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“A plan to make the United States the world leader in clean energy innovation and rise to an existential challenge—creating exciting new jobs along the way.”

—John F. Kerry, 68th US Secretary of State

ENERGIZING AMERICA

A Roadmap to Launch a National Energy Innovation Mission

Varun Sivaram, Colin Cunliff, David Hart,
Julio Friedmann, and David Sandalow

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Library of Congress Control Number: 2020917122

ISBN: 978-0-578-75852-7

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Foreword

Innovation is key to combating climate change, achieving a more secure and clean energy future, and maintaining American leadership in the growing energy industries of tomorrow. Today, the prospects for decarbonizing the power sector in the rapid timeframe climate change requires are far brighter because of dramatic cost declines in wind and solar power and battery storage capacity over the past decade, which in turn have expanded new industries and created economic opportunity.

According to the International Energy Agency, however, half of the cumulative reductions needed to achieve net-zero emissions by 2050 stem from technologies that are not commercially available today. Even with widespread electrification of certain sectors, such as passenger transport or heating, and dramatic increases in renewable energy to generate that electricity, so-called "hard-to-abate sectors," such as heavy-duty transport, shipping, aviation, and heavy industry, will likely require a broader suite of decarbonization technologies. New and improved technologies will also be needed to decarbonize the massive energy infrastructure that already exists.

The case for government investment in research, development and demonstration (RD&D) is clear. Because private firms cannot capture the full social value of their innovations, they underinvest relative to the benefits to society. Along with strong climate policy to set limits on carbon pollution, federal RD&D investments could be a catalyst to propel US innovation forward at the rate needed to outcompete rivals, bring clean energy technologies to market faster, and confront climate change. In the past, the federal government has too often neglected energy innovation, investing less than a quarter of what it invests in health innovation and less than a tenth of what it invests in defense innovation.

Although the case for energy innovation is clear, the question for policymakers remains: how best to accomplish it? If an administration or Congress sought to "go big" on clean energy innovation, how would it best spend those dollars, taking advantage of the lessons from past experience? What stages of research should policymakers invest in? Which technologies will yield the best results? How should the federal government structure itself to deploy those funds most effectively, across the national laboratories, America's great universities, and partnerships with the private sector?

Roughly one year ago, I identified these as key questions that would benefit from further analysis and research, ahead of the next administration and Congress taking office in 2021. Consistent with the mission of the Center on Global Energy Policy to advance smart, actionable, and evidence-based energy and climate solutions through research, education, and dialogue, our goal in undertaking this work was to provide a roadmap for energy innovation that would be useful to policymakers in the formats and timeframes they need.

Energizing America is the result of that effort and offers the next administration and Congress a strategic framework to triple US annual investment in energy innovation over the next five years, including detailed funding proposals across the full spectrum of critical energy technologies and recommendations for immediate implementation. I was thrilled we could recruit Dr. Varun Sivaram to Columbia University's Center on Global Energy Policy to work on this project with David Sandalow and Dr. Julio Friedmann, in collaboration with Dr. Colin Cunliff and Dr. David Hart from the Information Technology and Innovation Foundation (ITIF). I would like to thank them for their tremendous work on this important project and for producing such an excellent and valuable report.

The spectacular success driving down the cost of renewable energy, along with the increasing sense of urgency around climate change and clean energy investments in multiple government stimulus plans around the world, should give us optimism about the outlook for low-carbon technologies. At the same time, much more work is required to bring many other sustainable energy technologies to market and to scale, and to ensure clean energy technologies are deployed in ways that promote a just and equitable energy transition.

We hope you enjoy *Energizing America* and that it contributes to fostering dialogue and understanding on these urgent questions of how to better build a more prosperous, secure and sustainable global energy system.

Jason Bordoff
Founding Director, Center on Global Energy Policy

EXECUTIVE SUMMARY

Clean energy innovation is central to the fight against climate change. The dramatic success in lowering the costs of solar panels and wind turbines in the past decade must be replicated across a wide range of other energy technologies. Doing so will open extraordinary economic opportunities.

To rise to this challenge, the United States should launch a National Energy Innovation Mission. Led by the president and authorized by Congress, this mission should harness the nation's unmatched innovative capabilities—at research universities, federal laboratories, and private firms (both large and small), in all regions of the country—to speed the progress of clean energy technologies. To jumpstart this mission and unlock a virtuous cycle of public and private investment, the US federal government should triple its funding for energy research, development, and demonstration (RD&D) over the next five years.

Although a growing bipartisan chorus is calling for more ambitious public investment in clean energy innovation, no detailed roadmap exists for how Congress and federal agencies can most effectively increase funding. This volume aims to fill that gap. We offer policymakers a strategic framework to build a growing RD&D portfolio over the next five years, detailed funding proposals across the full spectrum of critical energy technologies, and recommendations for immediate action. In making these proposals, we have surveyed the scholarly literature, distilled decades of US historical experience, drawn on dozens of legislative proposals, and assembled the most up-to-date database of federal clean energy RD&D funding to derive lessons for maximizing the return on public investment.

This volume has two parts. Part I makes the case that the federal government should dramatically increase funding for clean energy innovation. Part II provides a detailed roadmap for doing so.

Part I: The need to increase federal investment in clean energy innovation

Leading the world to a clean energy future is in the US national interest. Unchecked climate change endangers our security, economy, and well-being. The devastating hurricanes and wildfires of recent years are a grim foretaste of a warmer future. Although the global slowdown from COVID-19 lowered greenhouse gas emissions, they are already surging back as the world economy recovers. Averting catastrophe will require new and improved clean energy technologies to enable the world to reach net-zero emissions in the coming decades, a herculean task known as "deep decarbonization."

The United States also stands to prosper by seizing the opportunity to lead the low-carbon industries of the future. Around the world, countries are eagerly investing in clean energy—to cut air pollution, reduce dependence on imported fossil fuels, and fight climate change. Today, China is the world leader in deploying clean energy technologies and invests heavily in clean energy innovation. The United States—with the world's best and largest innovation system—could lead the world in clean energy innovation in the decades ahead, but not without commitment and effort.

Federal funding is critical to US energy innovation. Emerging clean energy technologies face steep barriers to market success. Risk-averse incumbent firms, byzantine regulations, and the inertia of existing infrastructure and subsidies built around fossil fuels can sink even the most promising ventures. It will take strong and sustained public RD&D investment to stimulate the massive private investment needed for deep decarbonization. Such public funding could complement near-term stimulus measures to help the economy recover from the COVID-19 crisis. RD&D investments should be paired with policies to support the market deployment and export of clean energy technologies, so that innovative energy industries of the future sustain long-term prosperity and inclusive economic growth.

The National Energy Innovation Mission would open a new chapter in the storied history of US innovation. Federal funding has accelerated the development of life-saving drugs, modernized the military's arsenal, and put a man on the Moon. These past missions have helped make the United States the world's science and technology superpower.

By comparison, the federal government has neglected energy innovation. Prior surges in federal energy RD&D spending have been short-lived, and recent funding increases have been tepid. Today, the federal government invests less than $9 billion per year on energy innovation, less than a quarter of what it invests in health innovation and less than a tenth of what it invests in defense innovation. The United States remains well short of meeting its international commitment under the 2015 Mission Innovation compact to double public funding for RD&D to $12.8 billion by 2021.

This should change. The federal government should elevate energy innovation as a core national priority and fund it accordingly. Over the next five years, annual public funding for energy innovation, across a range of federal agencies, should triple to $25 billion. A wealth of research shows that US research institutions and private firms are capable of absorbing this scale of federal support and translating it into rapid technological progress—delivering economic returns that far outstrip public investments.

Part II: A National Energy Innovation Mission

Federal policymakers should develop a strategy for ramping up federal funding to most effectively invest in clean energy innovation—and take swift action to set this strategy in motion (Figure ES-1). To prioritize funding, they should build RD&D programs around ten technology pillars, each representing a critical challenge for deep decarbonization. In addition, as policymakers design and execute these programs, they should heed six principles that will maximize the effectiveness of federal investments. And following the inauguration in 2021, the next Congress and administration should take three immediate actions to launch the National Energy Innovation Mission.

FIGURE ES-1: Strategic and tactical guidance to the next administration and Congress

	Technology Pillars
1	Foundational science & platform technologies
2	Clean electricity generation
3	Advanced transportation systems
4	Clean fuels
5	Modern electric power systems
6	Clean and efficient buildings
7	Industrial decarbonization
8	Carbon capture, use, & sequestration
9	Clean agricultural systems
10	Carbon dioxide removal

	Strategic Principles
1	Match the funding portfolio to critical decarbonization needs
2	Support all stages of the innovation pipeline
3	Marshal the full capacity of the federal goverment
4	Harness the innovative capacity of National Laboratories, universities, and the private sector
5	Partner with state & local governments to support regional innovaton
6	Set predictable long-term funding targets, while adapting to new data

	Immediate Actions
1	The President should **launch the National Energy Innovation Mission**
2	Congress should increase energy RD&D funding by **30% in FY22**
3	The United States should **reassert international leadership** on energy innovation

Tripling the federal energy RD&D budget over five years will enable the United States to pursue the full deep decarbonization innovation agenda. The federal government's current energy RD&D portfolio focuses heavily on clean electricity generation—only one of the ten technology pillars. Organizing the National Energy Innovation Mission around all ten will significantly improve the prospects for rapid progress on a wide range of technologies. Few of these technologies have yet achieved widespread commercial success anywhere in the world, so the United States has an opportunity to lead in nascent and growing markets including carbon capture and storage, digital energy technologies, long-duration grid energy storage, advanced transportation technologies, and clean fuels such as hydrogen. For each of the pillars, we propose specific federal government initiatives.

In shaping the energy RD&D portfolio as it grows to $25 billion annually by 2025 (that is, by Fiscal Year 2026, which begins October 1, 2025), policymakers should follow six strategic principles. The first five call for diversification—across topics, stages of innovation, federal agencies, research partners, and regions of the United States. In addition to covering all ten technology pillars, federal energy RD&D investments should cover the entire innovation pipeline from early-stage research to commercial-scale demonstration projects. They should expand beyond the Department of Energy (DOE) and its National Laboratories (Figure ES-2). Although DOE and the Labs will continue to provide core expertise on energy innovation, Congress should also provide growing funding for energy innovation at the Departments of Defense (DOD) and Agriculture (USDA), the National Science Foundation (NSF), the National Aeronautics and Space Administration (NASA), and other federal agencies. Participating agencies should invest across the innovation ecosystem, from federal labs to universities to private ventures, and partner with local and state governments to build regional clusters of excellence. Finally, the sixth principle recommends a strategy for managing the portfolio over time: Policymakers should adopt long-term funding targets but adapt the portfolio over time as circumstances change and as they learn from experience.

In recent years, bipartisan momentum has grown in support of energy innovation investments, providing a window of opportunity. The 117th Congress and the presidential administration that will be sworn in in 2021 should take immediate action to set the National Energy Innovation Mission in motion by taking three concrete steps.

First, the president should issue a Presidential Policy Directive announcing the National Energy Innovation Mission, establishing energy innovation as a national priority, setting a goal of tripling federal funding for energy innovation in five years, and creating a White House Task Force to coordinate among agencies and speed implementation. (A draft of a Presidential Policy Directive is included as Appendix A.) Second, the next Congress should pass an ambitious budget for Fiscal Year 2022 (FY22) that sharply increases federal energy RD&D funding—focusing particularly on currently underfunded technology pillars—and sets the United States on a path to tripling the budget by 2025. (Figure ES-3 outlines a specific proposal for the FY22 energy innovation budget, summarizing the line-item recommendations in Table ES-1 to congressional appropriators for funding each agency and office.) Third, the United States should immediately reassert its international leadership by recommitting to Mission Innovation, courting bilateral collaborations to advance energy technologies, and stimulating a competitive race-to-the-top to raise global public funding for clean energy innovation.

FIGURE ES-2: Historical clean energy RD&D funding by federal agency and proposal to ramp up to an annual clean energy innovation budget of $25 billion by 2025

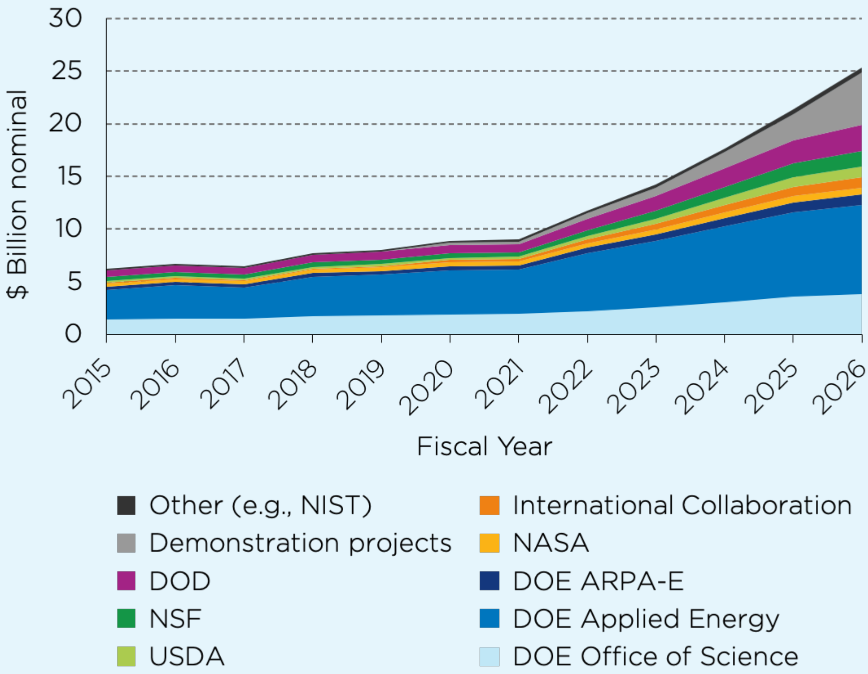
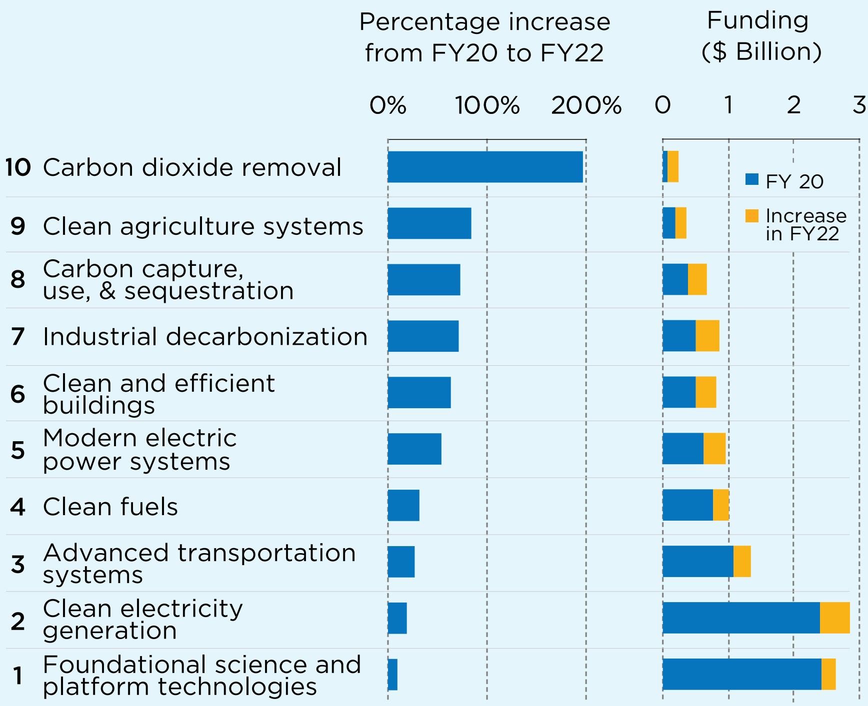


FIGURE ES-3: Proposed FY22 federal energy innovation budget by technology pillar, compared with FY20 levels



These three immediate actions will launch the next national innovation mission. 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 will repeat itself. On the heels of the global coronavirus crisis, the United States will lead the response to an even graver global threat—climate change—and prosper as the world transitions to clean energy.

TABLE ES-1: Proposed FY22 federal energy innovation budget, by agency and office ($ millions)

Funding Agency	Funding Office/Organization	FY 2020 Est.	FY 2022 Proposed	% change
Dept. of Energy	**Energy Efficiency and Renewable Energy (EERE)**	**2,228**	**2,682**	**20%**
	Vehicle Technologies Office (EERE/VTO)	396	488	
	Bioenergy Technologies Office (EERE/BETO)	260	320	
	Hydrogen & Fuel Cell Technologies Office (EERE/HFTO)	150	185	
	Solar Energy (EERE/SETO)	280	303	
	Wind Energy (EERE/WETO)	104	113	
	Water Power (EERE/WPTO)	148	160	
	Geothermal Technologies Office (EERE/GTO)	110	170	
	Adv. Manufact. Office (EERE/AMO)	350	432	
	Building Technologies Office (EERE/BTO)	230	301	
	Office of Carbon Management (CM)*	**472**	**812**	**72%**
	Carbon Capture (Power & Industrial)	115	300	
	Carbon Utilization	21	25	
	Carbon Storage	79	120	
	Adv. Energy Systems/Crosscutting	123	150	
	Negative Emissions Technologies (new office)	--	75	
	Methane Leak Detection & Mitigation	18	22	
	Office of Nuclear Energy (NE)	**1,493**	**2,028**	**36%**
	Versatile Test Reactor	65	450	
	Reactor Concepts RD&D	102	163	
	Fuel Cycle R&D	305	255	
	Advanced Reactor Research, Development and Demonstration	330	520	
	Office of Electricity (OE)	**190**	**520**	**174%**
	Office of Science (SC)	**2,151**	**2,572**	**20%**
	Advanced Scientific Computing Research (SC/ASCR)	173	200	

(continued from previous page)

Funding Agency	Funding Office/Organization	FY 2020 Est.	FY 2022 Proposed	% change
Dept. of Energy	Biological and Environmental Research (SC/BER)	451	523	
	Basic Energy Sciences (SC/BES)	661	766	
	Fusion Energy Sciences (SC/FES)	671	740	
	Advanced Resarch Projects Agency-Energy (ARPA-E)	**425**	**516**	**21%**
	Subtotal, DOE	**6,959**	**9,130**	**31%**
Dept. of Agricult.	Agriculture Advanced Research and Development Authority (AGARDA)		50	
	Agricultural Research Service (ARS)	99	158	
	NIFA Agriculture and Food Research Initiative (NIFA/AFRI)	106	169	
	Subtotal, USDA	**205**	**377**	**83%**
Dept. of Defense	U.S. Army Research Laboratory (ARL)	155	202	
	U.S. Naval Research Laboratory (NRL)	97	127	
	U.S. Air Force	254	332	
	Other (Defense-Wide, DARPA, ESTCP)	298	391	
	Subtotal, DOD	**804**	**1,053**	**31%**
NASA		**339**	**394**	**16%**
National Science Fndn.	Biological Sciences (BIO)	54	75	
	Computer and Information Science and Engineering (CISE)	24	34	
	Engineering (ENG)	156	219	
	Directorate for Mathematical and Physical Sciences (MPS)	162	227	
	Other NSF	21	29	
	Subtotal, NSF	**804**	**1,053**	**31%**
Other (NIST, NOAA, USGS, FHWA, EPA-ORD)		**169**	**221**	**31%**
Total	**N/A**	**8,894**	**11,758**	**32%**

**This is the proposed new name for the current Office of Fossil Energy*
FY 2020 funding levels for non-DOE programs are estimates of the portion of funding that goes to clean energy / clean agriculture. Agency and Office totals include estimates of program direction and RD&D facilities (not shown in the table) and may be greater than the sum of RD&D programs.

PART 1

THE NEED TO INCREASE FEDERAL INVESTMENT IN CLEAN ENERGY INNOVATION

Imagery supplied by Skynesher/Getty Images

Clean energy innovation is an essential national priority, and the following chapters make the case for raising federal funding to accelerate it. **Chapter 1** provides two motivations for policymakers to elevate energy innovation as a core national priority: speeding progress on combating climate change and prospering through the development of globally competitive US clean energy industries. **Chapter 2** explains why public funding is needed to supplement and stimulate private investment in energy innovation. **Chapter 3** surveys lessons from previous US innovation missions, such as the successful defense and health innovation missions, to guide a new National Energy Innovation Mission. **Chapter 4** makes the case for why the US federal government should set a target for annual energy RD&D funding of $25 billion per year by 2025—and why such a target is achievable.

CHAPTER 1
Clean energy innovation: an essential national priority

Clean energy is popular in the United States across the demographic and ideological spectrum—for good reason.[1] A transition to clean energy is essential to meet the challenge of climate change. The global market for clean energy products and services is exploding. Affordable clean energy promises enormous benefits for people in the United States and around the world.

Some clean energy technologies are delivering impressive results. Solar photovoltaic panels are the fastest-growing source of power, both in the United States and globally. Wind turbines almost as tall as the Eiffel Tower are producing electricity at costs cheaper than those of existing coal plants.

But meeting global climate policy goals will require innovations across a wide range of technologies. Countries that are expanding their investments in these technologies will be best positioned to reap the economic rewards of rapidly growing global markets. As China, Japan, the European Union, and others do just that, the United States risks being left behind. The urgency of addressing climate change and building globally competitive clean energy industries should motivate policymakers to elevate energy innovation as a core national priority.

Unlocking deep decarbonization

Greenhouse gas emissions must fall dramatically in coming decades to stave off the worst effects of climate change. The stakes for the United States are enormous. In recent years, the United States has faced harrowing climate-related disasters from Hurricane Sandy to western wildfires. Droughts, storms, sea-level rise, and disease exacerbated by climate change could ravage the United States in the decades ahead.[2]

Carbon dioxide (CO_2) emissions from energy are the most important contributors to climate change.[3] Over the last decade, global CO_2 emissions from energy have risen by 10 percent.[4] Although emissions declined in early 2020 as a result of the disastrous coronavirus pandemic, they are rebounding as the global economy begins to recover. Embarking on a swift path to net-zero emissions—deep decarbonization—will require dramatic changes to global energy systems.

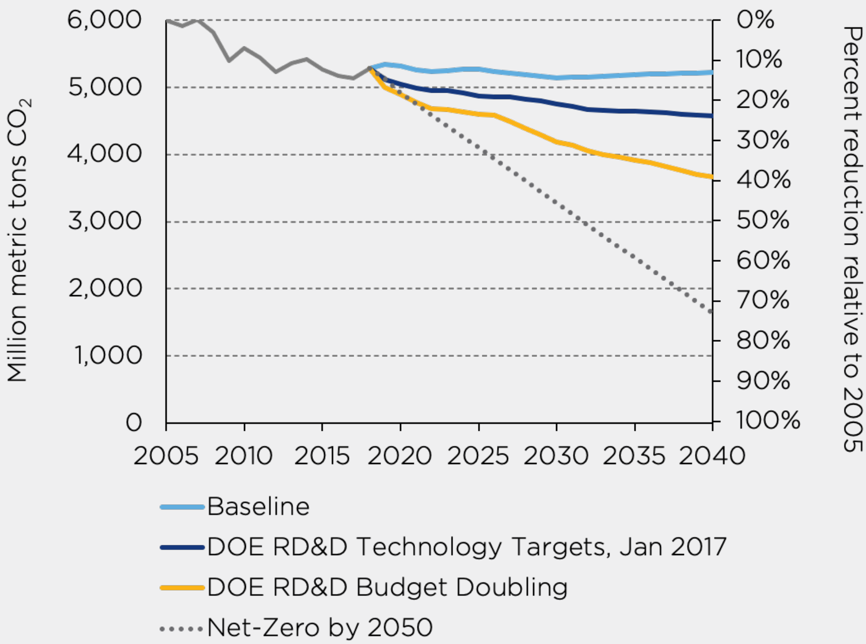
Unfortunately, current clean energy technologies alone are not up to the task. Some clean energy technologies, including solar panels and wind turbines, are already commercially competitive with market incumbents such as coal-fired power plants in many parts of the world. But in big, vital sectors—from shipping and aviation to steel and cement production to urban infrastructure—no high-performing clean energy technologies are available on a commercial scale and at costs that are competitive with those of dirty incumbents.

