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The Climate Innovation Blueprint

An analytical framework for aligning federal energy innovation budgets with climate goals

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About EDF

Environmental Defense Fund (EDF) is one of the world's leading environmental nonprofit organizations. EDF's mission is to preserve the natural systems on which all life depends. Guided by science and economics, EDF finds practical and lasting solutions to the most serious environmental problems.

Executive Summary

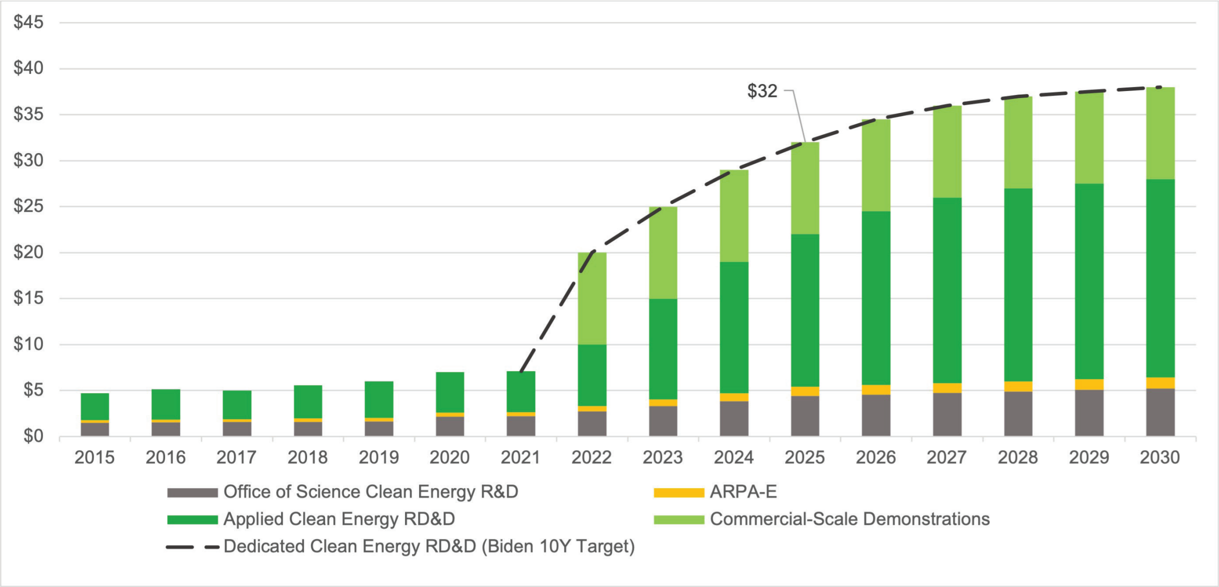
To confront the climate crisis and demonstrate international leadership, the United States must aim to achieve net-zero greenhouse gas emissions across the economy by no later than 2050, a path consistent with meeting global temperature goals to avert the worst effects of climate change. Innovation alone will not be enough to meet this target – we need policy to limit emissions across the economy – but innovation plays a critical role in lowering the costs and improving the performance of the technologies we have today, and in developing and commercializing the nascent technologies we will need to decarbonize fully. Recognizing this, many groups, including EDF, have called for at least a doubling of federal clean energy innovation funding within the decade.[1] As a candidate, President Biden committed to spending $400 billion over ten years – a goal EDF has supported.[2] While more funding will, in and of itself, spur technology progress, a larger clean energy innovation budget can be most effective at helping us achieve our climate goals if we prioritize the technologies that will drive the greatest reductions in greenhouse gas (GHG) emissions.

EDF worked with Evolved Energy Research (EER) to develop an analytical framework for assessing the emissions impact of potential cost and performance breakthroughs across a set of clean energy technologies, both individually and in tandem. This framework allows us to quantify the effect of different technology progress trajectories on system-wide CO_2 emissions under various policy scenarios. Put differently, we can see the emissions reductions driven by progress in each technology, allowing us to prioritize efforts to achieve the technology breakthroughs that result in the biggest climate benefits. In this paper, we describe how the framework can be applied to inform policy decisions, then offer specific recommendations for aligning innovation budgets at the U.S. Department of Energy (DOE) with climate targets.

First, we recommend an increase in appropriations for dedicated clean energy innovation at DOE to $32 billion in FY 2025, including nearly $17 billion in the applied energy programs. This puts us on track to meet the scale of investment that the Biden campaign committed to: $400 billion for clean energy and innovation over ten years.[3] It also makes up for lost time. In 2015, the U.S. pledged to double clean energy research across the U.S. government from $6.4 billion (including $4.8 billion at DOE) to $12.8 billion in five years; yet, in FY 2020, we committed just $7 billion at DOE and $9 billion across the U.S. government, well short of this goal.[4,5] Likewise, if DOE innovation funding had kept pace with U.S. economic growth since the 1970s, we would be spending about four times what we are today.[6]

Our recommendation focuses on DOE's clean energy-focused research, development, and demonstration (RD&D) efforts, including the applied energy programs, ARPA-E, and the portions of the Office of Science explicitly devoted to clean energy. Beyond pre-commercial demonstration efforts in the applied energy programs, we also recommend dedicating $10 billion per year for commercial-scale demonstration projects, which are important for reducing costs and solving real-world challenges of scale for emerging energy technologies. While not included under the umbrella of RD&D and the budgets depicted in Figure ES-1, DOE should also dedicate much more funding for clean energy deployment and commercialization efforts. This would include expanding existing efforts through the Loan Programs Office, Weatherization and Intergovernmental Programs, and the Office of Technology Transitions, for instance, but also will require additional programs or a dedicated office focused on deployment and commercialization.

ES-1. Recommended DOE clean energy RD&D spending (billions), FY15-FY30



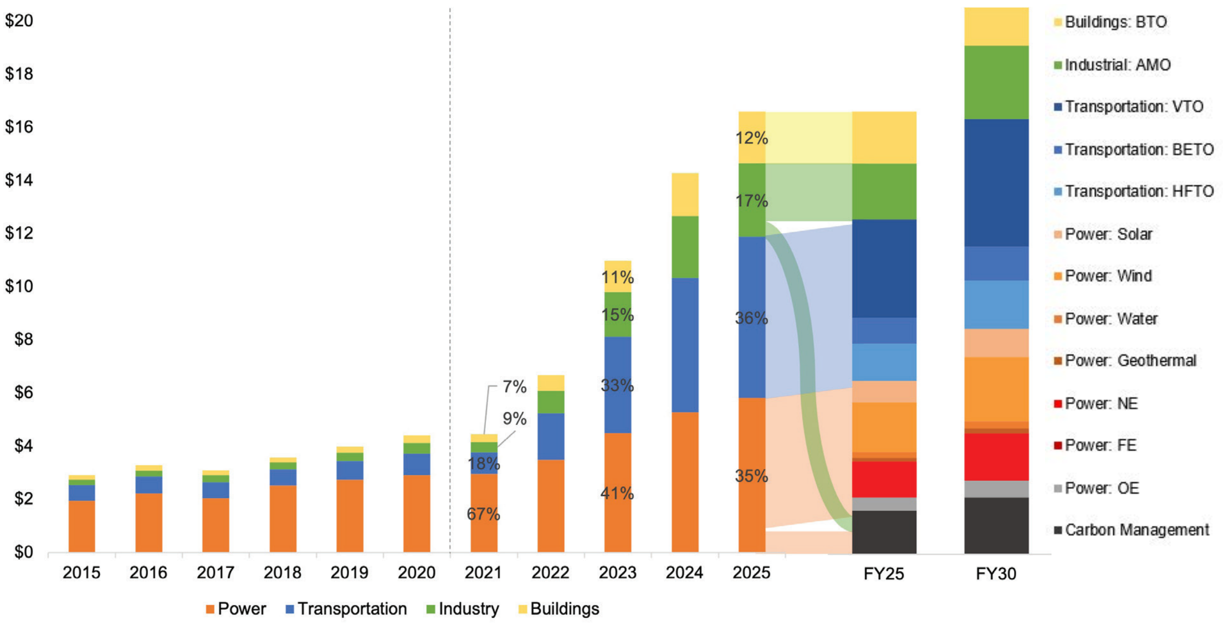
Second, we recommend Congress allocate the DOE RD&D budget in proportion to the current sectoral distribution of emissions *and* the cumulative emissions reduction potential of technologies within each sector. With additional funding, DOE's RD&D portfolio should be rebalanced to reflect the scale of CO_2 emissions from different energy-using sectors (transportation, power, industry, and buildings). Then, within those sectors, it should prioritize the technologies that are most likely to yield significant emissions reductions when they achieve breakthroughs across both modest and net-zero climate policy contexts. For climate change, warming is driven by the accumulation of greenhouse gas emissions in the atmosphere; thus, the benefits of technology breakthroughs should be judged by their *cumulative* emissions reductions over time (i.e., a technology that reduces emissions by half today has much greater climate benefit than a technology that reduces emissions by half in 2049, even if they both result in halved emissions before mid-century).

To determine technology prioritization, we use the EER analysis to compare technologies' emissions benefits, risk of failure, scale of deployment, and complementarity with other tools in a decarbonizing energy system. Figure ES-2 shows how we recommend RD&D spending in the applied energy programs increase by sector in order to rebalance the portfolio (left), and also translates the EER results into recommendations for each applied energy office in FY 2025 (right). However, this is just one snapshot in time and one set of technologies; as broader policy context changes, and as decision-makers gain a better understanding of the likelihood and cost of achieving technology breakthroughs, this analytical framework can be used to adjust RD&D funding to reflect those conditions.

Third, we recommend that DOE create cross-cutting programs that maximize complementary technological interactions in the energy system. The results of the EER analysis show complementarity between many low-carbon technologies in the energy system (e.g., a breakthrough in solar and wind accelerates lithium-ion deployment). DOE might consider establishing formal cross-cutting research and analysis topic areas, following the model of the existing Grid Modernization Initiative, to foster a systems thinking approach to complementary technologies. We propose four such programs: A formal Office of Carbon Management and cross-cutting initiatives on electrification, clean fuels, and industrial decarbonization. Policymakers may also wish to establish a formal cross-cutting initiative focused on a consideration beyond this particular analytical framework, such as one that codifies and incorporates consideration of equity, affordability, and environmental justice across DOE programs.

Finally, we recommend that Congress update the formal mission of the Department's energy and science offices to be focused first and foremost on reducing greenhouse gases and other harmful pollution, while also explicitly considering other key priorities. DOE needs an adjustment in mission and expansion in scope to ensure that program funding develops technologies that maximize climate benefits and improve public health. However, despite our enthusiasm for the approach outlined in this brief, we strongly caution against using metrics such as cumulative emissions reductions as the *sole factor* in setting DOE priorities and funding. We note a number of other considerations, including issues of environmental and energy justice; fairness for workers dependent on the energy systems of the past; and resilient, reliable, secure, and affordable energy systems, all of which are vital components of DOE's mission. These issues may justify larger increases in some sectors than we recommend. For example, innovations in the building sector may be particularly important to reduce energy burden and address energy injustice, and Congress should provide funding to specifically address these challenges.

ES-2. Recommended DOE RD&D budgets across the applied energy programs (billions), FY15-FY30



BTO = Building Technologies Office, AMO = Advanced Manufacturing Office, VTO = Vehicle Technologies Office, BETO = Bioenergy Technologies Office, HFTO = Hydrogen and Fuel Cell Technologies Office, NE = Office of Nuclear Energy, FE = Office of Fossil Energy, OE = Office of Electricity

SECTION 1

Background

In 2020, Environmental Defense Fund (EDF) commissioned Evolved Energy Research (EER) to develop an analytical framework for assessing the emissions and deployment impact of achieving technological breakthroughs in key clean energy technologies under different climate policy contexts. We wanted to use this framework to help identify the highest climate value investment opportunities available to the federal government and address key questions:

- How much do cost and performance breakthroughs in key climate technologies drive additional emissions reductions under various climate policy contexts?
- Are there technologies that play a big role in decarbonization regardless of further performance improvements?
- Do some prospective clean energy resources only matter if others fall short of expectations? Do some technologies have a greater impact if other technologies achieve innovation breakthroughs?
- To what extent can innovation breakthroughs unlock additional emissions reductions even in technologies that are cost-competitive in certain sectors and areas of the country today?

