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An Innovation Agenda for Deep Decarbonization: Bridging Gaps in the Federal Energy RD&D Portfolio

BY COLIN CUNLIFF | NOVEMBER 2018

Reducing carbon pollution to zero will require a broad set of technologies that cover all sectors of the economy and can provide energy that is as cheap and reliable as fossil fuels.

The world is not on track to achieve the deep reductions in carbon emissions necessary to avoid the worst impacts of climate change.[1] While the United States saw a modest decline in emissions in the 10-year period from 2007 to 2017—primarily due to the substitution of natural gas and renewables for coal in power generation—this trend may be coming to an end.[2] The situation is even less encouraging at the global level, where carbon pollution has yet to peak, and emissions increased 2 percent last year.[3] A substantial increase in and significant reorientation of federal energy research, development, and demonstration (RD&D) is needed to break out of this looming cul-de-sac.

The energy innovation agenda of the last 10 years has focused, with considerable success, on reducing the cost and expanding the use of wind and solar resources for electricity generation. It is time now to expand the agenda beyond this "low-hanging fruit." Reducing carbon pollution to zero will require a broader set of technologies that cover all sectors of the economy in order to provide energy that is as cheap and reliable as that from fossil fuels. The effort should extend to hard-to-decarbonize sectors such as air travel and shipping, and cement and steel production, for which there are currently no good zero-carbon options.

This report diagnoses the limits of the current clean energy innovation agenda and identifies sectors and technologies that are underrepresented in the RD&D portfolio. It develops a set of six "technology missions" to bridge these gaps, and offers the following recommendations to U.S. policymakers—although all of the missions and many of the recommendations are ones that should be embraced by all developed nations.

Mission 1: Advanced Nuclear Energy

- Re-prioritize the Department of Energy's (DOE) Office of Nuclear Energy (NE) to focus on advanced nuclear reactor technologies, and commit to the demonstration of at least one advanced reactor design.
- Expand linkages between basic science research in the DOE Office of Basic Energy Sciences and National Science Foundation (NSF), and the applied RD&D at NE and Department of Defense (DOD).
- Commit to constructing the Versatile Test Reactor to enable testing of materials and fuel designs in a fast neutron environment.
- Develop a domestic supply of high-assay, low-enriched uranium (HA-LEU) that is compatible with fueling requirements for advanced reactor concepts.
- Expand RD&D into other applications for nuclear energy, such as providing process heat or producing carbon-neutral fuels.

Mission 2: Long-Duration Grid Storage[4]

- Establish a second innovation hub modeled on Joint Center for Energy Storage Research to pursue science and technology for long-duration grid storage.
- Expand investments by DOE's applied energy offices and ARPA-E in grid storage R&D and focus them on long-duration problems.
- Expand DOE funding for long-duration grid storage technology demonstration projects in partnership with other stakeholders.
- Establish an interagency working group on long-duration grid storage within the National Science and Technology Council (NSTC) to facilitate interagency information exchange and coordination.
- Propose and lead a new innovation challenge on long-duration grid storage within the international Mission Innovation framework.

Mission 3: Carbon-Neutral Fuels

- Establish an innovation hub focused on hydrogen and ammonia production methods that do not use fossil fuels as feedstock.
- Expand R&D into applications of hydrogen and other carbon-neutral fuels in hard-to-decarbonize transportation sectors such as aviation and long-haul shipping.
- Establish an R&D program focused on applications of carbon-neutral fuels in the industrial sector (e.g., the provision of high-temperature process heat).
- Implement the recommendations from the recent National Academies report on carbon utilization that focus on chemical and biological pathways for the conversion of carbon dioxide into fuels and chemicals.[5]

Mission 4: Carbon Capture, Utilization, and Storage (CCUS)

- Establish a carbon capture demonstration program that funds first-of-a-kind demonstration projects for carbon capture at natural gas, steel, concrete, and other large sources of carbon dioxide.
- Expand the DOE Title XVII loan programs to cover carbon capture at industrial facilities.
- Establish a single carbon capture R&D program—outside the coal program office—that includes carbon sources across all sectors, including cement and steel.
- Expand a carbon utilization R&D program that addresses the research needs identified in the National Academies report on carbon utilization.
- Continue to support R&D in geologic storage in saline aquifers and depleted oil and gas fields, and expand storage R&D to include basalt and other carbon-absorbing mineral formations.

Mission 5: Carbon Dioxide Removal Technology

- Establish an applied RD&D program that implements the recommendations of the National Academies report on negative emissions technologies and prioritizes pilot-scale demonstrations of direct air capture.
- Research methods to increase carbon removal capacity and mitigate environmental impacts of land-based approaches, including approaches that enhance soil carbon sequestration.
- Establish an innovation hub that addresses basic science needs for carbon removal pathways.
- Establish an interagency working group within NSTC to coordinate federal research and facilitate information exchange across agencies.