Indeed, the International Energy Agency (IEA) warns that of 46 energy technologies critical for deep decarbonization, only 6 are progressing at a sufficient pace to avert catastrophic climate change.[5] Among the remaining 40 are technologies to capture and store carbon dioxide emissions from power production and industrial processes, produce and use clean hydrogen fuel, store intermittent renewable electricity for long durations, and manage complex energy systems such as power grids. Even in clean energy technology areas—such as solar panels, wind turbines, and batteries—that are already achieving commercial success, new and improved technologies can be even cheaper and unlock new market applications.[6] Roughly half of the reductions that the world needs to swiftly achieve net-zero emissions in the coming decades must come from technologies that have not yet reached the market today.[7]

Expanding public investment in energy RD&D would hasten decarbonization (Figure 1-1).[8] A 2017 DOE analysis concluded that if its current RD&D

programs were to meet their targets for reducing the cost and improving the performance of clean energy technologies, US carbon emissions could fall 23 percent by 2040. These projections may be conservative: Between 2012 and 2017, DOE met or exceeded 75 out of 76 technology targets.[9] And if the DOE were to double its RD&D budget, better technologies could reduce US emissions by a further 15 percent.[10] To be sure, federal investments in RD&D (known as "technology-push" policies) alone would not be sufficient to spur decarbonization at the rate needed to reach net-zero US emissions by 2050. "Demand-pull" policies, such as a carbon price or clean energy standard, will be needed as well to achieve a clean energy transition.

FIGURE 1-1: U.S. energy-related CO_2 emissions in different scenarios of technology progress



Source: DOE

Innovation at home would also yield reductions in emissions abroad. The global diffusion of clean energy technologies developed and produced domestically is critical because the United States accounts for only 15 percent of carbon emissions. Moreover, transitioning to cost-effective clean energy systems domestically would strengthen US credibility in its international climate diplomacy and could demonstrate to other countries viable pathways to deep decarbonization.

Roughly half of the reductions that the world needs to swiftly achieve net-zero emissions in the coming decades must come from technologies that have not yet reached the market.

Capturing growing global markets

Global annual energy investment was nearly $2 trillion in 2019.[11] The share of the global investment pool dedicated to clean energy systems is rising. For example, investment in renewable energy grew by 800 percent over the last fifteen years to nearly $300 billion in 2019.[12] Significant economic opportunities await countries that can supply new and growing clean energy markets.

The United States was once a global leader in developing the energy technologies of the future. Commercial nuclear reactor technology was born in America after World War II and then exported around the world. Modern solar photovoltaic power was invented in Bell Labs in the 1950s and is today the fastest-growing power source in the world. More recently, the shale revolution sprang from sustained research and development (R&D) investments by the federal government that, in tandem with investments by private industry, turned the United States into the world's largest producer of oil and gas.[13,14,15]

But increasingly, the United States is ceding leadership in energy innovation to competitors abroad. Around the world, countries are investing in innovation as part of the transition to clean energy—in part to reduce carbon emissions, but also to cut dependence on fossil fuel imports, reduce energy costs, and clean polluted air. Today, China is the world's largest producer, exporter, and user of solar panels, wind turbines, and batteries. By contrast, the United

States ranks a distant fourth place in terms of its manufacturing of these clean energy technologies in aggregate.[16]

China is not alone. Many countries are pursuing aggressive industrial policies that pair targeted investments in emerging clean energy technologies with export promotion. For example, Japan deploys financing from its export-import bank to sell hydrogen vehicles and electrolyzers abroad.[17] Similarly, countries from South Korea to Germany have made sustained investments in innovation central to their long-term strategies to take leadership positions in burgeoning clean energy industries. The technologies they are focusing on include gasifiers, ultra-high-voltage transmission lines, fuel cells, efficient ships, and more.[18,19]

The United States is well-placed to lead many nascent clean energy industries. Carbon capture technology is one such opportunity.[20] As countries seek to reduce their greenhouse gas emissions from fossil fuels, demand for technologies to separate carbon dioxide from the emissions from industrial facilities and power plants as well as directly from the atmosphere will grow. By 2040, the market for such technologies could be worth several hundred billion dollars.[21,22] Currently, more cutting-edge carbon capture facilities are operating or under development in the United States than anywhere else in the world.[23] But translating this early progress into long-term industrial leadership will require sustained investments in innovation. This holds true across a range of technology opportunities where the United States is well-placed to lead, from clean transportation technologies to digital tools for managing complex energy systems.

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.[24] Germany has gone even further, unveiling a national strategy targeting the "creation of a hydrogen economy and the leadership of German companies" and emphasizing investments in energy RD&D.[25] The Chinese government has announced a "new infrastructure" package worth $1.4 trillion that will include investments in advanced energy industries and infrastructure. Its plans include building out high-voltage transmission and high-speed rail networks, extending subsidies for electric and hydrogen-fueled vehicles and deploying networks of vehicle charging infrastructure, and producing advanced batteries for vehicles and the electric grid.

By contrast, funding for clean energy technologies has been notably absent from US stimulus measures so far, even though government support for energy innovation can underpin the long-term growth of competitive US clean energy industries. In addition to funding energy RD&D, policymakers should pursue measures to promote inclusive economic growth and clean energy technology exports in industrial clusters across the country. Although a broader industrial policy agenda is beyond the scope of this volume, Box 1-1 briefly surveys policies to cultivate clean energy industries that can help propel a long-term US economic recovery from the COVID-19 recession.

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 United States risks missing out on a lucrative opportunity to lead an overhaul of global energy infrastructure. To seize the opportunity, US policymakers should elevate clean energy innovation as a core national priority—on the level of biomedical, defense, space, and artificial intelligence innovation. Setting the right priorities is the first step.

BOX 1-1: Supporting long-term economic recovery from the COVID-19 recession through investments in clean energy innovation

The coronavirus pandemic plunged the US economy into recession and sparked widespread unemployment, prompting the federal government to pass major economic relief measures. Those measures focused on addressing the acute crisis and providing immediate relief. As the economy recovers from this shock, the federal government should pursue additional policies that promote long-term recovery, economic growth, and global competitiveness. Investments in clean energy RD&D are well suited to do just that.

A chorus of voices has called for a "green stimulus" comprising investments to both stimulate an economic recovery and reduce greenhouse gas emissions.[26] Given that the federal government's real cost of borrowing is currently negative and significant economic capacity is idle, there is a historic opportunity to make large-scale public investments, both to deploy mature clean energy technologies and bring emerging technologies to maturity through demonstration projects.[27] To complement short-term stimulus, investments in innovation should also be included in a green recovery package.

An array of research suggests that such investments would deliver both long-term economic and environmental benefits. A survey of more than 200 economists and central bankers from around the world found that public funding for clean energy R&D is a rare policy intervention in response to COVID-19 that will both produce high long-run economic returns and substantially reduce emissions.[28] Additionally, an assessment of US public investment in wind energy R&D since 1976 found that the resulting economic benefits—including lower energy costs and avoided health impacts from air pollution—have outweighed government investment costs by a factor of eighteen.[29]

Public funding for innovation can contribute to long-term employment. For example, doubling federal research funding for a US university has historically been associated with a 1 percent employment increase in that university's county, controlling for other drivers of employment. Similarly, federal research subsidies to private firms also stimulate employment. A survey of results from around the world, spanning US military RD&D funding to Finland's government subsidies for innovative firms, suggests that the cost of creating a job through public investments in innovation is anywhere from $2,100 to $28,000. Using a conservative estimate of $25,000, our target level in 2025 of $25 billion in annual federal RD&D funding could support one million jobs over the coming decades. For comparison, stimulus spending by the US government during the Great Recession resulted in a cost per created job of $50,000.[30]

Across technology areas that policymakers might consider funding, investments in clean energy technologies produce some of the highest returns on taxpayer investment. For example, patents for innovations in battery, hydrogen, and carbon capture technologies stimulate greater US economic growth, on average, than those for innovations in other areas from artificial intelligence to biotechnology.[31] Public RD&D funding can help firms translate breakthroughs into commercial success. For example, grants from the federal government's Small Business Innovation Research program have increased the patenting activity, revenue, and survival rates of start-up companies developing innovative energy technologies.[32]

Yet federal investments in innovation are not guaranteed to result in globally competitive, job-creating industries located in the United States. There is a risk that other countries will capitalize on US investments in technology innovation by then manufacturing and commoditizing those technologies abroad. Even though solar photovoltaic technology was invested and incubated in the United States, China manufactures and exports the large majority of solar panels. Similarly, China, Japan, and South Korea collectively dominate battery manufacturing, even though US scientists, supported by public funding, invented the types of lithium-ion batteries used for automotive and grid applications.[33]

To avoid this outcome, it will be essential to promote diverse elements of innovative industrial ecosystems, such as manufacturing capabilities, local supply chains, and engineering talent. In industries with a heavy emphasis on engineering—such as the automotive, semiconductor, and several clean energy industries—manufacturing plants are an important source of innovation.[34] Firms that locate manufacturing in close proximity to research and development facilities and to suppliers of components and services can improve the performance and cost of their products more quickly.[35] As the federal government triples energy RD&D funding to $25 billion by 2025, it should not narrowly target early-stage R&D. Rather, it will take public funding for demonstration, manufacturing, and export finance—along with immigration, education, and training policies that prepare a qualified workforce—in order to seed industrial clusters in communities across the country, promote inclusive growth, and reap the full economic benefits of energy innovation.

CHAPTER 2
How federal investment accelerates energy innovation

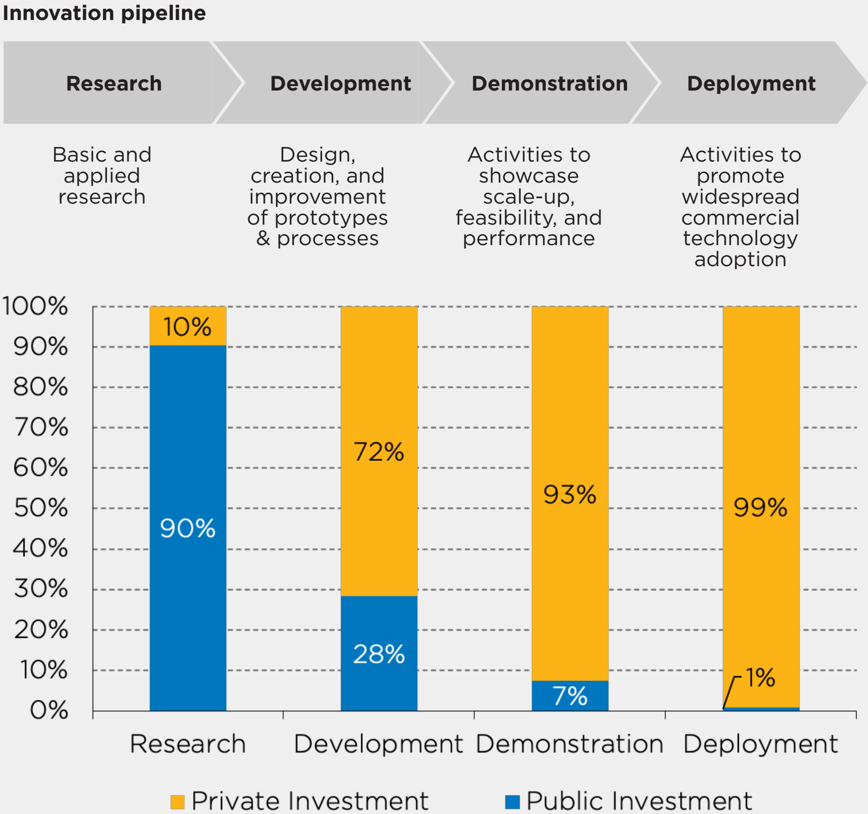
Commercializing new energy technologies requires surmounting intimidating barriers. Even though the United States is home to an intricate network of private firms and investors, academic and nonprofit institutions, and government entities at multiple levels, this energy innovation ecosystem often fails to translate promising technological advances into commercial success. Federal RD&D funding can improve the commercial prospects of promising technologies. Targeted correctly, such public investment can stimulate further private investment and unlock a virtuous cycle of learning, improvement, and reinvestment by both public and private sectors.

Barriers to energy innovation

The process of energy innovation is fundamentally different from innovation in many other sectors of the economy. Clean energy companies face high up-front capital requirements and highly regulated markets. New energy technologies often seek to eke out efficiencies near the limits of physics and thermodynamics, and they must meet daunting performance and cost demands from customers and regulators. Energy innovation cannot match the rapid cadence of product development and commercial diffusion achieved by software start-ups. New energy technologies often take decades of development and billions of dollars of investment before achieving commercial traction.

Figure 2-1 summarizes a highly stylized path that emerging energy technologies take as they progress from discovery to widespread use.[1] This "innovation pipeline" can be coarsely separated into the four stages of research, development, demonstration, and deployment. (To be clear, reality is messier, and there is no single technology pipeline with sharp boundaries demarcating the different stages.)

FIGURE 2-1: The energy innovation process and sources of U.S. investment by stage in 2016



Source: Breakthrough Energy, Energy Futures Initiative, and IHS Markit, 2019

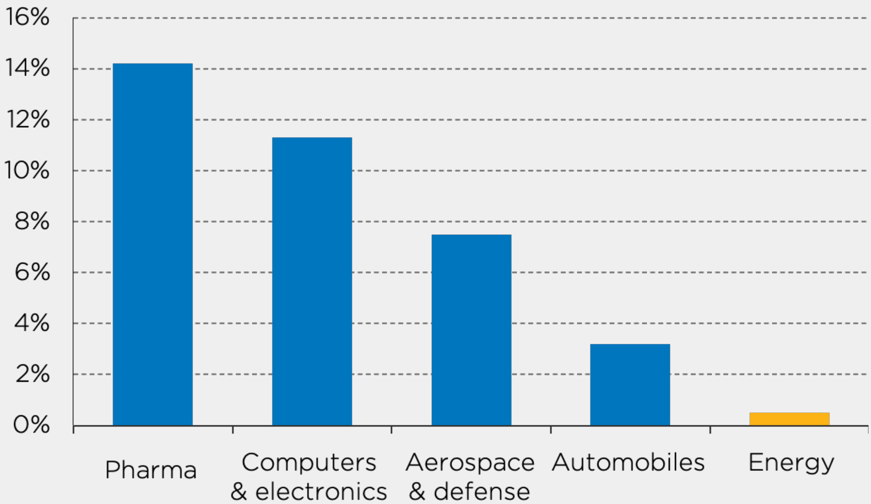
The public and private sectors play very different roles in each of the stages. The earliest stage—research, both basic and applied—is mostly funded by the federal government. Private firms are understandably reluctant to fund projects that may advance the frontiers of scientific knowledge and generate valuable economic spillovers for a range of industries but are not likely to result in measurable revenue.[2] The federal share diminishes in the later stages of innovation: energy firms and investors supply the bulk of the funding for development and demonstration (and nearly all the funding for deployment of mature technologies).

New energy technologies often take decades of development and billions of dollars of investment before achieving commercial traction.

Private investment alone is not sufficient to propel energy innovation at the rate needed for the United States to outcompete its rivals or bring clean energy technologies to market fast enough to confront climate change. Private investors remain focused on funding the deployment of mature technologies that are close to market viability. In 2019, less than 10 percent of private investment flows for clean energy in the United States supported innovative companies; nearly all capital flows financed projects such as wind and solar farms.[3] Promising clean energy technologies often remain stranded in so-called "valleys of death," where private returns are insufficient to induce investment, yet public funders shy away for fear of undercutting private opportunities. Few companies or investors will take the risk of turning laboratory research advances into commercial prototypes or fund pilot manufacturing lines. An even more dire lack of private funding awaits later in the innovation pipeline, at the demonstration stage.[4]

Overall, firms in the energy industry are stingy spenders on innovation, investing just 0.5 percent of revenues into research and development. They often face structural barriers that limit these investments. For example, US electric power utilities are regulated by state and local governments, which are generally hesitant to allow firms to spend funds collected from ratepayers on risky technology projects. Unregulated energy firms invest more in innovation than utilities but much less than companies in the R&D-intensive industries displayed in Figure 2-2.[5]

FIGURE 2-2: Research and development spending as a percentage of revenue across major global industries, 2018



Source: PwC, NSF

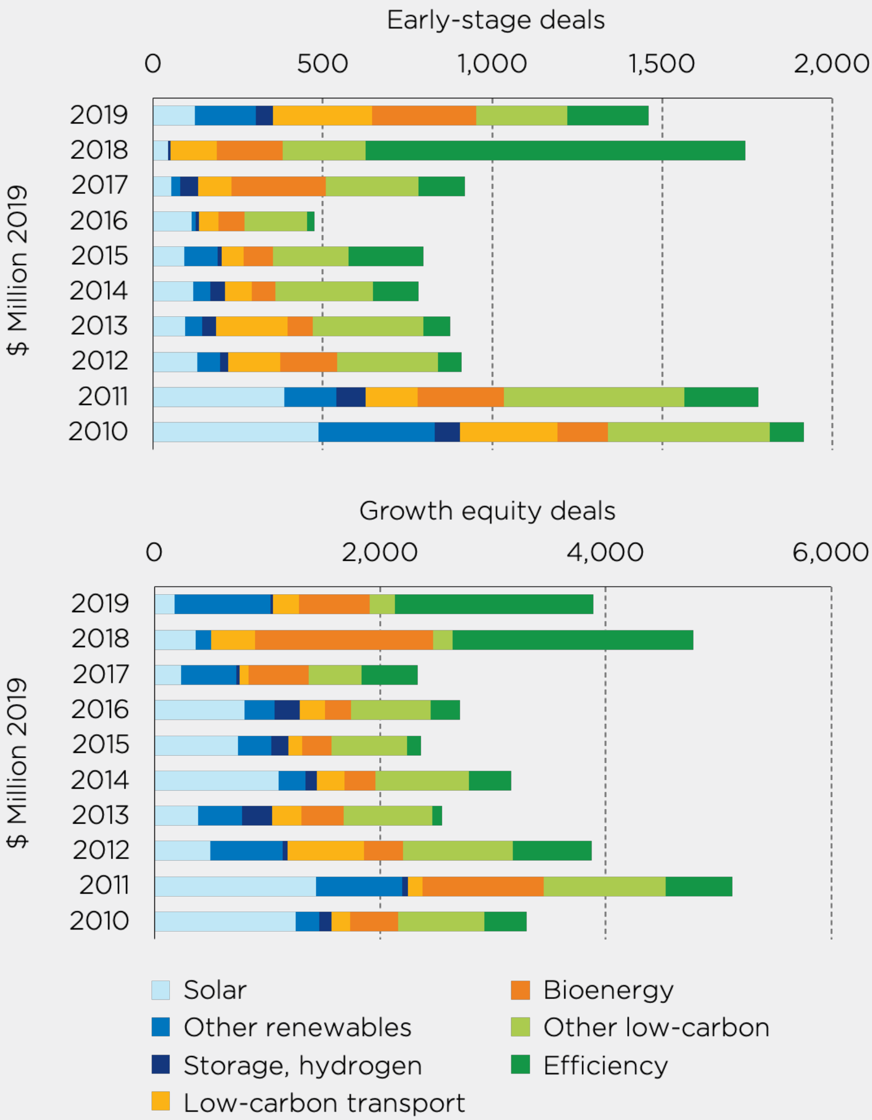
In the software and pharmaceutical industries, large infusions of venture capital (VC) advance innovation. Software start-up companies require comparatively less capital and can often deliver returns to their investors in fewer than five years. By contrast, pharmaceutical start-ups often require more than a decade to achieve market traction and require substantially higher levels of capital. But they and their investors benefit from a standardized approval process run by the Food and Drug Administration that lowers the risk of a drug or medical product as it moves through trials, as well as intellectual property rights that give them a higher probability of profiting once it is approved.[6]

Neither model works for the energy sector, where capital requirements are high, development timelines are long, and demonstration and de-risking opportunities are scarce. Not a few venture capitalists discovered this the hard way. From 2006 to 2011, over $25 billion in VC investment poured into clean energy technology start-ups. More than half of that money was lost.[7] The only bright spots were companies making energy software or simple hardware products for energy-related purposes such as Nest, a thermostat maker acquired by Google. Commercializing complex energy hardware technologies often takes a decade or longer and costs too much to meet the expectations of most VC funds that a few big winners in every portfolio will emerge within five years. In 2019, VCs invested just $1 billion into US energy companies, compared with about $20 billion for health care deals and $70 billion for information technology firms.[8]

Although VCs shifted their bets away from clean energy technologies, a new generation of investors is emerging.[9] Some self-dubbed "patient capital" investors are prepared to wait a decade or longer for their investments to mature and ultimately pay outsized returns.[10] Electric power utilities and oil and gas majors—especially those in Europe—are increasingly investing in start-ups directly or through pooled funds such as Energy Impact Partners and the Oil and Gas Climate Initiative. A range of other companies—from Microsoft to Amazon—have made commitments to put billions of dollars into clean energy in the coming years.[11,12] In 2019, corporate early-stage and growth equity investments in clean energy technology companies surpassed a record $5 billion. Overall, total global investment in clean energy technology companies in 2018 and 2019 rivals the levels last seen a decade ago (Figure 2-3).[13]

Private investors are increasingly betting on modular technologies, such as batteries, which comprise small, uniform units that can be scaled up incrementally, limiting investor risk.[14] Similarly, they are increasingly investing in modular equipment to directly capture carbon dioxide from the air.[15] Nevertheless, even in these fields, levels of private investment remain far below what is needed to rapidly commercialize emerging technologies. COVID-19 has dented private investments in clean energy technology companies, which fell by roughly 30 percent in the first half of 2020, compared with the two previous years.[16]

FIGURE 2-3: Early-stage and growth equity investment deals in U.S. clean energy technology companies, by technology area, excluding deals greater than $1 billion



Source: International Energy Agency

The need for federal investment in energy RD&D

Given the interdependence of public and private investment in energy innovation, it is not surprising that private-sector leaders are pressing the federal government to ramp up its commitment. In February 2020, for instance, the American Energy Innovation Council, comprising the CEOs of major energy companies, investment firm heads, and other industry leaders, renewed its call to triple the federal RD&D budget.[17] The American Energy Innovation Council argues that public funding for RD&D will stimulate additional private investment, rather than crowd it out.

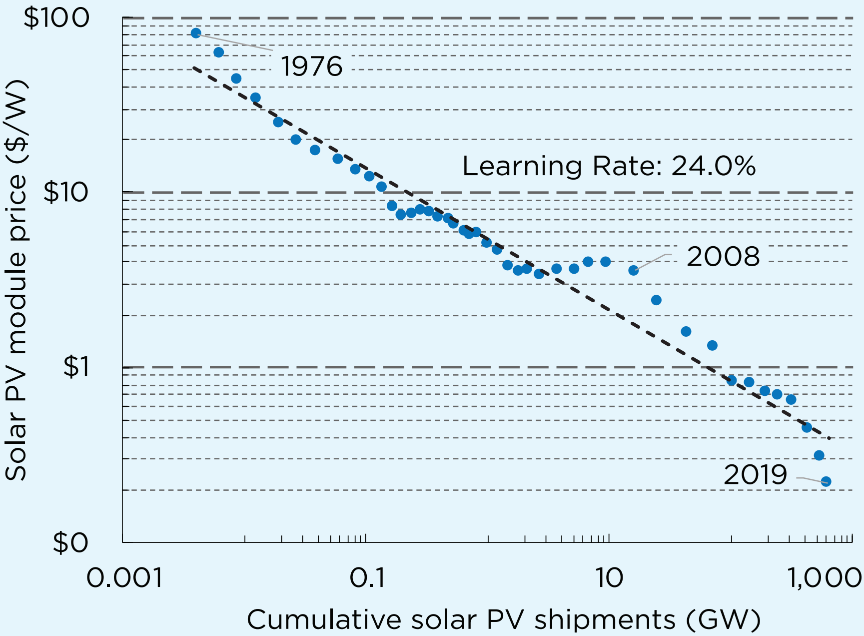
That argument has been borne out in multiple studies. One found that clean energy R&D funding reoriented private innovation funding toward clean technologies.[18] Another study found that patents filed for clean energy technologies are often widely cited in fields outside of clean energy, a phenomenon that does not carry over to patents related to dirtier energy technologies.[19] Public and private investment complement each other. As Box 2-1 explains, investments in RD&D accelerate cost reductions in clean energy technologies and enable private industry to further reduce costs through production and deployment at scale.

