ITIF | INFORMATION TECHNOLOGY & INNOVATION FOUNDATION

Testimony of

Colin Cunliff, Ph.D.

Senior Policy Analyst

Information Technology and Innovation Foundation

Before the

House Committee on Appropriations

Subcommittee on Energy & Water Development

Hearing on

"Strategies for Energy and Climate Innovation"

February 25, 2021

INTRODUCTION

Chairwoman Kaptur, Ranking Member Simpson, and Members of the House Appropriations Committee, thank you for the opportunity to appear before you to discuss federal investment in energy innovation.

My name is Colin Cunliff. I am here representing the Information Technology and Innovation Foundation (ITIF), a non-profit, non-partisan think tank that focuses on accelerating innovation to spur growth, opportunity, and progress. I co-authored the volume *Energizing America: A Roadmap to Launch a National Energy Innovation Mission*, which charts a course to accelerate U.S. clean energy research (ITIF and Columbia University, 2020). I am also currently serving on the National Academies of Sciences, Engineering, and Medicine (NASEM) committee that produced the recent report *Accelerating Decarbonization of the U.S. Energy System*.

Innovation is critical to combat climate change. The National Academies report on accelerating decarbonization finds that "deep decarbonization is technically feasible, but proactive innovation is essential."

Fortunately, bipartisan support for clean energy innovation is surging. Over the last four years, this committee has overseen a 40 percent increase in clean energy R&D programs at the Department of Energy (DOE).[1] The recently passed Energy Act of 2020 includes the legislative priorities of more than one hundred members of Congress and provides the first reauthorization of DOE programs in more than a decade.

As this committee considers how to implement the Energy Act, it must wrestle with questions about the scale and scope of DOE's programs. I hope my testimony can be useful as you begin consideration of fiscal year 2022 appropriations.

Main Points

My testimony today will have three core points:

First, greater federal investment in innovation is essential to address climate change and boost U.S. competitiveness in clean energy.

Second, prioritize funding to research, development, and demonstration (RD&D) and deployment programs around ten critical decarbonization needs.

Third, diversify the innovation portfolio (by technology, innovation stage, federal agency, research performer, and geographic region) to maximize the effectiveness of federal investments.

GREATER FEDERAL INVESTMENT IN INNOVATION IS ESSENTIAL TO ADDRESS CLIMATE CHANGE AND BOOST U.S. COMPETITIVENESS IN CLEAN ENERGY.

DOE currently invests about $7 billion in clean energy research, development, and demonstration (RD&D) across the applied energy programs, ARPA-E, and the basic energy sciences.[2]

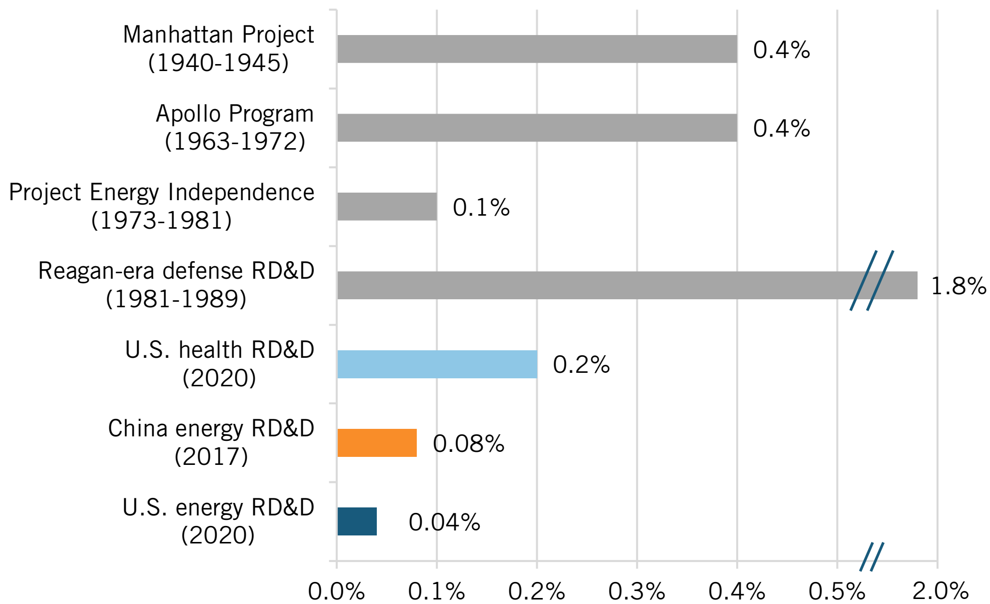
But current funding levels are not sufficient to generate the pace of innovation needed to address climate change. The International Energy Agency (IEA) finds that nearly half of the global annual emissions reductions necessary to decarbonize by 2050 will likely come from technologies that are in early stages of development but are not yet commercially available.[3] According to IEA, only 6 out of 40 critical energy technologies are "on track" to achieve a net-zero emissions energy system.[4]

In its recent report *Accelerating Decarbonization of the U.S. Energy System*, the National Academies of Sciences, Engineering, and Medicine (NASEM) calls for greater investment in innovation to match the scale of the climate challenge while also advancing U.S. competitiveness in clean energy. The Academies recommends **tripling investment in clean energy research, development, and deployment (RD&D) at the Department of Energy**.[5]

The tripling target has also been recommended by the American Energy Innovation Council (AEIC), the Center for Climate and Energy Solutions (C2ES), the *Energizing America* volume, and by the President's Council of Advisors on Science and Technology in 2010.[6]

This target is both ambitious and measured. Other national innovation missions in space, health, and defense show that the United States can marshal its innovative capacity on a much larger scale than it currently does for energy (figure 1). Federal investment in RD&D has accelerated the development of life-saving drugs, modernized the military's arsenal, and put a man on the Moon. By comparison, the federal government has neglected energy innovation.

Figure 1. Federal RD&D funding as a percent of GDP for selected national innovation missions.[7]



U.S. leadership in clean energy RD&D is now being challenged by China and Europe. China doubled its investment in clean energy RD&D between 2015-2020 to $8 billion annually, putting it ahead of the United States for the first time.[8] And 13 other countries invest more in energy RD&D as a share of their economies than the United States.[9] As other countries have stepped up their investments in clean energy, the share of cleantech patents granted to U.S. companies by the U.S. Patent and Trade Office has declined, from roughly 50 percent in 2001 to less than 40 percent in 2016, indicating that U.S. leadership in innovation is on the decline.[10]

Tripling DOE's energy RD&D programs can reverse this decline and restore U.S. leadership in clean energy innovation.

Capturing growing global markets

Greater investment in innovation can also improve the competitiveness of U.S. industries. Global annual investment in energy was nearly $2 trillion in 2019, and the share going to clean energy is increasing rapidly. Investment in renewable energy grew to $304 billion in 2020. Investment in electric vehicles surged to $139 billion in 2020, beating the previous year by 28 percent despite the economic disruption caused by the COVID-19 pandemic.[11] Significant economic opportunities await countries that can supply new and growing clean energy markets.

The United States was once a global leader in developing new energy technologies. For example, scientists at Bell Labs in New Jersey created the first solar cell in 1957, and strong and steady procurement from the Navy and NASA allowed American solar companies to serve the market in its early days.[12] Since the turn of the century, however, the United States has ceded much of its original leadership. Only one of the top 10 solar PV manufacturers, First Solar, is an American firm (eight are Chinese, one is South Korean), and U.S. companies' share of the global solar market has dropped below 10 percent.[13]

As countries around the world seek to stimulate their economies and recover from the COVID-19 crisis, the United States could fall further behind in a range of technology areas. The European Union announced more than $200 billion in climate-friendly economic recovery investments, such as clean hydrogen infrastructure.[14] The Chinese government has announced a "new infrastructure" package worth $1.4 trillion that will include investments in advanced energy industries and infrastructure. Japan, the European Union, and 11 other nations have launched national hydrogen strategies and are investing heavily in electrolyzers, fuel cells, and other hydrogen technologies.[15]

These trends are disturbing. The decline of the U.S. manufacturing sector has cost the economy high-quality jobs, increased income inequality, and contributed to public dissatisfaction. The National Academies accelerating decarbonization report argues that "**the United States should attempt to claw these industrial sectors and markets back, so that it leads the world both in innovation and in the manufacturing and marketing of advanced clean energy technologies**."

One cause for optimism cited in the Academies report is that the United States is the best-resourced nation in the world for a transition to a net-zero emissions energy system. It has abundant solar and wind resources both onshore and offshore. Additionally, 40 million acres already are devoted to producing biofuels. The country has plentiful and economically accessible natural gas, and enormous geologic and terrestrial reservoirs for CO_2 sequestration. A transformation to a net-zero economy could combine these natural assets with the nation's culture of innovation to regain global leadership and competitiveness in clean energy technology, modernize and transform the U.S. manufacturing base, and create a new generation of clean energy jobs.

PRIORITIZE DOE'S ENERGY RD&D PROGRAMS AROUND 10 CRITICAL DECARBONIZATION NEEDS.

The *Energizing America* report identifies a set of 10 critical decarbonization challenges that should form the basis of the federal innovation agenda. These decarbonization challenges group technologies based on distinct applications, each representing a particular set of technology solutions. For example, nuclear and renewable power generation are grouped in the "Challenge 4. Clean electricity generation." Energy storage and energy efficiency technologies are distributed across multiple challenges because they serve multiple functions.

This approach, rather than a technology-based structure, places the focus on achieving the functionality needed for deep decarbonization. This focus on critical applications should help policymakers decide which technologies to fund. The highest priorities include:

1. **Clean manufacturing and industrial decarbonization**, including electrification of process heat, hydrogen applications, and carbon capture for industrial sources such as cement and steel
2. **Advanced vehicles and transportation systems,** including battery and fuel cell electric vehicles, DC fast chargers, vehicle lightweighting, efficiency technologies for medium- and heavy-duty vehicles
3. **Energy efficient and net-zero energy buildings**, including advanced heat pumps, solid-state cooling, alternative building materials, high-performance windows, and grid-integration
4. **Clean electricity generation**, including advanced nuclear reactors, thin-film solar PV, floating offshore and high-altitude wind, run-of-river hydropower, and enhanced geothermal systems
5. **Zero- and low-carbon fuels**, including sustainable biofuels, hydrogen from electrolysis or biomass gasification, ammonia, and synthetic hydrocarbon fuels
6. **Grid modernization technologies,** including long-duration grid-scale energy storage, power electronics, and digital technologies that enable grid integration of buildings and vehicles
7. **Carbon capture, use, and sequestration (CCUS)**, including the Allam cycle for natural gas power generation; and carbon capture for industrial sources such as cement and steel
8. **Carbon dioxide removal / negative emissions technologies**, including direct air capture and storage (DACS), carbon mineralization, and bioenergy with carbon capture and storage (BECCS)
9. **Clean agricultural systems**, including fertilizer management, precision agriculture, soil carbon storage, and biotechnologies to enhance carbon storage
10. **Foundational science and platform technologies**, including advanced materials, electrochemistry, quantum computing, genomic sciences, 3D printing, smart manufacturing, and machine learning

The appendix of this testimony includes a set of more than 40 detailed, specific recommendations from the *Energizing America* report for new initiatives across DOE and other agencies to build out each pillar's portfolio of activities.