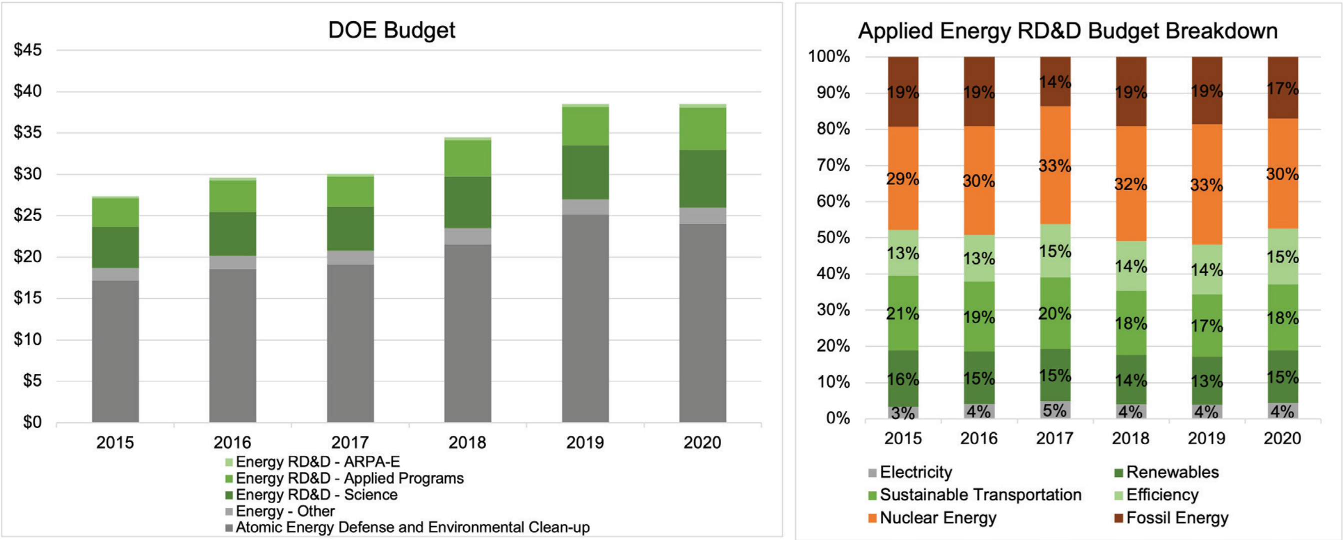
To answer these questions, we needed an energy system model that analyzed how technologies interact across the entire energy system under different policy scenarios, including by considering technology complementarity, technology substitution, and interactions across sectors. EER recently published a technical report explaining the analytical framework and the results of that analysis. This paper is the second phase of the effort, designed to explore the ways in which the analytical framework that we developed in partnership with EER can be leveraged to make recommendations on how DOE could better align its innovation funding and program structure with the goal of achieving a 100% clean economy in the United States no later than 2050. As we discuss throughout this paper, there are many other factors that policymakers should consider when setting DOE priorities, including the likelihood of achieving any given technological breakthrough, non-cost barriers to clean energy adoption such as social acceptance, and issues of equity. These considerations were outside of the scope of our analytical framework, so the recommendations we present here are limited to the conclusions we drew from our emissions- and deployment-focused analysis.

The remainder of this paper is organized as follows. First, in this **Background** section, we provide context for the current makeup of the federal energy innovation portfolio and explain the analytical framework, assumptions, and key insights from the EER analysis. In **Section 2**, we discuss five ways to leverage this analysis to understand which technology breakthroughs are likely to be most important in a federal innovation portfolio that is aligned with climate goals. In **Section 3**, we present a set of recommendations for policymakers setting innovation priorities and budgets at DOE, and acknowledge other important considerations that the analysis does not capture.

The Federal Energy Innovation Portfolio Today

The Department of Energy has long funded fossil and clean energy research, development, and demonstration (RD&D) programs, targeted at improving national security, fostering domestic energy production, and, more recently, addressing climate pollution. It also runs commercialization and deployment programs, such as the Weatherization Assistance Program and low-cost loans through the Loan Program Office, which are important parts of the innovation cycle – however, for the purposes of this particular analysis, we focus on RD&D. Today, funding for energy RD&D largely goes to DOE's Office of Science, Advanced Research Projects Agency-Energy (ARPA-E), and applied energy programs (the Offices of Energy Efficiency and Renewable Energy (EERE), which includes programs focused on energy efficiency, sustainable transportation, and renewable energy; Nuclear Energy (NE); Fossil Energy (FE); and Electricity (OE)). Figure 1 shows the top-line funding for these programs from FY2015 to FY2020, the five-year time period for which the U.S. committed to an international pledge to double clean energy R&D – a target we have failed to hit.[7]

Fig 1. **Historical DOE program budgets (billions), FY15-FY20**



Source: Department of Energy (2021)

Within the $7 billion appropriated to the Office of Science (SC), roughly $2 billion goes to programs that are dedicated or largely focused on clean energy, including Basic Energy Sciences (BES) and Fusion Energy Sciences (FES). The "Other" energy programs are not RD&D-focused; they include Indian Energy Policy and Programs, the Energy Information Administration, the Uranium Enrichment Decontamination and Decommissioning (D&D) Fund, and Non-Defense Environmental Clean-up. The main exception is the Loan Programs Office, which receives de minimus annual funding today, but has billions in existing loan authority to support clean energy commercialization.

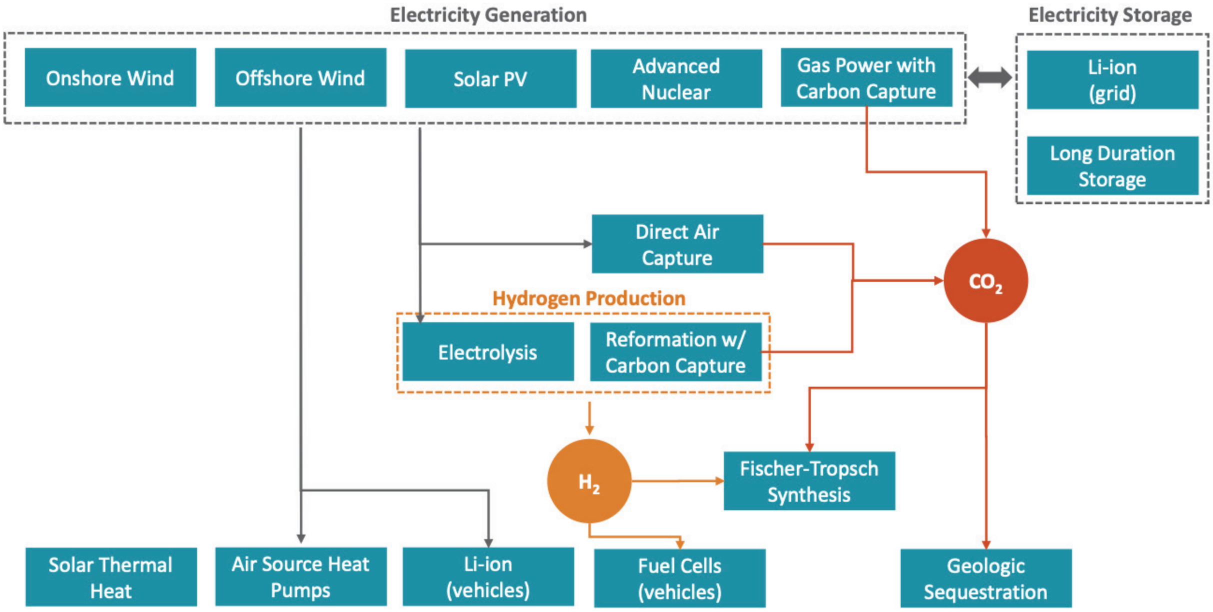
The "Atomic Energy Defense and Environmental Clean-up" category is mostly made up of the National Nuclear Security Administration (NNSA), which manages the U.S. nuclear stockpile, naval reactors, and other defense-based nuclear efforts. It also includes roughly $5 billion in defense-related environmental management focused on addressing the legacy of U.S. nuclear weapons development and testing. In contrast with the Energy portfolio, these activities are less focused on innovation.

Analytical Framework

The primary objective of the EER analysis is to quantify how individual clean energy technologies affect system-wide CO_2 emissions under various scenarios of technological progress and policy stringency. To do so, EER evaluated the impact of innovation on the uptake of 15 promising technologies (see Figure 2). The list was not comprehensive of all the technologies that can or will play a role in deep decarbonization; notably, we did not include breakthrough cases for a number of technologies that exist in DOE's innovation portfolio today, including various bioenergy applications, geothermal and hydropower electricity generation, and energy efficiency and demand-response technologies. This was a function of both (a) the need to prioritize a limited set of technologies for modeling purposes and (b) modeling and data limitations that constrained our ability to model technologies in certain sectors (industrial, buildings) with sufficient granularity. The results of the analysis should be viewed through that lens, and not as an indictment of technologies for which we did not model breakthroughs.

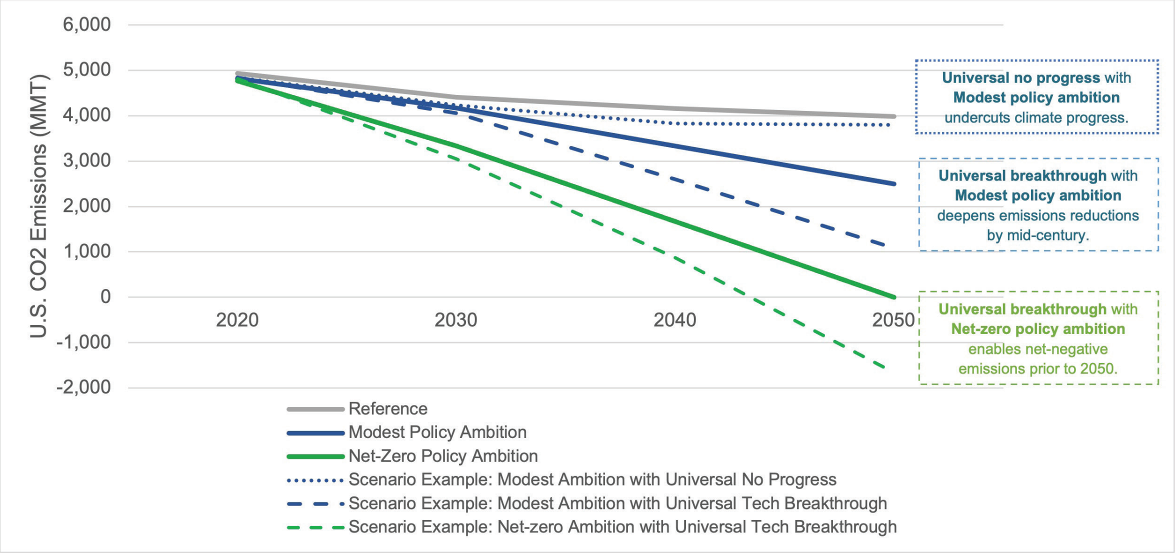
For each technology, EER considered three cost and performance trajectories reflecting alternative levels of innovation and two levels of climate policy ambition in the United States. Outputs from each simulation include technology deployment over time and, in turn, economy-wide emissions trajectories. These results allow us to compare the competitiveness and complementarity of individual technologies and sectors of the economy. For example, electrolysis uses electricity generated by wind and solar technologies to produce hydrogen that can be used as an input into Fischer-Tropsch synthesis (e.g., power-to-liquids), so a breakthrough in one of those technologies affects the deployment of the others. This dynamic is important when considering one or multiple breakthroughs across the considered technologies.

Fig 2. Technology breakthroughs modeled in EER analysis



For all 15 technologies, EER modeled **baseline** progress, reflecting likely progress under business-as-usual conditions; **no progress**, a failure case where technology cost and performance remains the same as today; and **breakthrough** progress, a future where technology progress accelerates towards optimistic cost and performance estimates. EER also placed these technology improvements within the context of three climate policy environments: (a) **Reference**, or no climate policy; (b) **Modest** policy ambition wherein net CO_2 emissions reach one-half of today's levels by 2050; and (c) **Net-zero** policy ambition wherein CO_2 emissions reach net-zero by 2050. For Modest and Net-zero policy ambition, we simulate the necessary abatement cost to reach these emissions targets under technology baseline assumptions, then reimpose that as a shadow carbon price in no progress and breakthrough technology cases. By using this artificial input, we are able to see how technology progress causes emissions to diverge from these paths (i.e., No progress in a key technology under Net-zero policy could mean we fall short of reaching net-zero in 2050, while a breakthrough could mean we achieve net-zero before 2050). These levels of policy ambition, as well as how technology progress scenarios change emissions outcomes, are illustrated in Figure 3.

Fig 3. U.S. CO_2 emissions trajectories combined with illustrative technology progress scenarios



Universal no progress with **Modest policy ambition** undercuts climate progress.

Universal breakthrough with **Modest policy ambition** deepens emissions reductions by mid-century.

Universal breakthrough with **Net-zero policy ambition** enables net-negative emissions prior to 2050.

High-level Analytical Results

Detailed methodology and results for each technology and policy scenario are distilled in EER's technical report, but we highlight a few high-level takeaways here.

First, it is important to note that even with no additional climate policy (our Reference policy environment) and baseline technology progress, emissions decline by roughly 20% from current levels by 2050. In contrast, emissions remain roughly at current levels with No progress across all technologies. These emissions reductions without stringent climate policy – which are largely attributable to increased deployment of renewables, lithium-ion batteries, and heat pumps in buildings – cannot be taken for granted by innovation decision-makers, even as our focus is on Modest and Net-zero policy ambition. RD&D progress is expected to deliver benefits even in the absence of significant policy support, and the technologies that show up heavily under the reference case could be considered no-regrets options for public deployment efforts.