BOX 2-1: The role of public RD&D in speeding cost reductions in clean energy technologies

Lowering the unit costs of clean energy technologies will be critical to their commercial competitiveness. Technologies can become cheaper over time for several reasons, but a wide cross-section of experts agree that government funding for RD&D is one of the most important—if not the most important—drivers of long-term technology cost reduction.

However, the most common way to illustrate the falling costs of a clean energy technology—a chart plotting what is known as a "learning curve" (used interchangeably with "experience curve")—can obscure the central role of RD&D. Such a chart plots a technology's unit cost as a function of its cumulative production. Across a range of technologies—from solar panels to natural gas turbines to other technologies outside of the energy sector—costs tend to decline with regularity as the production scale increases (Figure 2-4). The "learning rate" is measured by the percentage decline in unit cost for each doubling of cumulative production. Learning curves do not explicitly show the levels of RD&D investment from public or private sources and how they affect the learning rate.

FIGURE 2-4: Learning curve and learning rate for solar photovoltaic from 1976 to 2019



Source: Bloomberg New Energy Finance

In the case of solar photovoltaic (PV) technology, research and development was the most important driver of cost reductions from 1980 to 2012. Before 2001, R&D was critical for improving the performance of immature solar technology. After 2001, as solar PV technology matured and achieved commercial success, economies of scale production played an important role, but R&D continued to contribute a similar amount to the reduction of cost. Across both time periods, a final driver—the "learning-by-doing" that firms accrued as they produced greater quantities of solar panels—played only a small role in reducing costs.[20]

Therefore, the learning curve in Figure 2-4 does not imply that increasing production scale is the major explanatory factor behind falling costs.

Multiple studies have shown that failing to account for R&D leads to overestimating the contribution to cost reductions of learning-by-doing over greater production scale.[21,22]

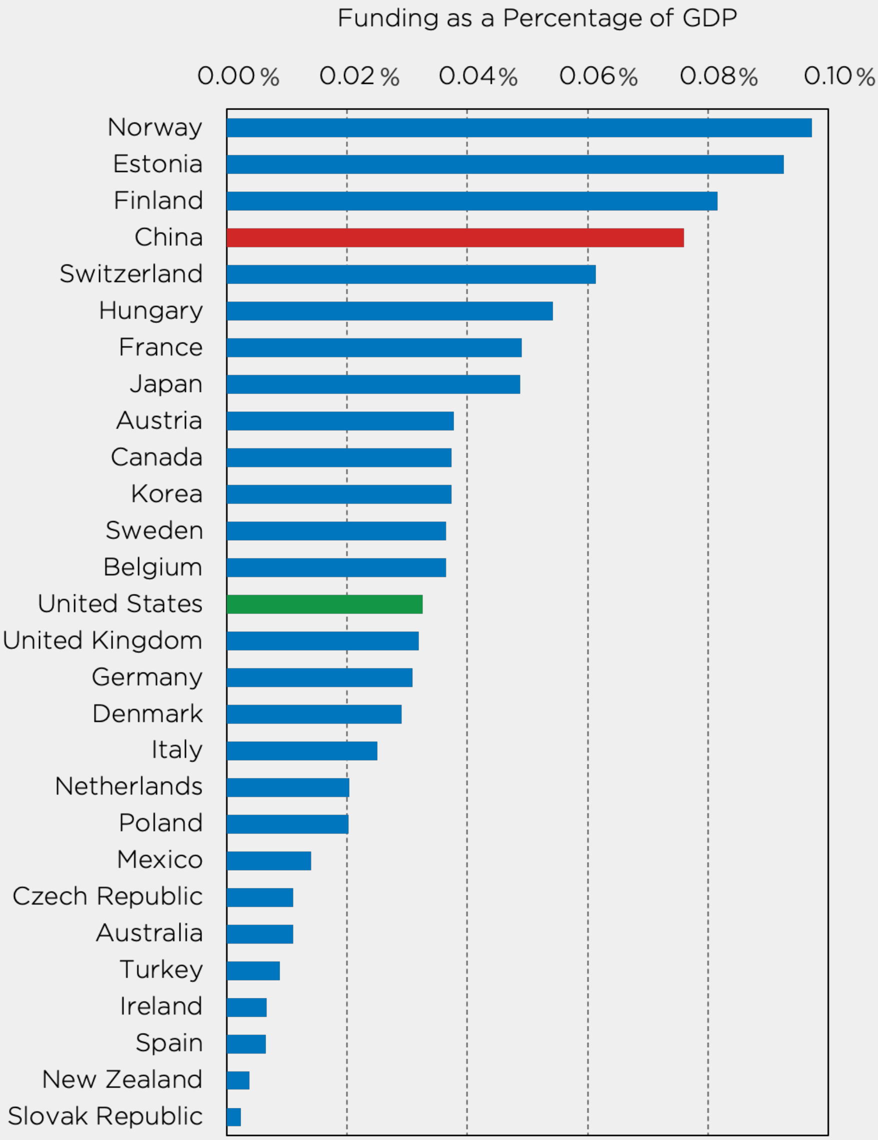
R&D matters not only when a technology is early in its development but also when it is produced at commercial scale. For example, R&D funding can improve novel components of complex, integrated systems, in which some components (e.g., boilers) are very mature while other components are not (e.g., novel reactors). In the case of wind energy, public R&D funding enabled manufacturers to develop new production processes and improve wind turbine technology.[23]

Government R&D funding is particularly helpful to drive cost reductions, compared with private R&D funding, because public funding tends to support transformative innovations that accelerate the pace of future cost reductions.[24] As a result, government-funded R&D is much more cost-effective than—and complementary to—public incentives to deploy clean energy technologies more rapidly.[25]

Bipartisan majorities in Congress have also supported increased funding for energy RD&D. In each of the last four years, Congress has rejected proposals from the Trump administration for significant cuts to clean energy programs, including the elimination of the widely popular Advanced Research Projects Agency-Energy (ARPA-E). Instead, federal funding for clean energy RD&D has risen by about one-third during this period.

Still, US government funding, particularly for later stages of innovation, has not kept pace with that of other governments. From 2015 to 2019, China led the world by increasing its investment in applied energy RD&D (that is, RD&D excluding basic scientific research) by $1.4 billion, more than double the increment in US funding. In proportional terms, the United Kingdom increased its investment five times faster than the United States.[26] The United States remains billions of dollars short of fulfilling the promise it made to the rest of the world in 2015, under the Mission Innovation compact, to raise spending to $12.8 billion by 2021. Normalized to its GDP, US federal funding for energy RD&D is no more than middling (Figure 2-5).[27]

FIGURE 2-5: Government funding for energy RD&D as a percentage of GDP, 2017



Source: International Energy Agency, "Energy RD&D Statistics Service"

Reaping both the climate and economic benefits of clean energy technologies—innovation-led growth—will require the federal government to fund all stages of the innovation pipeline and take an active role in formulating a national strategy to cultivate clean energy industries. Proposals to limit public funding only to early-stage research will not suffice. A large and growing body of research holds that policies that narrowly focus on just one stage in the innovation process are less effective than a holistic approach.[28,29,30]

A particularly glaring gap in the US energy RD&D portfolio is large-scale demonstration projects. The federal government virtually stopped funding such projects after the 2009 stimulus package (the American Reinvestment and Recovery Act or, simply, the Recovery Act) expired. The impact of the Recovery Act on clean energy innovation was itself mixed. DOE's loan guarantee program helped propel Tesla and First Solar to commercial success and also jumpstarted a decade-long boom in US utility-scale solar power deployment.[31] DOE's loan guarantee to the start-up solar manufacturer Solyndra, which ultimately went bankrupt, led many to question the federal government's role in later-stage energy innovation altogether, even though the portfolio as a whole actually made money.[32] And DOE's partnerships with the private sector on several carbon capture demonstration projects—including FutureGen, Kemper, and the Texas Clean Energy Project—had to be terminated, partially as a result of budget and schedule limitations set by Congress.[33,34] Today, the only federal funding for demonstration projects is under a new program for advanced nuclear reactors, which was approved by Congress for FY20.[35]

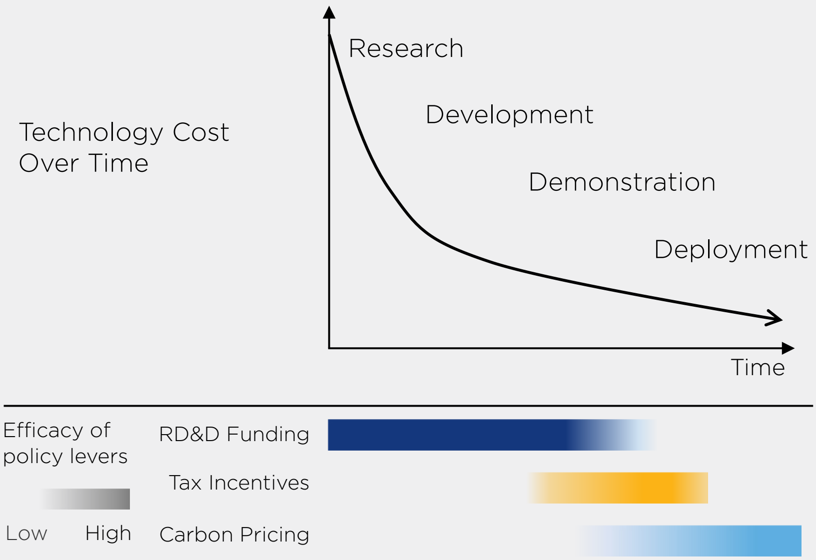
Bringing new energy technologies to market will require the federal government to invest in this critical segment of the innovation pipeline alongside private investors who may otherwise demur from taking risks on commercially unproven technologies.[36] Constructing large-scale demonstration projects may also advance long-term economic recovery efforts in response to COVID-19. It is critical that policymakers recognize that such investments will, by design, carry risk. The risk of occasional failures does not outweigh the benefits that successful demonstrations can deliver for the environment as well as the economy.

Chapter 6 presents several options for the federal government to build on the lessons from the past and most effectively fund demonstration projects, from using existing authority to providing loan guarantees to establishing new entities optimized for co-investing in risky demonstration projects. Without public co-investment in such projects, developers of complex, large-scale energy systems will remain unable to survive the valley of death and market their technologies widely. Promising clean energy technologies that have been proven at the laboratory scale but not yet at commercial scale will continue to be stranded.

Reaping both the climate and economic benefits of clean energy technologies—innovation-led growth—will require the federal government to fund all stages of the innovation pipeline and take an active role in formulating a national strategy to cultivate clean energy industries.

In tandem with "technology-push" investments in RD&D, policymakers should also adopt "demand-pull" policies that prime commercial markets to favor the speedy deployment of the most cost-effective clean energy technologies. Although these policies are not the subject of this volume, they are essential complements to public investments in RD&D. For example, a nationwide carbon price would level the playing field between clean and dirty technologies by penalizing polluters who can currently emit carbon emissions without any consequence. In addition, standards for clean electricity, vehicles, buildings, and fuels can stimulate demand for emerging clean energy technologies to meet low-carbon mandates. Even more targeted policies can help scale up promising clean energy technologies. Tax incentives that focus on emerging technologies—from advanced nuclear reactors to offshore wind turbines to carbon capture projects—can partially support early commercial deployment (Figure 2-6).[37,38] Finally, public procurement can be a powerful tool to stimulate early markets for emerging technologies.[39]

FIGURE 2-6: Efficacy of selected policy levers in supporting the various stages of clean energy innovation



Source: Columbia University

A decisive increase in public funding for energy RD&D, as called for by the American Energy Innovation Council, would hardly be unprecedented. The United States has ramped up public investment in innovation across a range of fields over the past half-century. The lessons from these experiences—some of which have gone well and others not so well—should inform policymakers contemplating how to accelerate energy innovation.

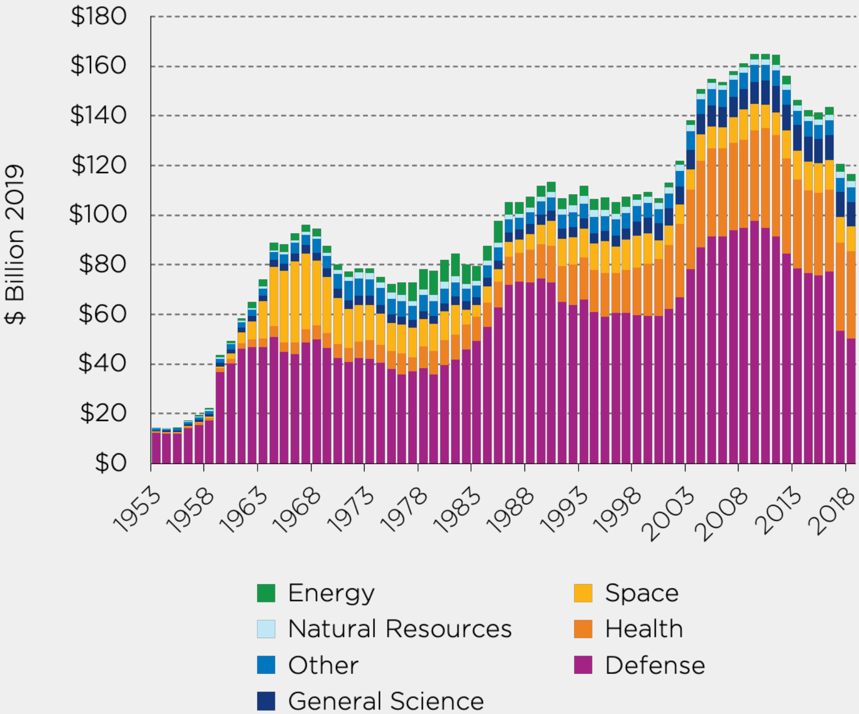
CHAPTER 3

Lessons from previous US national innovation missions

The United States is the world leader in science, technology, and innovation. US-based authors are vastly overrepresented among the most highly-cited scientific publications. US universities and companies are magnets for global talent, pulling in more than three times as many foreigners holding college degrees than any other country. Ten of the world's fifteen largest corporate R&D spenders are headquartered in the United States. The top two, Amazon and Alphabet, were founded in the past 25 years, signaling the dynamism of the US innovation economy.[1,2,3]

The United States holds this leadership position in large part because the federal government has carried out innovation policies to achieve national missions from World War II onward.[4] "Mission agencies" such as the Department of Defense (DOD; dark blue bars in Figure 3-1), National Institutes of Health (NIH; orange bars in Figure 3-1), and National Aeronautics and Space Administration (NASA; yellow bars in Figure 3-1), dominate federal R&D spending. The general search for knowledge, represented by the National Science Foundation, and generic support for industrial innovation, represented by the National Institutes for Standards and Technology (NIST), play puny roles by comparison.[5] (In addition to technology-push funding of R&D, the federal government's demand-pull policies, such as procurement of defense technologies and subsidies for health insurance, also contribute to national missions by creating market conditions that help emerging technologies succeed commercially.)

FIGURE 3-1: Historical U.S. federal spending on R&D



Source: AAAS

The two largest missions today—defense and health—have spawned research agendas and industrial developments that extend far beyond what policymakers envisioned when they seeded those investments in the 1940s and 1950s. Semiconductors, computers, the global positioning system (GPS), and the Internet are just a few civilian spinoffs of innovations initially cultivated by the US military. Indeed, it was federal investment that launched the information technology industry and enabled the success of Silicon Valley. Federally funded biomedical R&D inadvertently birthed the biotechnology industry in the 1970s and 1980s, transforming agriculture as well as medicine. Science supported by NIH, long the top source of nondefense federal research funding, underpinned every single one of the 210 new drugs approved by the Food and Drug Administration from 2010 to 2016.[6]

The innovation systems that federal investments helped create are now self-sustaining to a great extent, with private financial institutions, companies, and philanthropies all making large-scale investments. Yet the federal role remains far from trivial, yielding rapid advances in autonomous systems and gene editing, for instance, over the past decade.

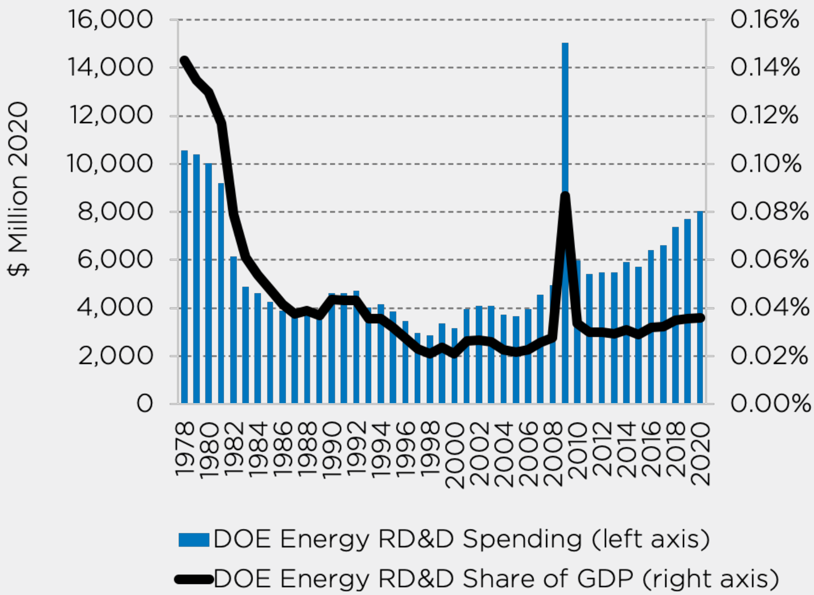
The United States holds its leadership position in large part because the federal government has carried out innovation policies to achieve national missions from World War II onward.

Countries around the world have sought to imitate America's postwar success in innovation policy. In doing so, they have revealed the extent to which that success, for all its spillovers, depended on the defense and health missions and left gaps elsewhere. Global leadership in many industries that fall outside these two domains, such as chemicals and machine tools, and supporting disciplines, such as mechanical and chemical engineering, shifted to nations that chose to invest in them, such as Germany, Japan, South Korea, and China. These countries made investments in these sectors as they pursued economic development—a mission that the US federal government largely eschewed in the twentieth century.[7]

The history of energy innovation policy sharpens the point. Federal support for energy innovation has waxed and waned dramatically since World War II. Early investments occurred mostly within the frame of the defense mission, as the US Navy developed nuclear reactors to power submarines in the 1950s. Civilian nuclear power was spun off from this effort. Federally financed, privately constructed demonstration projects led to a wave of nuclear plant openings in the 1960s and 1970s.[8,9] These plants make up most of the current fleet of reactors, which today provides a majority of US low-carbon electricity. The oil crises of the 1970s prompted US presidents of both parties to declare "energy independence" a new national mission. They backed it with a burst of R&D spending and created the Department of Energy, which accounts for the growth of the purple bars in Figure 3-1 during these years. That investment yielded significant breakthroughs in boosting the efficiency of solar photovoltaic cells and reducing their cost, among other advances.[10]

When oil prices dropped during the 1980s, however, the federal government sharply curtailed its investment in energy RD&D, with the sharpest cuts falling on development and demonstration. As Figure 3-2 shows, DOE energy RD&D spending as a percentage of GDP has never regained its level in 1978, the year the department was founded, even in 2009, when the Recovery Act gave it a major boost.[11] Soon after public RD&D funding began plummeting, private investment also fell, as the virtuous cycle of public investments stimulating private ones broke down. Starting in 1984, private funding for energy RD&D and US energy patents declined for the next two decades.[12]

FIGURE 3-2: DOE energy RD&D spending from FY 1978–2020



Source: ITIF

As US interest in the energy mission waned, other countries stepped to the forefront. Japan and Germany took turns leading in solar PV manufacturing until China overtook them in 2008. It has dominated the industry ever since. In civilian nuclear energy, France, South Korea, Russia, and China power the global industry today while the United States, once front and center, recedes into the background.

The record of federal innovation policy displayed in Figure 3-1 is marked by sustained emphases on defense and health, large but volatile funding for space, and both inconsistent and limited support for energy. That history offers lessons that the nation's leaders should heed as they consider a renewed energy innovation push.

1. <u>Scale matters.</u> Defense and health are high public priorities, involve large industries and organizations, and represent the two biggest slices of the federal budget pie. To have a significant impact on such a large sector, an innovation ecosystem must be big, too. Only by operating on a large scale can innovation policy address such a sector's many components and specific needs, whether they are military missions on land, sea, air, and space or health maladies with diverse causes and myriad manifestations in the human body. High-value opportunities also come from integration across the ecosystem that develops over time. Operating on a large scale has less obvious benefits as well. Bigger implementing agencies are somewhat more insulated from political oversight than smaller ones, allowing technical judgments to have greater weight and tolerating a greater degree of failure. Since a non-trivial level of failure is necessary to drive innovation—if every project succeeds, the portfolio is too cautious—an oversight structure that sets broad direction and assesses progress at the level of missions and programs, rather than drilling down on projects, is desirable. Federal support for energy innovation has not attained this scale and, as a result, enjoys neither a thriving and self-sustaining innovation ecosystem nor sufficient political independence to tolerate failures in the portfolio.

2. <u>Ambitious innovation policies must be sustained and flexible.</u> The systems that defense and health innovation policies seek to transform are dynamic and complex. They have human and societal components—among them, patients, soldiers, and fearful and hopeful publics—that are dimly perceived by scientists and technologists and can only be fully discovered in practice. Successful transformation requires solving a series of interconnected techno-social problems over a period of decades that cannot be fully specified at the outset. Innovation policies must be

adapted as surprises emerge and opportunities arise. To take a recent example, over the last decade NASA repeatedly adapted the milestones in its Commercial Crew Program; ultimately, the program succeeded in 2020 when SpaceX became the first private company to launch a crewed space mission.[13,14] Decarbonizing the energy system will be even more challenging—more similar to fighting the Cold War than the more bounded and calculable missions of launching a space mission or building the atomic bomb.[15]

3. Steady, sustained growth beats boom and bust. The defense and health innovation systems were built in fits and starts. Sometimes, funding ramped up at double-digit rates, as during the Reagan-era defense buildup and turn-of-the-century doubling of the NIH. In other periods, funding stagnated or even declined, as in recent years. Steady, sustained growth, which can be observed at other points in the postwar period, is preferable. Consistent funding for innovation, including demonstration projects, has yielded striking advances from agricultural to aerospace technologies.[16] Innovation requires specialized expertise that takes years to develop, which in turn involves career judgments by many individuals. Busts waste these investments of human capital (as well as physical capital such as buildings and instruments), while booms tend to over-reward those who have the luck to be in a field when the spigots of capital open. For example, after the federal government doubled the NIH budget from 1998 to 2003, it promptly reduced its budget in real terms over the next four years, leading to layoffs, cancellations of promising projects, and permanent loss of human capital.[17] The energy sector has also learned this lesson the hard way; policymakers must not follow increases in energy RD&D funding with a reversal.

4. Steady, sustained growth requires a durable bipartisan consensus. Any policy that is to last for decades in the United States must withstand shifts in partisan control of the presidency, the Senate, and the House of Representatives, not to mention periods of divided government. The Cold War consensus, which underpinned a strategy of military technological supremacy and thus heavy RD&D investments, was forged in the Truman administration and endured through the turbulent Vietnam-era presidencies of Lyndon Johnson and Richard Nixon. The consensus on biomedical research spending emerged in part to compensate for the

failure to achieve bipartisan agreement on national health insurance, which was put in place in other high-income countries in the immediate postwar period. The consensus was often expressed in an annual bidding war in which the president and House and Senate appropriators, regardless of party, sought to top one another's proposed budget increase. The consensus on energy independence, by contrast, was brief and came to an end with Republicans ridiculing President Carter's "Moral Equivalent of War" speech with the acronym MEOW. Now, to advance a new National Energy Innovation Mission, policymakers must bolster the emerging bipartisan consensus that such a mission would advance the fight on climate change and boost US global competitiveness. Widely communicating the successes and promise of energy innovation—just as NASA broadcasts space launches or the NIH advertises cancer research—will be critical to sustain public support for federal RD&D investment.