DIVERSIFY THE FEDERAL INNOVATION PORTFOLIO ACROSS MULTIPLE DIMENSIONS—BY TECHNOLOGY, INNOVATION STAGE, FEDERAL AGENCY, RESEARCH PERFORMER, AND GEOGRAPHIC REGION—TO MAXIMIZE THE EFFECTIVENESS OF FEDERAL INVESTMENTS.

These six strategic principles should guide federal funding for energy innovation. The first five of these principles recommend ways that the federal government can diversify its investments—across decarbonization challenge, stages of innovation, federal agencies, research partners, and regions of the United States. This sixth principle recommends a strategy for managing the portfolio over time.

These principles are grounded in a wealth of academic research on designing RD&D portfolios and lessons from previous funding increases, and are intended to maximize the effectiveness of federal investments.

1. **Match the funding portfolio to critical decarbonization needs.** As federal funding ramps up, increases should be targeted to under-resourced sectors, particularly the end-use sectors (manufacturing, buildings, and transportation) and crosscutting technologies such as clean fuels and CCUS.

2. **Support all stages of the innovation pipeline, particularly technology scale up and commercialization.** Demonstration projects and market formation are needed to complement technology R&D.
3. **Marshal the full capacity of the federal government.** DOE should collaborate with other agencies where missions overlap, particularly DOD and NASA for dual-use technologies (e.g. high-density batteries, fuel cells, advanced solar, advanced nuclear and microreactors, and smart grids).
4. **Expand collaborations with external research partners at universities and in the private sector** through public-private partnerships such as the energy innovation hubs and the Manufacturing USA institutes.
5. **Partner with state and local governments to support regional innovation.** Federal facilities, from National Laboratories to Manufacturing USA institutes, should work with state and local governments to cultivate regional innovation clusters.
6. **Set predictable long-term funding targets**. The federal government should commit to a high-level funding roadmap, to reduce volatility in energy innovation funding.

My testimony explores three of these principles in more depth.

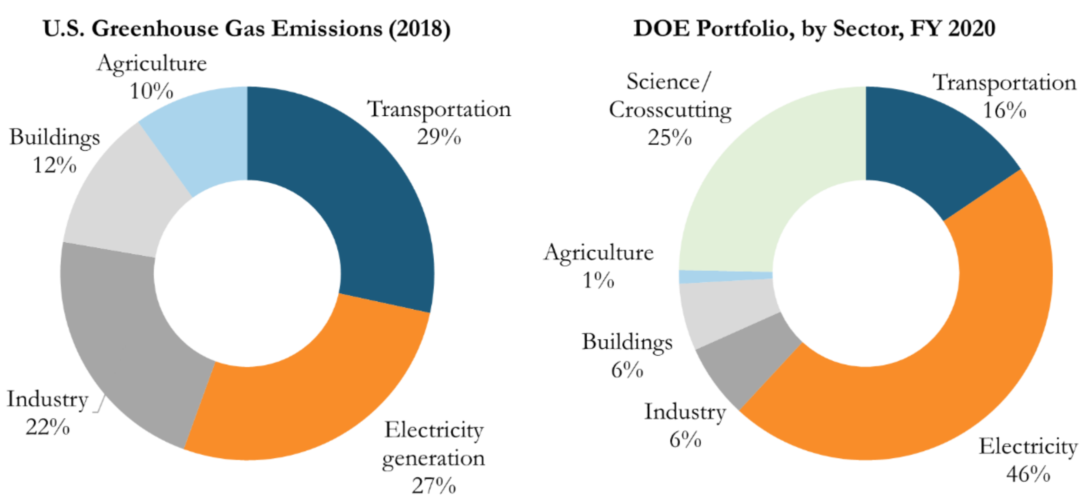
Match the research portfolio to critical decarbonization needs

U.S. federal funding for energy innovation is grossly imbalanced across the key decarbonization challenges. As figure 2 illustrates, half of current DOE funding for energy RD&D supports technologies to generate and deliver electricity. Energy science and crosscutting technologies account for a quarter of the portfolio. The end-use sectors—transportation, buildings, and industry—account for disproportionately small shares. For example, the industrial sector accounts for 22 percent of direct U.S. greenhouse gas emissions but only 6 percent of DOE's research portfolio.

The United States is not alone in failing to align its public RD&D funding with critical decarbonization technology needs. The International Energy Agency as found that the world's major economies allocate too much funding to "supply side technologies, rather than the types of end-use innovations needed for sectors that currently have no commercially available and scalable options for achieving deep emissions reductions."

As federal funding ramps up, increases should target the under-resourced pillars for the largest increases. These include the end-use sectors, as well as clean fuels, carbon capture, and carbon dioxide removal.

Figure 2. U.S. GHG emissions compared with the FY20 allocation of DOE energy RD&D funding



Support later-stage demonstration and commercialization activities

Shepherding clean energy technologies from concept to commercialization requires a holistic approach that supports all stages of the innovation pipeline. DOE's current portfolio is heavily weighted toward early-stage research and development. The government devotes less than 5 percent of its energy RD&D funding to demonstration projects, mostly in advanced nuclear.[16]

Multiple gaps in private funding, or valleys of death, exist on the path to commercialization. The National Academies of Sciences, Engineering, and Medicine (NASEM) accelerating decarbonization report highlights the "critical gap in government funding between basic research and commercialization," noting that the demonstration stage is particularly underfunded. Demonstration projects are important for scaling up technologies that show promise in the laboratory setting and for validating technologies under real-world conditions. But demonstration projects generally entail too much technology and financial risk to for the private sector to bear on its own.

Congress has recognized this gap, and repeatedly affirmed its support for later-stage R&D and demonstration activities. The Energy Act of 2020 directs DOE to support 17 technology demonstration projects across four technology areas: carbon capture; advanced nuclear; energy storage; and geothermal. This is a promising start, and I hope this committee will fully fund these projects. But more demonstrations are needed, across a wider set of technologies.

Congress also authorized the Office of Technology Transitions and the Technology Commercialization Fund, and included a number of other provisions in the Energy Act of 2020 aimed at facilitating commercialization of DOE-funded research and improving public-private partnerships.[17] These are key steps in addressing the commercialization gap, and I look forward to working with Congress and DOE toward their successful implementation.

Support states in fostering regional clean energy innovation ecosystems

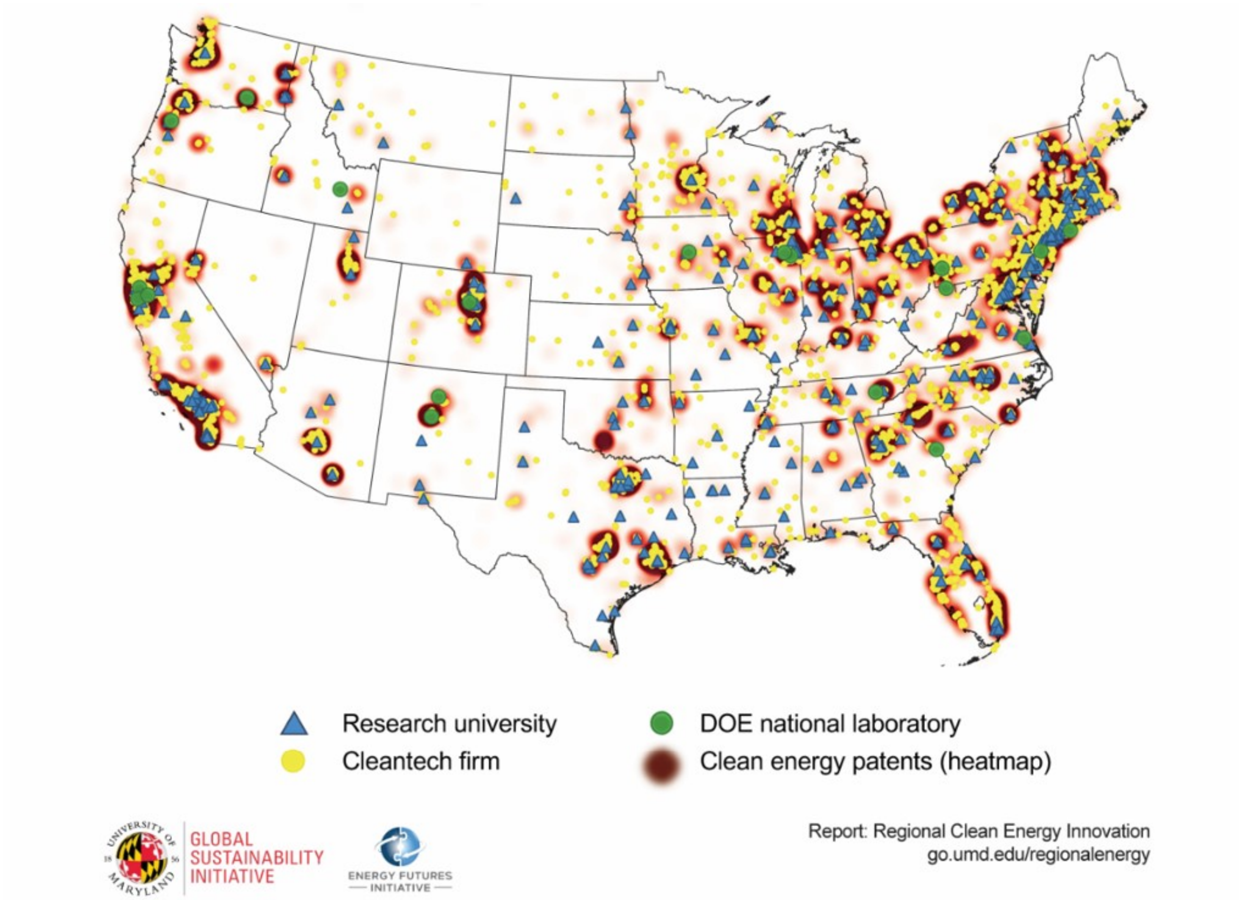
States bring different energy priorities, energy resources, and regional industries to clean energy innovation. Policymakers should leverage this diversity by ensuring that federal funding helps cultivate flourishing regional innovation ecosystems. Doing so will bring local economic benefits to communities around the country and stimulate globally competitive industries.

Many states are engaged in energy technology transition, commercialization, and early deployment in a way that complements federal research programs, making states a natural partner for federal tech transfer and commercialization efforts. Because their goal is often to promote an in-state cleantech industry, states typically invest at a later stage of technology maturation, when they can more readily capture a return on their investment. State support for clean energy innovation is usually focused on scaling up and commercializing energy technologies; supporting and incubating cleantech startups; helping innovative companies apply for federal research grants; supporting early market formation; and attracting greater private sector investment.[18]

The federal government should support more states in fostering regional clean energy innovation ecosystems. Federal policymakers have several options to do so. They can provide funding to state and local governments, which are well-placed to invest in local energy RD&D. Federal agencies can also offer technical assistance to state and local governments designing energy innovation programs and strategic economic development plans. Moreover, federal facilities, from National Laboratories to Manufacturing USA institutes, should work with state and local governments on coordinated strategies to cultivate regional innovation clusters. Such clusters would benefit from clean energy start-up incubators and accelerators, as well as public support for locally sited demonstration projects.[19]

Another opportunity to facilitate commercialization and support regional innovation clusters is through a DOE Foundation, which ITIF described in its Minding the Gap report last year.[20] In its fiscal year 2020 bill, this committee requested a National Academy of Public Administration (NAPA) report on this topic from DOE.[21] I look forward to seeing the report soon.