Mission 6: Basic Energy Research

- Double the number of Energy Frontier Research Centers (EFRCs) and ensure alignment with the hard-to-decarbonize technology missions.
- Provide full funding for the next generation of DOE user facilities, as well as planned upgrades at existing facilities.
- Evaluate whether the capacity of existing user facilities is sufficient to accommodate all research applications with scientific merit, and develop a plan to build additional user facilities where warranted.
- Expand NSF funding for energy-related research that advances the science underpinning clean energy technology breakthroughs.

The following section explains why the world needs zero-carbon energy. The subsequent section examines the current global and domestic emissions trajectory, finding that without further innovation, domestic emissions are projected to level off, while global emissions will continue to increase through 2050. The report then identifies gaps in the current U.S.

energy RD&D portfolio and outlines an innovation agenda to address "difficult-to-eliminate" carbon emissions. The final sections develop the technology missions to bridge these gaps.

THE WORLD NEEDS ZERO-CARBON ENERGY

Climate change is occurring and is already harming society. Over the last century, the burning of fossil fuels, deforestation, and land-use changes have significantly increased the concentration of heat-trapping greenhouse gases in our atmosphere.[6] As a result, global average surface temperatures have increased by about 1.8 degrees Fahrenheit (1.0 degree Celsius), and global average sea levels have risen by 8 inches since 1900.[7] Temperature extremes and severe storms are increasing in frequency and intensity, and the number of billion-dollar weather- and climate-related disasters has been on an upward trend since the 1980s.[8] What were once considered 100-year floods or heatwaves are now occurring far more frequently.

In the absence of a market that values the carbon-free attributes of clean energy, cost and performance competitiveness will be the main drivers of clean energy adoption.

Addressing climate change requires restoring the natural balance of carbon in the atmosphere and reducing carbon pollution to zero, or even net-negative, before the end of the century. The recent Intergovernmental Panel on Climate Change (IPCC) special report found that emissions must fall to zero by mid-century to have a reasonable chance of limiting average warming to 2.7°F (1.5°C). Even a more relaxed target of 3.6°F (2°C) requires annual carbon pollution to fall to zero before 2100 in most scenarios.[9]

Achieving a low-carbon economy will require zero-carbon energy sources.[10] Natural gas, which has about half the carbon content of coal, is often discussed as a "bridge fuel" to a carbon-neutral energy system, and has already been the primary driver of current emissions reductions. But natural gas, by itself, is not a long-term solution.[11] Reaching net-zero emissions will require virtually all unabated fossil fuel combustion to be replaced by zero-carbon energy sources. Deep decarbonization (defined here as 80 to 100 percent reduction in carbon emissions) is much more challenging than more modest reductions, and there is strong agreement in the literature that a diverse portfolio of options—including renewables, storage, nuclear, and carbon capture for fossil energy—provides the best chance of achieving a low-carbon energy system.[12]

But low-carbon energy needs to be cheaper and better in order to realize widespread adoption. Energy is largely a fungible commodity—there is no tangible difference in the electricity coming out of the wall socket if it comes from a coal plant or a wind farm. The only immediate differences are cost and reliability. In the absence of a market that values the carbon-free attributes of clean energy, cost and performance competitiveness will be the main drivers of clean energy adoption.[13] This will be especially true for the developing economies, which are projected to account for the lion's share of new energy demand, and unlikely to willingly to pay a price premium (either directly or through a carbon tax) for clean energy.

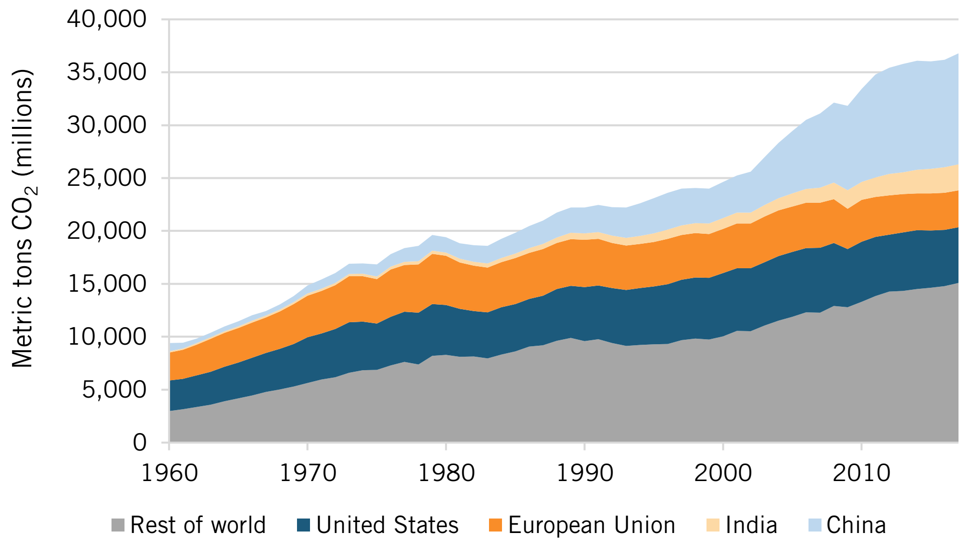
WITHOUT INNOVATION: AN EMISSIONS CUL-DE-SAC?