5. Distributing funding broadly benefits innovation and sustains growth. Complex problems demand multifaceted solutions. Innovation funding strategies that draw on diverse institutions with differing capabilities—such as research universities, government laboratories, start-up ventures, and large corporations—are more likely to devise and implement such solutions. US defense and health policies have nurtured intricate innovation ecosystems that encompass all of these institutional types. This strategy pays political benefits as well, all the more so if capable institutions are spread widely across the country. Members of Congress representing states and districts in the South and the West joined the postwar consensus on defense and health innovation as new academic-industrial clusters emerged in places like Birmingham, Alabama; Houston, Texas; and San Diego, California. (To be sure, political considerations on occasion lead to ill-advised funding decisions, but such inefficiencies are dwarfed by the benefits of a durable political coalition in support of innovation.) In energy, policymakers should similarly seek to marshal regional centers of innovation—and the attendant political support—to advance the national mission.

CHAPTER 4
$25 BILLION BY 2025: AN AMBITIOUS AND ACHIEVABLE TARGET

In Fiscal Year 2020, Congress appropriated roughly $8.9 billion for energy RD&D. Roughly 80 percent of these funds went to the Department of Energy, with the remainder spread across almost a dozen federal agencies (Figure 4-1). As set forth above, these funding levels are low in comparison to federal RD&D budgets for other critical priorities and spending on energy RD&D by other nations.

We propose a goal to guide a rapid scale-up of federal funding for energy RD&D: $25 billion per year by FY26 (which begins October 1, 2025).

Why $25 billion per year by 2025 is an appropriate target for federal energy RD&D funding

Significant increases in federal energy RD&D funding are needed, and soon. But what is the right amount? RD&D outcomes are by their nature uncertain. The optimal level of RD&D spending can never be known with certainty in advance. But setting funding targets that National Laboratories, universities, businesses, and others can rely on is important for building sustained, first-rate RD&D capacity.

Choosing the right funding target requires policymakers to balance two objectives: (1) providing sufficient funds to maximize the potential for transformational clean energy innovation, and (2) limiting funds to amounts that can be well-spent. A rapid scale-up of funding is needed, but increases cannot outpace the ability of recipients to spend those funds in ways likely to deliver results.

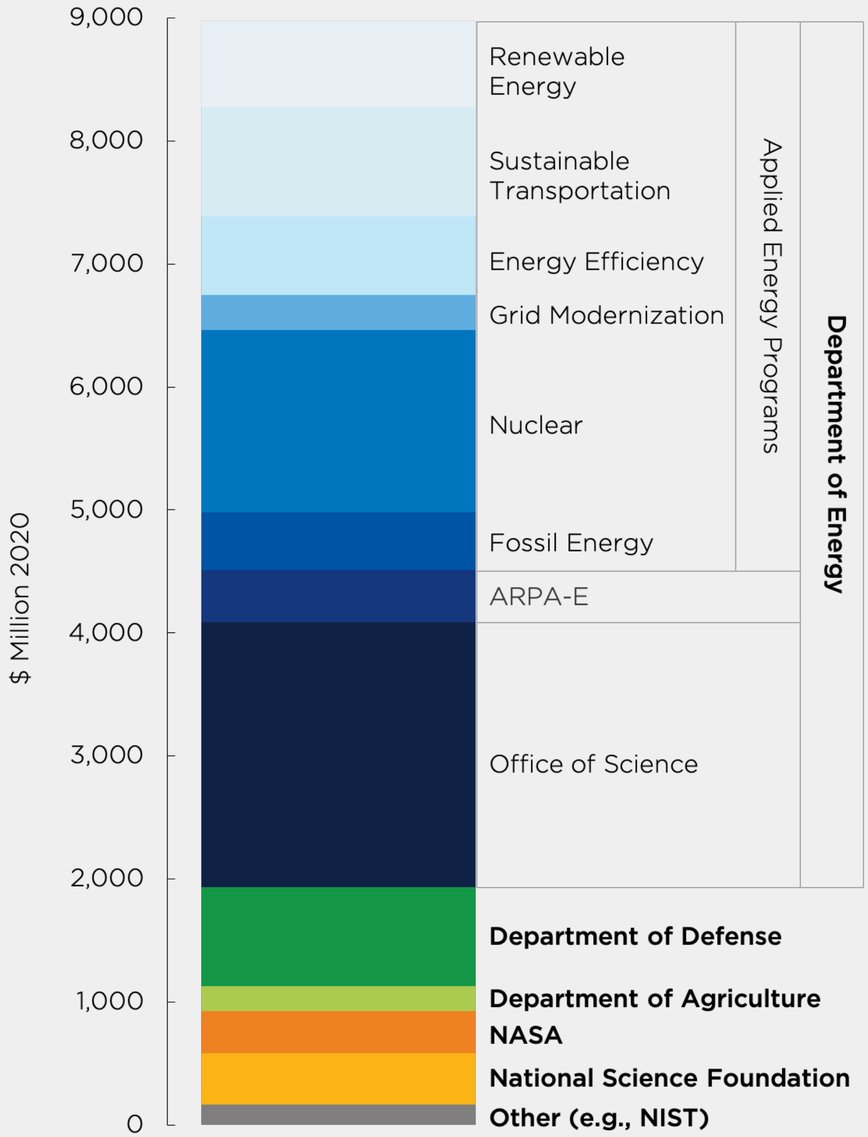
A target of $25 billion per year by FY26 strikes that balance. The target is high enough to address critical gaps in the US clean energy RD&D funding portfolio, yet measured enough to deliver attractive returns on taxpayer investments in innovation.

First, our bottom-up analysis of funding needs for federal energy RD&D program produces budgets totaling roughly $25 billion by FY26. (See Chapter 5 and Appendix B.) The federal government's energy RD&D portfolio has large funding gaps. RD&D activities for industrial emissions and efficiency, advanced clean fuels, net-zero energy buildings, carbon capture from the atmosphere and oceans, and other critical functions lack sufficient funds to achieve meaningful outcomes. Significantly more federal funding in these areas is needed to speed progress toward deep decarbonization.

Second, research suggests that increases in federal RD&D funding in roughly this range will translate into net economic benefits and rapid technological progress. One study considered a tenfold increase of US energy RD&D funding levels in 2010, which at the time were $2.1 billion. The authors found that an annual spending level of $21 billion in 2010 dollars—$25 billion in 2020 dollars—would result in net economic benefits.[1] Other research has found greater risk in underinvesting in energy RD&D than overinvesting because of the low cost of innovation and high rewards of technological progress.[2]

Third, federal funding of $25 billion per year would bring US public investment in energy RD&D as a percent of GDP to roughly the same level as that in China, boosting US competitiveness. An investment of $25 billion per year in 2025 would be roughly 0.1 percent of GDP—comparable with China's funding for energy RD&D in 2017 (the last year for which data on government and state-owned-enterprise funding for energy RD&D is available). The Chinese government has signaled that it plans to expand RD&D investment in clean energy technologies in its 14th Five-Year Plan, which runs from 2021–2025.[3]

FIGURE 4-1: U.S. budgeted federal funding for clean energy RD&D in FY20



Source: Agency Budgets

At the same time, an increase to $25 billion by FY26 is measured enough that the funds can be spent well.

First, DOE has proven it can absorb new RD&D funds at an even faster pace and invest them effectively. For example, the 2009 Recovery Act instantly tripled the DOE budget for solar energy RD&D (the SunShot Initiative), helping reduce the cost of solar power below $0.06 per kilowatt-hour by 2020. An independent academic review of the SunShot Initiative in 2014 concluded that "the program as a whole is wisely using taxpayer dollars" and that projects focused on systems integration were particularly helpful in reducing costs. The independent review also revealed areas for improvement, such as the need to diversify funding outside of the National Laboratories and support collaborations with private firms and universities.[4]

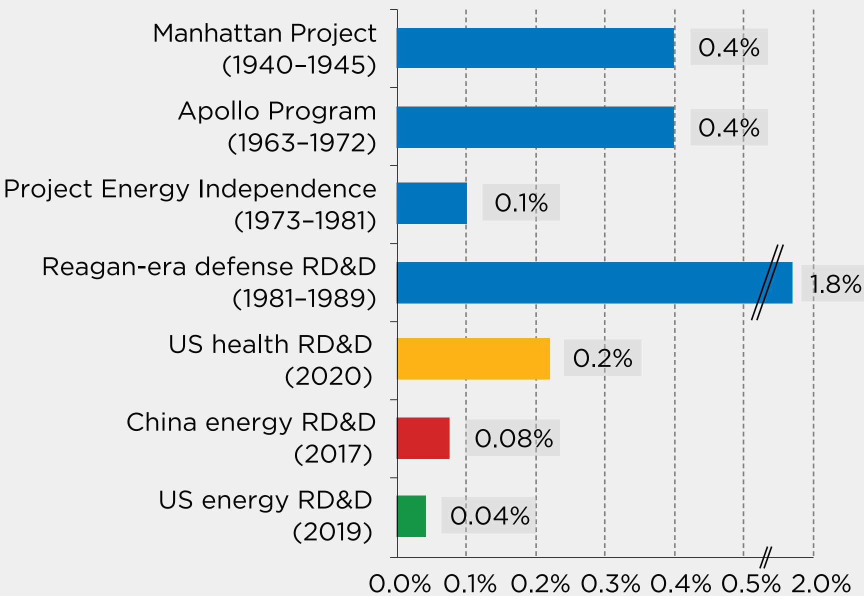
A target of $25 billion per year by FY26 is high enough to address critical gaps in the US clean energy RD&D funding portfolio, yet measured enough to deliver attractive returns on taxpayer investments in innovation.

Second, the history of US innovation missions demonstrates that the federal government can rapidly increase RD&D funding and deliver net economic benefits. The Apollo Program required RD&D funding increases at three times the rate we propose for the National Energy Innovation Mission. (At the peak of the Apollo Program, the federal government spent ten times more as a percentage of GDP on space RD&D than it currently does on energy RD&D. See Figure 4-2.[5]) The money was well-spent: over the ensuing decades, the ratio of economic benefits to RD&D costs was roughly ten to one.[6] Similarly, in the 1980s, the federal government raised defense RD&D over five years by twice the amount, in absolute 2020 dollars, than that by which we propose raising federal clean energy RD&D funding. Retrospective analysis demonstrates that this innovation mission also delivered net economic benefits by accelerating private-sector innovation.[7]

Third, a whole-of-government approach to increasing funding (as we propose in Chapter 5, Chapter 6, and Appendix B) will help ensure that funds are well-spent. In our proposal, the National Energy Innovation Mission marshals a dozen federal agencies beyond the DOE to support clean energy innovation, with the most rapid increases in agencies that have the infrastructure in place to quickly increase energy RD&D funding. For example, the DOD, NASA, and NSF each have vast RD&D budgets, of which much less than 5 percent is currently devoted to clean energy RD&D. Each has the capacity to absorb significant additional funds and spend those funds well. Spreading funding in manageable increments across the federal government can help ensure recipients have the capacity to spend funds well.

Such a whole-of-government approach to funding will also bring a wide range of skills and backgrounds to the National Energy Innovation Mission. The various federal agencies all bring distinct approaches and experience to funding RD&D. These approaches include a variety of ways to co-invest with the private sector, foster regional innovation hubs, and target all stages of the innovation pipeline, from early-stage research through late-stage demonstration projects.

FIGURE 4-2: Peak federal funding for RD&D as a percentage of GDP for selected national initiative



Source: Third Way, ITIF

Some have pointed to the federal government's doubling of health innovation funding through the NIH from 1998 to 2003 as a cautionary tale with respect to federal budget increases. But the problems related to federal government funding for health innovation during this period resulted from budget volatility, not the rate of increase. Immediately after doubling the NIH budget, the federal government reduced funding in real terms from 2003 to 2007. As a result, universities that had just hired researchers and launched research projects had to cut research staff positions and abandon promising projects.[8,9] This lesson from the health innovation mission is directly applicable to energy. Multiple historical analyses of DOE RD&D programs have concluded that booms and busts in funding can waste taxpayer investments.[10]

Therefore, policymakers should sustain and further increase funding levels beyond 2025, treating the $25 billion annual target as a waypoint rather than the final destination. Even though reaching the target would require roughly tripling the federal energy innovation budget, the resulting level would still fall far short of what the United States must spend to enable deep decarbonization and build the advanced energy industries of the future. An abrupt halt to funding increases would undermine the benefits of RD&D investment.

Innovation is a long-term process. It is essential to start making investments to seed the innovation pipeline now and reap payoffs in the future. Government investments successfully generate new research, with the number of granted patents peaking a decade after the funding increase, even after very large increases in government funding.[11] Therefore, the federal government should commit to a long-term national mission to raise—and sustain—public funding for energy innovation. Given the recent groundswell of bipartisan support for energy innovation, policymakers have a historic political opportunity to get started.

Why $25 billion per year is an achievable target

Not only is $25 billion the right target, it is politically achievable as well. In a polarized political system, energy innovation has long enjoyed bipartisan support. Lawmakers from diverse backgrounds have embraced energy innovation as a strategy to combat climate change and promote US competitiveness.

From 2011 to 2020, Congress increased federal funding for energy RD&D in every single year except 2015. And support is growing. In the House, liberal Democrats and conservative Republicans alike have called for boosting research to advance energy technologies.[12,13,14] In the Senate, members from both parties have been even more vocal. In 2019, Senator John Cornyn (R-TX), the second-ranking Republican in the chamber, sponsored legislation to establish an R&D program for carbon capture technologies; Senator Jeff Merkley (D-OR), at the other end of the political spectrum, put forward legislation to promote next-generation hydropower; and Senator Lamar Alexander (R-TN), the centrist who chairs the Senate energy appropriations subcommittee, called for doubling federal funding for RD&D to spark a "New Manhattan Project for Clean Energy."[15]

By contrast, many other energy policies are controversial in the US Congress, and climate policies have been especially controversial. Although the Senate unanimously ratified the UN Framework Convention on Climate Change in 1992, the 1997 Kyoto Protocol met with widespread resistance in Congress. In 2009, the Waxman-Markey bill, which would have established a nationwide cap-and-trade program for greenhouse gases, passed the House of Representatives but not the Senate. Over the last decade, only a trickle of related measures has passed both chambers, including tax credits for renewable energy, nuclear power, and carbon capture and sequestration. Many climate policies enacted by the Obama administration through executive authority, from fuel economy standards to power plant standards, were replaced or rescinded by the Trump administration.

To be clear, investments in energy innovation are no substitute for a full suite of climate policies. Demand-pull policies, such as carbon pricing or clean energy standards, complement technology-push support for RD&D and are essential for deep decarbonization. Although energy innovation enjoys broad and growing political support, policymakers should not lose sight of other climate policy priorities in the process.

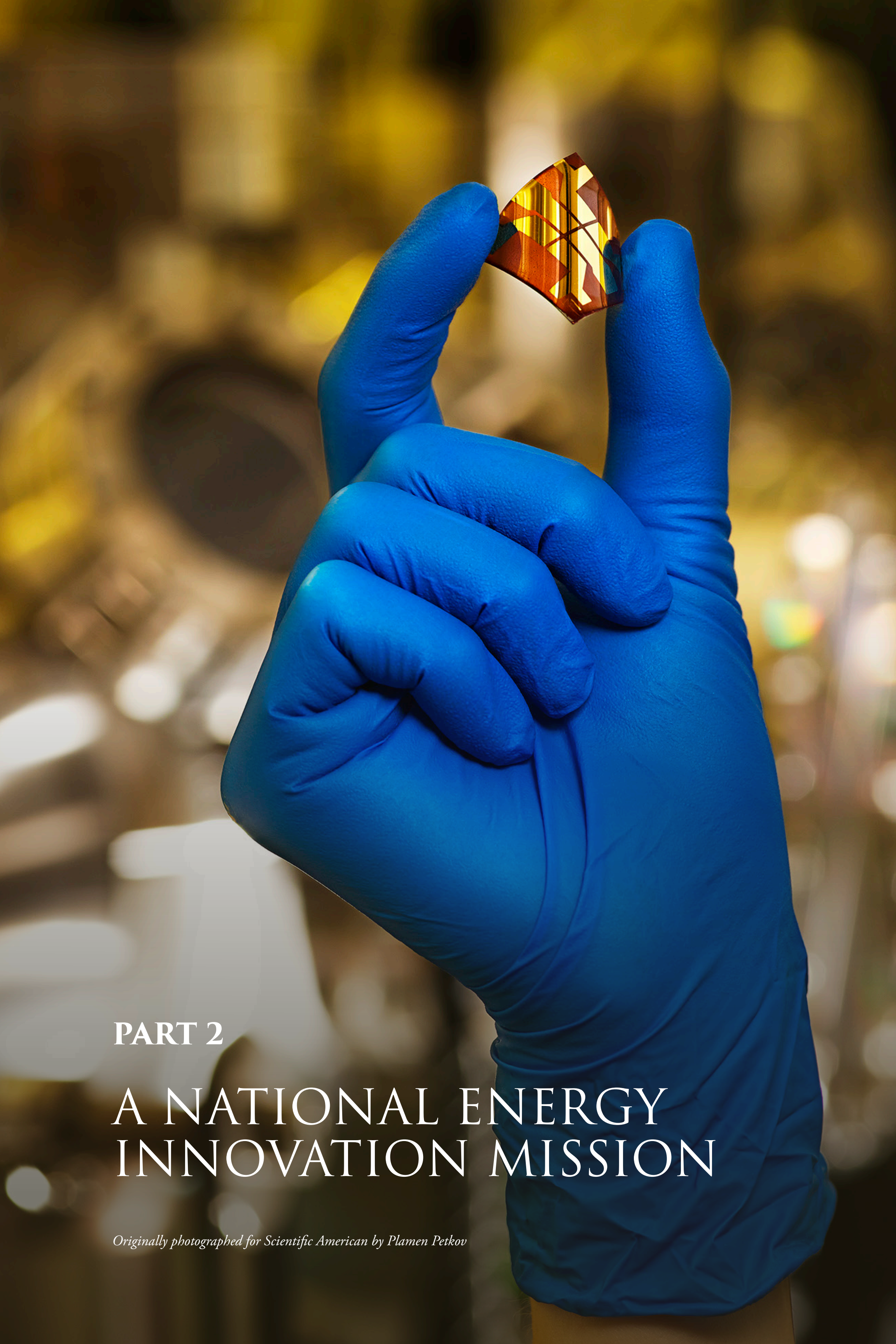
The American Energy Innovation Act of 2020 highlights the broad bipartisan support for energy innovation. Sponsored by Senators Lisa Murkowski (R-AK) and Joe Manchin (D-WV), the chair and ranking member of the Energy and Natural Resources Committee during the 116th Congress, it incorporates priorities from more than seventy Senators. The main provisions boost federal RD&D funding for a range of clean energy technologies and authorize seventeen demonstration projects.[16]

In addition, every energy and climate plan offered by Democratic presidential candidates during the 2020 primary process included significant increases in federal funding for energy innovation. Former Vice President Joe Biden, Senator Elizabeth Warren (D-MA), Senator Bernie Sanders (I-VT) and Gov. Jay Inslee (D-WA), among others, each pledged to spend at least $400 billion on energy R&D over the next decade, a fivefold increase over current levels; Mayor Pete Buttigieg's platform set a target of $25 billion by 2025.[17] Vice President Biden's plan calls for the creation of a cross-agency federal body to invest in technologies critical for decarbonization as well as to "reclaim the mantle as the world's clean energy leader and top exporter."[18]

To be clear, investments in energy innovation are no substitute for a full suite of climate policies.

The COVID-19 crisis has strengthened the argument for acting with urgency to jumpstart energy innovation. Biomedical research will rightfully be a top priority to better prepare the United States for future pandemics. but policymakers are also actively seeking ways to stimulate the economy to recover from the coronavirus-induced recession. Building the energy industries of the future can deliver near- and long-term economic stimulus to the beleaguered US economy.[19,20]

This is an urgent matter of US competitiveness. The European Union and its member countries, the United Kingdom, South Korea, China, and others are designing their economic strategies for a long-term recovery from the COVID-19 recession, with many seeking to carve out niches of the new energy economy. Giving US firms a fighting chance to catch up with, and surpass, their international competitors is an opportunity both parties can get behind.



PART 2

A NATIONAL ENERGY INNOVATION MISSION

Originally photographed for Scientific American by Plamen Petkov

The US federal government should launch a National Energy Innovation Mission, increasing federal energy RD&D funding to $25 billion per year by FY26. The following chapters lay out a roadmap for doing so. **Chapter 5** identifies ten technology pillars and proposes initiatives to advance progress within each. **Chapter 6** articulates six strategic pillars to guide policymakers in managing the growing RD&D portfolio. **Chapter 7** details three immediate actions the federal government should take to jumpstart the National Energy Innovation Mission.

CHAPTER 5
Ten technology pillars

The federal government should organize the National Energy Innovation Mission around ten "technology pillars." Each pillar represents a set of solutions to a major challenge for achieving deep decarbonization at home and abroad. By making simultaneous progress across all ten pillars, the United States will best position itself to prosper from clean energy transitions around the world.

Historically, the United States has organized energy RD&D around resources such as oil, gas, coal, nuclear, or renewable energy. We propose a different approach. The ten technology pillars group clean energy technologies together based on distinct functions. So, for example, renewable and nuclear power are grouped together within the clean electricity generation pillar. Energy storage and energy efficiency technologies are distributed across multiple pillars because they serve multiple functions. This organizational approach places the focus on achieving ends, which is what ultimately matters for deep decarbonization.

Establishing technology pillars will enable interagency coordination in funding energy innovation and bring much-needed focus to an effort that has lacked it. 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.[1,2] In energy, the federal government's existing innovation activities already include initiatives that could be classified under each of the technology pillars. But the levels of investment across pillars 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 pillars.

The technology pillars do not encompass all of the valuable energy innovation topics that the federal government should fund. In addition to these ten pillars, it is vital to sustain cross-cutting priorities, such as on the energy-water nexus and critical minerals, where RD&D is needed across a number of technology pillars. At the same time, policymakers will have to make hard choices about which technologies not to fund. Tripling energy innovation funding levels is not a license to fund every conceivable technology; rather it is a vehicle for adequately investing in technologies that could materially advance deep decarbonization. The focus of the ten technology pillars on critical applications should help policymakers decide not only which technologies to fund but also which not to fund.

The focus of the ten technology pillars on critical applications should help policymakers decide not only which technologies to fund but also which not to fund.

The sections below introduce each of the ten technology pillars 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.)

The ten technology pillars are listed in descending order of current (FY20) federal funding. This ordering does not imply that the pillars listed first are more critical to deep decarbonization than those listed last. In fact, the least-funded pillars, such as carbon dioxide removal and clean agricultural systems, are the ones most in need of urgent funding increases. Therefore, the FY22 budget proposal detailed in Chapter 7 allocates increases in federal funding to each pillar in inverse relation to that pillar's current funding levels.

Pillar 1. Foundational 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.[3]

Each of the other nine pillars is focused on developing distinct categories of technologies to address critical decarbonization needs. All of them can benefit from advances in this first pillar. 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.[4,5] This approach would greatly benefit energy innovation as well.

Recent initiatives

There are 46 active EFRCs spanning a diverse range of technologies—from molten salts for nuclear reactors to advanced catalysts for batteries. They are all 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; advancing models, mathematics, algorithms, data, and computing; and exploiting transformative advances in imaging capabilities across multiple scales.[6,7]

In FY20, DOE launched a new Artificial Intelligence and Technology Office to coordinate department-wide artificial intelligence (AI) activities and integrate AI research into other energy R&D programs.[8] On the international stage, Mission Innovation (MI) 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.[9]

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).[10]
- DOE should expand its use of machine learning and high-performance computing in the applied energy technology RD&D programs.[11]
- DOD should expand its investments in advanced materials and nanotechnology research to advance technology pillars that also meet national security objectives.[12]
- DOE should add 45 new EFRCs and align the objectives of EFRCs with advancing the nine other technology pillars.[13]
- 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.[14]

Pillar 2. 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 US electric power sector declined by more than 33 percent from 2007 to 2019. Wind or solar power is now the cheapest source of electricity generation in 34 percent of US counties.[15] In addition, clean electricity offers a route to decarbonize other sectors, including transportation, building heating and cooling, and some important industrial processes. But countervailing trends are likely to limit further emissions reductions without increased innovation: Low-cost domestic natural gas could drive increased generation (and consequent emissions) from unabated natural gas power plants, while increased carbon-free generation from renewables (primarily wind and solar) may be offset by the retirement of zero-carbon nuclear power plants.[16]

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.[17] (Electricity generation utilizing fossil fuels in combination with carbon capture, use, and sequestration is addressed in Pillar 8.)