Figure 3. Clean energy innovation activity (patents and startups) is dispersed across the United States, but clusters around DOE national laboratories and research universities.[22]



CONCLUSION

The United States has a proud history of rising to global challenges by unleashing its potential to innovate. If policymakers decisively invest in the clean energy technologies of the future and sustain that investment, history can repeat itself. On the heels of the global coronavirus crisis, the United States should lead the response to climate change and prosper as the world transitions to clean energy. As this committee considers its fiscal year 2022 appropriations, it has a tremendous opportunity to accelerate the domestic clean energy industry and shape the U.S. response to climate change. It should build off the foundation paved by the Energy Act of 2020, and continue to elevate energy innovation as a national priority.

APPENDIX 1: TEN DECARBONIZATION CHALLENGES—TARGETED RECOMMENDATIONS

(modified from Energizing America: A Roadmap to Launch a National Energy Innovation Mission*)*

The federal innovation agenda should be organized around ten critical decarbonization challenges, each representing a particular set of technology solutions. These decarbonization challenges group technologies based on distinct applications. For example, nuclear and renewable power generation are grouped in the "Challenge 4. Clean electricity generation." Energy storage and energy efficiency technologies are distributed across multiple challenges because they serve multiple functions.

Historically, the United States has organized energy RD&D around resources such as oil, gas, coal, nuclear, or renewable energy, which has weighted the portfolio heavily toward the supply side. We propose a different approach: Rather than a technology-based structure, place the focus on achieving the functionality needed for deep decarbonization. This focus on critical applications should help policymakers decide which technologies to fund. This approach places the focus on achieving ends, which is what ultimately matters for deep decarbonization.

This approach is conceptually similar to how the various institutes within NIH focus on diseases and conditions, even as the agency as a whole advances a broad range of scientific and engineering disciplines, clinical practices, and treatment technologies.[23] In energy, the federal government's existing innovation activities already include initiatives that could be classified under each of the key decarbonization challenges. But the levels of investment across the challenges are highly imbalanced, leaving a range of critical gaps. Going forward, policymakers should construct more coherent, robust, and targeted portfolios of RD&D investments to advance each of the ten sectors.

The sections below introduce each of the ten decarbonization challenges with:

- A **description** of the pillar and an explanation of its role in deep decarbonization
- An overview of selected **recent initiatives** within the federal energy RD&D portfolio that advance the pillar
- **Recommendations** for selected new initiatives across the federal government to build out each pillar's portfolio of activities (To be clear, these recommendations are not intended to be comprehensive; rather, they represent near-term, high-value opportunities identified in legislative proposals, agency program reviews, and the research literature.)

1. Clean manufacturing & industrial decarbonization

Description: The industrial sector is the third largest source of direct US greenhouse gas emissions, accounting for 22 percent of the total (not including indirect emissions from electricity consumption). Since 2008, US industrial emissions have stubbornly remained at about 1.4 billion metric tons per year.[24] Heavy industry—including cement, iron and steel, and chemicals production—is especially challenging to decarbonize.[25] Additionally, the long lifetime and slow stock turnover of industrial manufacturing facilities impedes the transition to clean manufacturing. Despite these challenges, the industrial sector accounts for a relatively small share—about 6 percent—of the total clean energy innovation funding portfolio.[26]

Recent initiatives: Existing federal programs in the DOE Advanced Manufacturing Office (AMO) and the NIST Hollings Manufacturing Extension Partnership (MEP) focus primarily on reducing the energy intensity of manufacturing. DOE's energy bandwidth studies identify opportunities for improving the manufacturing energy intensity across 16 industry subsectors.[27] The DOE-AMO Clean Energy Manufacturing Innovation (CEMI) Institutes are collaborative partnerships with manufacturers to develop clean manufacturing processes in six key technology areas: wide band-gap semiconductor manufacturing; carbon-fiber composite manufacturing; smart manufacturing; chemical process intensification; reducing embodied emissions; and improving cybersecurity. The first five areas are a subset of fourteen high-priority, energy-related advanced manufacturing technologies identified in the 2015 *Quadrennial Technology Review*.[28] In FY20, Congress directed AMO to develop a series of sector-specific decarbonization roadmaps to guide RD&D activities across DOE.[29]

Recommendations: The federal government should increase investment in industrial decarbonization programs, and expand their mandate to encompass all decarbonization opportunities, including efficiency, electrification, clean fuels, and industrial carbon capture:

- Congress should fully fund the Industrial Emissions Reduction Technology Development Program (authorized in the Energy Act, Division Z Sec. 6003) to provide greater direction and long-term program stability in this area.[30]
- DOE should expand programs in clean fuels—which currently focus on transportation fuels—to include applications in the industrial sector.
- DOE should expand programs in carbon capture technologies—which currently focus on power plant applications—to include their use in heavy industry, particularly cement, steel and chemicals.
- DOE-AMO should establish additional CEMI institutes in the other high-priority advanced manufacturing technologies identified in the *Quadrennial Technology Review.*[31]
- NSF should expand its the Engineering Research Center and Industry/University Cooperative Research Center Programs and develop more centers oriented toward clean manufacturing.[32]

2. Advanced vehicles and transportation systems

Description: The transportation sector accounts for nearly 70 percent of petroleum use and 28 percent of US greenhouse gas emissions, recently surpassing power as the top-emitting sector.[33] Electric vehicles (EVs) are an increasingly cost-competitive low-carbon alternative to gasoline and diesel passenger cars and trucks. The purchase price for electric vehicles is projected to reach parity with conventional gasoline vehicles between 2020 and 2030.[34] Barriers to greater electrification include the higher purchase price of EVs, range anxiety, lack of charging infrastructure, and long charging times. Air travel, shipping, and long-distance trucking require very energy-dense fuels, with limited opportunities for electrification, unless far more energy-dense batteries are developed.[35] For these sectors, clean fuels such as hydrogen, ammonia, synthetic fuels, and advanced biofuels are long-term decarbonization options. Vehicle lightweighting, improved fuel economy, mode-shifting, and other efficiency improvements can reduce emissions and fuel use and contribute to US energy security in the near-term, even as clean fuel options are being developed for the long-term.

Recent initiatives: DOE's Vehicle Technologies Office (VTO) has established targets of reducing the cost of batteries to 100 dollars per kilowatt-hour ($100/kWh), increasing their range to 300 miles, and decreasing charging time to 15 minutes or less by 2028, with an ultimate cost goal of $60/kWh for batteries.[36] The SuperTruck II program set a target of doubling the freight-hauling efficiency of heavy-duty Class 8 long-haul trucks by 2020, over the 2009 efficiency level.[37] DOE has established targets for fuel cell cost and durability that would make fuel cell electric vehicles cost-competitive with internal combustion engine vehicles by 2030.[38] The Department of Transportation's (DOT) Federal Transit Authority funds public transportation infrastructure research and demonstration projects to reduce transit emissions.[39]

Recommendations: The federal government should expand investment in advanced transportation systems to enable rapid near-term electrification of passenger cars and trucks and efficiency improvements across all transportation subsectors, while at the same time investing in the long-term zero-carbon technologies for heavy-duty transport.

- DOE should increase RD&D funding levels to accelerate cost reductions in advanced batteries and fuel cells. For example, DOE's current goal is to reduce the cost of batteries for EVs to $100/kWh by 2028, but market analysis such as Bloomberg New Energy Finance's *Electric Vehicles Outlook* suggests this cost target could be met on an accelerated timeline.[40]
- DOE should expand R&D and demonstration of fast-charging for EVs, as charging time has been identified as one of the barriers to deployment of EVs.[41]
- DOE should launch a SuperTruck III program to double the freight-hauling efficiency of heavy-duty Class 8 trucks by 2025.[42]
- DOE and the DOT should create new programs for shipping; aviation; and energy management and electrification at ports and airports, which have traditionally been overlooked in federal transportation RD&D programs.[43]
- DOT should expand its programs for RD&D in low-carbon urban transit and rail systems.

3. Energy efficient and net-zero energy buildings

Description: Residential and commercial buildings are the single largest energy-consuming sector in the US economy, accounting for roughly 75 percent of the nation's electricity use and 40 percent of its total energy demand.[44] As a result, Americans spend nearly $400 billion each year to power their homes, offices, schools, hospitals, and other buildings.[45] There are substantial opportunities to improve efficiencies in lighting, space conditioning and refrigeration, water heating, appliances, and building envelopes and windows, as well as opportunities to improve building-grid integration. DOE estimates that advances in solid-state lighting (SSL) alone can save up to 5 quadrillion British thermal units (quads) per year by 2035, or about $50 billion in annual energy savings.[46] Emerging refrigerant-free technologies such as advanced evaporative cooling and solid-state cooling can reduce reliance on high-global-warming-potential refrigerants. Cheaper and more efficient heat pumps can enable homes and buildings to use clean electricity for heating in place of fossil-fueled furnaces. Alternative building materials such as cross-laminated timber can substantially reduce the carbon content of buildings compared with materials such as reinforced concrete.[47] Improving efficiencies in urban, suburban, and rural infrastructure saves consumers in energy costs, improves indoor and outdoor air quality, avoids unnecessary electricity and natural gas capacity buildouts, and reduces carbon dioxide emissions. Despite the multiple benefits, the buildings sector accounts for just 6 percent of the clean energy innovation funding portfolio.

Recent initiatives: The DOE Building Technologies Office (BTO) has set the goal of reducing the average energy use per square foot of all US buildings by 30 percent by 2030, with a long-term goal of reducing the energy intensity of homes and commercial buildings by 50 percent or more. In addition to whole-building targets, DOE has set standards and goals for improved efficiency of energy services within buildings, including lighting, water heating, HVAC, building envelope and windows, appliances, and sensors and controls.[48] The Better Buildings Initiative supports collaborative partnerships with businesses, schools, state and local governments, residential organizations, and other stakeholders to accelerate the uptake and continued improvement of building innovations.[49]

Recommendations: The federal government should scale up its investments to take full advantage of all building technology decarbonization opportunities.

- Congress should increase federal investment in buildings and appliances RD&D programs, so that funding is commensurate with the scale of decarbonization needs.
- DOE and EPA should increase research in low-global-warming-potential alternatives to F-gas refrigerants, and DOE should develop refrigerant-free air conditioning technologies, such as solid-state cooling.[50]
- DOE should expand investment in advanced air flow, air sealing, and ventilation controls, as well as high-performance windows.
- DOE should expand investment in grid-integrated efficient buildings (GEBs) and connected communities, which enable more flexible and resilient energy systems.[51]

4. Clean electricity generation

Description: Clean electricity supply can power much of a future low-carbon economy. The United States has made notable progress already on this pillar, thanks in no small part to significant federal RD&D investment. Emissions from the U.S. electric power sector declined by more than 33 percent from 2007 to 2019. As of 2018, wind or solar power was the cheapest source of new electricity generation in 34 percent of U.S. counties.[52] In addition, clean electricity offers a route to decarbonize other sectors, including transportation, building heating and cooling, and some important industrial processes.