Second, EER found that, across all levels of policy ambition, "continued progress on renewable electricity generation [solar, onshore wind, offshore wind] technologies is of foremost importance, given the dual role as a power sector decarbonizer and an enabler of zero-emissions technologies in other sectors." Their analysis finds that breakthrough progress in renewable technologies unlock immense emissions reductions, even in comparison to a baseline trajectory that already assumes continued cost declines and drives significant deployment in the Reference policy environment. The second cluster of technology breakthroughs that drive significant emissions reductions across all levels of policy ambition are those that "use clean electricity at scale" in hard to decarbonize sectors, whether at the household level (e.g., lithium-ion batteries in electric vehicles) or commercial level (e.g., hydrogen electrolysis).

For most of the remaining technologies EER analyzed, "breakthroughs can accelerate decarbonization, but only under certain circumstances." Identifying these particular circumstances can help decision-makers prioritize investments. For instance, a breakthrough in geologic sequestration is insufficient to drive additional emissions reductions under a Modest policy ambition, but significantly accelerates emissions reductions under Net-zero policy ambition that drives higher-cost abatement. Other technologies often serve as a "backup" technology when others fail (e.g., advanced nuclear deployment increases dramatically when renewables do not achieve expected cost declines) or are not complementary to many other innovation priorities (e.g., solar thermal used for industrial heat).

In addition to the emissions benefits of RD&D across various technologies, the analysis revealed several important design considerations for innovation policy, including the significance of broader climate policy context in influencing how technology breakthroughs propagate, the importance of a systems approach, and the value of considering non-economic factors in technology adoption.

The Climate Impact of Clean Energy Innovation

Public spending on innovation is widely recognized as an important driver of technological progress, with several recent notable successes in the energy sector.[8] Several recent analyses have noted that the past few decades of clean energy innovation have armed us with many of the tools that we need to decarbonize our power sector and get on track to net-zero emissions by mid-century, including cheap renewable power and lithium-ion batteries. Yet, the International Energy Agency (IEA) suggests that 40 out of 46 important technologies for deep decarbonization are behind schedule for its Sustainable Development Scenario, which matches the global temperature targets of the Paris Agreement.[9] And those clean energy resources that are already proven will deploy more rapidly, and achieve deeper and more widespread emissions reductions, if they become cheaper, more efficient, and higher performing.

The EER analysis provides a framework through which to understand the climate impact of clean energy innovation at the U.S. Department of Energy. Each of the 15 technologies examined in the EER analysis is relevant to at least one applied innovation program at DOE (Figure 4). In this section, we discuss five dimensions through which policymakers can leverage the EER framework to understand the climate benefits of RD&D: (1) Historical decarbonization progress, (2) potential cumulative emissions reductions, (3) substitution and the cost of failure, (4) scale of deployment, and (5) complementarity.

Fig 4. Clean energy technologies in the EER analysis, allocated by DOE applied energy office

Office	FY21 Budget ($M)	%	Technologies Analyzed
Energy Efficiency & Renewable Energy (EERE)	**$2,137**	**48%**	
Renewable Power	$646	14%	
Solar Energy	$280	6%	Solar PV, Solar Thermal Heat
Wind Energy	$110	2%	Onshore Wind, Offshore Wind
Water Energy	$150	3%	
Geothermal Energy	$106	2%	
Sustainable Transportation	$805	18%	
Vehicle Technologies (VTO)	$400	9%	Li-ion Batteries
Bioenergy Technologies (BETO)	$255	6%	Fischer-Tropsch
Hydrogen & Fuel Cell Technologies (HFTO)	$150	3%	Mobile fuel cells, Hydrogen (H2) Electrolysis, H2 Reformation with CCS
Efficiency*	$686	15%	
Advanced Manufacturing (AMO)	$396	9%	Sequestration, Solar Thermal Heat, Direct Air Capture (DAC)
Building Technologies (BTO)	$290	7%	Heat Pumps
Fossil Energy (FE)	**$750**	**17%**	
CCUS Sub-programs†	$228	5%	Sequestration, DAC, Gas Power with Carbon Capture and Utilization, Fischer-Tropsch
Nuclear Energy (NE)‡	$1,360	30%	Advanced Nuclear
Electricity (OE)	$212	5%	Li-ion Batteries, Long-Duration Storage
Total	**$4,247**	**100%**	

* We exclude the Weatherization and Intergovernmental Programs office and other explicitly deployment-focused Efficiency programs, but include full funding for AMO and BTO.

† We call out the CCUS sub-programs, since they cover technologies assessed in the EER analysis. The remaining FE RD&D funding primarily goes to efforts to increase efficiency, reliability, and availability of coal, gas, and petroleum technologies.

‡ We exclude the roughly $150 million in Environmental and Other Defense Activities funding that goes to the NE office.

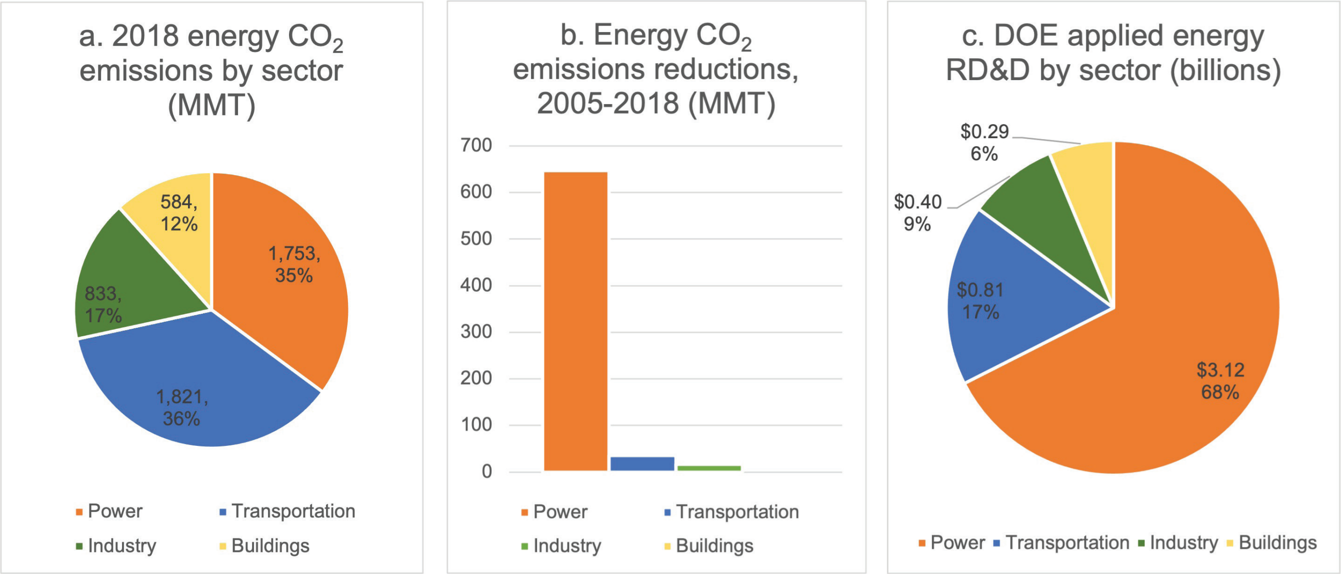
Historical Decarbonization Progress

An important factor in assessing the climate mitigation benefit of innovation in any given technology area is the scale of the emissions challenge in the sector or industry that technology serves. The slower the progress made to date, the greater the need for additional innovation. To take an extreme example, once LEDs are ubiquitous and affordable, there is little reason to invest in compact fluorescent lightbulbs. Inversely, if a certain unabated industry – say, petrochemicals – represented a growing portion of annual emissions, it may be worth prioritizing RD&D for alternatives. These considerations are doubly important for federal innovation spending, since DOE often takes on early-stage risk in areas where there has been limited private sector appetite for RD&D.

The EER framework provides a useful tool for understanding which functions and sectors have a shortage of clean energy solutions. Figure 2 showcased the 15 technologies examined in the EER analysis. Some major sources of emissions, such as industrial heating or heavy-duty freight, have minimal representation in the analysis. Others, such as clean power generation, have a range of viable options. When making funding recommendations, we should avoid penalizing sectors that are underrepresented in the analysis, whether due to selection bias or a lack of easily-modeled options.

Policymakers should consider whether Department of Energy innovation efforts, both in funding levels and administrative structure, match the largest sources of emissions of across the energy system. In Figure 5, we see that DOE's innovation budgets are overbalanced toward power generation technologies, despite 70 percent of emissions coming from fossil fuel combustion or process emissions in industry, transportation, and buildings (Figure 5a), and the fact that these sectors have made little progress on emissions reduction (Figure 5b). Furthermore, the structure of the agency is such that most RD&D in non-power sector technologies is housed under the Assistant Secretary for the Office of Energy Efficiency and Renewable Energy (EERE). Put another way, there are four Senate-confirmed Assistant Secretaries for the applied energy programs (one each for NE, FE, OE and EERE). Of these, two are completely or virtually completely devoted to the power sector (OE and NE), one is predominantly focused on the power sector (FE), and the remaining one is split between the power, transportation, industrial, and buildings sectors (EERE).

Fig 5. Current innovation priorities remain overwhelmingly focused on the power sector

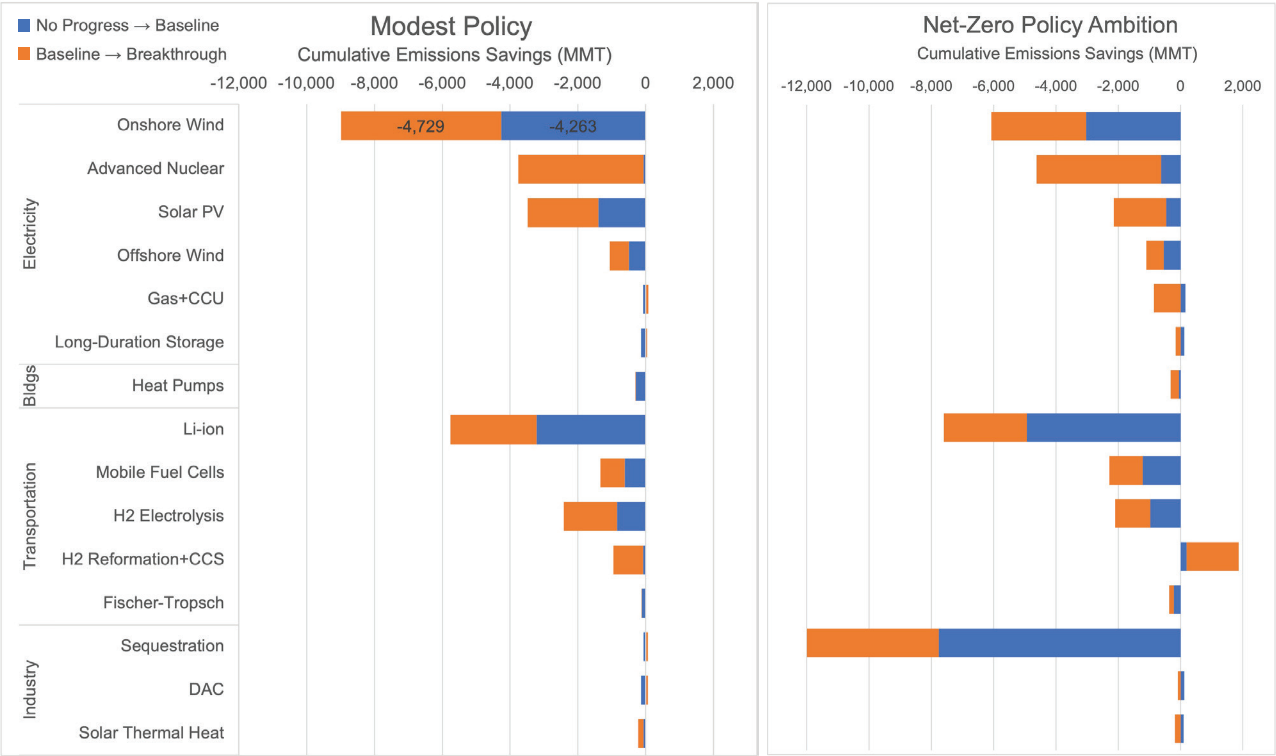


Our takeaway: Applying a sectoral lens to innovation priorities can ensure that DOE efforts are aligned with the scale of the climate challenge. In a 2019 report, the Natural Resources Defense Council suggested "tripl[ing] funding for DOE's Sustainable Transportation and Energy Efficiency portfolios over the next 5 years… and elevat[ing] the offices of deputy assistant secretaries for Sustainable Transportation and for Buildings and Manufacturing."[10] The EER framework and historical emissions trends can calibrate our understanding of which sectors are underrepresented in clean energy RD&D funding today, so that the DOE portfolio can be rebalanced to be more reflective of where the need for innovation is greatest.

Potential Cumulative Emissions Reductions

The systems approach used by this analytical framework allows us to see emissions reductions generated not only by the cost and performance trajectory of an individual technology, but also by the knock-on effects that technological progress generates throughout the energy system. In Figure 6, we show system-wide climate benefits generated by a lone technological breakthrough, compared to the baseline and no progress scenarios under representations of both Modest policy ambition and Net-zero policy ambition.