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.[18] 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.[19] 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.[20] 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.[21] 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.[22] In April 2020, DOE released the report *Strategy for Restoring America's Competitive Nuclear Energy Advantage*.[23]

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.[24]
- 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.[25]) 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.[26]
- 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.[27] 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 proposed in the bipartisan House Nuclear Energy R&D Act and Senate Nuclear Energy Leadership Act. DOE and DOD should partner to develop advanced microreactors.[28]

Pillar 3. Advanced 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.[29] Nearly all of the world's road, rail, air, and marine transportation runs on internal combustion engines using petroleum-based fuels. Advanced transportation systems can reduce greenhouse gas emissions, improve air quality, reduce urban congestion, improve energy security, and lower costs to consumers. Electric vehicles (EVs) are an increasingly cost-competitive low-carbon alternative to gasoline and diesel passenger cars and trucks. In 2019 alone, auto manufacturers announced plans to invest $225 billion in electric vehicles.[30] The purchase price of electric vehicles is projected to reach parity with conventional gasoline vehicles between 2020 and 2030.[31] 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.[32] As these sectors grow, their global emissions may soon overtake those of light-duty cars and trucks.[33] 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.[34] 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.[35] 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.[36] The Department of Transportation's (DOT) Federal Transit Authority funds public transportation infrastructure research and demonstration projects to reduce transit emissions.[37]

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.[38]
- 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.[39]
- DOE should launch a SuperTruck III program to double the freight-hauling efficiency of heavy-duty Class 8 trucks by 2025.[40]
- 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.[41]
- DOT should expand its programs for RD&D in low-carbon urban transit and rail systems.

Pillar 4. Clean 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.[42] 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. Although most current hydrogen production releases carbon emissions, advances in carbon capture could enable cost-effective clean hydrogen production from fossil fuels; in addition, next-generation electrolyzers could pair with renewable energy to cost-effectively produce clean hydrogen. 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.[43] 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 (HFTO) 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.[44] 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.[45] 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.[46] 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.[47] 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.[48]

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 HFTO, BETO, ARPA-E, and FE) should include ammonia and direct air capture to fuels (DAC-to-fuels).[49] AMO should research potential applications of clean fuels in industrial sectors (e.g., for the provision of clean heat), consistent with the Clean Industrial Technology Act.[50]
- 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.[51]
- DOE should create a new solar fuels program—building off the success of JCAP—in the applied energy offices.[52]
- Biofuels programs at USDA and DOE should focus on developing drop-in fuels for aviation, shipping, and other hard-to-electrify transportation sectors.[53]

Pillar 5. Modern electric power systems

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.[54] Power electronics such as solid-state power substations offer the potential for greater standardization and improved resilience of grid components and systems.[55] 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.[56]

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.[57] Additionally, the administration began construction on the Grid Storage Launchpad to develop, test, and evaluate batteries and other storage technologies for grid applications.[58] 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.[59]

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 distribution grid operation to harness communication infrastructure, digital controls, and a hierarchical architecture of networked autonomous systems to flexibly marshal distributed generation, storage, and demand resources, consistent with the Grid Modernization R&D Act.[60] 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.[61]

- Congress should pass the Better Energy Storage Technology (BEST) Act 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.[62]
- DOD and DOE should launch a joint storage demonstration program to leverage and coordinate research in high-energy-density storage media.[63]
- 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.[64]
- 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.[65,66]

Pillar 6. Clean and efficient 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.[67] As a result, Americans spend nearly $400 billion each year to power their homes, offices, schools, hospitals, and other buildings.[68]

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.[69] 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.[70] 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 4 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.[71] 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.[72]

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. In addition, DOE should invest in developing energy-efficient air conditioners tailored to hot or humid climates, potentially in collaboration with US international partners such as India.[73]

- DOE should expand investment in advanced air flow, air sealing, and ventilation controls, as well as high-performance windows.

Pillar 7. 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.[74] Heavy industry—including cement, iron and steel, and chemicals production—is especially challenging to decarbonize, due to two sets of emissions which are difficult to eliminate: high-temperature heat, which is not easily electrified; and direct carbon dioxide emissions that result from chemical transformations.[75] 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.[76]

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.[77] 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*.[78] In FY20, Congress directed AMO to develop a series of sector-specific decarbonization roadmaps to guide RD&D activities across DOE.[79]

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:

- DOE should expand programs in clean fuels—which currently focus on transportation fuels—to include applications in the industrial sector. Congress should pass the Clean Industrial Technologies Act to provide greater direction and long-term program stability in this area.[80]
- 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. Congress should pass the Clean Industrial Technologies Act to provide greater direction and long-term program stability in this area.[81]
- DOE-AMO should establish additional CEMI institutes in the other high-priority advanced manufacturing technologies identified in the *Quadrennial Technology Review*.[82]
- NSF should expand its Engineering Research Center and Industry/University Cooperative Research Center Programs and develop more centers oriented toward clean manufacturing.[83]

Pillar 8. Carbon capture, use, and sequestration

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.[84] 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.[85,86] 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.[87] 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), ethanol refinery (Archer Daniels Midland, 2017), and coal-fired power plant (Petra Nova, 2017; in 2020, this carbon capture project was shut down). 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.[88] DOE is also supporting technologies such as coal gasification and the Allam cycle for CCUS on power generating facilities.[89] 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.[90] 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.[91]

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).

- Consistent with proposed legislation such as the Enhancing Fossil Fuel Energy Carbon Technology (EFFECT) Act, Congress should provide new authorizations for this office to fund RD&D programs.[92] 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 create a new RD&D program for carbon capture at natural gas-fired power plants—consistent with the Launching Energy Advancement and Development through Innovations for Natural Gas (LEADING) Act—and should aim to demonstrate carbon capture at multiple natural gas power plants by 2025.[93]
- 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.[94]
- 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.[95]
- 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.[96]

Pillar 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.[97,98] 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.[99]

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.[100] 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.[101] Similarly, its 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.[102]

- Congress should fully fund AGARDA.[103]
- The United States should join and take a leadership role in the 4 per 1000 Initiative.[104]

Pillar 10. Carbon dioxide removal

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.[105] 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.[106] 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.[107] 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).[108,109] Both the

EFFECT Act (S. 1201) and FERD Act (H.R. 3607) 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 $GtCO_2$.[110] Currently, the SMART program at ARPA-E researches quantifying and monitoring soil carbon content and fluxes.[111]

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.[112,113]
- 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.[114]
- 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[115] The FY21 House Energy and Water Appropriations bill would establish such an office, as would the House Fossil Energy R&D Act and the Senate EFFECT Act.[116]

CHAPTER 6
Six strategic principles

Six strategic principles should guide federal funding for energy innovation. The first five of these principles recommend ways that the federal government should diversify its investments—across topics, stages of innovation, federal agencies, research partners, and regions of the United States. The 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 for innovation. They reflect analyses of the capacity of federal agencies, National Laboratories, universities, and other institutions to translate funding increases into technological progress. The principles are especially important as funding levels under the National Energy Innovation Mission increase significantly in the years ahead.

Principle 1: Match funding to critical decarbonization needs

The ten pillars of a National Energy Innovation Mission represent the most critical technological challenges for deep decarbonization. US leadership on each of those pillars will position the United States to prosper from a global clean energy transition. Yet US federal funding for energy innovation is grossly imbalanced across the pillars. As federal funding ramps up, increases should be targeted to under-resourced pillars. By 2025, the federal funding portfolio for energy innovation should be much more balanced.

By 2025, the federal funding portfolio for energy innovation should be much more balanced.

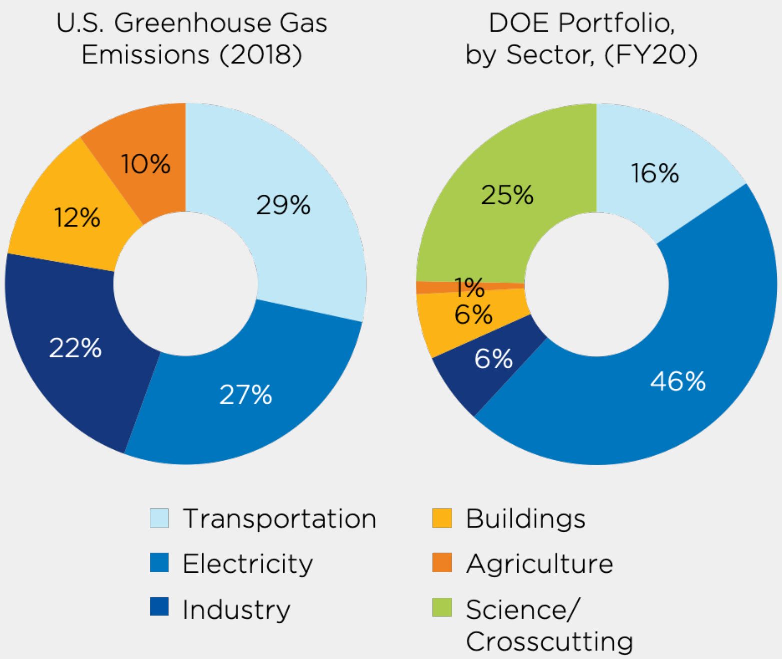
The United States is not alone in failing to align its public RD&D funding with critical decarbonization technology needs. The International Energy Agency has found that the world's major economies allocate too much funding to "supply-side technologies, rather than the types of end-use innovations needed for sectors that currently have no commercially available and scalable options for achieving deep emissions reductions." Underfunded innovation priorities include hydrogen, energy storage, and carbon capture, utilization, and storage technologies.[1]

One reason US federal energy innovation funding does not track critical decarbonization needs is that federal institutions have not been set up to do so. For example, the structure of the Department of Energy, which accounts for more than 75 percent of federal energy RD&D funding, reflects decades of shifting national priorities. A majority of the DOE budget funds the maintenance of the national nuclear weapons arsenal, national security R&D, and environmental cleanup of nuclear test sites—all legacy holdovers from the 1977 consolidation of various security and energy agencies.

As federal funding ramps up, increases should be targeted to under-resourced pillars.

DOE funds dedicated to energy innovation are allocated through offices predominantly corresponding to energy sources, such as coal, oil, gas, nuclear, and renewable energy. This structure is far from optimal for mission-driven funding across the ten technology pillars critical to deep decarbonization. As Figure 6-1 illustrates, half of current DOE funding for energy RD&D supports various technologies to generate and deliver electricity. (Setting aside foundational and cross-cutting science would reveal an even more skewed distribution of applied energy RD&D.) Urban infrastructure, clean fuels, and industrial decarbonization are all underfunded technology pillars that should receive sharply increased funding levels in coming years. Although clean electricity will play an important role in deep decarbonization, today's federal funding portfolio neglects other critical sectors and technologies.

FIGURE 6-1: Breakdown of 2018 U.S. greenhouse gas emissions, compared with the FY20 allocation of DOE energy RD&D funding



Source: Environmental Protection Agency and ITIF

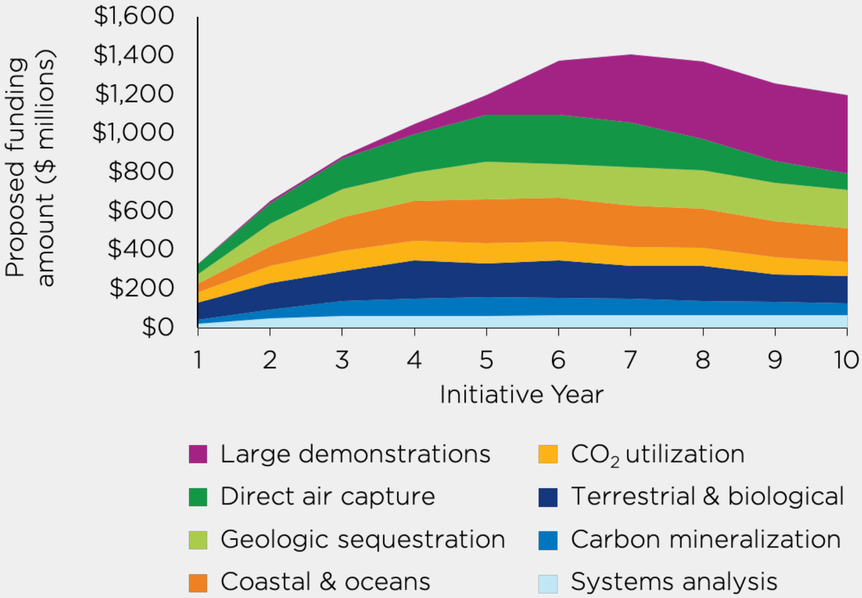
DOE leadership should consider organizational changes with the potential to improve coordination of activities on the ten technology pillars within the department. However, reorganizations can be time-consuming and resource-intensive, sapping productivity for extended periods of time. A reorganization should only be undertaken after careful evaluation of the time and resources required and extent to which mission performance will be impeded during the transition. Cross-cutting structures, such as Energy Innovation Hubs, may be able to more quickly improve on the existing situation. (One area in which the benefits of organizational changes may exceed the costs is the management of energy demonstration projects. We offer several options in the discussion of Principle 2.)

By committing to a National Energy Innovation Mission and tripling energy innovation funding by 2025, policymakers will have an opportunity to invest across the gamut of important clean energy technologies. A significant insight from the academic literature is that there is a minimum threshold for funding energy technologies in order for public investment to substantially accelerate technological progress. Therefore, under a low budget constraint, a government should only fund a handful of energy technologies at a meaningful level rather than squander those limited funds by dispersing paltry amounts across several technologies. As the budget constraint eases, a public funding portfolio that is optimized for reducing greenhouse gas emissions will support many more technologies.[2]

For each technology pillar, policymakers should design a long-term roadmap for ramping up federal funding, in consultation with experts from private industry as well as research institutions. An excellent example of such a roadmap is the one for carbon dioxide removal assembled by the National Academy of Sciences and enhanced by the Energy Futures Initiative (Figure 6-2).[3] Guided by a critical decarbonization need, this roadmap lays out a diverse but coherent set of technology priorities and proposes to provide funding across the stages of the innovation pipeline to rapidly bring new technologies to market.[4]

By preparing similar roadmaps for each technology pillar, policymakers should identify underfunded areas that need to be ramped up fastest. The federal government will need to build the capability to monitor funding levels for each technology pillar from across a dozen or more federal agencies. Doing so will enable policymakers to orchestrate and monitor a rapid increase of funding that balances the ten technology pillars. By 2025, each of the pillars should be funded at a level of at least one billion dollars. Rebalancing the federal funding portfolio will enable the United States to align its National Energy Innovation Mission with the most impactful uses of taxpayer funding.

FIGURE 6-2: A funding roadmap for a ten-year federal RD&D initiative for carbon dioxide removal (CDR)



Source: Energy Futures Initiative

Principle 2: Support all stages of the innovation pipeline

Shepherding clean energy technologies from conception to commercialization will require a holistic, coordinated strategy by policymakers to support all stages of the innovation pipeline. It is not enough for the federal government to only fund basic research and expect the private sector to take over thereafter. Multiple gaps in private funding, or valleys of death, exist on the road to commercialization. Therefore, in addition to following Principle 1—to match funding to critical decarbonization needs—policymakers should also provide funding across the stages of the innovation pipeline, spanning research, development, and demonstration.

Of these three stages, demonstration is the most seriously underfunded (see Chapter 2). For a range of reasons, private industry is hesitant to fund the first several demonstrations at commercial scale of complex, large-scale technologies. Firms correctly anticipate they are unlikely to capture all the benefits of such a demonstration. Indeed, the firm that waits to see if a demonstration carried out by someone else succeeds or fails will benefit from that knowledge and from the greater willingness of investors to supply capital. Investors are also wary of the high capital costs and risk of expensive project delays from large-scale demonstrations of unproven technology. As a result, a yawning valley of death can swallow firms that lack the capital to demonstrate promising clean energy technologies that they have developed.[5]

Yet today, the federal government devotes less than 5 percent of its energy RD&D funding to demonstration projects. Most of that funding is for a single DOE program to demonstrate advanced nuclear reactors. Demonstration projects are the most capital-intensive innovation stage, often costing hundreds of millions of dollars for a single project. But when they are successful, the benefits can be very large. For instance, federal loan guarantees for the first five utility-scale solar power projects in the United States jumpstarted a decade-long boom in massive solar projects. Today, solar power is the fastest-growing power source in the country.[6]

The federal government should ramp up funding for demonstration projects. In the near-term, policymakers should use agency programs that can fund such demonstrations under existing statutory authorizations, including the DOE's Applied Energy offices, its Loan Programs Office, and DOD's Environmental Security Technology Certification Program.[7] Indeed, Congress has already authorized $39 billion in loan guarantees that could leverage up to $100 billion of private investment in infrastructure across the energy sector.[8] Although energy demonstration projects have previously been plagued by cost overruns and political criticism, lessons from the past can inform a much more effective approach to managing such projects. For example, the federal government should make final investment decisions and begin construction after the majority of plant engineering has been completed.[9,10]

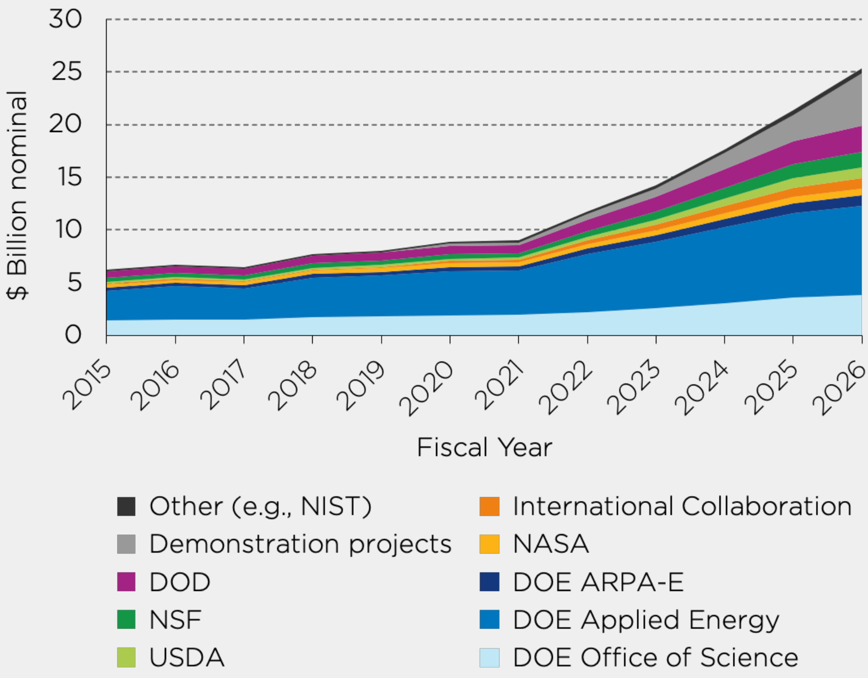
Existing channels for funding demonstration projects are not enough. The federal loan guarantee program, for example, is best suited for supporting technologies that have already been proven in a commercial setting. New entities could facilitate investments in riskier, first-of-a-kind demonstration projects. One option is for Congress to create an independent corporation to fund energy technology demonstration projects.[11] Such a corporation would be capitalized through a one-time appropriation and then be empowered to use a range of financing tools—from equity investments to loan guarantees—outside of the control of the political branches of government. Some have called for Congress to create a Clean Energy Deployment Administration, which would co-invest with the private sector in a range of clean energy infrastructure projects that include late-stage demonstrations.[12] Another alternative would be to establish a new Office of Major Demonstrations within the DOE.[13] In addition, DOD has extensive experience funding risky technology demonstration projects and could be a valuable investment partner.

The federal government should connect "technology-push" support for energy RD&D with "demand-pull" policies that prime commercial markets to demonstrate and scale up promising clean energy technologies.

The federal government should fund demonstration projects across the ten technology pillars at a level of at least $5 billion per year by 2025 (Figure 6-3). This is both a conservative and ambitious target. It is conservative because demonstration projects would account for just one-fifth of public energy RD&D funding by 2025, even though demonstration is much more capital-intensive than research and development, and there is a yawning private funding gap for demonstration projects. At the same time, this level of annual funding far outstrips any recent level of public investment in demonstration projects. It would more than triple the funding rate for demonstration projects compared with those from 2009 to 2011 under the Recovery Act.[14] Nevertheless, this level is an important target to aspire to. It corresponds to spending several hundred million dollars per year on demonstration projects within each technology pillar, enabling rapid commercial derisking of many critical technologies. Because it will take time to identify the most promising projects and set up the institutions and management teams to support them, demonstration funding in our proposal sharply ramps up from 2023–2025.

Finally, the federal government should connect "technology-push" support for energy RD&D with "demand-pull" policies that prime commercial markets to demonstrate and scale up promising clean energy technologies. Options include carbon pricing, clean electricity standards, fuel economy standards, targeted tax incentives, and more. Tax incentives have an especially strong track record of attracting bipartisan support and have succeeded at fostering market development for clean energy technologies including wind and solar power. In 2018, Congress enacted the 45Q tax incentive, which encourages investment in carbon capture and storage projects.[15]

FIGURE 6-3: Historical clean energy RD&D funding by federal agency and illustrative five-year ramp to $25 billion



Policymakers should design a new generation of tax incentives that mirror the ten technology pillars of the National Energy Innovation Mission.[16,17] Rather than predetermining which technologies to support, each of these tax incentives would fund the commercial scale-up of any emerging technology that advances a technology pillar. The goal of these tax incentives would be to pull promising technologies from each of the ten technology pillars into the market—technologies that the federal government would have pushed through the innovation pipeline through federal funding for RD&D. Policymakers should also experiment with a range of other demand-pull policies, from advance market commitments for public procurement of new technologies (an approach that has been used to great effect to pull pharmaceutical vaccines onto the market), prize competitions, and payments for innovative technologies as they reach performance and cost milestones.[18,19]

Principle 3: Marshal the full capacity of the federal government to support energy innovation

The needs for public energy innovation funding are diverse, spanning ten technology pillars and every stage of the innovation pipeline. Fortunately, the capacity of the federal government to meet those diverse needs is expansive—if its full resources are brought to bear. Today, the DOE's Office of Science and its Applied Energy offices account for more than 75 percent of existing federal funding for energy innovation. But by 2025, as the illustrative roadmap in Figure 6-3 illustrates, those offices should account for a proportion closer to half of the federal government's overall energy RD&D funding portfolio. The remaining half should be funded by a diverse collection of federal entities that will bring fresh approaches and mandates to support flourishing energy innovation ecosystems.

To be sure, the DOE brings decades of experience funding energy innovation. Its leading role should continue as the federal government embarks on a National Energy Innovation Mission. Over the next five years, Congress should double the budgets of the DOE Office of Science and its Applied Energy offices, which fund scientific research and applied energy research and development, respectively.[20] Maximizing the effectiveness of DOE spending will require it to pursue the institutional reforms discussed above, such as aligning its investments with the ten technology pillars and better connecting investments in basic scientific research with those in applied technology development.

Elsewhere, budgets should rise even faster. For example, ARPA-E, a semiautonomous DOE agency, is already structured to fund mission-driven RD&D, and just over a decade after its creation, it has already proven that its model is effective at spurring rapid technological progress. Projects funded by ARPA-E are far more likely to yield patents, publications, and follow-on funding from private investors than projects funded by other DOE offices.[21] Congress should increase ARPA-E's funding from $425 million in 2020 to $1 billion per year in 2025, in line with recommendations from the National Academy of Sciences and others.[22,23] This level of funding would also enable ARPA-E to expand its "SCALEUP" program that supports early demonstration of breakthrough technologies.