Next-generation renewables—including advanced, thin-film solar PV; floating offshore and high-altitude wind; enhanced geothermal systems; and run-of-river hydropower—may expand carbon-free renewable electricity to parts of the country with untapped potential. Advanced nuclear reactors, including small modular reactors, with standardized components may enable a new generation of low-cost, flexible dispatchable nuclear power.[53] (Electricity generation utilizing fossil fuels in combination with CCUS is covered in decarbonization challenge 7.)

Recent initiatives: DOE has set aggressive solar energy and wind energy cost goals (e.g., $30/MWh for utility-scale solar PV and $23/MWh for land-based wind energy by 2030) that would make electricity from wind and solar among the cheapest sources of electricity for most of the country.[54] DOE's 2019 *GeoVision* report provides a roadmap for developing enhanced geothermal systems (EGS) technologies. However, the geothermal cost target of $60/MWh by 2050 may not be sufficiently aggressive for geothermal energy to contribute on a climate-relevant timeline.[55] DOE recently completed construction on the Frontier Observatory for Research in Geothermal Energy (FORGE), the agency's flagship geothermal research facility where industry and government researchers can test and validate EGS technologies in a deep-rock environment.[56] DOE's *Hydropower Vision* and *Powering the Blue Economy* reports provide roadmaps for jumpstarting innovation in hydropower and marine and hydrokinetic (MHK) technologies, respectively, but Congress must now provide sufficient funding to address the RD&D needs identified in the reports.[57] Congress established a new Advanced Reactor Demonstration Program to build and demonstrate two advanced reactor designs by the mid-2020s, and also directed DOE to build a Versatile Test Reactor user facility to enable private-sector companies to test and validate advanced reactor materials and fuel designs.[58] In April 2020, DOE released the report *Strategy for Restoring America's Competitive Nuclear Energy Advantage*.[59]

Recommendations: The federal government should expand investment in advanced clean electricity generating technologies.

- DOE should partner with DOD to develop the next generation of solar PV technologies, including low-cost and scalable manufacturing techniques.[60]
- DOE should set a more aggressive 2030 cost target for offshore wind to frame its RD&D activities, especially large-scale demonstration projects. (The current target is $51/MWh by 2030, but the National Renewable Energy Laboratory (NREL) Annual Technology Baseline (ATB) 2019 report uses bottom-up technology and cost modeling to conclude that a cost less than half the current target is achievable by 2030.[61]) Congress should provide additional funding for DOE to meet its new targets on an accelerated schedule.
- Congress should increase funding for marine and hydrokinetic and advanced hydropower technologies, in order to meet innovation targets identified in the *Hydropower Vision* and *Powering the Blue Economy* roadmaps on an accelerated timeline.[62]
- DOE should increase the ambition of its geothermal program and set a more aggressive cost target (the current target is $60/MWh by 2050) to frame its RD&D program, in line with the NREL ATB low technology cost scenario.[63] Congress should provide additional funding for the federal government to meet its geothermal goals on an accelerated timeline.
- Congress should provide sufficient funding for DOE to build the fast neutron Versatile Test Reactor and to demonstrate at least two advanced reactor technologies by 2030, as authorized in the Energy Act of 2020. DOE and DOD should partner to develop advanced microreactors.[64]

5. Zero-carbon fuels

Description: Clean fuels—including sustainable biofuels, hydrogen, ammonia, and synthetic hydrocarbon fuels that are made using energy from renewables or other low-carbon energy sources—will be needed for multiple hard-to-decarbonize sectors.[65] Hydrogen can be used for propulsion in fuel cell electric vehicles, combusted to provide high-temperature heat for industrial processes, or converted to electricity when needed to balance variable generation from renewables. Synthetic hydrocarbon "drop-in" fuels made from hydrogen and captured carbon dioxide can be used as transportation fuels in conventional engines. Biofuels produced from crops that are sustainably harvested and converted using low-carbon energy might provide a backstop for transportation sectors where energy density requirements preclude electrification via batteries (i.e., aviation, shipping, and long-distance road transport). And ammonia—already synthesized in large quantities for fertilizer use—can be used as a fuel in combustion turbines, maritime engines, or fuel cells.[66] But current clean fuels programs focus on a limited set of clean fuel options (primarily biofuels and hydrogen) for a limited set of applications (primarily for use in passenger cars and trucks).

Recent initiatives: The DOE Hydrogen and Fuel Cells Technologies Office (FCTO) is currently targeting a system-wide hydrogen cost (production plus delivery and storage) of $4/kg in order to be cost-competitive with gasoline on a cents-per-mile-driven basis.[67] In June 2020, DOE announced its intent to invest up to $100 million over five years in two new National Laboratory–led consortia to develop hydrogen and fuel cell technologies.[68] ARPA-E's REFUEL program funds research in both the production of clean fuels (including ammonia and dimethyl ether) and their conversion to electricity or hydrogen.[69] The Joint Center for Artificial Photosynthesis (JCAP) funded by the Office of Science (SC) funds basic research in the production of synthetic fuels from sunlight, water, and carbon dioxide.[70] In FY20, the Department of Defense launched a new program (SEA FUEL) to develop technologies that can convert carbon dioxide captured from the air or from sea water into fuel, for use on remote bases and ships at sea.[71]

Recommendations: The federal government should expand its research to include a broader set of clean fuel options, and should research applications of clean fuels in hard-to-electrify transportation sectors and heavy industry.

- DOE should expand its applied clean fuels programs—which currently focus on hydrogen and biofuels for the transportation sector—to include a broader range of fuels and applications. Clean fuels production programs (in the DOE offices FCTO, BETO, ARPA-E, and FE) should include ammonia and direct air capture to fuels (DAC-to-fuels).[72] AMO should research potential applications of clean fuels in industrial sectors (e.g., for the provision of clean heat), consistent with the Industrial Emissions Reduction Technology Development Program (authorized in the Energy Act of 2020, Division Z, Sec. 6003).[73]
- DOE-SC should establish a second innovation hub, in the model of JCAP, that focuses on novel, low-cost methods of hydrogen and ammonia production that do not lead to CO_2 emissions.[74]
- DOE should create a new solar fuels program—building off the success of JCAP—in the applied energy offices.[75]
- Biofuels programs at USDA and DOE should focus on developing drop-in fuels for aviation, shipping, and other hard-to-electrify transportation sectors.[76]

6. Grid modernization

Description: Modern electric power systems featuring enhanced flexibility and digital capabilities are needed to accommodate greater penetrations of distributed and variable energy resources, enable greater consumer preference over consumption, support electrification of building, transportation, and industrial energy applications, and provide enhanced emergency preparedness and resiliency. The current grid does not provide sufficient flexibility and resilience to meet the needs of a 21st century clean electricity system. Long-duration grid-scale energy storage is critical to help match electricity supply and demand, so that electricity generated by intermittent sources such as wind and solar can be stored for when it is needed.[77] Power electronics such as solid-state power substations offer the potential for greater standardization and improved resilience of grid components and systems.[78] Digital technologies to monitor and manage the grid—including turning buildings, factories, and vehicles into flexible resources for demand response and storage—can enhance efficiency, reduce peak demand, and avoid expensive investments in generating capacity and grid infrastructure that raises electricity bills.[79]

Recent initiatives: In 2020, the Trump administration launched the cross-cutting Energy Storage Grand Challenge Initiative to coordinate storage R&D efforts across DOE offices.[80] Additionally, the administration began construction on the Grid Storage Launchpad to develop, test, and evaluate batteries and other storage technologies for grid applications.[81] In 2015, DOE launched a multiyear, cross-cutting Grid Modernization Initiative bringing together government and industry researchers to identify and coordinate research activities across DOE.[82]

Recommendations: The federal government should expand investment in electricity transmission, storage, and distribution technologies that provide greater flexibility and enable clean electrification and energy systems integration.

- Congress should increase funding for RD&D for operating advanced distribution grids that harness communication infrastructure, digital controls, and a layered architecture of autonomous systems to flexibly marshal distributed generation, storage, and demand resources, consistent with the Grid Modernization programs authorized in the Energy Act of 2020 (Title VIII).[83] DOD should redouble investments in demonstrating advanced microgrids to secure military bases, and DOD and the Department of the Interior (DOI) should expand collaboration to develop advanced energy systems on public lands.[84]
- Congress should fully fund the Better Energy Storage Technology (BEST) Act (authorized in the Energy Act of 2020, Title III, Subtitle C) to support energy storage research and expand DOE's RD&D program to develop and validate storage technologies across multiple timescales—spanning hourly to seasonal storage—and multiple technologies, including batteries and pumped hydropower.[85]
- DOD and DOE should launch a joint storage demonstration program to leverage and coordinate research in high-energy-density storage media.[86]
- Congress should establish a DOE research program on recycling lithium, cobalt, and other materials used in energy storage in order to reduce supply chain risks and dependence on imports. DOE recently launched a new battery critical materials recovery and recycling research initiative under its existing authorities, and Congress should pass authorizing legislation to provide greater direction and long-term budget certainty for the new program.[87]
- Congress should increase funding for RD&D in high-voltage direct current (HVDC) transmission, including advancing power electronics, converter, and conductor technologies and demonstrating meshed networks of HVDC lines.[88]

7. Carbon capture, use, and sequestration (CCUS)

Description: Carbon capture, use, and sequestration (CCUS) technologies prevent greenhouse gases from reaching the atmosphere. The Intergovernmental Panel on Climate Change has found that CCUS is essential to achieve net-zero emissions.[89] CCUS is best known for its potential to allow fossil-fueled power plants to continue to be used in a carbon-constrained world. But it will also likely be necessary to decarbonize many industrial processes—such as ethanol, fertilizer, plastics, cement, and steel production—for which low-carbon alternatives are not currently available.[90] The federal CCUS RD&D portfolio has been largely limited to coal in the past. It urgently needs to expand to other sources of emissions and prioritize demonstrations at natural gas power plants and cement and steel production facilities, in order to address the technical challenges unique to each type of operation. Captured carbon dioxide can either be converted into fuels, building materials, plastics, and other products or stored in a geologic repository. The National Academies recently released a roadmap to develop carbon utilization technologies, noting that current federal funding levels are not sufficient to address all RD&D needs.[91] The majority of captured carbon dioxide will need to be stored underground, and continued work is needed to characterize and validate geologic storage opportunities.