Fig 6. Cumulative emissions reductions (MMT CO_2) from no progress to breakthrough, 2020-2050



The stacked bars show cumulative emissions reductions – the metric that matters for climate change mitigation – from 2020 to 2050. The blue portion represents the emissions impact from technologies achieving their baseline cost and performance trajectories, relative to holding flat at their current cost and performance. The orange portion represents the emissions impact from technologies exceeding baseline progress and achieving their breakthrough cost and performance trajectories. Orange bars to the left of the y-axis indicate that a technology breakthrough has enabled emissions across the energy system to decline more deeply and rapidly than the policy environment would require under baseline expectations. For example, as illustrated by the data callout in Figure 6, a breakthrough in onshore wind reduces emissions by 4.7 $GtCO_2$ beyond baseline expectations over the next three decades under Modest policy ambition, thereby deepening net CO_2 reductions by 2050 beyond the 50% anticipated in that policy environment. On the other hand, as indicated by the 4.2 $GtCO_2$ in the blue bar, achieving baseline progress in wind accounts for a significant portion of cumulative emissions benefits needed to achieve the 50% net CO_2 reduction by 2050 anticipated under Modest policy ambition. In the next section, on *Substitutability and the Cost of Failure*, we talk more about how the blue bars can be used to identify which technologies have viable substitutes.

In Figure 6, we see that some of the biggest emissions impacts are from technology breakthroughs in the electricity sector, where a cost breakthrough in low-carbon electricity generation, such as solar photovoltaics, can contribute to climate targets by both reducing CO_2 emissions in the power sector and increasing the emissions benefits and deployment levels of end-use technologies, such as battery electric vehicles. As discussed in the technical report and shown in the difference between the left and right panels above, we also notice that a breakthrough in certain technologies – most notably geologic sequestration – has a much bigger emissions impact in the context of Net-zero policy ambition than in Modest policy ambition.

Net-zero policy ambition also changes deployment and emissions outcomes in no progress cases. Even without further technological progress, the larger price signal in the Net-zero policy case increases deployment of several technologies like onshore wind and solar PV, which in turn can make the emissions benefits of progress under baseline or breakthrough cases seem smaller. For hydrogen reformation, breakthrough progress under the Net-zero policy case actually results in an *increase* in cumulative emissions by driving cost reductions that displace technologies with greater emissions benefits. Finally, since these bars are cumulative totals over thirty years, some technologies that appear to have a small effect on emissions could still play a big role in later decades, such as direct air capture.

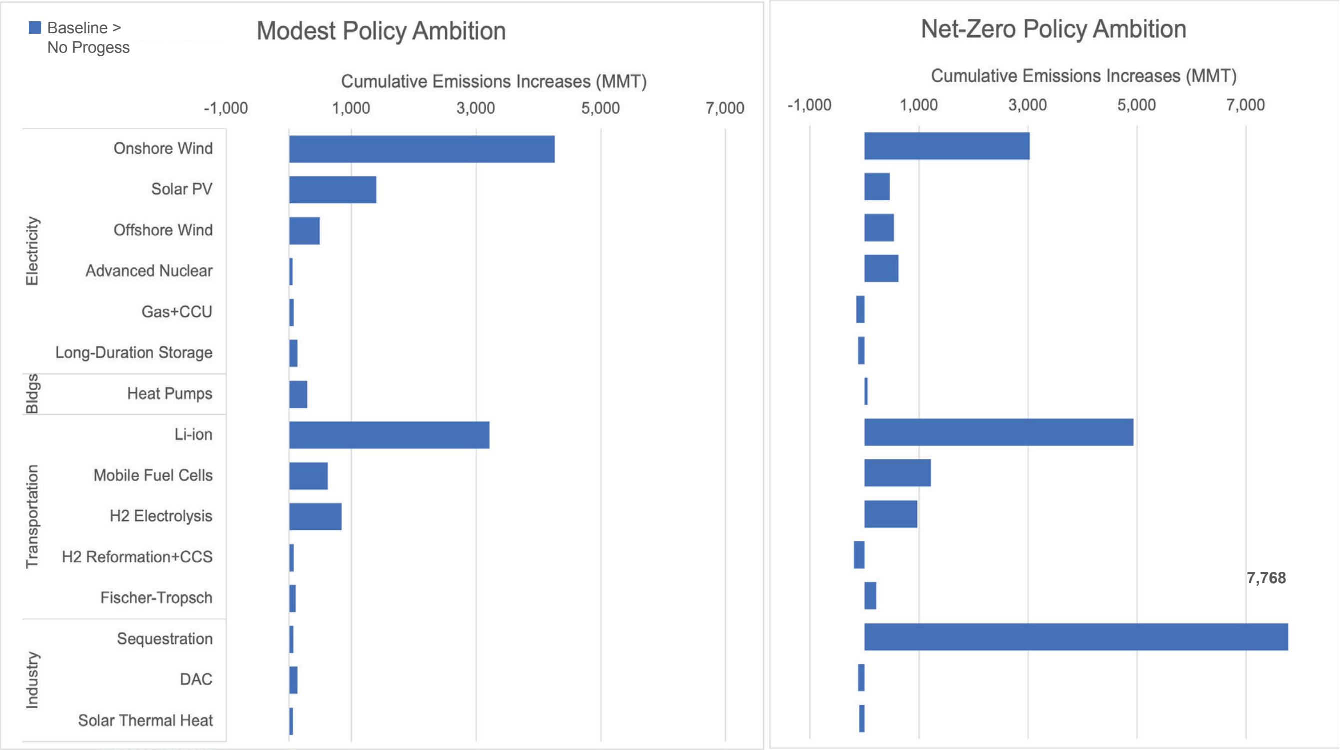
Our takeaway: For climate action, cumulative emissions reductions are the essential metric of success, so the potential of a technological breakthrough to reduce cumulative emissions is one of the most important considerations for policymakers. All else equal, we recommend that policymakers use the potential cumulative emissions reductions impacts of technology progress to set innovation priorities. The data in Figure 6 does not tell the whole story, however, as it shows the benefits of technologies experiencing individual breakthroughs. In reality, some technologies are likely to compete with one another, while others could breakthrough in tandem. In subsequent pages, we discuss how policymakers can use our framework to explore issues of substitutability and complementarity.

Substitution and the Cost of Failure

When assessing the impact of breakthroughs in specific technologies, it is important to consider the technology's function within the energy system and whether other technologies could serve the same role, or if a technology plays a unique and essential role in decarbonization. This helps us avoid overestimating the impact of emissions benefits from breakthrough scenarios in technologies with several potential substitutes. For instance, in Figure 6, we showed how individual breakthroughs in wind energy, solar PV, and advanced nuclear can all generate several gigatons of cumulative emissions savings over the course of the next three decades. But if all three of these technologies achieved simultaneous breakthroughs, these savings would not be additive, as many of the reductions achieved by one technology could be captured instead by one of the other competing clean electricity generation options. In other words, there may be viable substitute technology candidates that dampen the relative emissions benefit of a breakthrough in any single technology. Policymakers should consider substitution to avoid "double-counting" RD&D benefits, and to separate the truly essential technologies from those with multiple viable substitutes.

One way to use the EER analysis to understand whether a technology has viable substitutes is by looking at the consequences, in terms of emissions, of a technology failing to make progress. In Figure 7, we extract and invert the blue bars from Figure 6; rather than showing the emissions *reductions* of no progress to baseline progress, we present these as system-wide emissions *increases* when a technology fails to make progress. Technologies that generate significant emissions increases when they fail to achieve the baseline are likely to have fewer substitutes – and therefore may be deemed more essential – than some technologies with smaller emissions consequences.

Fig 7. Cumulative emissions increases (MMT CO_2) from baseline to no progress cases, 2020-2050



For the most part, failure to make technological progress has significant cumulative emissions impacts for the same set of policies under Modest and Net-zero policy scenarios, with a few exceptions, most notably geologic sequestration. Under Modest policy ambition, very little carbon capture, utilization, and storage is deployed even with baseline progress; therefore, the emissions cost of failing to achieve baseline progress in sequestration is minimal. In contrast, under Net-zero ambition, carbon storage is an essential tool with few substitutes, particularly in the industrial sector; thus, falling short of expected progress in the availability and cost of geologic sequestration in this policy case is very damaging, increasing cumulative CO_2 emissions by 7.8 Gt.

Some other results might seem counterintuitive, but reveal important insights. For instance, the emissions increase as a result of no progress for onshore wind and solar PV is actually lower under Net-zero policy ambition than Modest policy ambition. This does not mean solar and wind are not essential technologies for deep decarbonization, but rather reflects the fact that, even at today's costs and performance, these technologies are already sufficiently cost-competitive to see significant deployment with the price signal seen in the Net-zero policy scenario, so the emissions downside is less stark. Another counterintuitive finding is that some technologies with large emissions benefits from breakthrough progress have small emissions downside from no progress. For instance, Advanced Nuclear – which had the second-largest emissions benefits from baseline to breakthrough (the orange bar) in Figure 6 – has a relatively small emissions increase from the failure case in Figure 7. This suggests that Advanced Nuclear could become a major factor if it achieves a breakthrough, especially if competing technologies fail to achieve breakthroughs, but has limited deployment and climate benefit under baseline conditions. Inversely, Li-ion batteries have higher emissions costs from baseline to no progress (3-5 Gt) than benefits from baseline to breakthrough (~2.5 Gt). If batteries fail to hit innovation expectations, it could become significantly more challenging for us to achieve our climate targets.

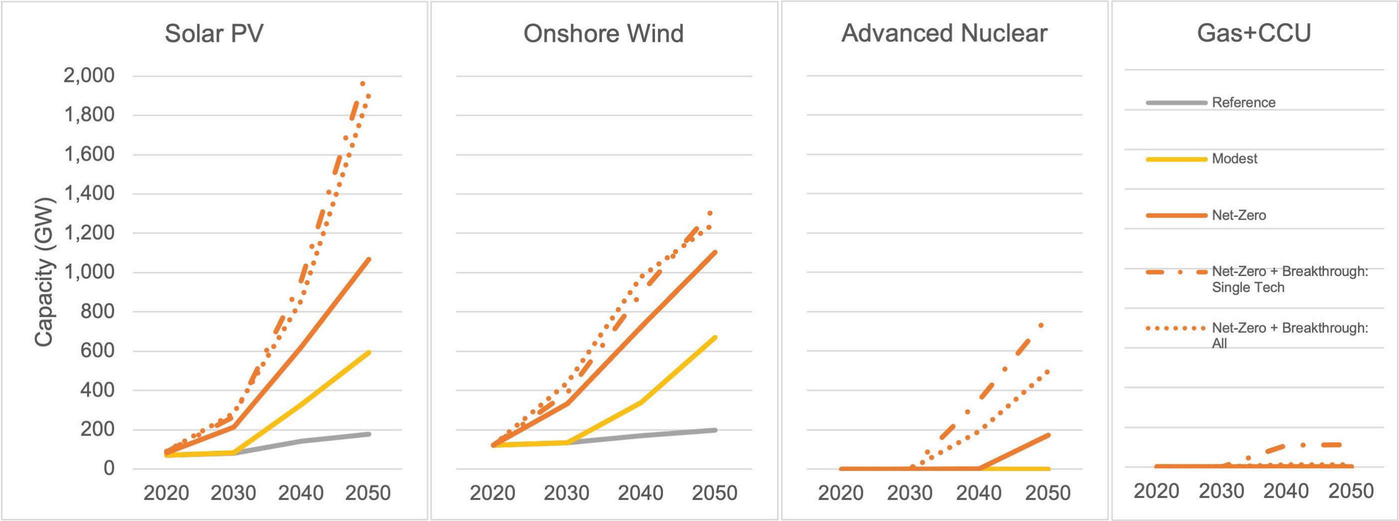
Our takeaway: RD&D may be more important for technologies that have higher emissions consequences if baseline technology progress is not achieved. When setting innovation priorities, policymakers should not focus solely on the emissions upside of a breakthrough, but should also consider the emissions downside of no progress. We cannot take baseline progress as a given.

Scale of Deployment

Certain technologies deploy heavily under many scenarios. For policymakers that wish to prioritize innovation to meet objectives in addition to emissions reductions, including increasing access and affordability, reducing co-pollutants, and overcoming non-cost factors in energy adoption, clean energy technologies that consistently deploy at scale can be thought of as "least regrets" areas for those RD&D objectives.