Many other federal agencies have missions that align with advancing energy innovation. The Department of Defense, in particular, is already a central player in energy innovation, but it should do more. Energy is central to the military's operations abroad and at home, and the DOD is eager to develop advanced energy technologies to bolster national security. The opportunities are diverse. For example, lightweight and highly efficient solar power materials, along with high-energy-density batteries, could make it easier for soldiers and bases to operate abroad in remote settings. At home, advanced microgrid technologies could secure military installations against threats from natural disasters and manmade disruptions. To be clear, the military's primary objective is not—and should not be—deep decarbonization. But many of the energy technologies that would advance its national security mission would also advance a clean energy transition.[24]

The DOD would be a valuable and complementary partner to the DOE in executing a National Energy Innovation Mission. For example, the DOD spends much more on demonstrating and validating new technologies than on research and development. Similarly, the DOD provides most of its RD&D funding to non-governmental researchers and companies, whereas the DOE allocates a majority of its RD&D budget to the National Laboratories.[25] The current level of military funding for clean energy innovation is unclear. Although the DOD reports an annual budget of $1.6 billion for energy research, development, testing, and evaluation, some of that funding supports technologies such as directed energy weapons that are unrelated to civilian clean energy technologies.[26] By 2025, Congress should appropriate at least $2.5 billion for the DOD to fund clean energy innovation that also promotes national security. Moreover, the DOD should coordinate its efforts with the DOE. A good model is the proposal in the 2021 National Defense Authorization Act to fund a $60 million joint program between the DOD's Environmental Security Technology Certification Program and the DOE's ARPA-E to invest in long-duration energy storage demonstration projects.[27]

The DOD would be a valuable and complementary partner to the DOE in executing a National Energy Innovation Mission.

Aside from the military, several other federal agencies have mandates that dovetail with advancing clean energy technologies and which have ample institutional capacity to sharply scale up funding. For example, the National Science Foundation is a leading federal funder of research in the physical sciences at universities around the country. All ten of the technology pillars of the National Energy Innovation Mission depend on advances in fields such as advanced materials that are squarely within the NSF's ambit. Yet in 2016 (the last year that the federal government calculated clean energy spending across the government), only 5 percent of NSF research funding, or roughly $400 million, supported clean energy technologies. Congress should increase this level to at least $1.5 billion by 2025. There is support from both sides of the aisle to expand NSF in this fashion. In 2020, a bipartisan group of legislators proposed the "Endless Frontier Act," which would create a new technology directorate within the NSF that would fund ten technology areas including "advanced energy" at a total level of $20 billion per year.[28]

NASA spent even less on clean energy innovation—just 2 percent of its R&D budget, or $300 million, in 2016. But NASA's goals align well with clean energy innovation needs. Over its history, NASA has used its mission and procurement authorities to reduce the costs and advance the performance of technologies such as solar panels, batteries, and fuel cells, which then reach commercial readiness on Earth. The first significant market for solar cells was on satellites, and fuel cells developed for use on Mars are now used to power data centers and hospitals.[29] In 2018, NASA collaborated with ARPA-E to sponsor a competition for breakthrough clean energy technologies, such as fuel cells, high-energy-density batteries, high-efficiency solar power systems, and smart grids.[30] By 2025, Congress should double NASA's funding for clean energy RD&D.

The National Institute of Standards and Technology, a unit within the Department of Commerce, should also receive support and encouragement to play an important role in the energy innovation mission. NIST's scientific user facilities, which complement those of DOE's National Laboratories, provide valuable testbeds for industries that will contribute to, and be impacted by, the energy transition. NIST is the federal government's lead agency for advanced manufacturing, overseeing the federal-state Manufacturing Extension Partnership, which helps small and medium-sized manufacturers become more efficient and innovative, and coordinating the interagency network of Manufacturing USA institutes. NIST also works closely with industry on standards issues, such as those raised by grid modernization and cybersecurity, that must be resolved for an effective transition.[31]

The US Department of Agriculture should also play an important role in the National Energy Innovation Mission. Multiple technology pillars, including carbon dioxide removal and clean agricultural systems, will require marshaling the expertise and experience of the USDA, which has previously supported pilot projects in these realms.[32] Congress should fund the USDA to support the development of technologies to measure soil carbon, sequester carbon through new crops, and reduce the carbon intensity of agricultural inputs.[33] In turn, the USDA should partner with the extensive national network of land-grant universities, which boast deep and practical expertise in these fields.

Finally, the federal government should devote a substantial annual budget to international energy RD&D collaboration, at the level of $1 billion or more by 2025. At present, funding for such activity is dominated by the $240 million that the United States contributes to fusion energy research. But across the ten technology missions, there is ample scope for substantial international cooperation. To be sure, there is fierce international competition among countries vying for a share of the growing advanced energy economy. But international collaboration in many fields, especially those still far from the market, will make the most of scarce resources, engage diverse project teams, and diffuse knowledge quickly. International collaboration in the early phases of energy innovation can and should complement robust international competition in the later phases.[34]

Principle 4: Harness the innovative capacity of National Laboratories, universities, and the private sector

Today, the primary way that the federal government supports energy innovation is by funding the National Laboratories to perform RD&D. These laboratories are often called the "crown jewels" of the US research infrastructure and should be central players in the National Energy Innovation Mission.

In addition, policymakers should better harness the talents of innovators outside of the federal government—in the nation's research universities and private sector. As the federal government ramps up funding for energy innovation, it should find more ways to collaborate with external partners and leverage federal funding to stimulate much more private investment in innovation.

Universities are a natural partner for advancing basic and translational research. Three-quarters of the NIH's funding supports extramural research across more than 2,500 universities, medical schools, and other research institutions, for example. In energy innovation, the federal government should sharply increase funding to research universities. It should build on the successful Energy Frontier Research Center model that facilitates collaboration among universities and research laboratories to solve challenging problems in foundational science. Similarly, it should expand DOE's Energy Innovation Hubs program, which brings research institutions together with private-sector partners to conduct applied research and development on important technology areas. Public university systems, including land-grant institutions, often have specific authorities, facilities, private-sector partnerships, and areas of expertise (e.g., in agriculture, forestry, and soils) that can serve the National Energy Innovation Mission.

The private sector also offers enormous potential for energy innovation that policymakers should seek to unlock. In fact, previous public-private partnerships have been successful at accelerating clean energy innovation. Clean energy start-up companies that enter a licensing or technology development alliance with a governmental entity such as a National Laboratory file 74 percent more patents than start-ups without such a partnership, and they enjoy an increase of 155 percent in securing private financing deals.[35]

And start-ups that receive a grant from the DOE's Small Business Innovation Research program are twice as likely to receive follow-on venture capital funding and are likely to secure more patents and revenue, compared with firms that do not receive such grants.[36] Federal grant funding for private firms can complement other policy tools for stimulating high-value innovation activities, such as tax deductions for R&D spending.[37]

The federal government should expand its support for private firms to conduct RD&D to advance the ten technology pillars of the National Energy Innovation Mission as well as co-invest through public-private partnerships in demonstration and commercialization activities.[38] Congress and federal agencies should work together to direct more funding through the Small Business Innovation Research program to innovative energy firms focused on growth and commercialization.[39] Aside from supporting individual firms, the federal government should support industry-wide R&D consortia such as the Electric Power Research Institute to foster innovation across energy industries. To be sure, policymakers should design safeguards to ensure that funding to the private sector is impartially awarded. But the notion that the federal government should not fund private industry at all, and instead only fund basic research, is counterproductive. Today, firms underinvest across the innovation pipeline. Targeted funding from the federal government to help firms conduct applied technology development and demonstration activities is critical to bringing new technologies to market and advancing US competitiveness.

Around the world, national governments partner with industries to support RD&D. For example, the sixty-six German Fraunhofer Institutes are an integral element of the country's success in cultivating globally competitive industries. These non-profit RD&D centers receive long-term grants from the federal and state governments to cover two-thirds of their costs, while private firms supply the remaining third of the funding to support projects of interest to them. The Fraunhofer system has expanded globally in recent years and now includes five centers in the United States.[40]

At a smaller scale, the United States has similar institutions to help private firms conduct applied technology development and prototype manufacturing processes. Authorized by Congress in 2014, "Manufacturing USA" is a network of fourteen public-private institutes sponsored by federal agencies such the

Departments of Commerce, Defense, and Energy that derive a majority of their funding from nonfederal sources. Unlike the German Fraunhofer Institutes, they lack guaranteed long-term federal funding, endangering their long-term viability.[41,42] Congress should recommit to supporting advanced manufacturing for the long run and empower federal agencies to partner with the private sector to scale up promising clean energy manufacturing technologies.

Targeted funding from the federal government to help firms conduct applied technology development and demonstration activities is critical to bringing new technologies to market and advancing US competitiveness.

None of these priorities should be funded at the expense of the National Laboratories. Indeed, one study concludes that energy RD&D conducted by government labs produces the highest-value research publications and patents and plays an important translational role between basic science and applied technology development.[43] Moreover, the National Laboratories have great potential to collaborate with the private sector. Some pilot programs, such as Lab-Embedded Entrepreneurs, Small Business Ventures, and High Performance Computing for Manufacturing have proven successful models that pair private firms and entrepreneurs with National Laboratory research equipment and staff to commercialize promising technologies. Far more of this is needed. The National Laboratories should also encourage research staff to collaborate with industry and increase the use of public-private technology development partnerships.[44]

Policymakers can further increase the impact of the National Laboratories on commercializing clean energy technologies in two ways. First, Congress should authorize and fund an Energy Technology Commercialization Foundation. This Foundation would also raise private and philanthropic funding to connect innovators around the country with National Laboratory facilities, fund incubators, and facilitate public-private collaborations.[45] Second, DOE should devolve a greater share of federal funding for laboratory directors to allocate to promising projects, as well as to allow the National Laboratories to benefit from the rewards of innovations they commercialize.[46] Research projects that are internally chosen by the laboratories are three times as likely to result in inventions than centrally directed projects.[47] With sufficient autonomy and funding, each National Laboratory can anchor a regional cluster of innovation, partnering with the private sector to put advanced laboratory equipment and deep expertise to use in commercializing clean energy technologies. Recent legislation in the House introduced by Rep. Frank Lucas (R-OK) would encourage National Laboratories to pursue technology transfer through public-private partnerships and serve as regional energy innovation centers across the United States.[48]

As policymakers ramp up federal energy RD&D, they should craft a portfolio that blends the unique strengths of the National Laboratories, world-class research universities around the country, and innovative private firms. In many cases, entities from all three categories should compete for federal funding. Harnessing all three sectors will enable the success of the National Energy Innovation Mission.

Principle 5: Partner with state and local governments to support regional energy innovation

Although decisions on federal funding for clean energy RD&D are made by policymakers in Washington, DC, innovation activity is dispersed all over the country (Figure 6-4).[49] Different regions bring comparative strengths 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.

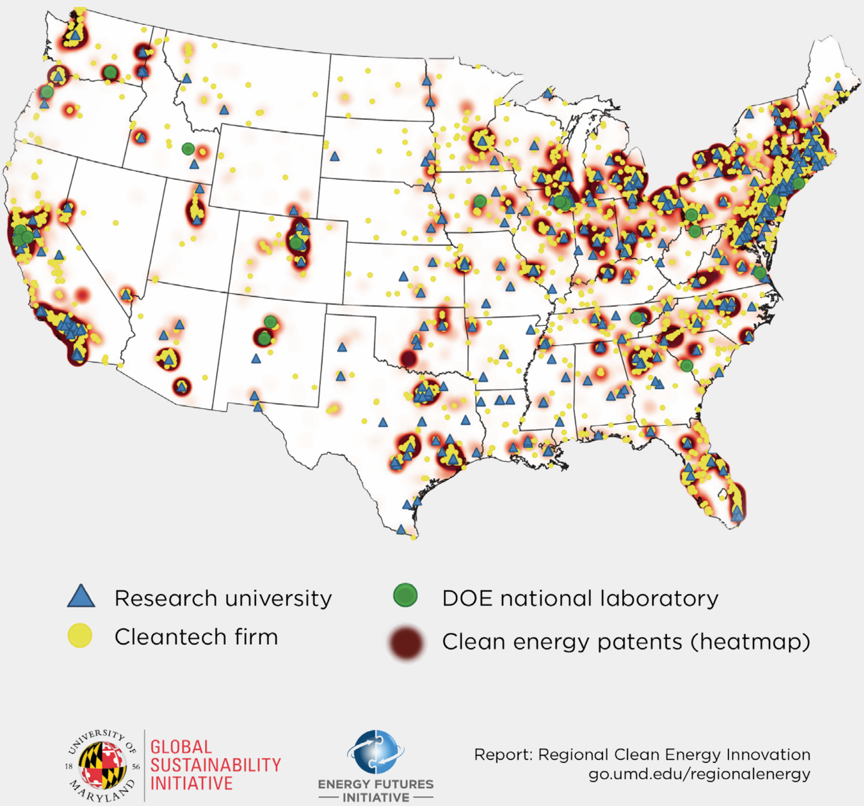
Clean energy innovation can progress rapidly when multiple firms, universities, and government laboratories are in close proximity and form regional innovation clusters. This is especially true when the production of a particular clean energy technology requires complex manufacturing processes; an innovation cluster can then enable rapid iteration among performers of early-stage research and development and firms that demonstrate and scale up technologies. The development of local supply chains and dense networks of specialized producers can reduce the costs of a clean energy technology. For example, advanced biofuel innovation clusters in the Midwestern United States and in São Paolo, Brazil, both integrate universities, public research institutions, and a dense network of suppliers and producers.[50]

State and local governments are well-placed to foster regional clean energy innovation. California and New York both use the proceeds from public benefit charges on residents' electricity bills to fund sizable state energy innovation agencies.[51] 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. State governments should be free to choose their clean energy innovation priorities, based on the unique assets of their regional economies, provided that they focus their efforts on one or more of the ten technology pillars. 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.[52]

The federal government should support more states in fostering regional clean energy innovation ecosystems.

In partnership with the federal government, state and local governments can spearhead efforts to invest in skilled and diverse workforces in each cluster. They can target economic development policies to address obstacles and biases that contribute to racial and gender disparities in clean energy technology industries. In addition, federal and state policies will be needed to invest in K–12 and higher education, promote high-skilled immigration, provide training and workforce development for existing professionals, and promote an equitable and just energy transition. Ultimately, the National Energy Innovation Mission will depend on the success of local innovators.[53]

FIGURE 6-4: Map of clean energy innovation activity across the United States



Source: Energy Futures Initiative, University of Maryland

Principle 6: Set predictable long-term funding targets, while adapting to new data

Historical experience with RD&D funding surges in energy, health, and other fields demonstrates the perils of volatile innovation funding. The federal government should commit to a high-level funding roadmap for ramping up funding for energy innovation. At the same time, it is important to ensure that additional RD&D funding is well-spent. Therefore, policymakers should also rigorously collect data on the innovation outcomes resulting from federal funding and periodically rebalance the RD&D portfolio to stay focused on the most critical needs for deep decarbonization.

Investments in innovation can take a decade or more to pay off in the form of commercial technologies. Recognizing this, the federal government should signal its long-term commitment to increasing annual energy RD&D funding over the next decade, even after reaching the target of $25 billion by 2025. Doing so will enable the US innovation ecosystem—including federal laboratories, research universities, and private firms and investors—to make long-term plans to best make use of federal funding, upgrade and maintain infrastructure and facilities, and augment public funding with private investments to bring new technologies to market.

As funding for energy RD&D increases, lawmakers and federal agencies should continually evaluate whether funds are being spent in ways that maximize progress across the ten technology pillars. For example, the federal government should carefully track technology commercialization and adoption indicators, such as follow-on investment, that result from federally funded RD&D, as well as more conventional indicators such as publications and patents.[54] And, following the example of ARPA-E, other federal agencies should redirect funding from projects that consistently fail to meet important milestones. As the National Energy Innovation Mission progresses, policy innovation and experimentation will be critical to advancing technological innovation.

The federal government should also adapt its RD&D funding portfolio based on the evolution of clean energy technologies and their market adoption.[55] If, for example, the commercial cost of producing clean hydrogen falls rapidly over the next decade, it could make sense to redouble investments in RD&D to use hydrogen as a feedstock to decarbonize industrial processes. Such course corrections require the federal government to update its forecasts of the most viable pathways to deep decarbonization and to develop the analytical and intelligence capabilities to understand global market dynamics. There are several methodologies for updating such forecasts. For example, policymakers can elicit expert opinions about which critical technologies will most benefit from additional RD&D funding. They can also use integrated assessment models of the economy to project the commercial success of various technologies under assumptions about the efficacy of different RD&D portfolio allocations.[56] Finally, they can survey the global landscape to determine in which technology areas the United States has comparative strengths and can build competitive industries. Based on these analyses, policymakers should seek to “skate to where the puck is going”—in other words, to allocate RD&D investments where they will be most needed for deep decarbonization and US competitiveness in the years ahead.

The federal government should build the capability to gather extensive data on the outcomes that result from funding from across the federal government.

Uncertainty is inevitable when considering the technology mix that will achieve the greatest commercial success and best help decarbonize energy systems over the next several decades. In the face of such uncertainty, diversification is the best strategy. The five principles above emphasize different dimensions of the RD&D funding portfolio’s diversity—technology area, innovation stage, federal agency, research performer, and geography. Policymakers should follow these principles as they adjust RD&D portfolios over time. Ultimately, corrections should not come at the expense of long-term predictability. At a high level, policymakers must stick to their roadmap for ramping up the federal budget for energy innovation.

CHAPTER 7
Three immediate recommendations

The 117th Congress and the presidential administration that will be sworn in in 2021 should take **three immediate steps** to accelerate clean energy innovation.

1. The president should launch a National Energy Innovation Mission.
2. Congress should increase funding for energy RD&D by 30 percent in its FY22 budget.
3. The United States should reassert leadership on international energy innovation.

1. The President should launch a National Energy Innovation Mission

Within one hundred days of the Inauguration, the president should issue a Presidential Policy Directive (PPD) launching a National Energy Innovation Mission. (A draft PPD is included in the Appendix.) The PPD should establish clean energy innovation as a core national priority and set the target of tripling federal clean energy RD&D funding by FY26 (which starts October 1, 2025).

White House leadership will be important to the success of the National Energy Innovation Mission.[1] Accordingly, the PPD should establish a White House Task Force on Energy Innovation, co-chaired by the Director of the Office of Management and Budget (OMB) and Assistant to the President with principal responsibility for climate change. Members of the Task Force should include the Secretary of Energy, Secretary of State, Secretary of Defense, Secretary of Agriculture, Secretary of Transportation, Secretary of Commerce, Secretary of the Treasury, Administrator of the Environmental Protection Agency, Administrator of NASA, Director of the National Science Foundation, Director of the Office of Science and Technology Policy, US Trade Representative, Chair of the Council of Economic Advisors and Chair of the Council on Environmental Quality.

Within one hundred days of the Inauguration, the president should issue a Presidential Policy Directive launching a National Energy Innovation Mission.

Within the federal government, the Department of Energy has core domain expertise with respect to clean energy innovation. Accordingly, the Secretary of Energy should be designated Agency Lead of the White House Task Force, with responsibility for providing strategic guidance on energy innovation to the Task Force and maintaining a small secretariat at the US Department of Energy to support the work of the Task Force. The Secretary of Energy should be tasked with drafting a national energy innovation strategy for consideration by the Task Force, which should submit the strategy to the president no later than summer 2021.

DOE should rebuild its policy planning capabilities and revive the Quadrennial Technology Review (QTR), which was published in 2011 and 2015 and should be a core element of the national energy innovation strategy. The QTR, in turn, should rest on and guide the Multiyear Program Plans for each DOE office. (Congress expressed its interest in and support for portfolio analysis and strategic planning by passing the DOE Research and Innovation Act of 2018.)

Each federal agency on the White House Task Force should prepare plans to invest in clean energy innovation in line with its mission and report to the president annually on its progress. The White House Task Force should meet quarterly to facilitate inter-agency collaboration on clean energy innovation, coordinate agency budgets, embed the National Energy Innovation Mission in official documents, and help remove obstacles to swift implementation.

The odds of success will be higher if expertise outside the federal government helps inform federal decision making. Accordingly, the president should establish a Federal Advisory Committee on Energy Innovation with representation from key stakeholders—including the states, the academic community, industry, labor, and environmental justice organizations. The committee would be constituted under the Federal Advisory Committee Act and could be embedded within the President's Council of Advisors on Science and Technology (PCAST) or another existing advisory body.

The Presidential Policy Directive should be revisited and adjusted as appropriate after three years.

2. Congress should increase funding for energy RD&D by 30 percent in its FY22 budget

The first federal budget of the 117th Congress will set funding levels for Fiscal Year 2022, which starts October 1, 2021. The budget process starts much earlier. House and Senate appropriations committees will hold hearings in March and April and aim to pass a budget by the fall.

It is critical that legislators make immediate progress in the FY22 budget on ramping up funding for energy innovation and addressing glaring gaps in the federal energy RD&D portfolio. Our recommendations (Table 7-1) are designed to be immediately actionable—no additional legislation is required. When the House and Senate appropriations committees begin their consideration of FY22 funding levels, they can readily evaluate the proposed funding levels in Table 7-1 within the existing appropriations framework.

In parallel, Congress should undertake a full assessment of innovation gaps—and whether new authorizing legislation is needed to address those gaps. The Senate Committee on Energy and Natural Resources and the House Committee on Science, Space, and Technology have already begun this process and approved many bipartisan bills for full consideration in their respective chambers.[2] In February 2020, Senators Murkowski (R-AK) and Manchin (D-WV) released the bipartisan American Energy Innovation Act, which incorporates some of the long-term recommendations in this volume.[3]

Our recommendations are designed to be immediately actionable—lawmakers can readily evaluate our proposed funding levels within the existing appropriations framework.

Table 7-1 lays out a proposal to decisively increase clean energy RD&D funding to $11.7 billion in FY22, which would be roughly a 30 percent increase from the FY20 level. It encompasses the specific initiatives recommended in Chapter 5 across the ten technology pillars. This proposal can guide the next administration's first budget request to Congress. (Additional details on the methodology for each line item recommendation and the mapping between funding lines and technology pillars are in Appendix B.)

This proposal focuses on boosting funding for DOE. The lawmakers most familiar with funding energy innovation are those on the energy and water appropriations subcommittees of the House and Senate, which control the DOE budget. Because of the tight timelines to propose and pass the first budget of the next administration and Congress, it will be most realistic to start the funding ramp-up by addressing important gaps in the DOE portfolio. In subsequent years, lawmakers should increasingly turn their focus to marshaling the full capacity of other federal agencies to co-invest in energy innovation.

Congress should focus on technology pillars that are currently underrepresented in federal RD&D funding. Therefore, this proposal targets the biggest increases in funding to the DOE offices best suited to invest in those underfunded pillars. Those offices cover carbon capture, utilization, storage, and removal; vehicle technologies; building and efficiency technologies; advanced manufacturing; advanced nuclear power; and electricity storage and modern grid systems. As a result, technology pillars that are currently underfunded receive the largest percentage increases in their budgets (Figure 7-1).