Recent initiatives: DOE's Industrial Carbon Capture and Storage (ICCS) program, which received a one-time appropriation through the 2009 Recovery Act, resulted in the successful public-private demonstrations of carbon capture at a fertilizer plant (Port Arthur, 2013) and ethanol refinery (Archer Daniels Midland, 2017). In FY20, the National Carbon Capture Center in Wilsonville, Alabama, began installing a natural-gas-fired system to test capture technologies under both natural gas and coal-fired flue gas conditions.[92] DOE is also supporting technologies such as coal gasification and the Allam cycle for CCUS on power generating facilities.[93] The DOE Loan Programs Office (LPO) issued a conditional loan guarantee of up to $2 billion to build the world's first clean methanol facility with carbon capture in Lake Charles, Louisiana, with construction slated to begin in mid-2020.[94] DOE's activities to develop, test, and validate geologic carbon storage have culminated in the successful storage of 11 million metric tons of CO_2 to date and continued site-specific characterization with the CarbonSAFE program. DOE has set a goal to develop an additional 50 million metric tons of annual CO_2 storage capacity by 2026.[95]

Recommendations: The federal government should invest across a range of CCUS technologies:

- The DOE should rename the Office of Fossil Energy as the Office of Carbon Management. This new office should coordinate with other DOE offices with complementary missions (e.g., AMO for industrial decarbonization, Office of Science for geoscience, and Bioenergy Technologies Office [BETO] for bioenergy with CCS).
- Congress should fully fund the new CCUS programs authorized in the Energy Act of 2020, Division Z, Title IV.[96] One such program would advance carbon capture at industrial facilities—including iron and steel, cement, chemicals, and hydrogen production facilities—as well as from biopower and biofuels facilities.
- Congress should fund commercial-scale demonstrations of carbon capture at coal power plants that build off the lessons learned from Petra Nova. Congress should fully fund a new RD&D program for carbon capture at natural gas-fired power plants—consistent with the Energy Act of 2020, Division Z, Title IV—and should aim to demonstrate carbon capture at multiple natural gas power plants by 2025.[97]
- The National Academies released a roadmap for improving carbon dioxide utilization technologies. DOE should identify the funding levels needed to address the National Academies' recommendations, and Congress should provide sufficient funding.[98]
- DOE should double the ambition of its current carbon storage goal (50 million metric tons of storage capacity by 2026) and develop a roadmap and funding levels to meet the new target and to expand exponentially in the latter part of the 2020s.[99]
- Congress should continue to invest in the development of methane leak detection and mitigation technologies and methods, consistent with the proposed Fossil Energy R&D Act.[100]

8. Carbon dioxide removal / negative emissions technologies

Description: Carbon dioxide removal (CDR) is needed to reverse emissions that are impossible or prohibitively expensive to eliminate, such as those from long-haul aviation. CDR also provides a hedge against the possibility that other climate mitigation technologies fail to advance as quickly as needed and provides a long-term pathway to removing legacy emissions. The latest Intergovernmental Panel on Climate Change (IPCC) reports find that removing carbon dioxide from the atmosphere and sequestering it permanently is no longer an option—it is a necessity.[101] Unfortunately, no carbon removal technologies have been deployed at a scale that can meaningfully address the magnitude of global climate pollution. Approaches that manage natural ecosystems (so-called "nature-based solutions") such as afforestation and coastal restoration are low-cost, near-term options but have limited sequestration capacity, draw down atmospheric carbon dioxide too slowly, and run into competition for land use. Technological approaches such as direct air capture and storage (DACS), carbon mineralization, and bioenergy with carbon capture and storage (BECCS) are relatively immature and expensive but have the potential to permanently remove large amounts of atmospheric carbon dioxide and restore the natural balance of carbon levels.[102] The National Academies released a carbon removal roadmap, but current US investments are too small and uncoordinated to meaningfully address all carbon removal RD&D needs.

Recent initiatives: Between FY 2009 and 2019, total congressional funding for CDR was less than $26 million.[103] In FY20, Congress provided $68 million—across all carbon removal technologies and pathways—for RD&D in carbon dioxide removal, and in March 2020, DOE released a new funding opportunity to provide $22 million in research for direct air capture (DAC).[104] Both the EFFECT Act (S. 1201) and FERD Act (H.R. 3607)—portions of which were folded into the Energy Act of 2020—would authorize a new direct air capture RD&D program at DOE. The United States Geological Survey (USGS) has conducted resource assessments and feasibility studies of carbon mineralization opportunities, finding that basalt formations just in the Pacific Northwest have the capacity to mineralize 144-768 $GtCO_2$.[105] Currently, the SMART program at ARPA-E researches quantifying and monitoring soil carbon content and fluxes.[106]

Recommendations: The federal government should create new federal programs to accelerate development of carbon dioxide removal technologies.

- Congress should establish a comprehensive interagency RD&D initiative that implements the recommendations of the National Academies report on carbon removal. The Energy Futures Initiative (EFI) provides a set of detailed implementation plans for the National Academies of Sciences, Engineering, and Medicine (NASEM) recommendations that includes agency funding levels and program structures for a comprehensive 10-year, $10.7 billion carbon removal innovation program that includes demonstration projects.[107]
- DOE, NSF, USGS, USDA, and other relevant agencies should expand carbon removal research within existing programs. The DOE Office of Basic Energy Sciences (BES) should solicit new EFRCs dedicated to direct air capture and carbon mineralization, and ARPA-E should launch new programs aimed at carbon removal.[108]
- DOE should create a permanent research program within the Office of Fossil Energy to develop negative emissions technologies—including direct air capture, carbon mineralization, and bioenergy with carbon capture and storage—that builds off its recent funding announcement for direct air capture[109] The FY21 House Energy and Water Appropriations bill would have established such an office, as would the House Fossil Energy R&D Act and the Senate EFFECT Act.[110]

9. Clean agricultural systems

Description: Agricultural soils have tremendous capacity to hold carbon within the top few meters of soil, currently hosting three times more carbon than is in the atmosphere. However, soils have recently been a net source of CO_2 emissions, rather than a sink, and heavily-cultivated agricultural soils can lose 50 to 70 percent of their original organic carbon.[111] Under current practices, the agriculture sector accounts for 10 percent of US greenhouse gas emissions. Advanced agricultural practices and technologies can reverse soil carbon losses, providing climate benefits while also improving soil structure, increasing crop yields, reducing fertilizer inputs, and reducing erosion. For example, precision agriculture uses sensors and data analysis to fine-tune the application of inputs, and genetic modification alters the traits of crops. Such techniques can reduce the use of fertilizer—a key source of nitrous oxide emissions—and other nutrient inputs, maximize crop yields, sequester carbon, reduce costs to farmers, and avoid environmental degradation or eutrophication. Biotechnology can help breed plants with deeper root structures, which helps increase the carbon absorbed in soils. Dietary changes can significantly reduce livestock methane emissions.[112]

Recent initiatives and activities: In 2018, Congress created the Agriculture Advanced Research and Development Authority (AGARDA) pilot program, modeled after DARPA and ARPA-E, to support high-risk, long-term R&D that protects the US agriculture and food supply, but the program has not yet been funded.[113] ARPA-E's Rhizosphere Observations Optimizing Terrestrial Sequestration (ROOTS) program aims to enhancing carbon absorbed in soils through selective breeding for plants with deeper and larger roots.[114] Similarly, their SMARTFARM initiative seeks to assess field-level carbon accounting and life-cycle analysis at the field level. The "4 per 1,000" Initiative is an international effort to promote clean agriculture practices that have the potential to increase soil carbon stocks by 0.4 percent per year.

Recommendations: The federal government should substantially increase investment in clean agriculture practices and technologies and provide technical and financial assistance to farmers to transition to best practices in soil carbon management and livestock methane reduction:

- Congress should substantially increase investment in soil carbon measurement technologies, fertilizer management research, and technical and financial assistance to farmers to transition to best carbon management practices. The National Academies recommends investing approximately $630 million over the next 10 years in soil carbon storage RD&D.[115]
- Congress should fully fund AGARDA.[116]
- The United States should join and take a leadership role in the 4 per 1000 Initiative.[117]

10. Foundation science and platform technologies

Description: Foundational scientific research across a range of fields—including advanced materials, electrochemistry, quantum computing, and genomic sciences—can enable breakthroughs in energy technologies. Moreover, platform technologies developed outside the energy sector—including 3D printing, smart manufacturing, machine learning, and digitalization—are already transforming energy systems and have the potential to unlock future emission reductions. Scientific research and platform technologies are often complementary: for example, machine learning for materials discovery can enable rapid discovery of novel materials for electrochemical devices such as batteries, fuel cells, and electrolyzers.[118] Each of the other nine decarbonization challenges is focused on developing distinct categories of technologies to address critical decarbonization needs. All of them can benefit from advances in foundational science. And federal agencies such as the National Science Foundation and the DOE's Office of Science already invest substantially in foundational, or basic, science and platform technologies. Yet historically, federal programs have rarely connected these investments with those in applied research, development, and demonstration. Experience in health, defense, and other sectors suggests that it is essential for end-use applications to drive much of the agenda of supporting science, while federal funding should also foster a healthy domain of investigator-initiated discovery science.[119] This approach would greatly benefit energy innovation as well.

Recent initiatives: The George W. Bush administration created Energy Frontier Research Centers (EFRCs) at DOE to bring together university, government, and industry researchers to connect early-stage research with grand energy challenges. There are 46 active EFRCs spanning a diverse range of technologies—from molten salts for nuclear reactors to advanced catalysts for batteries—all of which are organized around five "Transformational Opportunities" in basic energy sciences: mastering hierarchical architectures and beyond-equilibrium matter; understanding heterogeneity, interfaces, and disorder of non-ideal materials and systems; harnessing coherence in light and matter; advances in models, mathematics, algorithms, data, and computing; and exploiting transformative advances in imaging capabilities across multiple scales.[120]

In FY20, DOE launched a new Artificial Intelligence and Technology Office in 2020 to coordinate department-wide artificial intelligence (AI) activities and integrate AI research into other energy R&D programs.[121] On the international stage, Mission Innovation launched the Clean Energy Materials Innovation Challenge to integrate automated robotic laboratories with machine learning to identify new materials for batteries, solar cells, thermal storage, catalysts for conversion of captured CO_2, and other clean energy applications.[122]

Recommendations: The federal government should do more to align research in foundational science and platform technologies with decarbonization priorities.

- NSF and DOE should identify and prioritize key cross-cutting basic and use-inspired research programs that have multiple applications (e.g., in electrochemistry and composite materials).[123]
- DOE should expand its use of machine learning and high-performance computing in the applied energy technology RD&D programs.[124]
- DOD should expand its investments in advanced materials and nanotechnology research to advance technology pillars that also meet national security objectives.[125]
- DOE should add 45 new EFRCs and align the objectives of EFRCs with advancing the nine other technology pillars.[126]
- The United States should take a leadership role in the Mission Innovation Clean Energy Materials Innovation Challenge, and it should establish a domestic automated materials discovery facility.[127]
- Congress should double investment in R&D of artificial intelligence (AI) with energy applications across the federal government, including DOE programs in advanced grid R&D, grid-integrated efficient buildings, intelligent transportation systems, and energy systems integration. Congress should fully fund DOE's new AI Technologies Office, which should play a coordinating role for federal AI R&D both within DOE and between agencies.[128]