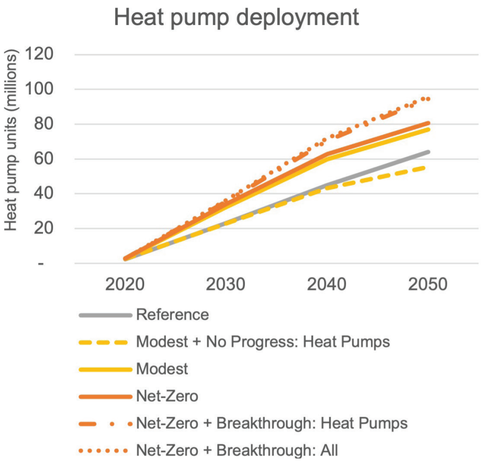
For instance, we saw in Figure 6 that the cumulative emissions benefits of a solo breakthrough in advanced nuclear and renewables are on roughly the same scale. Yet, as seen in Figure 8, renewables, advanced nuclear, and gas-fired power plants with carbon capture all have different scales and timelines of deployment. This may lead innovation decision-makers to prioritize differently than if one looks at cumulative emissions benefit alone. For instance, the fact that solar PV and onshore wind see considerable deployment under the reference case and other baseline cases, whereas advanced nuclear and gas with carbon capture require a breakthrough to deploy before the 2040s, emphasizes that RD&D in renewables is likely to yield substantial benefit regardless of which real-world policy and technology scenarios pan out. The near-term deployment of renewables also suggests they could help decarbonize end uses through electrification on a faster scale than advanced nuclear or gas with carbon capture.

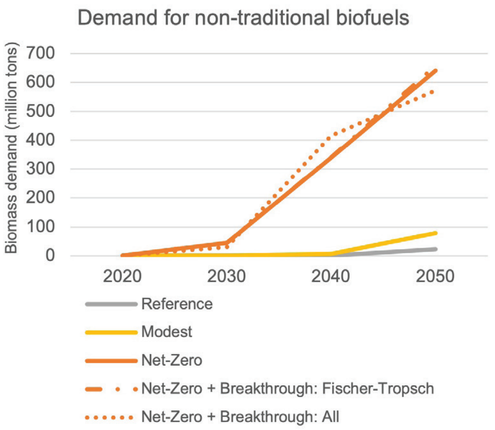
Fig 8. Deployment of power generation technologies under various policy and innovation scenarios



These graphs also highlight that tracking capacity deployment alone does not tell the whole story. It is notable that under the breakthrough cases, advanced nuclear achieves comparable emissions benefits at much lower capacity than wind or solar due to nuclear's ability to generate electricity 24 hours a day; policymakers may see this as an asset, showcasing the value of considering both deployment and emissions outcomes in tandem.

Considering deployment may also engender different policy decisions than only considering emissions impact, particularly in cases when technologies see large-scale deployment even if they do not necessarily drive system-wide emissions savings compared to the baseline. Heat pumps, for instance, are widely considered to be the most scalable solution for decarbonizing residential heating, and we see more than 50 million heat pump units deploy between 2020 and 2050 across all cases, even no progress. Regardless of how much incremental emissions benefit is driven by technology progress in our modeling, policymakers should recognize that there will be tens of millions of households adopting this technology, and they may want to invest in RD&D to drive down costs for consumers and businesses, improve equipment lifetime, eliminate non-CO_2 pollutants like refrigerants, improve performance in extreme weather to increase resilience, or generate other benefits.





Deployment trajectories can also help us identify technologies that could make unique contributions in a deeply decarbonized energy system under certain circumstances and timeframes. An example of this is Direct Air Capture (DAC), which the EER analysis sees deploy at substantial scale in the 2040s under Net-zero policy ambition– but only when there are breakthroughs in renewable power and CO2 sequestration alongside DAC improvements. DAC may also be deployed if progress in other technologies are less than anticipated. In our analysis, we kept costs constant and allowed emissions to change. If we instead had kept emissions constant, DAC could have played a larger role in some of the technology failure cases to ensure we achieve net zero emissions, even at high cost. Due to the important role carbon dioxide removal (CDR) might need to play in addition to emissions reductions, policymakers should be encouraged to fund early-stage R&D today to increase the likelihood we can achieve a gigatonne or more of annual net-negative emissions prior to 2050 if they are needed to achieve net-zero.

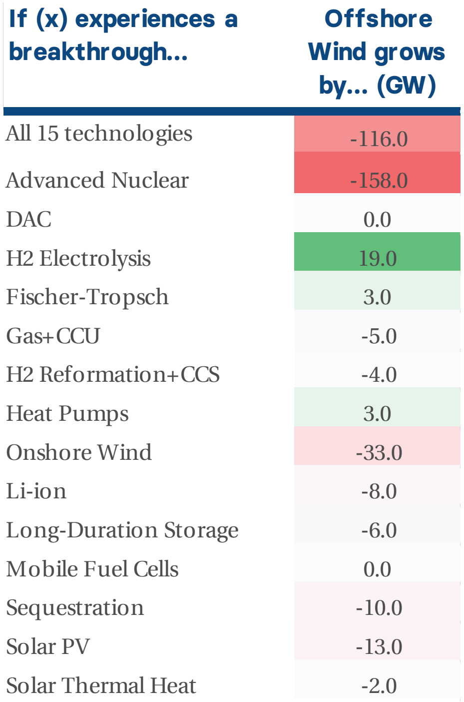
Finally, deployment projections can help us understand how to think about technologies that were not among the 15 selected to experience breakthroughs. For instance, we do not model breakthroughs in pyrolysis, synthetic natural gas, or other advanced bioenergy products and processes. However, we find that biomass demand for these applications consistently exceeds half a billion tons in 2050, so long as net-zero policy is in place. This reminds us not to underprioritize RD&D in bioenergy technologies, even if there is not a particular technology that we can point to with this analysis as game-changing from an emissions standpoint.

Our takeaway: Looking at projected deployment levels in the EER analysis can reveal areas of "least-regrets" RD&D, as technologies that consistently deploy at mass scale could benefit from RD&D to improve affordability, mitigate co-pollutants, or pursue other benefits. A focus solely on emissions improvements over the baseline is likely to understate the benefits of RD&D on technologies with robust deployment even under business-as-usual, like heat pumps.

Complementarity

Beyond the direct impact of cost and performance improvements on the adoption of any given clean energy technology, policymakers may wish to consider the spillover effects of RD&D on the uptake of other important technologies. We discuss the concept of technology interaction somewhat in the section on *Substitution and the Cost of Failure*; while that section is focused on system-wide emissions implications of technology interaction, this section considers the direct impacts of a breakthrough in specific technologies on the deployment of other technologies.

The systems approach leveraged in the EER analysis allows us to perceive how progress in individual technologies – and a universal breakthrough – can alter overall deployment within the energy system. In the table below, we show how breakthroughs in various technologies drive increased or decreased deployment in offshore wind by 2050 under Net-zero policy ambition. The colors give a sense for which technologies are the most complementary (green) or competitive (red) with offshore wind. For instance, a solo breakthrough in H2 electrolysis increases offshore wind deployment by 19 GW over baseline, as it provides an offtake pathway that enables higher penetration of renewables. In contrast, a breakthrough in advanced nuclear makes it more competitive with offshore wind and decreases wind deployment by 158 GW.



If (x) experiences a breakthrough...	Offshore Wind grows by... (GW)
All 15 technologies	-116.0
Advanced Nuclear	-158.0
DAC	0.0
H2 Electrolysis	19.0
Fischer-Tropsch	3.0
Gas+CCU	-5.0
H2 Reformation+CCS	-4.0
Heat Pumps	3.0
Onshore Wind	-33.0
Li-ion	-8.0
Long-Duration Storage	-6.0
Mobile Fuel Cells	0.0
Sequestration	-10.0
Solar PV	-13.0
Solar Thermal Heat	-2.0

> **"Innovation policy should take a systems approach. Our analysis reveals how changes in one R&D area influence another, suggesting that the best R&D efforts will coordinate clusters of technologies and consider interactions within the energy system."**
>
> Evolved Energy Research
> *Unlocking Deep Decarbonization: An Innovation Impact Assessment*

In the Appendix, we showcase these relationships across all technologies, illustrating whether a breakthrough in a certain technology (the independent variable) creates positive or negative effects on the deployment of other clean energy technologies (the dependent variable) compared to the baseline. The differences between units, capacity factors, and other characteristics make it difficult to compare across dependent variables, so we create heat maps that are self-contained to each technology. However, for technologies that have similar features, one can compare the magnitude of the complementarity. For instance, we find that a breakthrough in H2 electrolysis drives increases in multiple different technologies, but the scale of these increases varies greatly: as seen above, the related growth in Offshore Wind is 19 GW, whereas the increase in Solar PV deployment from an electrolysis breakthrough is 472 GW.

These observations on complementarity are not necessarily bidirectional. For instance, a breakthrough in Advanced Nuclear increases the deployment of several other technologies that benefit from high-capacity factor clean power, including heat pumps and fuel synthesis. However, no other technologies increase Advanced Nuclear deployment when they experience progress. This is largely because Advanced Nuclear relies heavily on improvements in its own economics relative to competitors, and has little to no deployment under baseline conditions, so breakthroughs in end-use technologies will benefit commercialized alternatives like solar and wind. Likewise, the only breakthrough that affects Solar Thermal Heat deployment is its own.

If (x) experiences a breakthrough...	Heat Pumps grow by... (units)
All 15 technologies	15,062,654
Advanced Nuclear	5,009,372

If (x) experiences a breakthrough...	Advanced Nuclear grows by...
All 15 technologies	242
Fischer-Tropsch	-2
Heat Pumps	0

We only explored the impacts of single technology breakthroughs and all technologies at once. Additional insights could potentially be revealed by exploring the impact of multiple complementary technological breakthroughs.

Our takeaway: RD&D in technologies with a significant number of complements in the energy system could result in positive spillover effects. The specific nature of the interactive effects between technologies can help innovation experts identify places for collaboration (such as cross-cutting programs at DOE, like the Grid Modernization Initiative). In Section 3, we recommend a handful of cross-programmatic RD&D priorities to harness the benefits of complementarity.

SECTION 3

Aligning DOE Priorities with Climate Goals

The U.S. Department of Energy was founded in 1977 in the shadow of the Cold War and 1970s oil crises. Its early activities were largely focused on atomic weapons and domestic energy security.[11] While DOE has evolved in many ways since its founding, including through an increased emphasis on clean energy, national security and domestic energy development continue to be among the most important priorities for the Department. In FY 2020, the agency devoted $24 billion to Defense Activities, compared to $14.5 billion for Energy Activities. In its final budget request, the Trump Administration's DOE requested an 8 percent increase in Defense Activities and a 52 percent cut in Energy Activities.[12] While Congress has consistently rebuffed suggestions to downsize energy programs, funding for these programs has been surprisingly stagnant since their origin in the 1970s; if U.S. energy innovation funding had kept pace with GDP growth since 1977, the DOE energy RD&D budget would be $32 billion today.[13]

Given the large portion of carbon dioxide emissions that come from energy production and use, climate and energy experts have called for the Department's mission and funding levels to be reoriented and scaled to the 21st century challenge of decarbonizing our energy system. In this section, we consider what a DOE portfolio would look like if budgets were better aligned with climate goals. We base our recommendations on a target of growing the total clean energy innovation budget from roughly $7 billion to $32 billion by FY 2025, including $17 billion for applied energy RD&D, in a manner consistent with the Biden campaign's clean energy spending target of $400 billion over ten years, historical DOE funding levels, and other expert literature. We consider the emissions impacts discussed in Section 2 – including a combination of historic decarbonization progress by sector, the emissions benefits of RD&D breakthroughs, the costs of failure, and scale of deployment – to propose adjustments in funding and program focus areas. Finally, we consider how DOE can use the analytical framework to shape "cross-cutting initiatives," which have historically leveraged money across different offices to address intersecting priorities.[14]

This is just one possible way to orient RD&D priorities. We recognize that there is no single, correct way to tackle climate innovation – and that Department of Energy RD&D programs have a public responsibility to do more than just reduce economy-wide emissions. Therefore, we conclude this section by raising other critical factors for policymakers to consider.

Setting the Ambition for DOE Clean Energy Innovation

When the United States committed to Mission Innovation, an international pact to double clean energy innovation funding within five years, the goal was to grow clean energy R&D from $6.4 billion in FY2016 to $12.8 billion in FY2021. Of that $6.4 billion baseline, $4.8 billion (75%) was housed at the Department of Energy, with the remainder distributed across other agencies, such as NASA, the Department of Defense, and USDA. At the time, the White House's estimate for DOE funding included applied energy programs – EERE, OE, FE, and NE – as well as ARPA-E and approximately $1.5 billion in clean energy R&D in the Office of Science (SC).[15] A recent estimate from the Columbia University Center on Global Energy Policy and the Information and Technology & Innovation Foundation (ITIF) finds that these DOE programs have grown to about $7 billion and that total government clean energy R&D has grown to $9 billion, well shy of the $12.8 billion target cited in the Mission Innovation pledge.[16]

In setting our level of ambition, we consider the historical Mission Innovation pledge and recommendations from leading scholarship, while ensuring that our aggregate funding aligns with the Biden campaign's commitment to spend $400 billion on clean energy innovation across the government over 10 years, which we take to mean FY21-FY30. We assume the split in innovation funding between DOE and other agencies stays the same as during the Mission Innovation pledge, so that 75%, or $300 billion, goes to DOE. Our baseline clean energy RD&D funding levels include FY 2021 appropriations for the applied energy programs, ARPA-E, and the clean energy research programs at the Office of Science (SC) that were identified by the recent *Energizing America* report.[18] While we consider pre-commercial demonstrations part of the applied energy budget, we also create a dedicated budget for commercial-scale demonstrations. Sustained funding for commercial-scale demonstration projects is critical for improving costs and de-risking of emerging technologies – particularly those with high upfront costs, like nuclear or direct air capture – in a real-world environment. Such programs were featured in the American Jobs Plan, which includes funding for 15 commercial-scale hydrogen demonstration projects and 10 low-carbon steel and cement plants.