Carbon emissions have declined in parts of the developed world, leading to a sense of premature triumphalism among many in the climate and energy policy community that we already have all the technology necessary to halt climate change.

At first glance, there appears to be reason for optimism. Countries such as Australia, Austria, Canada, Switzerland, and the United States have reached peak emissions and are now seeing modest year-over-year declines. The United States, for example, reached peak emissions in 2007. Since then, domestic carbon pollution declined in seven of the last ten years, reaching 14 percent below 2007 levels in 2017.[14] But even these modest emissions reductions are far below the rate needed to achieve a zero-carbon energy system by mid-century.[15]

Emissions from developing countries have continued to increase. During the last 10 years, global emissions rose by 18 percent, primarily driven by China (49 percent increase) and India (76 percent increase) as they grew their economies and expanded access to electricity and other energy services. Emissions in the rest of the world increased by 23 percent over that same timeframe (figure 1).

Figure 1: Annual CO_2 emissions from fossil fuels and industry by region[16]



The reason for the continued increase is simple: As developing nations bring more and more of their citizens into the middle class—with the attendant increases in per-capita energy consumption—emissions will to continue to rise in locations where fossil fuels remain the cheapest form of energy. Last year, only 43 percent of the population of Sub-Saharan Africa had access to electricity. Similarly, only 55 percent of the population in developing countries in Asia had access to clean cooking fuels. As the developing world expands access to energy services, it will turn to fossil fuels as long as they remain cheaper than zero-carbon energy. In 2017, for example, 72 percent of the growth in energy demand was met by fossil fuels, with carbon-free energy from renewables and nuclear power meeting the other 28.[17]

Rather than accelerating, there are signs that the transition to clean technologies could stall. In developed countries, the trends driving the current modest emissions reductions (e.g., increase in natural gas power) could stall, causing emissions to level off rather than continue to decline. And without additional innovation and cost reductions in clean energy, developing nations will continue to turn to cheaper fossil fuels to meet their growing energy needs, causing global emissions to continue to increase.

In short, the transition to a low-carbon energy system—both domestically and globally—is not occurring fast enough or at sufficient scale to address the climate challenge.

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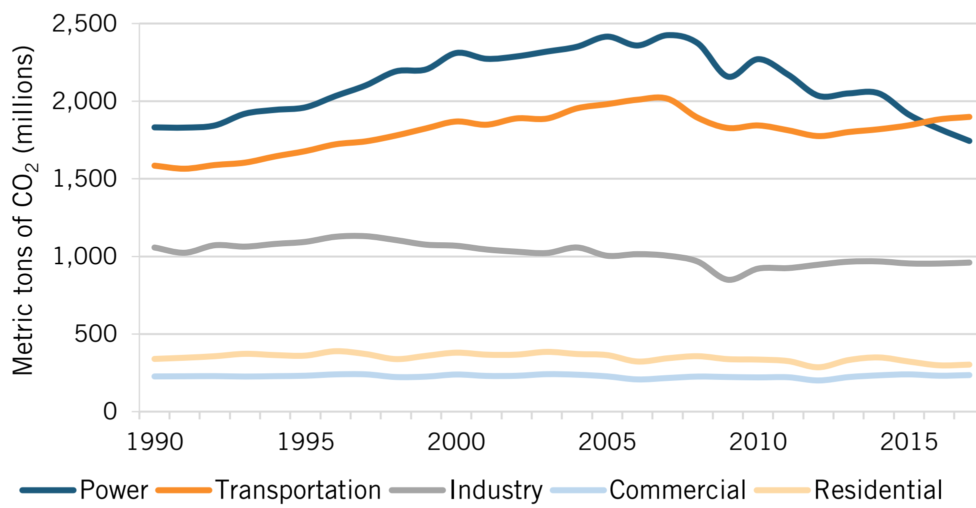
U.S. Carbon Emissions: Current Trends and Early Warning Signs