ENDNOTES

1. This definition of energy RD&D refers to the DOE applied energy programs (EERE, FE, NE, OE, and CESER), ARPA-E, and portions of the DOE Office of Science (BES, FES, and the bioenergy research centers within BER).
2. Varun Sivaram, Colin Cunliff, David M. Hart, Julio Friedmann, and David Sandalow, *Energizing America: A Roadmap to Launch a National Energy Innovation Mission*, Columbia University SIPA Center on Global Energy Policy, 2020, http://www2.itif.org/2020-energizing-america.pdf; K.S. Gallagher and Z. Myslikova, "Mission Innovation is Mission Critical," *Nature Energy* 5, https://www.nature.com/articles/s41560-020-00694-5.
3. International Energy Agency (IEA), *Energy Technology Perspectives 2020: Special Report on Clean Energy Innovation*, IEA, 2020, https://www.iea.org/reports/clean-energy-innovation.
4. International Energy Agency (IEA), "Tracking Clean Energy Progress," IEA, 2020, https://www.iea.org/topics/tracking-clean-energy-progress.
5. National Academies of Sciences, Engineering, and Medicine, *Accelerating Decarbonization of the U.S. Energy System*, National Academies Press, 2020, https://doi.org/10.17226/25932.
6. American Energy Innovation Council (AEIC), "Energy Innovation: Supporting the Full Innovation Lifecycle," Bipartisan Policy Center, February 2020, http://americanenergyinnovation.org/wp-content/uploads/2020/02/Energy-Innovation-Supporting-the-Full-Innovation-Lifecycle.pdf; Elliot Diringer et al., "Getting to Zero: A U.S. Climate Agenda," Center for Climate and Energy Solutions (C2ES), November 2019, https://www.c2es.org/document/getting-to-zero-a-u-s-climate-agenda/; President's Council of Advisors on Science and Technology (PCAST), "Report to the President on Accelerating the Pace of Change in Energy Technologies Through an Integrated Federal Energy Policy," Executive Office of the President, November 2010, https://obamawhitehouse.archives.gov/sites/default/files/microsites/ostp/pcast-energy-tech-report.pdf.
7. Josh Freed, Avi Zevin, and Jesse Jenkins, "Jumpstarting a Clean Energy Revolution with a National Institutes of Energy," Third Way and the Breakthrough Institutes, September 2009, https://grist.org/wp-content/uploads/2009/09/jumpstarting_clean_energy_sept_09.pdf.
8. K.S. Gallagher and Z. Myslikova, "Mission Innovation is Mission Critical," *Nature Energy* 5, https://www.nature.com/articles/s41560-020-00694-5.
9. Colin Cunliff, "Energy Innovation in the FY 2021 Budget: Congress Should Lead," Information Technology and Innovation Foundation, 2020, https://itif.org/energy-budget.
10. Devashree Saha and Mark Muro, "Patenting Invention: Clean Energy Innovation Trends and Priorities for the Trump Administration and Congress," Brookings, April 2017, https://www.brookings.edu/research/patenting-invention-clean-energy-innovation-trends-and-prioritiesfor-the-trump-administration-and-congress/.
11. Bloomberg New Energy Finance (BNEF), "Energy Transition Investment Hit $500 Billion in 2020 – For First Time," BNEF, January 2021, https://about.bnef.com/blog/energy-transition-investment-hit-500-billion-in-2020-for-first-time/.
12. Gregory Nemet, "Beyond the learning curve: factors influencing cost reductions in photovoltaics," *Energy Policy* 34, 2006, https://doi.org/10.1016/j.enpol.2005.06.020.
13. "Global market share of solar module manufacturers 2017*," Statista, July 2020, https://www.statista.com/statistics/269812/global-market-share-of-solar-pv-module-manufacturers.
14. Joel Jaeger, "Europe Charts a Course for Sustainable Recovery from COVID-19," World Resources Institute, June 2, 2020, https://www.wri.org/blog/2020/06/europe-charts-course-sustainable-recovery-covid-19.

15. Countries with national hydrogen strategies include Germany, France, Spain, Portugal, the Netherlands, Norway, Japan, Korea, New Zealand, Australia, Canada, and Chile. Italy, Poland, and the United Kingdom are currently developing national hydrogen strategies.

16. Varun Sivaram, Colin Cunliff, David M. Hart, Julio Friedmann, and David Sandalow, *Energizing America: A Roadmap to Launch a National Energy Innovation Mission*, Columbia University SIPA Center on Global Energy Policy, 2020, http://www2.itif.org/2020-energizing-america.pdf.

17. Consolidated Appropriations Act, 2021, Division Z, Title IX, https://rules.house.gov/sites/democrats.rules.house.gov/files/BILLS-116HR133SA-RCP-116-68.pdf

18. National Association of State Energy Offices (NASEO), "Technology-Based Economic Development: Assessment of States' Roles and Opportunities" (NASEO, 2015) https://www.naseo.org/data/sites/1/documents/publications/naseo-tbed-white-paper.pdf.

19. Hart, David M. Clean-Energy-Based Economic Development: Parallel Tracks for State and Local Policy. ITIF, February 25, 2019. https://itif.org/publications/2019/02/25/clean-energy-based-economic-development-parallel-tracks-state-and-local

20. Jetta Wong and David M. Hart, "Mind the Gap: A Design for a New Energy Technology Commercialization Foundation," Information Technology and Innovation Foundation, 2020, https://itif.org/publications/2020/05/11/mind-gap-design-new-energy-technology-commercialization-foundation.

21. Report to accompany the Energy and Water Development Appropriations Bill, 2020, https://www.congress.gov/116/crpt/srpt102/CRPT-116srpt102.pdf, 71.

22. Surana, Kavita et al. "Regional Clean Energy Innovation." EFI, 2020, https://cgs.umd.edu/research-impact/publications/regional-clean-energy-innovation.

23. Josh Freed, Avi Zevin, and Jesse Jenkins, "Jumpstarting a Clean Energy Revolution with a National Institutes of Energy," The Breakthrough Institute and Third Way, September 2009; Varun Sivaram, Teryn Norris, Colin McCormick, and David Hart, "Energy Innovation Policy: Priorities for the Trump Administration and Congress," ITIF, 2016, http://www2.itif.org/2016-energy-innovation-policy.pdf.

24. US Environmental Protection Agency, GHGI.

25. David Sandalow, Julio Friedman, Roger Aines, Colin McCormick and Sean McCoy, "Industrial Heat Decarbonization Roadmap," ICEF, December 2019, https://www.icef-forum.org/pdf2019/roadmap/ICEF_Industrial_201910.pdf.

26. Colin Cunliff, Robert D. Atkinson, David M. Hart, and Robert Rozansky, "Comments to the House Select Committee on the Climate Crisis," Information Technology and Innovation Foundation, 2019, 7, https://itif.org/publications/2019/11/22/comments-house-select-committee-climate-crisis.

27. Advanced Manufacturing, "Energy Analysis, Data and Reports," Office of Energy Efficiency and Renewable Energy, n.d. https://www.energy.gov/eere/amo/energy-analysis-data-and-reports.

28. US DOE, *2015 Quadrennial Technology Review*, Chapter 6, "Innovating Clean Energy Technologies in Advanced Manufacturing," http://energy.gov/downloads/chapter-6-innovating-clean-energy-technologies-advanced-manufacturing.

29. S. Rept. 116-102, *Energy and Water Development Appropriations Bill 2020*, to accompany S. 2470, 86, https://www.appropriations.senate.gov/imo/media/doc/FY2020%20Energy%20and%20Water%20Development%20Appropriations%20Act,%20Report%20116-1021.pdf.

30. US Congress, House, *Clean Industrial Technology Act of 2019*, HR 4230, 116th Cong., https://www.congress.gov/bill/116th-congress/house-bill/4230.

31. US DOE, *2015 Quadrennial Technology Review*, Chapter 6 "Innovating Clean Energy Technologies in Advanced Manufacturing," http://energy.gov/downloads/chapter-6-innovating-clean-energy-technologies-advanced-manufacturing.

32. Stephen Ezell, "Policy Recommendations to Stimulate U.S. Manufacturing Innovation," ITIF, May 18, 2020, http://www2.itif.org/2020-policy-recommendations-us-manufacturing.pdf.

33. Stacy C. Davis and Robert G. Boundy, *Transportation Energy Data Book Edition 38* (Oak Ridge, TN: Oak Ridge National Laboratory, 2020), Table 1.13 Consumption of Petroleum by End-Use Sector, https://tedb.ornl.gov/wp-content/uploads/2020/02/TEDB_Ed_38.pdf; U.S. Environmental Protection Agency (EPA), *Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-2018*, Table ES-2 (Washington, DC: EPA, 2020), https://www.epa.gov/sites/production/files/2020-04/documents/us-ghg-inventory-2020-main-text.pdf

34. BloombergNEF, "Electric Vehicle Outlook 2020," May 2020, https://bnef.turtl.co/story/evo-2020/; Nic Lutsey and Michael Nicholas, "Update on electric vehicle costs in the United States through 2030," (working paper, International Council on Clean Transportation, April 2, 2019); MIT Energy Initiative, *Insights into Future Mobility*, MIT Energy Initiative, 2019, http://energy.mit.edu/research/mobilityofthefuture/.

35. Kevin R. Antcliff, Mark D. Guynn, Douglas P. Wells, Steven J. Schneider, and Michael T. Tong, "Mission Analysis and Aircraft Sizing of a Hybrid-Electric Regional Aircraft," paper presented at the 54th AIAA Aerospace Sciences Meeting, held in San Diego, CA, January 4–8, 2016, https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20160007763.pdf.

36. US DOE, *FY 2021 Congressional Budget Justification, Volume 3 Part 1*, (Washington, D.C.: DOE/CF-0163, February 2020), 19, https://www.energy.gov/sites/prod/files/2020/04/f73/doe-fy2021-budget-volume-3-part-1.pdf.

37. US DOE, *FY 2021 Congressional Budget Justification, Volume 3 Part 1*, (Washington, D.C.: DOE/CF-0163, February 2020), 25, https://www.energy.gov/sites/prod/files/2020/04/f73/doe-fy2021-budget-volume-3-part-1.pdf.

38. US DOE, *FY 2021 Congressional Budget Justification, Volume 3 Part 1*, (Washington, D.C.: DOE/CF-0163, February 2020), 67–84, https://www.energy.gov/sites/prod/files/2020/04/f73/doe-fy2021-budget-volume-3-part-1.pdf..

39. Federal Transit Administration, *FTA Annual Report on Public Transportation Innovation Research Projects for FY 2019*, February 2020, https://www.transit.dot.gov/sites/fta.dot.gov/files/docs/research-innovation/148141/ftareportno0159.pdf.

40. US DOE, *FY 2021 Congressional Budget Justification, Volume 3 Part 1*, (Washington, D.C.: DOE/CF-0163, February 2020), 22, https://www.energy.gov/sites/prod/files/2020/04/f73/doe-fy2021-budget-volume-3-part-1.pdf.; BloombergNEF, "Electric Vehicle Outlook 2020: Executive Summary," https://about.bnef.com/electric-vehicle-outlook/.

41. Transportation Research Board and National Research Council, *Overcoming Barriers to Deployment of Plug-in Electric Vehicles*, (Washington, DC: The National Academies Press, 2015), https://doi.org/10.17226/21725.

42. Colin Cunliff and Batt Odgerel, "Federal Energy R&D: Vehicle Technologies," ITIF, March 2020, http://www2.itif.org/2020-budget-vehicle.pdf.

43. Colin Cunliff, "Innovation Agenda for Deep Decarbonization," ITIF, November 2018, http://www2.itif.org/2018-innovation-agenda-decarbonization.pdf.

44. US Energy Information Administration, "Monthly Energy Review," Table 2.1 and 7.6, US DOE, March 26, 2019, https://www.eia.gov/totalenergy/data/monthly/.