Fig 9. **DOE clean energy RD&D funding (billions) in line with Biden commitments, FY15-FY30**

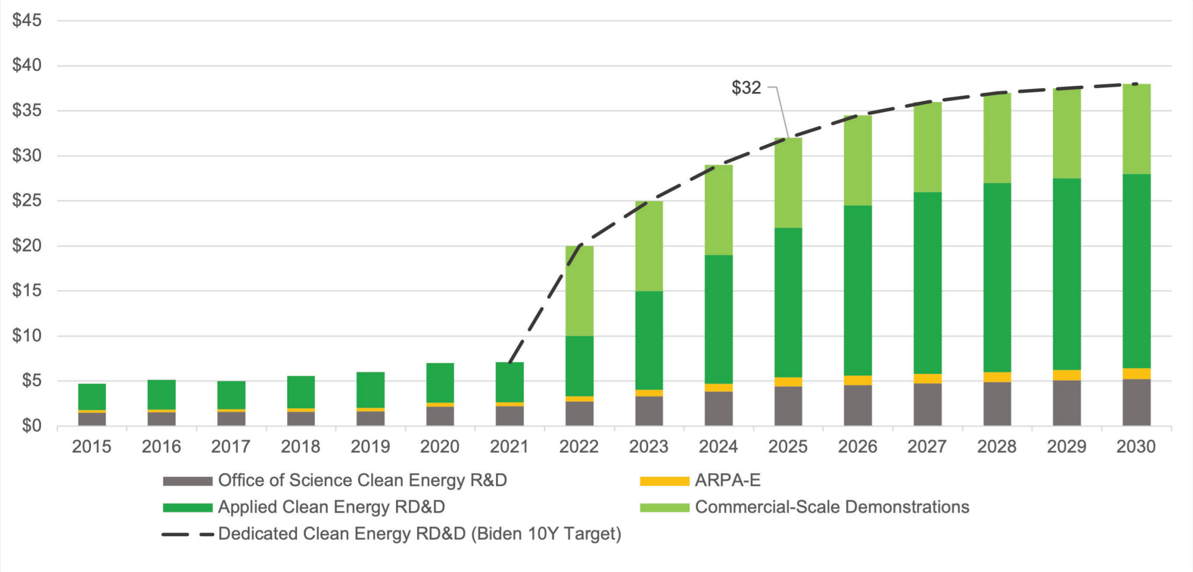


Figure 9 illustrates one possible version of meeting this decade-long commitment that seeks to make up for lost time on Mission Innovation by frontloading funding rather than following a linear growth path. Leveraging this approach, DOE reaches roughly $32 billion in annual clean energy RD&D funding by the end of the first Biden term and roughly $38 billion by FY 2030, totaling $300 billion over the decade. This funding trajectory aligns not only with the Biden commitment but with other literature:

- Our proposal to grow existing clean energy RD&D programs well beyond $20 billion by FY 2025 mirrors numerous reports that recommend annual funding at or exceeding those levels.[19,20,21] Bill Gates has called for a five-fold increase in U.S. clean energy innovation funding,[22] and a 2021 interdisciplinary study on deep decarbonization from the National Academies of Sciences, Engineering, and Medicine recommended tripling investment in clean energy RD&D to $20 billion, then sustaining those levels for 10 years.[23] A proposal from the American Energy Innovation Council, a collaboration of American CEOs, calls for $16 billion for advanced energy innovation – less than the Academies or Gates, but more than double current levels.[24]

- Our recommendation that ARPA-E grow to $1 billion by FY 2025 matches the recommendations of ARPA-E founding director Arun Majumdar,[25] Columbia University and the Information Technology and Innovation Foundation,[26] and the American Energy Innovation Council.[27]
- Our recommendation for an additional $10 billion per year in commercial-scale demonstrations echoes recent reports from Third Way, which has called on Congress to authorize $8 billion in demonstrations for storage, clean hydrogen, and carbon management;[28] the Center for Climate and Energy Solutions, which recommended $50-100 billion over 10 years;[29] and Data for Progress, which recommended $50 billion over the next 5 years.[30]

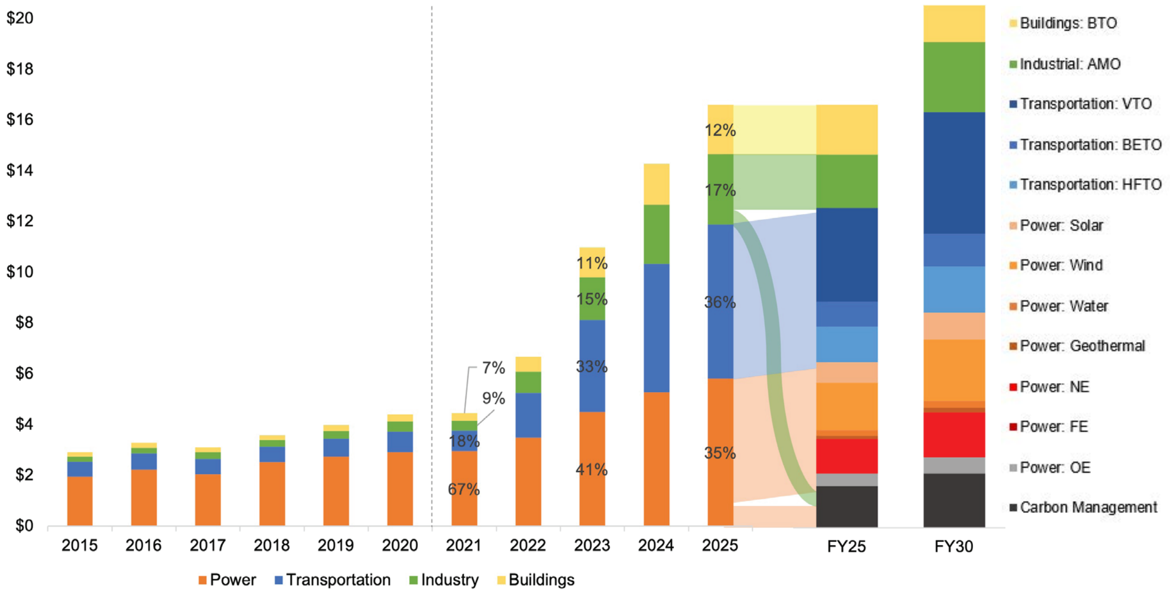
While reaching $32 billion in clean energy RD&D by FY 2025 is no small task, it would be – as we discuss above – roughly equivalent to historical levels if DOE RD&D budgets had kept pace with GDP. Growth of this magnitude is also not unprecedented for federal innovation programs; for instance, the budget for medical research at the National Institutes of Health (NIH) grew by a similar magnitude over five years, from $13.7 billion in FY 1999 to $27.2 billion in FY 2003.[31] Still, it is important to note that we show a relatively smooth trajectory, but there are many other pathways to the $400 billion target; for instance, this analysis does not consider the impact of a potential large influx of near-term funding, as might occur under the Biden Administration's American Jobs Plan.

Balancing the Agency's Applied Energy Portfolio

After setting the overall funding levels for early-stage innovation activities at DOE, we want to leverage insights from the EER analysis to ensure the DOE portfolio is focused on the technologies that are likely to play the biggest roles in tackling the climate crisis. The analysis is most easily applicable to the applied energy programs, which have dedicated technology offices, allowing us to quickly apply technology- and sector-specific insights. For the Office of Science and ARPA-E, we simply grow the overall budget, and do not conduct a rebalancing exercise, though we encourage policymakers to use this analysis to set priorities there as well. In keeping with the overall level of ambition, we anticipate that the applied energy programs could grow to nearly $17 billion by FY2025 – roughly four times current levels.

The first step in balancing DOE's applied energy portfolio is to use the increase in funding levels to size the programs in approximate proportion to their emissions by sector using the most recent EPA emissions data, from 2018. We illustrate this allocation of increased funding on the left-hand side of Figure 10. If DOE were to adopt this recommendation, it should update its allocations as the relative emissions of different sectors evolves. As discussed in Section 2, DOE funding is disproportionately focused on the power sector, which generates only one-third of energy related greenhouse gas emissions and is also the area in which the United States has made the most historic progress on decarbonization. A significant portion of this power sector funding currently goes to fossil fuel applications, which are elevated to a higher position within the agency's structure (e.g., the Office of Fossil Energy) than entire sectors (e.g., the Buildings Technology Office, which is part of the Office of Energy Efficiency and Renewable Energy). Furthermore, because there is a shortage of commonly recognized and scalable solutions in certain sectors, like industry, technological pathways tend to be underrepresented in models like EER's; by pegging funding to the real-world challenge of emissions, we can mitigate the concern that lack of information and modeling capacity in hard-to-decarbonize sectors will lead to underrepresentation in innovation budgets.

Fig 10. **DOE applied energy RD&D funding (billions), pegged to sectoral emissions** (LEFT) **and setting office funding levels based on EER analysis** (RIGHT)



BTO = Building Technologies Office, AMO = Advanced Manufacturing Office, VTO = Vehicle Technologies Office, BETO = Bioenergy Technologies Office, HFTO = Hydrogen and Fuel Cell Technologies Office, NE = Office of Nuclear Energy, FE = Office of Fossil Energy, OE = Office of Electricity

The second step in balancing DOE's applied energy portfolio is allocating funding *within* each sector to ensure that the most important technologies for achieving a 100% clean economy are being prioritized. To do so, we leverage the EER analysis to set intra-sector funding levels for FY 2025 and beyond, as seen on the right panel of Figure 10. We scale the proportion of funding for each office by the relevant technologies' emissions benefits of breakthrough and costs of failure. We factor in the results under both Modest and Net-zero policy contexts; however, as the legislative context changes, policymakers may seek to use the findings under one scenario or the other.

We also tweak funding levels by layering on other dimensions, such as substitution, complementarity, and scale of deployment, to reflect a more nuanced interpretation of the EER analysis than purely the quantitative emissions impact. For instance, we know that batteries consistently outcompete mobile fuel cells in light-duty applications if both technologies experience breakthroughs, so we tilt the balance to VTO funding over HFTO funding. Likewise, while technology breakthroughs in wind have a bigger impact on emissions than in solar in our analysis, we dampen the discrepancy between the offices somewhat given that both solar and wind see significant deployment even in our reference policy case, and since the value of many programs that are unique to the Solar Energy office, such as efforts to increase access to solar power among low-income communities, are unlikely to be captured in the analysis.

We also take care not to penalize technologies that were not in our selection of technologies for breakthroughs, such as bioenergy and geothermal. Since we could not possibly capture the full range of technologies in each office, and since it is unlikely we will shrink program budgets in a policy context where most programs grow dramatically, we ensure that no program loses appropriations in absolute terms. However, we do absorb Fossil Energy funding and a subset of industrial sector appropriations into a new Office of Carbon Management – an example of where the complementarity dimension of the EER framework comes into play. On the right-hand side of Figure 10, above, all of these considerations are combined in our recommended funding levels for the individual applied energy offices in FY25. Figure 11 shows growth by office, illustrating how no office's funding decreases in absolute terms as the portfolio is rebalanced, and all offices experience some funding increases by FY30. Figure 12 color-codes these offices by sector to illustrate the shift from overweighting the power sector to a more balanced applied energy portfolio.