TABLE 7-1: Proposed FY22 federal energy innovation budget, by agency and office ($ millions)

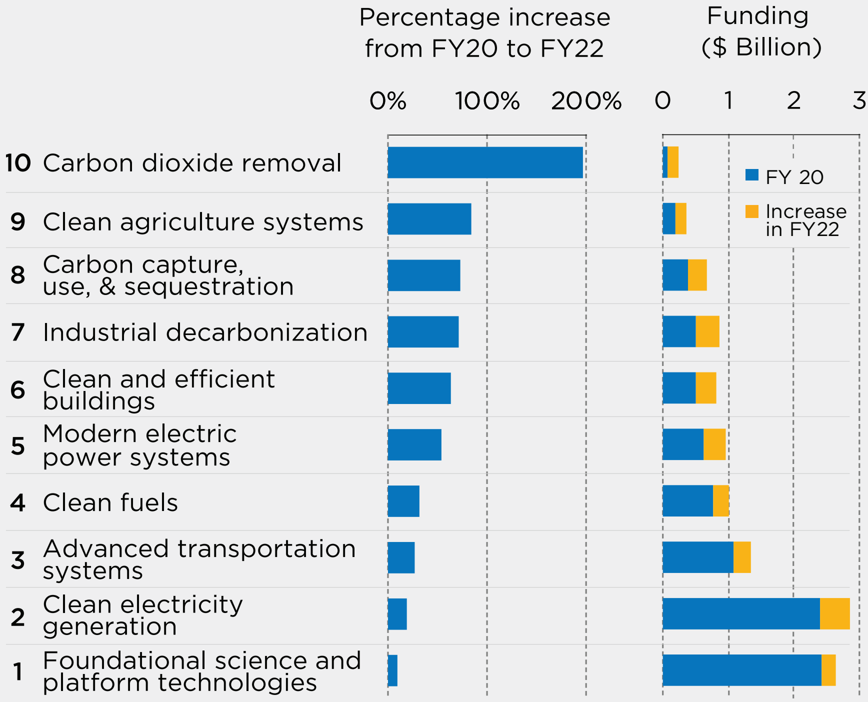
Funding Agency	Funding Office/Organization	FY 2020 Est.	FY 2022 Proposed	% change
Dept. of Energy	**Energy Efficiency and Renewable Energy (EERE)**	**2,228**	**2,682**	**20%**
	Vehicle Technologies Office (EERE/VTO)	396	488	
	Bioenergy Technologies Office (EERE/BETO)	260	320	
	Hydrogen & Fuel Cell Technologies Office (EERE/HFTO)	150	185	
	Solar Energy (EERE/SETO)	280	303	
	Wind Energy (EERE/WETO)	104	113	
	Water Power (EERE/WPTO)	148	160	
	Geothermal Technologies Office (EERE/GTO)	110	170	
	Adv. Manufact. Office (EERE/AMO)	350	432	
	Building Technologies Office (EERE/BTO)	230	301	
	Office of Carbon Management (CM)*	**472**	**812**	**72%**
	Carbon Capture (Power & Industrial)	115	300	
	Carbon Utilization	21	25	
	Carbon Storage	79	120	
	Adv. Energy Systems/Crosscutting	123	150	
	Negative Emissions Technologies (new office)	--	75	
	Methane Leak Detection & Mitigation	18	22	
	Office of Nuclear Energy (NE)	**1,493**	**2,028**	**36%**
	Versatile Test Reactor	65	450	
	Reactor Concepts RD&D	102	163	
	Fuel Cycle R&D	305	255	
	Advanced Reactor Research, Development and Demonstration	330	520	
	Office of Electricity (OE)	**190**	**520**	**174%**
	Office of Science (SC)	**2,151**	**2,572**	**20%**
	Advanced Scientific Computing Research (SC/ASCR)	173	200	

(continued from previous page)

Funding Agency	Funding Office/Organization	FY 2020 Est.	FY 2022 Proposed	% change
Dept. of Energy	Biological and Environmental Research (SC/BER)	451	523	
	Basic Energy Sciences (SC/BES)	661	766	
	Fusion Energy Sciences (SC/FES)	671	740	
	Advanced Resarch Projects Agency-Energy (ARPA-E)	**425**	**516**	**21%**
	Subtotal, DOE	**6,959**	**9,130**	**31%**
Dept. of Agricult.	Agriculture Advanced Research and Development Authority (AGARDA)		50	
	Agricultural Research Service (ARS)	99	158	
	NIFA Agriculture and Food Research Initiative (NIFA/AFRI)	106	169	
	Subtotal, USDA	**205**	**377**	**83%**
Dept. of Defense	U.S. Army Research Laboratory (ARL)	155	202	
	U.S. Naval Research Laboratory (NRL)	97	127	
	U.S. Air Force	254	332	
	Other (Defense-Wide, DARPA, ESTCP)	298	391	
	Subtotal, DOD	**804**	**1,053**	**31%**
NASA		**339**	**394**	**16%**
National Science Fndn.	Biological Sciences (BIO)	54	75	
	Computer and Information Science and Engineering (CISE)	24	34	
	Engineering (ENG)	156	219	
	Directorate for Mathematical and Physical Sciences (MPS)	162	227	
	Other NSF	21	29	
	Subtotal, NSF	**804**	**1,053**	**31%**
Other (NIST, NOAA, USGS, FHWA, EPA-ORD)		**169**	**221**	**31%**
Total	**N/A**	**8,894**	**11,758**	**32%**

**This is the proposed new name for the current Office of Fossil Energy*
FY 2020 funding levels for non-DOE programs are estimates of the portion of funding that goes to clean energy / clean agriculture. Agency and Office totals include estimates of program direction and RD&D facilities (not shown in the table) and and may be greater than the sum of RD&D programs.

FIGURE 7-1: Proposed FY22 federal energy innovation budget by technology pillar, compared with FY20 levels



Outside DOE, there are also immediate opportunities for Congress to increase energy RD&D funding. For example, the DOD already has a robust energy innovation funding portfolio, and Congress should increase that budget by roughly 50 percent in FY22 to enable the military to fund promising projects that both meet military objectives and fall within the ten technology pillars. Similarly, Congress should boost funding to NASA, the National Science Foundation, and the US Department of Agriculture. The incremental funding for energy innovation is tiny in comparison with the research budgets of these organizations, but it will greatly expand their activities in energy innovation and begin to diversify the federal government's portfolio.

Critically, lawmakers should not enact an ambitious FY22 budget only to backslide on their commitment to ramping up federal energy RD&D

spending in subsequent years. Volatility in annual funding is extremely damaging to the long-term enterprise of a national innovation mission. Therefore, lawmakers should supplement the annual appropriations process with alternative funding models that provide long-term stability and insulate the innovation portfolio from political uncertainty.

For example, Congress could assign particular revenue streams to fund clean energy RD&D programs, to reduce the dependence of those programs on annual appropriations decisions. Such revenue streams already exist, such as the royalties from oil and gas drilling on federal lands. (This approach was used by Congress in the 2005 Energy Policy Act to fund RD&D of unconventional oil and gas resources using federal lease royalties from oil and gas companies.) Other revenue streams could be created by lawmakers, such as a fee on electricity transmission. (A fee of less than 1 percent of the average price customers pay for electricity could pay for the entire $25 billion energy innovation budget target).

There are other proven avenues to provide long-term funding predictability. One is for Congress to provide advance appropriations that set funding levels for multiple years—an approach used to fund the DOE Clean Coal Technologies program in the 1980s and 1990s. Another approach is for Congress to authorize federal agencies that fund energy RD&D to submit a professional judgment budget, also known as a "bypass budget." For example, the NIH submits an annual budget for Alzheimer's research directly to Congress, bypassing the White House's budget process and better reflecting the scientific judgment of the agency of the funds needed to carry out its mission.

Finally, Congress should refrain from earmarks or being overly prescriptive in energy RD&D appropriations. Instead, Congress should follow the model it has pioneered with ARPA-E—to let scientists and experts at the agencies optimize the research portfolios of the federal government to best make progress on the ten technology pillars.

3. The United States should reassert leadership on international energy innovation

The National Energy Innovation Mission seeks to solve a global problem—climate change—and position US industries to best serve global markets.

Collaboration with international partners is essential to accomplishing both objectives. In parallel with sharply increasing energy RD&D funding at home, the United States should immediately project its leadership abroad to revitalize international cooperation on energy innovation.

At the 2015 Paris climate summit, the United States spearheaded the Mission Innovation compact, through which the world's largest economies pledged to double funding for energy RD&D. The United States had also cultivated bilateral research collaborations that held promise for US companies and researchers to collaborate with foreign counterparts and identify market opportunities for jointly developed technologies.

Yet in recent years, the United States has stepped back from its leadership role in these efforts, and global collaboration on energy innovation has stagnated. The US government officially withdrew the US pledge to double energy RD&D funding and scaled back its involvement in Mission Innovation. Absent US leadership, global energy innovation funding has grown only half as fast as countries had pledged five years ago.[4]

This must change. The United States should strike up new bilateral research collaborations with countries eager to invest in innovation and learn from the extensive experience of the United States. For example, the UK government has proposed spending over a billion dollars to stand up an agency modeled after the US ARPA-E.[5] Other potential international partners for bilateral research collaborations include Canada, India, and the European Union and its member states. The United States should collaborate with its partners across the innovation pipeline, spanning basic research and precompetitive technology development to demonstration projects in markets around the world.

Moreover, the United States should spearhead international collaborations that enable US firms to make inroads into global markets. One such avenue for global coordination is harmonizing technical standards for clean energy technologies and making it easier for US firms to export technologies that are subject to the same standards across geographies. For example, the United States should intensify efforts by NIST to lead the development of harmonized smart grid technical standards. Doing so can advance US competitiveness abroad. The NIST Smart Grid Advisory Committee recently urged the agency to accelerate its efforts to roll out new global standards in the face of

China's push to transfer its preferred technical standards to countries where it finances electricity grid infrastructure.[6]

In addition, the next administration should immediately recommit the United States to a leadership role in Mission Innovation, alongside countries such as the United Kingdom. The timing could be favorable. In 2021, Mission Innovation aims to launch a major set of initiatives to advance priority technology areas, or technology missions, which the United States should volunteer to lead. In November 2021, the most important United Nations climate summit since the 2015 Paris summit, known as the twenty-sixth Conference of the Parties to the UNFCCC (COP26), will convene in the United Kingdom. Not only must the United States reverse its withdrawal from the Paris Agreement, but its leaders should arrive at Glasgow for COP26 having passed an ambitious domestic budget for energy innovation and ready to inspire a global innovation push.

Publicly announcing its own target for tripling energy innovation funding will enable the United States to set off a competitive race to the top.

Publicly announcing its own target for tripling energy innovation funding will enable the United States to set off a competitive race to the top.[7] If the president and Congress can make tangible progress on jumpstarting the National Energy Innovation Mission, other countries will feel pressure to invest as well. To be sure, those countries will compete to capture market share in emerging clean energy applications. But the total economic value at stake will rise faster as the global energy sector becomes more innovative. Moreover, with the right federal policies to fund clean energy demonstration, support domestic manufacturing, and promote the export of US technologies, the United States can excel at this competition. In other industries that invest heavily in innovation, from semiconductors to pharmaceuticals, the world-class US innovation ecosystem enables US firms to anchor global supply chains. Similarly, the United States will be best poised to compete in clean energy industries by moving them away from producing commodity products—a paradigm that favors China's economic model—and toward an innovation-driven model of commercializing cutting-edge technologies.

Combating climate change will benefit from coordinated efforts by countries around the world to develop and deploy breakthrough energy technologies. The National Energy Innovation Mission will be most effective at advancing deep decarbonization if US investments in innovation at home inspire other countries to ramp up their own investments.

For too long, energy RD&D has been underfunded, in the United States and around the world. Now is the time for a National Energy Innovation Mission, to help lead the fight against climate change and build the industries of the future. Doing so will advance the US national interest for decades to come.

APPENDIX A

Proposed Presidential Policy Directive

This Presidential Policy Directive launches a National Energy Innovation Mission to fight climate change and promote US competitiveness.

Introduction

Clean energy innovation is in the United States' national interest. It is central to meeting the challenge of climate change and creates huge opportunities for the United States in the growing global market for clean energy technologies.

The United States is home to world's best and largest innovation system. Our universities, national laboratories, companies, and other institutions have unrivaled capabilities for innovation breakthroughs.

In prior decades, federal investment led to world-changing innovations, including life-saving drugs, the Internet, and solar photovoltaic cells. Federal investments in clean energy innovation can deliver significant returns.

Policy

This directive establishes clean energy innovation as a core national priority and launches a government-wide mission to promote clean energy innovation. It sets a goal of increasing federal funding for clean energy innovation to $25 billion per year by Fiscal Year 2026 (October 1, 2025–September 30, 2026). The directive defines the roles and responsibilities of federal agencies and offices in achieving that goal and promoting clean energy more broadly.

Roles and Responsibilities

1. A White House Task Force on Energy Innovation is hereby established. The Task Force will be co-chaired by the Director of the OMB and Assistant to the President with principal responsibility for climate change.

2. Members of the Task Force will include the Secretary of Energy, the Secretary of State, Secretary of Defense, Secretary of Agriculture, Secretary of Transportation, Secretary of Commerce, Secretary of the Treasury, Secretary of the Interior, Administrator of the Environmental Protection Agency, Administrator of NASA, Director of the National Science Foundation, Director of the Office of Science and Technology Policy, US Trade Representative, Chair of the Council of Economic Advisors, and Chair of the Council on Environmental Quality.

3. The Secretary of Energy will serve as Agency Lead of the Task Force, providing strategic guidance on energy innovation to Task Force members and maintaining a small secretariat at the US Department of Energy to support the work of the Task Force. The Secretary of Energy will draft a national energy innovation strategy for consideration by the Task Force by no later than May 31, 2020.

4. The Task Force will review the national energy innovation strategy drafted by the Secretary of Energy and submit a final strategy to the President no later than July 31, 2020.

5. Each federal agency or office on the Task Force will (i) prepare plans to invest in clean energy innovation in line with the agency's mission, and (ii) report to the President annually on its progress in promoting clean energy innovation on or before the anniversary of this directive.

6. The Task Force will meet at least quarterly to facilitate inter-agency collaboration on clean energy innovation, coordinate agency budgets, embed the National Energy Innovation Mission in official documents, and help remove obstacles to swift implementation.

7. This directive establishes a Federal Advisory Committee on Energy

Innovation. Members will be appointed by the President based on recommendations from Task Force members. The Advisory Committee will meet with the Task Force at least twice each year.

Review

Together with their annual reports in 2024, each member of the Task Forces will submit an assessment of the mechanisms established under this directive, together with recommendations for refinement or improvement in the years ahead.

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President of the United States of America

APPENDIX B
Current and Proposed Funding Levels

Estimating current FY20 funding levels for clean energy RD&D

Federal support for clean energy RD&D in FY20 is estimated using a variety of sources, including congressional budget justifications, agency reports, appropriations bills, and government-wide assessments developed by the White House Office of Management and Budget in the run-up to Mission Innovation.[1]

Department of Energy estimates are developed from the Information Technology and Innovation Foundation's (ITIF) energy budget database.[2] The Office of Energy Efficiency and Renewable Energy (EERE) funding includes the nine energy technology R&D programs included in Table 7-1, plus a proportional amount of program direction and funding for NREL. The technical assistance program in the AMO, the standards and codes program in the BTO, and non-R&D programs such as the Weatherization and Intergovernmental Programs (WIP) office and the Federal Energy Management Program (FEMP) are not included in clean energy R&D totals. FE estimates were developed using original Mission Innovation documentation and include carbon capture, utilization, and storage (CCUS), portions of the Advanced Energy Systems and Cross-cutting programs that fund CCUS-ready advanced combustion technologies, methane mitigation programs, and a proportional amount of program direction and funding for the National Energy Technology Laboratory (NETL). All of Nuclear Energy (NE), the Office of Electricity (OE), and ARPA-E is counted toward clean energy. The share of Office of Science programs funding clean energy was identified from DOE's FY17 congressional budget justification—which tracked what portion of SC funding was allocated to Mission Innovation—and was assumed to be constant through FY20.

Investments in clean energy RD&D at other agencies are more difficult to track. For the Department of Defense, estimates were developed using both a top-down and bottom-up approach. DOD invested about $1.6 billion in energy research, development, testing, and validation (RDT&E) in FY19, but some of that investment funds technologies with military-specific applications.[3] We developed bottom-up estimates of Army, Navy, and Air Force investments in clean energy RDT&E using the FY20 Operational Budget Energy Certification Report and using expert judgment to classify roughly 200 energy-related RDT&E projects based on their potential for civilian clean energy applications.[4] We estimate that around $800 million, or about half of the military's energy investments, goes to projects in lightweight solar PV, energy-dense batteries, microgrids for military bases, fuel-efficient vehicle technologies, wide band-gap semiconductors, fuel cell electric vehicles, and basic materials science. This estimate is consistent with analysis conducted by OMB in 2016 to inform the US Mission Innovation pledge, which found that 5 percent of total DOD investment in RDT&E supported clean energy applications.

National Science Foundation funding levels were estimated using FY16 and FY17 budget documents, which identified the portion of NSF funding at each directorate that was allocated to Mission Innovation. At the US Department of Agriculture, we assume that 25 percent of the NIFA/AFRI budget funds bioenergy and clean agriculture, consistent with OMB estimates of Mission Innovation funding in FY16. Additionally, we estimate that 25 percent of funding for food and animal production and crop production at the Agricultural Research Service (ARS) goes to clean agriculture activities. Funding for clean energy R&D at other agencies, including the National Oceanic and Atmospheric Administration (NOAA), NIST, USGS, DOT, and EPA, is estimated at $170 million, consistent with Mission Innovation documentation.

At the time of publication, Congress had not yet approved a budget for FY21. However, top-line spending is bound under the agreement reached between

Congress and the White House that caps total non-defense discretionary spending to a 1 percent increase, and congressional leaders have said they do not intend to revisit this agreement.[5] As a first approximation, we have assumed that this increase is spread evenly across agencies, and that DOE programs will each receive a 1 percent increase in FY21.

Proposing future funding levels

The proposed funding levels for FY22 for federal agencies and their constituent offices, summarized in Table 7-1, were derived using multiple inputs to identify the highest priorities for advancing the ten technology pillars. The inputs used to make future funding recommendations included:

- Estimated costs of the list of recommended initiatives summarized in Table A-1 for each of the technology pillars,
- Funding levels from selected proposed legislation targeting critical decarbonization needs, and
- Other proposals, such as the carbon dioxide removal funding roadmap proposed by the Energy Futures Initiative and based on a National Academy of Sciences roadmap.

TABLE A-1: Recent initiatives and future recommendations for the Technology Pillars

Technology Pillar	Recent initiatives and technology goals	Recommendations
1. Foundational science and platform technologies	• 46 active EFRCs organized around 5 "Transformative Opportunities" • New DOE Artificial Intelligence Technology Office in FY20 • International: Mission Innovation's clean energy materials challenge	• 45 new EFRCs organized around technology pillars • Machine learning applied to technology pillars • US should lead MI clean materials challenge
2. Clean electricity generation	• Sunshot Initiative 2030 goal: $0.03/kWh for utility solar-PV • WindVision 2030 goals: $0.023/kWh for onshore, $0.051/kWh for offshore • GeoVision 2050 goal $0.06/kWh for EGS • Hydropower Vision and Powering the Blue Economy roadmaps • Nuclear: VTR (design phase), new Adv. Reactor Demonstration program in FY20	• 45 new EFRCs organized around technology pillars • Offshore wind demonstrations, more aggressive cost target ($0.051/kWh by 2025) • EGS pilot wells at FORGE, more aggressive cost target ($0.06/kWh by 2030) • Complete VTR by 2026; demonstrate two advanced reactors by 2030; DOE/DOD partnership to develop microreactors
3. Advanced transportation	• Electric vehicle battery goal: $100/kWh by 2028, 300-mile range, 15 min charging time • SuperTruck II program to double efficiency of heavy-duty trucks • Fuel cell vehicle goal: cost-competitive with gasoline cars and trucks by 2030	• Accelerated goals for battery and fuel cell EVs • Demonstrate fast-charging for EVs • SuperTruck III to double freight-hauling by 2025 • DOE/DOT programs in aviation and shipping
4. Clean fuels	• System-wide hydrogen cost target (production + storage + delivery): $4/kg • ARPA-E's REFUEL program for ammonia and di-methyl ether • Joint Center for Artificial Photosynthesis to create synthetic solar fuels • DOD program to develop fuels from CO_2 captured from air & ocean	• Expanded clean fuels production programs to include ammonia, synthetic fuels • Innovation hub in electrofuels, modeled on JCAP • Biofuels programs for drop-in aviation/shipping fuels • Solar fuels program in applied programs
5. Modern electric power systems	• DOE Energy Storage Grand Challenge Initiative • DOE Grid Modernization Initiative Grid Storage Launchpad (design phase)	• Joint DOD/DOE energy storage demonstrations • Lithium battery recycling research program • Expanded grid storage program, incl. long-duration storage • Expand smart distribution and HVDC transmission programs

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Technology Pillar	Recent initiatives and technology goals	Recommendations
6. **Clean and efficient buildings**	• Whole-building goal: 30% reduction in energy use per square foot for all US buildings by 2030 • Efficiency goals for lighting, water heating, HVAC, building envelop and windows, appliances, and controls	• Accelerated efficiency goals for buildings and appliances • Expanded DOE/EPA programs in low-GWP f-gas alternatives
7. **Industrial decarbonization**	• DOE-AMO and NIST-MEP programs to improve energy efficiency of manufacturing • DOE energy bandwidth studies for 16 industrial sectors • DOE-AMO Industrial decarbonization roadmaps (in progress) • Clean Energy Manufacturing Innovation (CEMI) Institutes in 5 of 14 "high-priority" manufacturing technologies identified in the QTR	• Expand AMO mandate beyond efficiency, to include carbon capture, electrification, and clean fuels • Elevate AMO to Assistant Secretary level • Establish additional CEMI institutes in the other high-priority areas identified in the QTR
8. **Carbon capture, use, and storage**	• Carbon capture demonstrations at fertilizer, ethanol, and coal power plants • National Carbon Capture Center testing capabilities for coal and gas • LPO loan guarantee for the Lake Charles Methanol facility • Capture cost target: $30/tCO_2$ • Storage goal: 50 Mt storage capacity by 2026 • National Academies roadmap for carbon utilization	• Demonstrate post-combustion capture at 3+ natural gas power plants and 2+ coal power plants • New capture RD&D program for industrial facilities (e.g. steel and cement) • Double storage goal to 100 Mt capacity by 2026 • Expanded carbon utilization program
9. **Clean agriculture**	• Agriculture Advanced Research and Development Authority (AGARDA), authorized in 2018 Farm Bill but currently unfunded • ARPA-E ROOTS program • International "4 per 1000" initiative to promote clean agriculture practices	• Fully fund AGARDA • New programs in soil carbon farming, based on National Academies recommendations • US to the international join 4 per 1000 Initiative
10. **Carbon dioxide removal**	• New (FY20) DOE and DOD programs in direct air capture to fuels • USGS resource assessments in carbon mineralization • National Academies & EFI roadmap for carbon dioxide removal	• Interagency carbon removal program that implements National Academies roadmap • New program office in DOE-FE • New carbon removal programs in BES and ARPA-E • Expanded carbon removal research in existing programs at DOE, NSF, USGS

The following sections provide additional explanations for selected funding proposals across federal agencies.

Department of Energy

DOE Office of Nuclear Energy

Proposed funding levels for the DOE Office of Nuclear Energy come from the bipartisan House Nuclear Energy R&D Act (NERDA), H.R. 6097, introduced in the 116th Congress to refocus DOE's current nuclear energy program on advanced, next-generation reactor technologies.[6] A companion bill in the Senate—S. 903, the Nuclear Energy Leadership Act—contains similar provisions as NERDA, but without recommended funding levels. NELA passed out of the Senate Committee on Energy and Natural Resources by voice vote, with one no.

- Versatile Test Reactor (VTR): NERDA authorizes new funding to build a fast-spectrum VTR, which would operate as a user facility and enable private-sector companies to test new materials and fuel designs for advanced nuclear reactors. Congress appropriated $65 million in FY19 and FY20 (out of the Reactor Concepts program budget) to design and develop the VTR concept. As the project transitions from the design phase to construction, the VTR is moving to its own line item, and construction costs in FY22 are estimated at $450 million.[7]
- Advanced Reactors Demonstration: NERDA also authorizes an Advanced Reactor Demonstration program, with the goal of demonstrating two advanced reactor concepts by 2025, to be funded at $520 million in the first year, and $670 million for FY23-26.
- Reactor Concepts, Fuel Cycle R&D, and Nuclear Science and Engineering Support: NERDA modernizes and updates these programs, with recommended funding at $163 million, $255 million, and $40 million, respectively, in FY22.

ARPA-E

The National Academies recommended funding ARPA-E at $1 billion annually in its 2007 *Rising Above the Gathering Storm* report, but funding has never approached that level. ARPA-E was funded at its highest level ever at $425 million in FY20. The bipartisan, bi-cameral ARPA-E Reauthorization Act (S. 2714/H.R. 4091) authorizes a linear ramp from FY20 levels to $750 million in FY24.[8] Given ARPA-E's proven track record of generating new patents and launching innovative technology companies, we recommend extending that ramp to $1 billion in FY26.

DOE EERE Renewable Power

The House Science and Senate Energy committees have both introduced legislation for renewable power technologies (solar, wind, water power, and geothermal technologies). But the solar, wind, and water power bills are straightforward reauthorization bills that would renew existing DOE programs, with modest year-over-year increases.[9] We recommend a steeper increase in these programs. The exception is geothermal, for which the Senate conducted a more thorough assessment of innovation challenges and RD&D funding needs, leading to legislation from which we have derived funding recommendations.