The United States provides an illustrative example of the limits of current trends and technologies, and the barriers to deep decarbonization. The electric power sector has been the real workhorse of emissions reductions, with emissions from electricity generation declining by 28 percent from 2005 to 2017. Emissions from other U.S. sectors have not declined as rapidly: Transportation and industrial-sector emissions have declined a meager 4 percent each, while emissions from commercial and residential buildings—the smallest source of energy-related carbon emissions—declined by 9 percent (figure 2).[18]

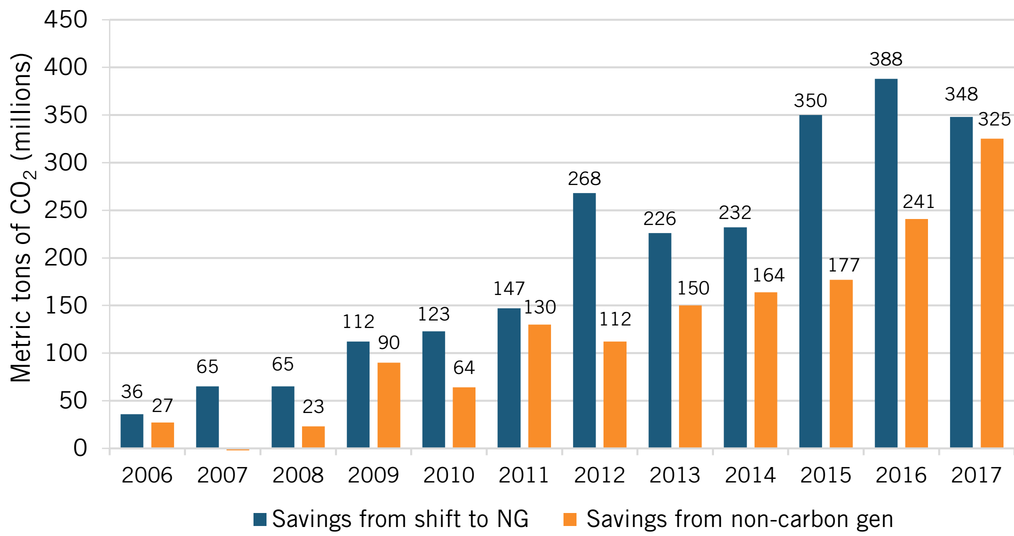
Figure 2: U.S. Energy CO_2 emissions by sector[19]



Trends driving emissions reductions in the electric power sector include low growth in electricity demand and decreasing carbon intensity of electricity generation. Low load growth is the result of greater electricity productivity in the economy, i.e., the ratio of economic output (as measured in dollars of GDP) per electricity consumption. In the U.S. economy, electricity productivity has increased in 8 of the last 10 years, in response to greater energy efficiency as well as structural changes in the economy, including a shift to less electricity-intensive manufacturing.[20]

The decline in the carbon intensity of electricity generation is due to changes in the generation mix. The share of electricity from coal plants has declined from 49 percent in 2007 to 30 percent in 2017 as older, uneconomic coal plants have retired.[21] During the same time, the share of generation from natural gas has risen from 22 percent in 2007 to 32 percent in 2017, while the share of generation from zero-carbon sources—including nuclear power, hydropower, biomass, geothermal, solar, and wind—increased from 28 percent to 37 percent.[22] According to the U.S. Energy Information Administration (EIA), 61 percent of the cumulative emissions reductions from electricity generation since 2005 are attributable to fuel switching from coal to natural gas, with the remaining 39 percent due to greater shares of electricity from zero-carbon sources (figure 3).[23]

Figure 3: Emissions reductions in the U.S. power sector[24]



In 2016, the transportation sector surpassed the electric power sector as the largest source of U.S. carbon emissions. The carbon intensity of the fuels has declined slightly due to increasing levels of biofuels such as corn ethanol, yet fuel consumption—determined both by the fuel economy of vehicles (e.g., miles per gallon for passenger cars) and the total vehicle-miles traveled (VMT)—continues to be the primary driver of transportation emissions. Improved fuel economy and fewer VMT as a result of the recession and high gas prices combined to reduce fuel consumption in the years following the recession. But in recent years, increases in VMT have more than offset improved fuel economy, leading to a slight emissions increase.[25] And according to the Department of Transportation, VMT is expected to grow 0.9 percent per year through 2046.[26]

