doesn't fall behind in science and technology. With a Congressional mandate to overcome long-term and high-risk technological barriers to the development of advanced energy technologies, ARPA-E supports disruptive, pre-commercial projects that have the greatest potential to transform the energy system and improve U.S. productivity and economic growth. Projects are selected through a competitive application process and receive funding for a limited amount of time, along with guidance to meet ambitious project milestones. Teams that fail to demonstrate success or meet milestones are terminated, ensuring funds are used efficiently and only on the most promising technologies.

ARPA-E's Technology-to-Market program – which puts technology scale-up experts onto project development teams to accelerate the pace of commercialization – has been so successful that even DARPA has copied it. As of early 2017, 74 of more than 262 completed projects supported by ARPA-E have attracted over $1.8 billion in private sector follow-on funding, and 56 projects have formed new companies.

Office of Science:

The DOE Office of Science is our Nation's primary supporter of basic physical sciences research. It also plays a critical role in U.S. leadership in other fields including the biological sciences, advanced materials, geosciences, computing and engineering. In subfields such as high energy and nuclear physics, heavy-element chemistry, plasma physics, magnetic fusion, and catalysis the Office of Science is the primary government sponsor. Office of Science-supported research, for example, has led to high-energy storage capacity lithium batteries, energy efficient superconducting wires, DNA sequencing technologies, advanced medical imaging technologies and detectors to identify concealed nuclear weapons and land mines.

The Office of Science supports a diverse portfolio of research at colleges and universities. It sponsors half of all university physics research and more than 22,000 Ph.D. scientists, engineers, graduate students, undergraduates and technical personnel at over 300 institutions through competitively awarded grants. DOE-funded research and education programs strengthen our Nation's scientific knowledge base and prepare the next generation of scientists and engineers.

The Office of Science also supports the operation of the largest collection of major scientific user facilities in the world. Annually, more than 32,000 researchers from U.S. industry,

universities and federal agencies rely on these facilities to meet their scientific and engineering needs. Located at national laboratories and universities around the country, these facilities include particle accelerators, experimental reactors, high-precision instruments, synchrotrons and light sources, leadership-class supercomputers, and high-resolution mass spectrometers. Nearly half of the DOE facility users are university and federal researchers working to answer fundamental science questions. Industry uses these facilities to do the underlying research required to develop new pharmaceuticals, advanced materials for use in manufacturing, telecommunications equipment, and new industrial products that drive the economy. Without these state-of-the-art facilities, U.S. scientists and engineers will carry out their research elsewhere in the world and contribute to the innovation ecosystem abroad.

Office of Technology Transitions (OTT)

OTT was established in 2015 to expand the commercial impact of research conducted within the Department of Energy portfolio. Working across the entire DOE complex, OTT facilitates the transfer of research and technologies from the lab to private sector partners who are best positioned to develop them into products and services that can thrive in the market. The innovation process is dynamic, and successful technology transitions require regular interaction and hand offs between researchers, entrepreneurs, and investors, often in non-linear fashion. OTT works to strengthen the entire ecosystem and set the strategic direction for DOE's efforts to expand the commercial impacts of its investments. OTT also streamlines private sector access to DOE labs and facilities.

Technology Commercialization Fund: The Energy Policy Act of 2005 directs the Secretary of Energy to utilize 0.9% of annually appropriated funding for applied energy research offices to establish a technology commercialization fund. The fund currently provides roughly $20 million per year to both further mature technologies to the point of commercial interest and support cooperative development with high-quality private sector partners to bolster the commercial applications of technologies developed in the national lab system.

Energy Investment Center: The DOE Energy Investment Center (EIC) was established in 2016 to serve as a single point of access for investors to identify a range of resources available to connect with leading experts, locate the latest research, identify promising investment opportunities and develop strategic partnerships. EIC provides technical assistance, project information and hosts stakeholder meetings to facilitate partnerships that accelerate technology transitions.

The Loan Program Office (LPO)

LPO was created in 2005 as a way for the federal government to help commercialize innovative clean energy technologies. Often, new technologies face the "valley of death" -- a period between early stage development and commercial maturity where it is typically difficult to secure financial support. Without federal support during this period, many promising new technologies would likely fail to reach full commercial deployment.

The LPO currently administers two programs: Title XVII and Advanced Technology Vehicle Manufacturing (ATVM). Title XVII provides loan guarantees that help reduce financing costs for innovative clean energy technologies, including solar, wind, geothermal, storage, advanced nuclear, carbon capture, and biofuels. Currently, Title XVII has more than $25 billion in remaining loan guarantee authority across technology these areas, with $12.5 billion available for nuclear, $8.5 billion for advanced fossil, and $4.5 billion for renewables and energy efficiency.

ATVM provides direct loans for advanced, fuel-efficient vehicle technologies with the aim of reducing vehicle emissions, decreasing oil dependence, and supporting domestic manufacturing. To date, ATVM support has resulted in the production of over 4 million advanced technology vehicles. Around $8 billion in loans has been dispersed and roughly $16 billion is still available.

Appendix B: Fiscal Year 2015-2018 Energy Innovation Budget Table

(table below in thousands of dollars)

	FY 2016 Enacted Approp.	FY 2017 Enacted Approp.	FY 2018 Congressional Request	FY 2018 Final House Mark	FY 2018 Senate Mark
Energy Efficiency and Renewable Energy	2,069,194	2,034,582	636,149	1,085,508	1,936,988
Renewable energy:					
Solar energy	241,600	207,600	69,700	90,000	167,500
Wind energy	95,450	90,000	31,700	31,753	72,500
Water power	70,000	84,000	20,400	53,000	82,000
Geothermal technologies	71,000	69,500	12,500	15,000	67,500
Energy efficiency:					
Advanced Manufacturing	228,500	257,500	82,000	102,000	252,000
Building Technologies	200,500	199,141	67,500	91,406	195,000
Sustainable transportation:					
Vehicle technologies	310,000	306,959	82,000	125,000	277,988
Bioenergy technologies	225,000	205,000	56,600	90,000	190,000
Hydrogen and fuel cell technologies	100,950	101,000	45,000	53,000	85,000
Electricity Delivery and Energy Reliability	206,000	229,585	120,000	228,500	213,141
Grid Modernization	99,500	123,000	36,000	110,000	115,141
Cyber Security for Energy Delivery Systems	62,000	62,000	42,000	65,000	53,000
Fossil Energy Research and Development	632,000	661,153	280,000	668,000	572,701
Carbon Capture	101,000	101,000	16,000	95,000	93,930
Carbon Storage	106,000	95,300	15,000	89,073	88,629
Fossil Power and Combustion Systems	170,000	174,500	83,800	203,550	159,495
Nuclear Energy	986,161	1,015,821	703,000	969,000	917,020
Science	5,347,000	5,390,972	4,472,516	5,393,200	5,550,000
Advanced Research Projects Agency - Energy (ARPA-E)	291,000	305,245	20,000	----	330,000