Fig 11. Funding growth by office (including new Office of Carbon Management), FY21, FY25, and FY30

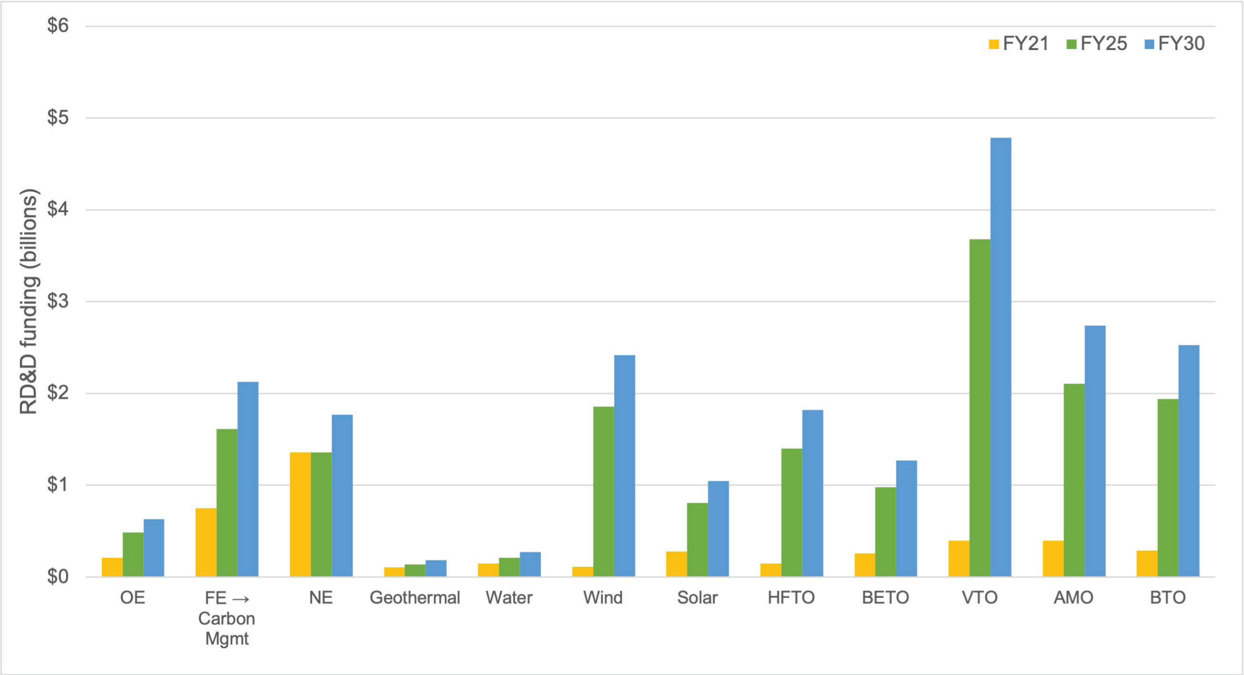
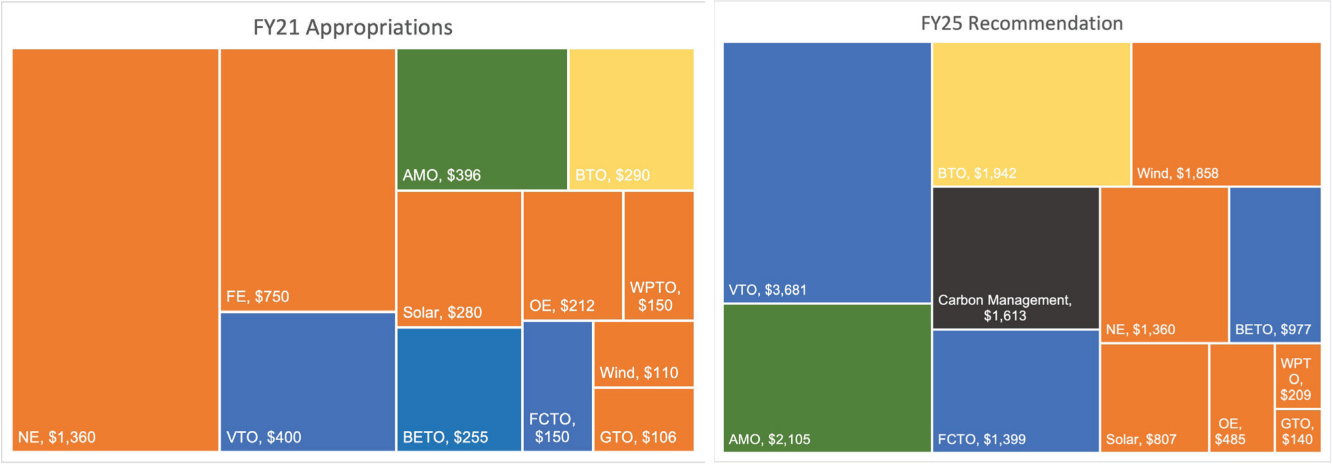


Fig 12. Comparing FY21 and recommended FY25 applied RD&D portfolios at DOE (millions)



Notes: The figures above show each applied energy office's grown in budget under the scenario illustrated in Figure 10. This is just one possible approach for increasing DOE funding based on the quantitative and qualitative outputs of a single analysis. For instance, the Geothermal and Water Power Technologies Office are shown here continuing a modest growth trajectory in line with the past five years; this is to account for the fact that we did not model these technologies specifically, but a future iteration of this exercise that includes enhanced geothermal, tidal power, or other relevant technologies could result in higher or lower funding for these offices. Additionally, many offices are likely to contribute a significant portion of their budgets to cross-cutting initiatives. No offices budget shrinks in absolute terms, even if they may on a percentage basis, though FE is absorbed into a new Office of Carbon Management.

Most of these recommendations are presented within the confines of the current DOE structure, but policymakers may be interested in insights from the analysis that suggest we deviate from that mold. The systems approach leveraged in the EER analysis does enable us to identify technological complements and areas for cross-office collaboration. We offer four recommendations for new or augmented cross-cutting RD&D programs, including the Office of Carbon Management shown in the figures above:

- **New Program: Office of Carbon Management (OCM).** OCM is designed to elevate and coordinate RD&D efforts on carbon capture, utilization, and sequestration, which have applications across all four major sectors. Initially, the office would absorb the current Office of Fossil Energy as well as some portion of recommended funding increases in the industrial sector. Given the robustness of sequestration in the EER analysis and its complementarity with technologies across sectors, the need for carbon removal for deep decarbonization, and the existing work on carbon utilization at DOE, carbon management efforts deserve to be made permanent and elevated to higher status than an FE subprogram. OCM would coordinate on efforts to decarbonize heat and process emissions at the Advanced Manufacturing Office (AMO), synthetic fuels and bioenergy with carbon capture and storage (BECCS) work at the Bioenergy Technologies Office (BETO), hydrogen production work in the Hydrogen and Fuel Cell Technologies Office (HFTO), and more.

- **Cross-cut: Electrification and Grid Modernization Initiative (EGMI).** EGMI would expand the existing Grid Modernization Initiative (GMI) cross-cut to capitalize on the complementarity we find between clean power generation and electrification of end-uses in other sectors in the EER analysis, such as renewables, Li-ion batteries, and heat pumps. The office would coordinate RD&D across the Renewable Power programs, Office of Electricity (OE), Building Technologies Office (BTO), Vehicle Technologies Office (VTO), and AMO to promote high renewable penetration alongside electrification of end-use appliances and electric vehicles.

- **Cross-cut: Clean Fuels Initiative (CFI).** This cross-cut would coordinate RD&D across HFTO, BETO, AMO and OCM to develop and demonstrate clean fuels and fuel production processes, such as hydrogen electrolysis or synthetic hydrocarbons. The EER analysis demonstrates complementarity between H2 electrolysis, mobile fuels cells, and Fischer-Tropsch fuel synthesis, all of which can play important roles in decarbonizing freight, industry, and other hard-to-electrify applications, but currently reside in different offices at DOE. This would build upon the agency's existing cross-programmatic H2@Scale program.

- **Cross-cut: Clean Industrial Technologies (CITA).** The industrial sector is a major source of U.S. emissions, but has limited commercially-available decarbonization options today. In its current form, AMO is primarily focused on energy management and efficiency, but we need to rapidly scale up RD&D into industrial emissions reduction approaches, many of which have synergies with the activities of non-AMO offices and other cross-cuts. Given how far behind we are in this sector, this initiative would dramatically amplify industrial decarbonization by actualizing the industrial emissions reduction RD&D program authorized in the Energy Act of 2020, and based on the Clean Industrial Technologies Act.

These recommendations reflect our interpretation of how EER's analytical framework and systems thinking approach can inform DOE priorities. However, they only reflect one set of technologies, policy contexts, and input assumptions. These will change as technological and political realities evolve. There may also be other important cross-programmatic initiatives that are not captured by the model; for instance, we would argue that incorporating consideration of equity, affordability, and environmental justice across DOE programs is of vital importance and should be codified in a departmental cross-cut. We discuss this, and other important factors that policymakers may wish to consider, below.

Additional Considerations

There are limitations on the insights we can glean from a cost-optimized model of the energy system, and therefore on our funding recommendations. There are a range of other qualitative issues for policymakers to consider when designing and resourcing DOE RD&D efforts. These include the following:

- **Equity and Distributional Effects.** As mentioned above in our discussion of cross-cutting programs, equity must be a central consideration in innovation policy. Who sets innovation priorities? Who is poised to benefit the most? How can innovation funding prioritize technologies, applications, and processes that bring the many benefits of clean energy – for the climate, health, energy costs, jobs, economy, and more – to the communities that bear the greatest burden of today's polluting energy system and for whom the cost of energy is the most significant? Some R&D investments may have relatively small cumulative emissions benefits but large equity and justice benefits. For example, investments in building energy efficiency technologies, distributed solar and storage for households who lack electricity access, or electrification of ports all could significantly improve energy services or health outcomes for disadvantaged communities but may not have a large emissions benefit. Similarly, applying equity and justice princples across the innovation portfolio will lead to different outcomes. For instance, Congress and DOE may wish to expand the agency's focus on low-income solar, expand the low-income weatherization program, ensure loans and grants are made available to minority-owned businesses, prioritize investments in environmental justice communities, and grow workforce development efforts to support workers affected by the energy transition.
- **Syncing RD&D and Deployment Programs at DOE.** The funding recommendations we include here focus on earlier stage innovation at DOE, including research, development, and demonstration programs. However, the Biden Administration has also committed to significant later-stage deployment and commercialization efforts, and it will be important to synchronize RD&D and deployment efforts – both in terms of high-level priorities and in practice to ensure DOE-researched technologies are being commercialized and deployed. Policymakers might also look to which clean energy technologies deploy the most under business-as-usual scenarios – such as solar PV and heat pumps, which show up heavily in the EER reference case – to identify "least regrets" deployment priorities.
- **Social License.** The EER analysis and other research show that meeting climate targets will require massive deployment of clean energy technology and infrastructure. Furthermore, innovation programs will undoubtedly include technologies that come with controversy and significant tradeoffs, whether it be nuclear waste management, moral hazard risks for carbon capture, or critical minerals needs for batteries. How should RD&D programs at DOE account for social acceptance of the technologies they pursue? Should funding be directed to innovation efforts that specifically seek to improve social license (e.g., solar applications that minimize biodiversity impacts or land use conflict)?

- **Global Implications.** Public innovation programs can create spillover effects that accelerate international decarbonization, as evidenced by Germany's early leadership on solar PV that bought down global costs. This can in turn generate domestic benefits, by growing domestic manufacturing of clean energy technologies and then unlocking international demand. Yet, most modeling, including the EER analysis, focuses on the U.S. energy system. How can innovation policymakers factor global demand for clean technologies into federal RD&D priorities?

- **Breakthrough Probability:** The EER analysis attempts to input technology breakthrough assumptions with relatively similar probabilities of success, but experts may disagree over reasonably ambitious trajectories for different technologies. These results are quite sensitive to these cost and performance trajectories. Certain technologies might have high upside but low likelihood of success based in part on their track records. It is also important to consider which technologies rely on other technologies' failures, and which have multiple pathways to success.

- **Legacy Programming.** With the exception of FE being absorbed into a new Office of Carbon Management, our analysis does not grapple with legacy priorities at DOE. Are there other areas where funding should be decreased in absolute terms, rather than staying fixed or rising at a slower rate? Do old programs favor fossil fuels? How should priorities within offices shift? For instance, the Office of Nuclear Energy currently receives nearly half of all funding in the power sector and more than double the funding across four renewable power offices, despite nuclear generation also receiving significant additional R&D funding from the Office of Science and the challenges in deploying nuclear generation over the last few decades. That could be cause for policymakers to revisit legacy programming at NE; alternatively, some may argue that nuclear simply has higher RD&D costs and it is worth staying the course.

One possible first step in addressing these concerns is to update the Department's mission – and the missions of individual offices – to explicitly target the largest sources of greenhouse gas emissions and harmful pollution in America's energy system. The authors and others [32,33,34] have called for DOE to modify its mission to address our 21st century climate challenge, and President Biden and Secretary Jennifer Granholm have positioned DOE at the center of the Administration's climate and equity strategies. Quite simply, DOE should ensure that all energy investments are helping to achieve net-zero GHG emissions by 2050. In updating its mission, DOE can ensure that it keeps greenhouse gas emissions reductions and other harmful pollution at the center of its technology and science priorities. It can also begin to institutionalize the considerations outlined above into its decision-making processes and analyses, such as the Quadrennial Technology Review – accounting for equity and climate justice, global emissions implications, legacy programming that favors fossil fuels, and more.

SECTION 4

Conclusion

To confront the climate crisis and demonstrate international leadership, the United States must aim to achieve net-zero greenhouse gas emissions across the economy by no later than 2050, a path consistent with meeting global temperature goals to avert the worst effects of climate change. Innovation plays a critical role in lowering the costs and improving the performance of the technologies we have today, and in developing and commercializing the nascent technologies needed to decarbonize fully. Amid calls for dramatic growth in federal clean energy innovation – including a pledge from the Biden campaign to deliver $400 billion in clean energy investments over the next decade – it is useful to evaluate where the federal government should put its innovation dollars to maximize climate benefits. In this paper, we discuss key factors policymakers should consider when aligning innovation to climate targets, and outline one scenario for structuring DOE funding and priorities to do so. These recommendations are supported by an Evolved Energy Research (EER) analysis, which EDF commissioned to assess the energy system-wide emissions impact of failures and breakthroughs in 15 clean energy technologies.