45. US DOE, *FY 2020 Congressional Budget Justification, Volume 3 Part 2*, 183.

46. US DOE BTO Lighting R&D Program, "2019 Lighting R&D Opportunities,", 2019, https://www.energy.gov/sites/prod/files/2020/01/f70/ssl-rd-opportunities2-jan2020.pdf.

47. Francesca Pierobon, Monica Huang, Kathrina Simonen, and Indroneil Ganguly, "Environmental benefits of using hybrid CLT structure in midrise non-residential construction: An LCA based comparative case study in the U.S. Pacific Northwest," *Journal of Building Engineering* 26, November 2019, https://www.sciencedirect.com/science/article/pii/S2352710219302542.

48. US DOE, *FY 2020 Congressional Budget Justification, Volume 3 Part 2*, 183.

49. US DOE, "2018 Better Buildings Progress Report: Innovation Through Collaboration: Securing a More Affordable and Reliable Energy Future," 2018, 2, https://betterbuildingssolutioncenter.energy.gov/sites/default/files/attachments/DOE_BBI_2018_Progress_Report_051018.pdf.

50. International Energy Agency, *Clean Energy Innovation* (Paris: IEA, 2020), https://www.iea.org/reports/clean-energy-innovation; IEA *Cooling* (Paris: IEA, 2020), https://www.iea.org/reports/cooling.

51. Colin Cunliff, Ashley Johnson, and Hodan Omaar, "How Congress and the Biden Administration Could Jumpstart Smart Cities with AI," Information Technology and Innovation Foundation, *forthcoming*.

52. US Energy Information Administration, "Monthly Energy Review, Table 11.6," March 26, 2020, https://www.eia.gov/totalenergy/data/monthly/archive/00352003.pdf; University of Texas at Austin Energy Institute, "Levelized Cost of Electricity Version 1.4.0," accessed April 19, 2020, http://calculators.energy.utexas.edu/lcoe_map/#/county/tech.

53. Massachusetts Institute of Technology (MIT) Energy Initiative, *The Future of Nuclear Energy in a Carbon-Constrained World,* 2018, http://energy.mit.edu/research/future-nuclear-energy-carbon-constrained-world/.

54. US DOE, *FY 2017 DOE Annual Performance Report / FY 2019 Annual Performance Plan*, (Washington, DC: US Department of Energy, 2018), https://www.energy.gov/sites/prod/files/2018/11/f57/fy-2017-doe-annual-performance-report-fy-2019-annual-performance-plan.pdf.

55. US DOE, *GeoVision: Harnessing the Heath Beneath Our Feet*, (Washington, DC: US Department of Energy, 2019), https://www.energy.gov/eere/geothermal/downloads/geovision-harnessing-heat-beneath-our-feet.

56. Alexis McKittrick et al., *Frontier Observatory for Research in Geothermal Energy: A Roadmap*, IDA Science and Technology Policy Institute, February 2019, https://www.ida.org/idamedia/Corporate/Files/Publications/STPIPubs/2019/D-10474.pdf.

57. US DOE, Hydropower Vision: A New Chapter for America's 1st Renewable Electricity Source, (Washington, DC: US Department of Energy, July 2016). https://www.energy.gov/sites/prod/files/2018/02/f49/Hydropower-Vision-021518.pdf; US DOE, *Powering the Blue Economy: Exploring Opportunities for Marine Renewable Energy in Maritime Markets* (ton, DC: US Department of Energy EERE, April 2019), https://www.energy.gov/sites/prod/files/2019/03/f61/73355.pdf.

58. For a brief review of recent activity, see Colin Cunliff, "An Innovation Agenda for Deep Decarbonization: Bridging Gaps in the Federal Energy RD&D Portfolio," ITIF, November 2018, https://itif.org/publications/2018/11/28/innovation-agenda-deep-decarbonization-bridging-gaps-federal-energy-rdd.

59. DOE Office of Nuclear Energy, *Restoring America's Competitive Nuclear Energy Advantage: A strategy to assure U.S. national security*, (Washington, DC: US Department of Energy, 2020), https://www.energy.gov/sites/prod/files/2020/04/f74/Restoring%20America%27s%20Competitive%20Nuclear%20Advantage_1.pdf.

60. Dorothy Robyn and Jeffrey Marqusee, "The Clean Energy Dividend," ITIF, March 2019, http://www2.itif.org/2019-clean-energy-dividend.pdf.

61. NREL, “Annual Technology Baseline: Electricity, 2019,” https://atb.nrel.gov/electricity/2019/index.html.

62. Marine Energy Research and Development Act of 2019, H.R. 3203, 116th Cong. (2019).

63. NREL, “Annual Technology Baseline: Electricity, 2019,” https://atb.nrel.gov/electricity/2019/index.html.

64. Dorothy Robyn and Jeffrey Marqusee, “The Clean Energy Dividend,” ITIF, March 2019, http://www2.itif.org/2019-clean-energy-dividend.pdf.

65. Energy Transitions Commission, *Mission Possible: Reaching Net-Zero Carbon Emissions from Harder-to-Abate Sectors by Mid-Century Energy Transitions Commission*, 2018, http://www.energy-transitions.org/sites/default/files/ETC_MissionPossible_FullReport.pdf.

66. Advanced Research Projects Agency-Energy, “Renewable Energy to Fuels Through Utilization of Energy Dense Liquids (REFUEL) Program Overview,” (Washington, DC: DOE ARPA-E, 2016), https://arpa-e.energy.gov/sites/default/files/documents/files/REFUEL_ProgramOverview.pdf.

67. US DOE, *FY 2021 Congressional Budget Justification, Volume 3 Part 1* (Washington, D.C.: DOE/CF-0163, February 2020), 67–84, https://www.energy.gov/sites/prod/files/2020/04/f73/doe-fy2021-budget-volume-3-part-1.pdf.

68. US DOE, “DOE Announces New Lab Consortia to Advance Hydrogen and Fuel Cell R&D,” 2020, https://www.energy.gov/articles/doe-announces-new-lab-consortia-advance-hydrogen-and-fuel-cell-rd.

69. ARPA-E, “Renewable Energy to Fuels Through Utilization of Energy-Dense Liquids (REFUEL) Program Overview,” https://arpae.energy.gov/sites/default/files/documents/files/REFUEL_ProgramOverview.pdf.

70. Joint Center for Artificial Photosynthesis, accessed November 15, 2018, https://solarfuelshub.org/technology-transfer.

71. Bobby Magill, "Military Researching Ways to Suck Carbon From Air to Make Fuel," *Bloomberg Law*, January 15, 2020, https://news.bloombergenvironment.com/environment-and-energy/military-researching-ways-to-suck-carbon-from-air-to-make-fuel.

72. Colin Cunliff, “Innovation Agenda for Deep Decarbonization,” ITIF, http://www2.itif.org/2018-innovation-agenda-decarbonization.pdf.

73. US Congress, House, *Clean Industrial Technology Act of 2019*, HR 4230, 116th Cong., https://www.congress.gov/bill/116th-congress/house-bill/4230.

74. Colin Cunliff, “Innovation Agenda for Deep Decarbonization,” ITIF, http://www2.itif.org/2018-innovation-agenda-decarbonization.pdf.

75. US DOE, *FY 2017 Congressional Budget Request*, *Volume 3*, 120, https://www.energy.gov/sites/prod/files/2016/02/f29/FY2017BudgetVolume3_2.pdf.

76. Energy Transitions Commission, *Mission Possible: Reaching Net-Zero Carbon Emissions from Harder-to-Abate Sectors by Mid-Century Energy Transitions Commission*, 2018, http://www.energy-transitions.org/sites/default/files/ETC_MissionPossible_FullReport.pdf.

77. David M. Hart, “Making ‘Beyond Lithium’ a Reality: Fostering Innovation in Long-Duration Grid Storage,” Information Technology and Innovation Foundation, 2018, https://itif.org/publications/2018/11/28/making-beyond-lithium-reality-fostering-innovation-long-duration-grid.

78. Klaehn Burkes, Joe Cordaro, Tom Keister, and Kerry Cheung, “DRAFT Solid State Power Substation Roadmap,” US DOE Office of Electricity Delivery and Energy Reliability, 2017, https://www.energy.gov/sites/prod/files/2018/03/f49/SSPS%20Roadmap%20Draft%20-%20Public.pdf.

79. Colin Cunliff, “Beyond the Energy Techlash: The Real Climate Impacts of Information Technology,” ITIF, July 2020, https://itif.org/publications/2020/07/06/beyond-energy-techlash-real-climate-impacts-information-technology.

80. US DOE, *FY 2021 Congressional Budget Request Volume 2*, 277, https://www.energy.gov/sites/prod/files/2020/03/f72/doe-fy2021-budget-volume-2.pdf.

81. Faith M. Smith, “Why DOE’s FY20 Budget Request Has Exciting News for Storage” ClearPath, April 4, 2019, accessed March 7, 2020, https://clearpath.org/our-take/why-does-fy20-budget-request-hasexciting-news-for-storage/.

82. US DOE, *Grid Modernization Multi-Year Program Plan* (Washington, D.C.: November 2015), https://www.energy.gov/sites/prod/files/2016/01/f28/Grid%20Modernization%20Multi-Year%20Program%20Plan.pdf; US DOE, “2019 Grid Modernization Lab Call Awards,” accessed February 20, 2020, https://www.energy.gov/2019-grid-modernization-lab-call-awards; US DOE, “Department of Energy Announces $80 Million For New Grid Modernization Lab Call Projects,” November 6, 2019, https://www.energy.gov/articles/department-energy-announces-80-million-new-grid-modernization-lab-call-projects.

83. US Congress, House, *Grid Modernization Research and Development Act of 2019*, HR 5428, 116th Cong.

84. “Memorandum of Understanding between the Department of Defense and the Department of the Interior on Renewable Energy and a Renewable Energy Partnership Plan,” 2012, https://www.acq.osd.mil/dodsc/library/DoD_DOI%20MOU%20Signed%2020%20Jul%202012.pdf.

85. US Congress, House, *BEST Act*, HR 2986, 116th Cong., 2019.

86. Dorothy Robyn and Jeffrey Marqusee, “The Clean Energy Dividend,” ITIF, March 2019, http://www2.itif.org/2019-clean-energy-dividend.pdf.

87. US DOE, “Vehicle Technologies Office's Research Plan to Reduce, Recycle, and Recover Critical Materials in Lithium-Ion Batteries,” June 2019, https://www.energy.gov/sites/prod/files/2019/07/f64/112306-battery-recycling-brochure-June-2019%202-web150.pdf.

88. US Energy Information Administration, *Assessing HVDC Transmission for Impacts of Non-Dispatchable Generation*, US DOE, June 2018, https://www.eia.gov/analysis/studies/electricity/hvdctransmission/pdf/transmission.pdf; Liza Reed, M. Granger Morgan, Parth Vaishnav, and Daniel E. Armanios, “Converting existing transmission corridors to HVDC is an overlooked option for increasing transmission capacity,” *Proceedings of the National Academy of Sciences* 116, no. 28 (June 20, 2019), https://www.pnas.org/content/116/28/13879.

89. Intergovernmental Panel on Climate Change, “Summary for Policymakers,” in *Global Warming of 1.5°C*, an IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty (World Meteorological Organization, 2018), https://www.ipcc.ch/sr15/chapter/spm/.