- Wind energy: Ramp to $156 million in FY26 (50 percent increase above FY20).
- Water power: Ramp to $222 million in FY26 (50 percent increase above FY20), with most of the increase going to marine and hydrokinetic (MHK) technologies and advanced pumped storage, which are less mature than conventional hydropower.
- Geothermal: Ramp to $220 million in FY26 (100 percent increase above FY20), with FY22 funding levels from the Senate Advanced Geothermal Innovation Leadership (AGILE) Act, S. 2657.[10]

DOE EERE Advanced Transportation and Clean Fuels

The House Science and Senate Energy committees have both introduced legislation reauthorizing existing DOE programs in advanced transportation and clean fuels, with modest year-over-year increases. Given the historic underrepresentation of these programs in the energy innovation budget and the challenge of decarbonizing fuels and transportation, we recommend a steeper increase in these programs.

- Vehicle Technologies: Ramp to $990 million in FY26 (150 percent increase above FY20).
- Bioenergy Technologies: Ramp to $650 million in FY26 (150 percent increase above FY20).
- Hydrogen and Fuel Cell Technologies: Ramp to $375 million in FY26 (150 percent increase above FY20).

DOE EERE Energy Efficiency

- Building Technologies: Ramp to $690 million in FY26 (200 percent increase above FY20).
- Advanced Manufacturing: Ramp to $875 million in FY26 (150 percent increase above FY20).

DOE Office of Electricity

- Grid Modernization: Ramp to $275 million in FY26 (120 percent increase above FY20), with funding levels adopted from the House Grid Modernization Act, H.R. 5428.[11]
- Energy Storage R&D: Flat funding of $280 million for FY22–26 (400 percent increase above FY20), with funding levels adopted from the Senate Better Energy Storage Technologies (BEST) Act, S. 1602.[12]

DOE Office of Carbon Management

We recommend that the Office of Fossil Energy (FE) focus on carbon management technologies—including CCUS; advanced combustion technologies that facilitate carbon capture integration; methane mitigation; and negative emissions technologies. Recommended funding levels are taken from the House Fossil Energy R&D Act (FERDA), H.R. 3607.[13]

- Carbon Capture: $300 million in FY22 (from FERDA), ramping to $350 million in FY26 (200 percent increase over FY20).
- Carbon Storage: $120 million in FY22 (from FERDA), ramping to $160 million in FY26 (100 percent increase over FY20).
- Carbon Utilization: $25 million in FY22 (from FERDA), ramping to $45 million in FY26 (100 percent increase over FY20).

- Advanced Energy Systems: $150 million in FY22 (from FERDA), ramping to $190 million in FY26 (50 percent increase over FY20).
- Negative Emissions Technologies (new office): $75 million in FY22 (from FERDA), with future funding levels adopted from the EFI report *Clearing the Air*. While this would be a new office, it may not require new authorizing legislation because DOE is already conducting research in these technologies.[14] In the FY20 budget cycle, congressional appropriators established a new "budget control point" for advanced nuclear reactor demonstrations—essentially establishing a new program in NE.[15] We recommend that Congress do the same for negative emissions technologies in FY22.

Department of Energy – Office of Science

In FY16, DOE-SC invested about $1.6 billion in clean energy research across four offices—Advanced Scientific Computing Research (ASCR), BES, Biological and Environmental Research (BER), and Fusion Energy Sciences (FES). We have assumed the portion of funding in these offices dedicated to clean energy research has remained constant, to arrive at the FY20 estimates in Table A-2. We recommend doubling investment in clean energy research by FY26, with greater funding allocated to Energy Innovation Hubs and energy frontier research centers that address science challenges in the other nine technology pillars.

Department of Defense

We estimate that about half of the military's energy investments, about $800 million in FY20, have potential applications for civilian clean energy technologies. Increasing funding in these areas would enable enhanced capabilities for the military, while also allowing civilian applications to benefit from DOD's unique abilities as a technology innovator. Our mission would ramp funding for clean energy RDT&E to $2.4 billion in FY26 (200 percent increase over FY20).

Department of Agriculture

We recommend increasing total USDA funding in clean agriculture to $1 billion in FY26, and scaling up clean agriculture funding in Agriculture and

Food Research Institute (AFRI) and ARS proportionally. The Agriculture Advanced Research and Development Authority—established as a pilot program in the 2018 Farm Act—was envisioned as USDA's version of ARPA-E or DARPA but has never been funded.[16] We recommend fully funding at $50 million in FY22–23, and consider making AGARDA permanent thereafter.

National Science Foundation

In FY16, NSF invested about $370 million in clean energy research across four directorates: Biological Sciences (BIO), Computer and Information Science and Engineering (CISE), Engineering (ENG), and Mathematical and Physical Sciences (MPS). We have assumed the portion of funding in these directorates dedicated to clean energy research has remained constant, to arrive at the estimates of FY20 funding in Table A-2. The ramp in Table A-2 increases top-line investment in clean energy research at NSF to $1.5 billion in FY26.

Other Agencies

Funding for clean energy R&D at other agencies, including NIST, NOAA, USGS, DOT, and EPA, is estimated at $170 million, consistent with Mission Innovation documentation. The ramp in Table A-2 would triple investment in clean energy R&D at these agencies to $500 million in FY26.

Table A-2 summarizes our proposed funding levels through FY26. These levels are meant as a guideline, but we also recommend that policymakers identify changes to the way clean energy RD&D is funded, potentially including the creation of new entities, for example to fund demonstration projects.

Table A-2: Proposed federal clean energy RD&D funding levels from FY22 to FY26

All figures in billions of nominal dollars		FY 2020	FY 2021	FY 2022	FY 2023	FY 2024	FY 2025	FY 2026
US Federal Agency	**DOE Office of Science**	1.909	1.928	2.214	2.596	3.073	3.551	3.818
	DOE ARPA-E	0.425	0.429	0.516	0.631	0.774	0.918	1
	DOE Applied Energy	4.153	4.217	5.521	6.274	7.174	8.019	8.449
	EERE	2.228	2.251	2.682	3.198	3.841	4.485	4.832
	EERE-VTO	0.396	0.400	0.488	0.606	0.754	0.901	0.990
	EERE-BETO	0.260	0.262	0.320	0.397	0.494	0.591	0.649
	EERE-HFTO	0.150	0.152	0.185	0.230	0.286	0.341	0.375
	EERE-SETO	0.280	0.283	0.303	0.331	0.365	0.399	0.420
	EERE-WTO	0.104	0.105	0.113	0.123	0.136	0.148	0.156
	EERE- WPTO	0.148	0.149	0.160	0.175	0.193	0.211	0.222
	EERE-GTO	0.110	0.111	0.170	0.192	0.219	0.246	0.220
	EERE-AMO	0.350	0.354	0.432	0.536	0.666	0.797	0.875
	EERE-BTO	0.230	0.232	0.301	0.392	0.507	0.621	0.690
	EERE-Other	0.201	0.203	0.209	0.215	0.222	0.228	0.235
	CM*	**0.472**	**0.498**	**0.811**	**0.884**	**0.974**	**1.048**	**1.095**
	CM-CC	0.115	0.116	0.300	0.311	0.323	0.335	0.348
	CM-CS	0.079	0.080	0.120	0.129	0.138	0.149	0.160
	CM-CU	0.021	0.021	0.025	0.029	0.033	0.037	0.042
	CM-Adv Energy	0.123	0.124	0.150	0.158	0.167	0.176	0.186
	CM-CDR		0.022	0	0.108	0.156	0.186	0.186
	CM-Methane Mitigation	0.018	0.018	0.022	0.023	0.024	0.025	0.027
	CM-Other	0.116	0.117	0.120	0.126	0.132	0.139	0.146
	NE	**1.263**	**1.276**	**1.508**	**1.664**	**1.821**	**1.940**	**1.967**
	NE-Adv Reactor RD&D	0.330	0.333	0.520	0.670	0.670	0.670	0.670
	NE-VTR	0.065	0.066	0.450	0.565	0.680	0.755	0.735
	NE-Reactor Concepts	0.102	0.103	0.163	0.168	0.174	0.179	0.186
	NE-Fuel Cycle R&D	0.305	0.308	0.255	0.268	0.281	0.295	0.310

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All figures in billions of nominal dollars		FY 2020	FY 2021	FY 2022	FY 2023	FY 2024	FY 2025	FY 2026
US Federal Agency	NE-NEET	0.113	0.115	0.040	0.044	0.049	0.054	0.060
	NE-Other	0.577	0.583	0.601	0.619	0.637	0.656	0.676
	OE	0.190	0.192	0.520	0.529	0.537	0.546	0.555
	OE-Storage	0.056	0.057	0.280	0.280	0.280	0.280	0.280
	OE-Grid Mod	0.127	0.128	0.240	0.249	0.257	0.266	0.275
	NASA	0.339	0.343	0.394	0.461	0.546	0.631	0.678
	International Collaborations	0.242	0.244	0.358	0.510	0.699	0.889	1
	USDA	0.205	0.208	0.377	0.536	0.735	0.933	1
	NSF	0.417	0.421	0.584	0.800	1.071	1.342	1.5
	DOD	0.804	0.812	1.053	1.374	1.776	2.178	2.411
	Demonstration projects	0.230	0.232	0.520	0.8	1.5	2.5	5
	Other (e.g., NIST)	0.169	0.171	0.221	0.289	0.373	0.458	0.507
	Total	**8.89**	**9.00**	**11.75**	**14.27**	**17.72**	**21.42**	**25.36**

**This is the proposed new name for the current Office of Fossil Energy*
FY 2020 funding levels for non-DOE programs are estimates of the portion of funding that goes to clean energy / clean agriculture. Agency and Office totals include estimates of program direction and RD&D facilities (not shown in the table) and may be greater than the sum of RD&D programs.

Translating funding for federal programs into funding by technology pillar

In many cases, due to the complexity of energy systems, a single program office funds research across multiple pillars. For example, the Solar Energy Technologies Office (SETO) funds research in photovoltaics and concentrating solar power technologies, which are assigned to the clean electricity generation pillar, as well as grid integration, which we assign to the grid modernization pillar. Below, we summarize our methodology for assigning agency funding to technology pillars.

DOE EERE – Advanced Transportation

Vehicle Technologies Office (VTO)

The majority of funding falls in the Advanced Transportation pillar, with 10 percent of funding allocated to grid integration of electric vehicles (Grid Modernization pillar) and 5 percent of funding allocated to buildings integration of EV chargers (Buildings pillar).

Bioenergy Technologies Office (BETO)

The majority of funding is attributed to Clean Fuels production, with 15 percent of funding split between the use of bioenergy in the transportation and industrial sectors, and 5 percent of funding allocated to biomass-based carbon removal technologies, such as bioenergy with carbon capture and storage.

Hydrogen and Fuel Cells Technologies Office (HFTO)

This office is evenly split between Clean Fuels production and the use of hydrogen in end-use sectors. The office has historically focused on the primarily on the use of hydrogen in transportation systems. We recommend an expanded focus, with 10 percent of funding going applications of hydrogen in the industrial sector.

DOE EERE – Renewable Power

Solar Energy Technologies Office (SETO)

The majority of funding seeks to develop clean electricity generation technologies. We estimate that 20 percent funds grid integration research (Grid Modernization pillar), and 15 percent of research is aimed at reducing the soft costs of distributed solar, which we assign to the Buildings pillar. Additionally, we recommend that 10 percent of SETO's budget fund a new subprogram in solar fuels, which would build off the early-stage solar fuels research in the Office of Science.

Wind Energy Technologies Office (WETO)

The majority of funding is attributed to clean electricity generation, with approximately 10 percent of funding toward grid integration (Grid Modernization pillar) and an estimated 5 percent for integration of distributed wind with buildings.

Water Power Technologies Office (WPTO)

The majority of funding is attributed to clean electricity generation, with approximately 10 percent support Grid Modernization R&D.

Geothermal Technologies Office (GTO)

The majority of funding is attributed to clean electricity generation, with approximately 20 percent split between direct geothermal heating for buildings and industrial processes.

<u>DOE EERE – Energy Efficiency</u>

Advanced Manufacturing Office (AMO)

All funding is attributed to the Clean Industry pillar.

Building Technologies Office (BTO)

All funding is attributed to the Clean Buildings pillar.

<u>DOE Carbon Management</u>

Carbon Capture, Utilization, and Storage

The majority of funding from these subprograms is attributed to the CCUS pillar, with some funding (10 percent of carbon capture) exploring applications of carbon capture in the industrial sector, and some funding (20 percent of carbon utilization) aimed at using captured CO_2 in clean fuels production.

Advanced Energy Systems

This program funds research into advanced combustion systems (such as gasification and solid oxide fuel cells) that are designed for easy integration with carbon capture technologies, so funding is split between the Clean Electricity pillar and the CCUS pillar.

Negative Emissions Technologies

All funding is attributed to the carbon removal pillar.

DOE Nuclear Energy

Versatile Test Reactor and Fuel Cycle RD&D

All funding is attributed to the clean electricity pillar.

Reactor Concepts RD&D

We adopt the House Nuclear Energy R&D Act's funding authorizations, which allocates about a third of the funding to "hybrid energy systems"—including applications such as desalination, hydrogen production, heat for industrial processes, and CCUS. Accordingly, we split one-third of the program evenly among the CCUS, clean fuels, and clean industry pillars, and assign the remaining two-thirds to the clean electricity pillar.

Advanced Reactor RD&D

The majority of funding is attributed to clean electricity generation, with 15 percent split evenly between the fuels, buildings, and industrial pillars due to the ability of many advanced reactor designs to provide non-electric services such as high-temperature heat.

Nuclear Science and Engineering

Funding is split evenly between the science pillar and clean electricity.

DOE Office of Electricity

The majority of funding is attributed to the grid modernization pillar. We recommend 10 percent fund research in grid-integrated buildings, and 5 percent split evenly between integration of electric vehicles (advanced transportation pillar) and industrial demand response.

DOE Office of Science

Advanced Scientific Computing Research (ASCR)

All funding is attributed to the science/platform technologies pillar.

Biological and Environmental Research (BER)

In FY20, $100 million (22 percent of clean funding) supported the four bioenergy research centers (clean fuels pillar), and the remainder is attributed to the science/platform technologies pillar. We recommend maintaining the ratio.

Basic Energy Sciences (BES)

We recommend $15 million (2 percent) to support new energy frontier research centers in each pillar, maintaining the Joint Center for Energy Storage Research ($24 million, or 3 percent, in the grid modernization pillar), maintaining the solar fuels hub ($15 million, in clean fuels), adding a new electrofuels hub ($15 million, in clean fuels), and adding new innovation hubs for the three energy end-use sectors (transportation, buildings, and industry). The remainder is allocated to the science/platform technologies pillar.

Fusion Energy Sciences (FES)

Approximately a third of funding supports the International Thermonuclear Experimental Reactor (ITER, clean electricity pillar), with the remainder allocated to the science/platform technologies pillar.

ARPA-E

Funding is evenly split among the technology pillars.

US Department of Agriculture

Agriculture Advanced Research and Development Authority (AGARDA)

The Energy Futures Initiative recommends $20 million (40 percent) of funding support soil carbon storage and other agricultural carbon removal research. We allocate the remainder to the clean agriculture pillar.

Agricultural Research Services (ARS)

All funding is attributed to clean agriculture.

Agriculture and Food Research Institute (AFRI)

Funding is split evenly between clean agriculture and biocrops for fuels (clean fuels pillar).

National Aeronautics and Space Administration (NASA)

All funding is attributed to advanced transportation.

Department of Defense (DOD)

We make no recommendations for how DOD should allocate its funding. Instead, these numbers represent our estimates of how DOD currently allocates its funding, based on our review of the FY19 and FY20 Operational Budget Energy Certification Reports. The Securing Energy for our Armed Forces Using Engineering Leadership (SEA FUEL) Act of 2019—which was incorporated into the National Defense Authorization Act and signed into law—requires a small portion of DOD RDT&E to support direct air and direct ocean capture of carbon dioxide for distributed clean fuels production.[17]

National Science Foundation (NSF)

Computer and Information Science and Engineering (CISE) and Mathematical and Physical Sciences (MPS)

All funding is attributed to the science/platform technologies pillar.

Biological Sciences (BIO)

The majority of funding as allocated to the science/platform technologies pillar, with 30 percent split evenly between the clean fuels, carbon removal, and clean agriculture pillars.

Engineering (ENG)

The majority of funding is allocated to the science/platform technologies pillar, with the remainder split between the other technology pillars. Due to the challenge of decarbonizing the energy end-use sectors (transportation, buildings, and industry) and their historic underrepresentation in the federal budget, we recommend more funding for these engineering challenges in these pillars.

National Institute of Standards and Technology (NIST)

All funding is attributed to the clean industry pillar.

Other Agencies

Funding is allocated evenly across the pillars.

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Chapter 6

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List of Abbreviations

A

AAAS
American Association for the Advancement of Science

AFRI
Agriculture and Food Research Initiative

AGILE Act
Advanced Geothermal Innovation Leadership Act

AGARDA
Agriculture Advanced Research and Development Authority

AI
Artificial intelligence

AMO
Advanced Manufacturing Office, Department of Energy

ARL
Army Research Laboratory

ARPA-E
Advanced Research Projects Agency-Energy

ARS
Agricultural Research Service

ASCR
Advanced Scientific Computing Research

ATB
Annual technology baseline

B

BECCS
Bioenergy with carbon capture and storage

BER
Biological and Environmental Research program, Department of Energy

BES
Basic Energy Sciences program, Department of Energy

BEST Act
Battery Energy Storage Technology Act

BETO
Bioenergy Technologies Office, Department of Energy

BIO
Directorate for Biological Sciences, National Science Foundation

BTO
Building Technologies Office, Department of Energy

C

CCS
Carbon, capture and storage

CCUS
Carbon, capture, use, and sequestration

CDR
Carbon dioxide removal

CEMI Institute
Clean Energy Manufacturing Innovation Institute

CISE
Directorate for Computer and Information Science and Engineering, National Science Foundation

CM
Office of Carbon Management, Department of Energy

COP
Conference of the Parties

D

DAC
Direct air capture

DACS
Direct air capture and storage

DARPA
Defense Advanced Research Projects Agency

DOD
Department of Defense

DOE
Department of Energy

DOI
Department of the Interior

DOT
Department of Transportation

E

EERE
Office of Energy Efficiency and Renewable Energy, Department of Energy

EFFECT Act
Enhancing Fossil Fuel Energy Carbon Technology

EFI
Energy Futures Initiative

EFRC
Energy Frontier Research Center

EGS
Enhanced geothermal systems

ENG
Directorate of Engineering, National Science Foundation

EPA
Environmental Protection Agency

ESTCP
Environmental Security Technology Certification Program, Department of Defense

EV
Electric vehicle

F

FE
Office of Fossil Energy, Department of Energy

FEMP
Federal Energy Management Program

FERD Act
Federal Energy Research and Development Act

FERDA
Fossil Energy R&D Act

FES
Fusion Energy Sciences program, Department of Energy

FHWA
Federal Highway Administration

FORGE
Frontier Observatory for Research in Geothermal Energy

FY
Fiscal year

G

GDP
Gross domestic product

GPS
Global positioning system

$GtCO_2$
Gigatons of carbon dioxide

GTO
Geothermal Technologies Office, Department of Energy

GW
Gigawatt

GWP
Global warming potential

H

HFTO
Hydrogen and Fuel Cell Technologies Office, Department of Energy

HVAC
Heating, ventilation, and air conditioning

HVDC
High-voltage direct current

I

ICCS
Industrial carbon capture storage program, Department of Energy

IEA
International Energy Agency

IPCC
Intergovernmental Panel on Climate Change

ITER
International Thermonuclear Experimental Reactor

ITIF
Information Technology Information Foundation

J

JCAP
Joint Center for Artificial Photosynthesis

K

kg
Kilogram

kWh
kilowatt-hour

L

LEADING
Launching Energy Advancement and Development through Innovations for Natural Gas Act

LPO
Loan Programs Office

M

MEP
Manufacturing Extension Partnership

MHK
Marine and hydrokinetic energy

MI
Mission Innovation

MPS
Directorate of Mathematical and Physical Sciences, National Science Foundation

$MtCO_2$
Megatons of carbon dioxide

MWh
Megawatt-hour

N

NASA
National Aeronautics and Space Administration

NASEM
National Academies of Sciences, Engineering, and Medicine

NE
Office of Nuclear Energy, Department of Energy

NELA
Nuclear Energy Leadership Act

NERDA
Nuclear Energy R&D Act

NETL
National Energy Technology Laboratory

NIFA
National Institute of Food and Agriculture

NIH
National Institutes of Health

NIST
National Institutes for Standards and Technology

NOAA
National Oceanic and Atmospheric Administration

NREL
National Renewable Energy Laboratory

NRL
Naval Research Laboratory

NSF
National Science Foundation

O

OE
Office of Electricity, Department of Energy

OMB
Office of Management and Budget

P

PCAST
President's Council of Advisors on Science and Technology

PPD
Presidential Policy Directive

PV
Photovoltaic

Q

QTR
Quadrennial Technology Review

R

R&D
Research & development

RD&D
Research, development, & demonstration

RDT&E
Research, development, testing, and evaluation

REFUEL
Renewable Energy to Fuels through Utilization of Energy-dense Liquids program

ROOTS
Rhizosphere Observations Optimizing Terrestrial Sequestration program

S

SC
Office of Science, Department of Energy

SCALEUP
Seeding Critical Advances for Leading Energy Technologies with Untapped Potential program

SEA FUEL
Securing Energy for our Armed Forces Using Engineering Leadership Act

SETO
Solar Energy Technologies Office, Department of Energy

SIPA
School of International and Public Affairs

SMARTFARM
Systems for Monitoring and Analytics for Renewable Transportation Fuels from Agricultural Resources and Management program

SSL
Solid-state lighting

U

UN
United Nations

UK
United Kingdom

UNFCCC
United Nations Framework Convention on Climate Change

US
United States

USDA
United States Department of Agriculture

USGS
United States Geological Survey

V

VC
Venture Capital

VTO
Vehicle Technologies Office, Department of Energy

VTR
Vertical test reactor

W

WETO
Wind Energy Technologies Office, Department of Energy

WIP
Weatherization and Intergovernmental Programs, Department of Energy

WPTO
Water Power Technologies Office, Department of Energy

Acknowledgments

This volume has benefited from detailed feedback and suggestions from an array of respected experts to whom we are grateful, including Laura Anadon Diaz, Rob Atkinson, Bill Bonvillian, Jason Bordoff, Steve Capanna, Joseph Curtin, Jennie Dodson, Joshua Freed, Greg Gershuny, David Hayes, Joseph Hezir, Richard Kauffman, Henry Kelly, Melanie Kenderdine, Melissa Lott, John Loughhead, John MacWilliams, Monica Medina, Elizabeth Noll, Batt Odgerel, Dan Reicher, Dorothy Robyn, Rob Rozansky, Tarak Shah, Elizabeth Sherwood-Randall, Robert Trezona, David Turk, David Victor, Jetta Wong, and Ali Zaidi, as well as from the support and guidance of Wayne and Catherine Reynolds. We would also like to thank three anonymous external expert reviewers and multiple anonymous Columbia University reviewers for providing insightful feedback on the manuscript.

At Columbia University, we are grateful to the formidable team that made this volume possible, including Laurie Fitzmaurice, Jesse McCormick, Matt Robinson, Christina Nelson, Nicolina DueMogensen, Artealia Gilliard, Genevieve Morton, Caitlin Norfleet, Anna Gossett, Stephanie Damassa and others. We are especially indebted to Jason Bordoff for his vision in conceiving this project and support and guidance throughout the process. We were helped by the invaluable research support of two phenomenal student researchers, Jonah Messinger and Siddhant Sinha. We are also grateful to colleagues at ITIF including Randolph Court and Sintia Radu.

Writing this volume during the coronavirus pandemic of 2020 strained the boundaries of work and home; *Energizing America* would not have been possible without the love and support of our families, particularly our spouses: Laxmi Parthasarathy, Babak Hosseini, Lois Frankel, Lara Webber, and Holly Hammonds.

Finally, we are grateful to Breakthrough Energy and particularly Robin Millican, Mike Boots, Maria Martinez, and Trisha Miller for generously supporting this project and the Columbia Global Energy Innovation Initiative. This project was also made possible by ongoing support from the Spitzer Trust to the Information Technology and Innovation Foundation and from Jane Flegal and the Hewlett Foundation to the Center on Global Energy Policy.

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ISBN 978-0-578-75852-7

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