In our final recommendations, we suggest that Congress begin increasing appropriations to DOE energy innovation programs to get on track to reach at least $32 billion by 2025 in dedicated clean energy research, development, and demonstration (RD&D), including nearly $17 billion for applied energy programs, $1 billion for ARPA-E, $4 billion for the Office of Science's clean energy programs, and $10 billion for commercial-scale demonstration projects. Our funding trajectory only includes RD&D, but DOE-wide funding for clean energy deployment and commercialization efforts – which also count as innovation – should be much larger. We recommend Congress leverage this increased funding to first rebalance DOE's portfolio to address all of the sectors and functions in the U.S. energy system that contribute most to climate change, addressing the fact that industry, buildings, and transportation currently generate two-thirds of U.S. emissions but only receive one-third of DOE innovation funding.

Within any given sector, the applied energy offices should prioritize the technologies that are most likely to yield significant cumulative emissions reductions when they achieve breakthroughs. We provide one set of recommendations for distributing the increased applied energy RD&D funding in FY25, based in large part on the EER analysis. Among the 15 technologies we analyze, solar PV, onshore wind, geologic sequestration, H2 electrolysis, lithium-ion batteries, and heat pumps play significant roles in the decarbonizing energy system across a range of scenarios, and are prominent in our recommended office funding levels. We also utilize the systems thinking approach embodied in the analysis to identify areas of cross-functional synergy. This leads us to recommend a formal Office of Carbon Management and cross-cutting initiatives for electrification, clean fuels, and industrial decarbonization.

Our set of recommendations is merely illustrative of one avenue to scaling and targeting DOE innovation activities to the climate challenge. We recognize the limitations of our approach (and any single model), and thus emphasize a number of other considerations for policymakers setting DOE RD&D priorities, including the global benefits of innovation, equity and affordability, the likelihood of breakthroughs, and more. As a small step towards codifying this framework, we also recommend that Congress update the Department of Energy's mission, and the mission of individual offices, to prioritize emissions reductions.

Appendix: Complementarity

The tables below indicate how a breakthrough in the technologies in the first column increase or decrease deployment of each of the technologies listed across the first row. The numbers in the cells show the magnitude of the difference in deployment by 2050. Several examples of how to read this data are shown on this page and the next.

The heat map coloring is unique to each column, with greens representing the most positive complementary effects *within that column* and reds representing the most negative complementary effects *within that column*. As denoted by the thick borders, number and colors should not be compared across columns. Since different technologies have different units, characteristics, and capacity factors, this allows us to see which breakthroughs matter most for each technology.

If (x) technology experiences a breakthrough...	**Advanced Nuclear grows by...(GW)**	**Gas+CCU grows by...(GW)**	**Onshore Wind grows by...(GW)**	**Offshore Wind grows by...(GW)**	**Solar PV grows by... (GW)**	**Long-Duration Storage grows by...(GW)**	**Li-ion Stationary grows by...(GW)**
All	242.0	10.0	151.0	-116.0	836.0	2.0	-25.0
Advanced Nuclear	–	0.0	-446.0	-158.0	-593.0	-1.0	-29.0
DAC	-1.0	0.0	1.0	0.0	4.0	1.0	2.0
H2 Electrolysis	-9.0	0.0	99.0	19.0	472.0	0.0	-15.0
Fischer-Tropsch	-2.0	0.0	25.0	3.0	22.0	1.0	2.0
Gas+CCU	-25.0	–	-26.0	-5.0	-7.0	1.0	-14.0
H2 Reformation+CCS	-6.0	0.0	-8.0	-4.0	-83.0	1.0	14.0
Heat Pumps	0.0	0.0	1.0	3.0	3.0	1.0	3.0
Onshore Wind	-35.0	0.0	–	-33.0	-112.0	1.0	-15.0
Li-ion	-17.0	0.0	-12.0	-8.0	183.0	1.0	–
Long-Duration Storage	-3.0	0.0	5.0	-6.0	16.0	–	-12.0
Mobile Fuel Cells	-36.0	0.0	-15.0	0.0	78.0	1.0	-10.0
Offshore Wind	-21.0	0.0	-12.0	–	-17.0	1.0	-5.0
Sequestration	-12.0	22.0	-87.0	-10.0	-121.0	1.0	7.0
Solar PV	-53.0	0.0	-36.0	-13.0	–	2.0	76.0
Solar Thermal Heat	-1.0	0.0	-6.0	-2.0	-29.0	0.0	2.0

Transportation Sector Technologies

If (x) technology experiences a breakthrough...	H2 Electrolysis grows by...(GW)	Fischer-Tropsch grows by...(GW)	H2 Reformation+ CCS grows by...(GW)	Mobile Fuel Cells grows by...(GW)	Li-ion Mobile grows by... (GWh)
All	242.0	10.0	151.0	-25.0	2.0
Advanced Nuclear	-69.0	22.0	-14.0	-307.0	658.0
DAC	0.0	0.0	-2.0	0.0	0.0
H2 Electrolysis	–	87.0	-26.0	107.0	-116.0
Fischer-Tropsch	22.0	–	-1.0	-33.0	0.0
Gas+CCU	-19.0	-8.0	2.0	-10.0	6.0
H2 Reformation+CCS	-64.0	66.0	–	12.0	-49.0
Heat Pumps	0.0	1.0	-2.0	0.0	0.0
Onshore Wind	139.0	75.0	-6.0	-33.0	-63.0
Li-ion	-27.0	-1.0	-12.0	-1,892.0	–
Long-Duration Storage	-10.0	-1.0	-2.0	0.0	0.0
Mobile Fuel Cells	68.0	-12.0	9.0	–	-6,091.0
Offshore Wind	11.0	5.0	-1.0	5.0	5.0
Sequestration	-124.0	-11.0	21.0	89.0	-73.0
Solar PV	354.0	64.0	-19.0	-20.0	-11.0
Solar Thermal Heat	-15.0	2.0	3.0	5.0	-5.0

By 2050, a breakthrough in li-ion batteries decreases deployment of mobile fuel cells, its competitor, by 1.9 TW below the baseline.

By 2050, a breakthrough in Advanced Nuclear increases mobile li-ion battery deployment by 658 GWh over the baseline.

Industrial, Building, and Carbon Management Technologies

If (x) technology experiences a breakthrough…	Heat Pumps grows by…(units)	DAC grows by…(MMT CO_2/yr)	Sequestration grows by…(MMT CO_2)	Solar Thermal Heat grows by… (GW)
All	15,062,654	1,506.7	980.0	24.0
Advanced Nuclear	5,009,372	0.0	-91.0	0.0
DAC	-4,092	–	2.0	0.0
H2 Electrolysis	-27,664	0.0	-216.0	0.0
Fischer-Tropsch	5,297	0.0	-10.0	0.0
Gas+CCU	-4,510	0.0	115.0	0.0
H2 Reformation+CCS	-2,035	0.0	104.0	0.0
Heat Pumps	–	0.0	1.0	0.0
Onshore Wind	-118,681	0.0	-137.0	0.0
Li-ion	68,361	0.0	-20.0	0.0
Long-Duration Storage	20,024	0.0	7.0	0.0
Mobile Fuel Cells	-6,677	0.0	84.0	0.0
Offshore Wind	-6,623	0.0	-4.0	0.0
Sequestration	-3,358	0.0	–	0.0
Solar PV	333,669	43.8	-160.0	0.0
Solar Thermal Heat	-12,762	0.0	8.0	–

References

[1] Arostegui, D. (2021). The U.S. needs more economic stimulus: Here's how it can create jobs and tackle climate change. *Environmental Defense Fund*. http://blogs.edf.org/climate411/2021/01/25/economic-stimulus-policies-can-create-jobs-and-tackle-climate-change/

[2] Carbon180, et. al. (2021). Letter to OMB Advocating Robust Energy Innovation Investment in FY22 and Beyond. http://thirdway.imgix.net/Letter-to-OMB-Advocating-Robust-Energy-Innovation-Investment-in-FY22-and-Beyond.pdf

[3] Biden Presidential Campaign (2020). 9 Key Elements of Joe Biden's Plan for a Clean Energy Revolution. https://joebiden.com/9-key-elements-of-joe-bidens-plan-for-a-clean-energy-revolution/

[4] The White House (2016). Domestic Implementation Framework for Mission Innovation. *The White House*. https://obamawhitehouse.archives.gov/sites/default/files/omb/reports/final_domestic_mission_innovation_framework_111616_700pm.pdf

[5] Sivaram, V., Cunliff, C., Hart, D., Friedmann, J., & Sandalow, D. (2020). Energizing America: A Roadmap to Launch a National Energy Innovation Mission. *Columbia University*. https://www.energypolicy.columbia.edu/sites/default/files/file-uploads/EnergizingAmerica_FINAL_DIGITAL.pdf

[6] Cunliff, C. (2020). Energy Innovation in the FY 2021 Budget: Congress Should Lead. *Information Technology and Innovation Foundation*. https://itif.org/publications/2020/03/30/energy-innovation-fy-2021-budget-congress-should-lead

[7] Mission Innovation (2021). About MI. *Mission Innovation*. http://mission-innovation.net/about-mi/overview/

[8] See, for example, https://www.energy.gov/revolution-now (and, for more recent data, https://www.nrdc.org/revolution-now)

[9] International Energy Agency (2021). Tracking Clean Energy Progress. *International Energy Agency*. https://www.iea.org/topics/tracking-clean-energy-progress

[10] Shah, T. & Krishnaswami, A (2019). Transforming the U.S. Department of Energy in Response to the Climate Crisis. *National Resources Defense Council*. https://www.nrdc.org/sites/default/files/transforming-doe-response-climate-crisis-report.pdf

[11] U.S. Department of Energy (2021). Brief History of the Department of Energy. *U.S. Department of Energy*. https://www.energy.gov/lm/doe-history/brief-history-department-energy

[12] U.S. Department of Energy (2020). FY 2021 Congressional Budget Request. *U.S. Department of Energy*. https://www.energy.gov/sites/prod/files/2020/03/f72/doe-fy2021-budget-volume-1_2.pdf

[13] Cunliff (2020).

[14] Congressional Research Service (2016). DOE's Office of Energy Efficiency and Renewable Energy: FY2016 Appropriations. *Congressional Research Service*. https://crsreports.congress.gov/product/pdf/R/R44004/14

[15] The White House (2016).

[16] Sivaram, et. al. (2020).

[17] Biden-Harris Campaign (2020). 9 Key Elements of Joe Biden's Plan for a Clean Energy Revolution. https://joebiden.com/9-key-elements-of-joe-bidens-plan-for-a-clean-energy-revolution/

[18] Sivaram, et. al. (2020).

[19] Sivaram, et. al. (2020).

[20] Diringer, E., Townsend, B., Bobeck, J., Huber, K., Leung, J., Meyer, N., Vine, D., Ye, J., Grossman, D. (2019). Getting to Zero: A U.S. Climate Agenda. Center for Climate and Energy Solutions. https://www.c2es.org/document/getting-to-zero-a-u-s-climate-agenda/

[21] Krishnaswami, A. & Higdon, J. (2020). A Progressive Climate Innovation Agenda. *Data For Progress*. https://www.dataforprogress.org/climate-innovation-agenda

[22] Gates, B. (2020). Here's how the U.S. can lead the world on climate change innovation. *Gates Notes*. https://www.gatesnotes.com/Energy/How-the-US-can-lead-on-climate-change-innovation

[23] National Academies of Sciences, Engineering, and Medicine (2021). Accelerating Decarbonization of the Energy System. *National Academies Press*. https://www.nap.edu/read/25932/chapter/7#129

[24] American Energy Innovation Council (2018). Energy Innovation: Fueling America's Economic Engine. *Bipartisan Policy Center*. http://americanenergyinnovation.org/wp-content/uploads/2018/11/Energy-Innovation-Fueling-Americas-Economic-Engine.pdf

[25] Majumdar, A. (2019). Written Statement on of Dr. Arun Majumdar, Hearing on the Future of ARPA-E. *Subcommittee on Energy, House Committee on Science, Space and Technology*. https://energy.stanford.edu/sites/g/files/sbiybj9971/f/majumdar-testimony-futureofarpa-e-02202019.pdf

[26] Sivaram, et. al. (2020); Cunliff, C. (2020).

[27] American Energy Innovation Council (2018).

[28] Benahmed, F. & Noll, E. Clean Energy Demonstration Projects: Critical for Economic Recovery and Mitigating Climate Change. *Third Way*. https://www.thirdway.org/memo/clean-energy-demonstration-projects-critical-for-economic-recovery-and-mitigating-climate-change

[29] Diringer et. al. (2019).

[30] Krishnaswami & Higdon (2020).

[31] Sekar, K. (2021). National Institutes of Health (NIH) Funding: FY1995-FY2021. *Congressional Research Service*. https://fas.org/sgp/crs/misc/R43341.pdf

[32] Shah & Krishnaswami (2019).

[33] Krishnaswami & Higdon (2020).

[34] Breakthrough Energy (2021). Priority Innovation Policies: U.S. Federal. *Breakthrough Energy*. https://www.breakthroughenergy.org/us-policy-overview/priority-innovation-policies/us-federal