90. Global CCS Institute, “Global Status of CCS 2019,” https://www.globalccsinstitute.com/wp-content/uploads/2019/12/GCC_GLOBAL_STATUS_REPORT_2019.pdf; Energy Transitions Commission, *Mission Possible: Reaching Net-Zero Carbon Emissions from Harder-to-Abate Sectors by Mid-Century Energy Transitions Commission*, 2018, http://www.energy-transitions.org/sites/default/files/ETC_MissionPossible_FullReport.pdf.

91. National Academies of Sciences, Engineering, and Medicine, *Gaseous Carbon Waste Streams Utilization: Status and Research Needs* (Washington, D.C.: The National Academies Press, 2019), https://doi.org/10.17226/25232.

92. US DOE, "Carbon Capture, Utilization, and Storage R&D Programs," accessed February 20, 2020, https://www.energy.gov/sites/prod/files/2019/10/f67/Carbon%20Capture%2C%20Utilization%2C%20and%20Storage%20R%26D%20Programs_2.pdf.

93. US DOE Office of Fossil Fuel Energy, "U.S. Department of Energy Invests $7 Million for Projects to Advance Coal Power Generation under Coal FIRST Initiative," October 11, 2019, https://www.energy.gov/fe/articles/us-department-energy-invests-7-million-projects-advance-coal-power-generation-under-coal.

94. US Department of Energy, "Energy Department Offers Conditional Commitment for First Advanced Fossil Energy Loan Guarantee," 2016, https://www.energy.gov/articles/energydepartment-offers-conditional-commitment-first-advanced-fossil-energy-loan-guarantee; Lake Charles Methanol, "About Lake Charles," accessed March 20, 2020, https://www.lakecharlesmethanol.com/about.

95. DOE National Energy Technology Laboratory, "Safe Geologic Storage of Captured Carbon Dioxide: Two Decades of DOE's Carbon Storage R&D Program in Review," 2020, https://www.netl.doe.gov/node/9687.

96. US Congress, Senate, *EFFECT Act of 2019*, S1201, 116th Cong.

97. US Congress, Senate, *Launching Energy Advancement and Development through Innovations for Natural Gas Act of 2019*, S1685, 116th Cong.

98. National Academies of Sciences, Engineering, and Medicine, *Gaseous Carbon Waste Streams Utilization: Status and Research Needs* (Washington, D.C.: The National Academies Press, 2019), https://doi.org/10.17226/25232.

99. Colin Cunliff and Batt Odgerel, "Carbon Storage and Utilization," ITIF, 2020, http://www2.itif.org/2020-budget-carbon-storage.pdf.

100. US Congress, House, *Fossil Energy Research and Development Act of 2019*, HR 3607, 116th Cong., https://www.congress.gov/bill/116th-congress/house-bill/3607.

101. Intergovernmental Panel on Climate Change, "Summary for Policymakers," in *Global Warming of 1.5°C*, an IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty (World Meteorological Organization, 2018), https://www.ipcc.ch/sr15/chapter/spm/.

102. David Sandalow, Julio Friedman, Colin McCormick, and Sean McCoy, "Direct Air Capture Roadmap," ICEF, December 2018, https://www.icef-forum.org/pdf2018/roadmap/ICEF2018_DAC_Roadmap_20181210.pdf.

103. Joseph S. Hezir, Addison K. Stark, Tim Bushman, and Erin Smith, "Carbon Removal: Comparing Historical Federal Research Investments with the National Academies' Recommended Future Funding Levels," Carbon Removal: Comparing Historical Federal Research Investments with the National Academies' Recommended Future Funding Levels, BPC & EFI, April 2019. https://bipartisanpolicy.org/wp-content/uploads/2019/06/Carbon-Removal-Comparing-Historical-Investments-with-the-National-Academies-Recommendations.pdf

104. Carbon180. "2019 Annual Report.," 2019 https://static1.squarespace.com/static/5b9362d89d5abb8c51d474f8/t/5e93237f14b45c6b9b8b49be/1586701204146/2019annualreport.pdf; "Department of Energy to Provide $22 Million for Research on Capturing Carbon Dioxide from Air." Department of Energy, March 30, 2020. https://www.energy.gov/articles/department-energy-provide-22-million-research-capturing-carbon-dioxide-air.

105. Blondes, M.S., Merrill, M.D., Anderson, S.T., and DeVera, C.A., 2019, Carbon dioxide mineralization feasibility in the United States: U.S. Geological Survey Scientific Investigations Report 2018–5079, 29 p., https://doi.org/10.3133/sir20185079.

106. ARPA-E. "Systems for Monitoring and Analytics for Renewable Transportation Fuels from Agricultural Resources and Management." SMARTFARM. ARPA-E, May 11, 2020. https://arpa-e.energy.gov/?q=arpa-e-programs/smartfarm

107. Energy Futures Initiative, Clearing the Air: A Federal RD&D Initiative and Management Plan for Carbon Dioxide Removal Technologies, (EFI, 2019), https://energyfuturesinitiative.org/s/EFI-Clearing-the-Air-Fact-Sheet.pdf; National Academies of Sciences, Engineering, and Medicine, Negative Emissions Technologies and Reliable Sequestration: A Research Agenda, (National Academies Press, 2019) https://doi.org/10.17226/25259.

108. For example, the DOE Office of Science received $20 million in its FY20 appropriations for negative emissions technologies, https://www.govinfo.gov/content/pkg/CPRT-116HPRT38679/pdf/CPRT-116HPRT38679.pdf, p 465; and ARPA-E just announced a new program in carbon-optimized bioconversion, https://arpa-e-foa.energy.gov/#FoaIdb25db4d9-7cce-49a1-a917-a451f78f6144.

109. US DOE, "Department of Energy to Provide $22 Million for Research on Capturing Carbon Dioxide from Air," March 20, 2020, https://www.energy.gov/articles/department-energy-provide-22-million-research-capturing-carbon-dioxide-air.

110. FY21 House Energy and Water Appropriations bill, https://appropriations.house.gov/sites/democrats.appropriations.house.gov/files/EW21%20-%20R16_xml.pdf, 79; US Congress, House, *Fossil Energy Research and Development Act of 2019*, HR 3607, 116th Cong., https://www.congress.gov/bill/116th-congress/house-bill/3607; and US Congress, Senate, *EFFECT Act of 2019*, 116th Cong., https://www.congress.gov/bill/116th-congress/senate-bill/1201.

111. Advanced Research Projects Agency- Energy, "Rhizosphere Observations Optimizing Terrestrial Sequestration (ROOTS) Program Overview," US DOE, 2016, https://arpa-e.energy.gov/sites/default/files/documents/files/ROOTS_ProgramOverview.pdf; National Research Council, *Climate Intervention: Carbon Dioxide Removal and Reliable Sequestration* (The National Academies Press, 2015), 43, https://doi.org/10.17226/18805.

112. Jeff Mulhollem, "Feed supplement for dairy cows cuts enteric methane emissions by 25%," Phys.org, February 24, 2020, https://phys.org/news/2020-02-supplement-dairy-cows-methane-emissions.html.

113. Mark A. McMinimy, "The 2018 Farm Bill (P.L. 115-334): Summary and Side-by-Side Comparison," US Congressional Research Service, February 22, 2019.

114. ARPA-E, "Rhizosphere Observations Optimizing Terrestrial Sequestration (ROOTS) Program Overview," December 15, 2016, https://arpa-e.energy.gov/sites/default/files/documents/files/ROOTS_ProgramOverview.pdf.

115. EFI, "Clearing the Air," Linden Trust for Conservation & ClimateWorks Foundation, September 2019, https://static1.squarespace.com/static/58ec123cb3db2bd94e057628/t/5d899dcd22a4747095bc04d5/1569299950841/EFI Clearing the Air Summary.pdf.

116. Association of American Universities, "AAU, Organizations Request $50 Million for AgARDA Program in FY21," March 4, 2020, https://www.aau.edu/key-issues/aau-organizations-request-50-million-agarda-program-fy21.

117. "Welcome to the '4 per 1000' Initiative," 4Pour1000, 2018, https://www.4p1000.org/.

118. Mission Innovation, *Mission Innovation, Materials Acceleration Platform: Accelerating Advanced Energy Materials Discovery by Integrating High-Throughput Methods with Artificial Intelligence*, January 2018, http://mission-

innovation.net/wp-content/uploads/2018/01/Mission-Innovation-IC6-Report-Materials-Acceleration-Platform-Jan-2018.pdf.

119. Iain M. Cockburn and Scott Stern, "Finding the Endless Frontier: Lessons From the Life Sciences Innovation System for Technology Policy," *Capitalism and Society* 5, no. 1 (2010): 1-6, https://papers.ssrn.com/sol3/papers.cfm?abstract_id=2208693; Dorothy Robyn and Jeffrey Marqusee, "The Clean Energy Dividend: Military Investment in Energy Technology and What It Means for Civilian Energy Innovation," ITIF, March 2019, http://www2.itif.org/2019-clean-energy-dividend.pdf.

120. DOE Office of Science, "46 EFRCs in 36 States," accessed April 30, 2020, https://science.osti.gov/bes/efrc/Centers; EFRC Transformative Opportunities, US DOE Office of Science (SC), November 18, 2019, https://science.osti.gov/bes/efrc/Research/Transformative-Opportunities.

121. DOE, "FY 2021 Congressional Budget Request – Budget in Brief," https://www.energy.gov/sites/prod/files/2020/02/f72/doe-fy2021-budget-in-brief_0.pdf.

122. Mission Innovation, *Materials Acceleration Platform: Accelerating Advanced Energy Materials Discovery by Integrating High-Throughput Methods with Artificial Intelligence, Report of the Clean Energy Materials Innovation Challenge Expert Workshop*, 2018, http://mission-innovation.net/wp-content/uploads/2018/01/Mission-Innovation-IC6-Report-Materials-Acceleration-Platform-Jan-2018.pdf.

123. International Energy Agency (IEA) *Clean Energy Innovation*, (Paris: IEA, 2020), https://www.iea.org/reports/clean-energy-innovation.

124. David Rolnick, et al., "Tackling Climate Change with Machine Learning," November 5, 2019, https://arxiv.org/abs/1906.05433.

125. Pacific Northwest National Laboratory, *Application of Nanomaterials to National Security*, U.S. Department of Energy, December 2010. https://www.pnnl.gov/nano/research/pdf/Nano_for_National_Security_Flier_12-02-2010.pdf.

126. Colin Cunliff, "An Innovation Agenda for Deep Decarbonization: Bridging Gaps in the Federal Energy RD&D Portfolio," ITIF, November 28, 2018, https://itif.org/publications/2018/11/28/innovation-agenda-deep-decarbonization-bridging-gaps-federal-energy-rdd.

127. Mission Innovation, *Mission Innovation, Materials Acceleration Platform: Accelerating Advanced Energy Materials Discovery by Integrating High-Throughput Methods with Artificial Intelligence*, January 2018, http://mission-innovation.net/wp-content/uploads/2018/01/Mission-Innovation-IC6-Report-Materials-Acceleration-Platform-Jan-2018.pdf.

128. Colin Cunliff, Ashley Johnson, and Hodan Omaar, "How Congress and the Biden Administration Could Jumpstart Smart Cities with AI," Information Technology and Innovation Foundation, *forthcoming*.