In the industrial sector, direct carbon emissions (not including indirect emissions from electricity purchases) have barely budged in recent years. The majority of direct emissions are due to on-site combustion of fossil fuels for heat and power, with smaller amounts resulting from various industrial processes.[27] Fuel-switching from coal to natural gas has led to a decrease in the carbon intensity of the industrial sector by 6 percent between 2007 and

2017, but this has been offset by a 2 percent increase in direct fuel consumption over the same time period, resulting in a net 4 percent decrease in emissions reductions.[28]

In the commercial and residential sectors, collectively referred to as the "buildings sector," most direct on-site emissions result from the use of natural gas (or other gases such as propane) for heating and cooking. In both residential and commercial buildings, the carbon intensity of fuels has barely budged, declining by less than 4 percent since 2007. In the residential sector, a rising population and increase in the number of residential homes have been offset by improved efficiency and switching from natural gas to electricity, resulting in a net 12 percent decrease in direct carbon emissions since 2007. In the commercial sector, as building floorspace has increased, the demand for fuels has outpaced efficiency and electrification, resulting in greater fuel consumption and a net 9 percent increase in carbon emissions in the last 10 years.[29]

Going forward, there are several countervailing trends in each sector that will shape U.S. energy production and consumption over the next several decades—and determine the United States' ability to reduce carbon pollution. The U.S. Energy Information Administration's (EIA's) *Annual Energy Outlook 2018* provides projections of domestic energy markets based on current market trends and energy policies:

- In the **electric power sector**, generation from coal is projected to decline slightly through 2020 as older, uneconomic plants retire. After the early 2020s, coal generation is projected to stay constant, as the remaining coal plants are either younger and more efficient or located in regulated (noncompetitive) markets and are therefore shielded from market forces. Low-cost domestic natural gas will drive increased generation from natural gas power plants, while increased carbon-free generation from renewables (primarily wind and solar) will be offset by the retirement of zero-carbon nuclear power plants. All told, changes in the generation mix and growth in the demand for electricity will contribute to near-flat emissions of carbon dioxide from the electric power sector through 2050.[30]

- In **transportation**, emissions are projected to decline until the mid-2030s, as improved vehicle efficiency for road transportation will more than offset rising air travel. Emissions are then projected to rise through 2050 as increases in VMT will outpace efficiency gains. Although electric vehicles are projected to grow to 19 percent of new sales by 2050, overall demand for petroleum-based fuels (e.g., gasoline, diesel, and jet fuel) is projected to remain roughly constant for road transportation, and to increase for air travel and shipping.[31]

- In the **industrial sector**, direct (on-site) energy consumption, excluding electricity purchases, is projected to increase by 39 percent by 2050, driven primarily by economic growth and relatively low energy prices. Consumption of natural gas and petroleum are projected to grow, while demand for coal will remain relatively flat, resulting in a direct emissions increase of 26 percent by 2050. Emissions from manufacturing of bulk chemicals and plastics, food products, construction, and fabricated metal products are projected to increase the most.[32]

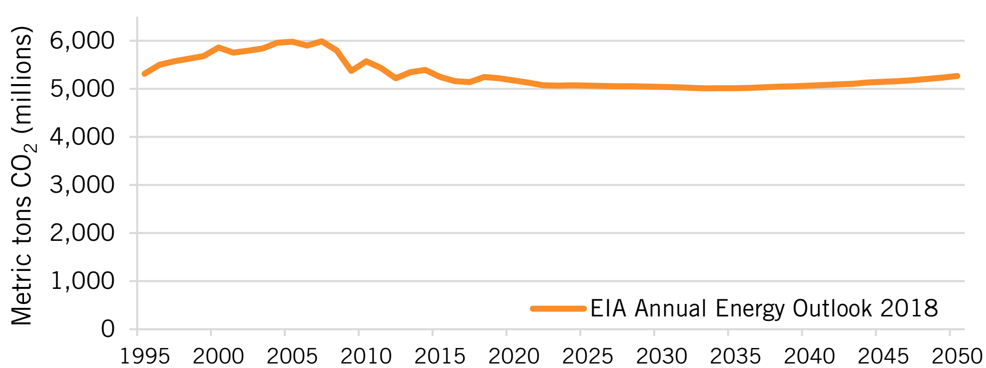
- In **residential buildings**, efficiency gains, lower consumption of heating oil, and greater electrification will more than offset a rising population and greater housing supply, resulting in a projected emissions reduction of 6 percent by 2050. In **commercial buildings**, growing office space will lead to greater on-site consumption of natural gas, resulting in a projected 18 percent increase in emissions by 2050.

A consistent theme across all end-use sectors (transportation, industry, and buildings) is that there are few good zero-carbon substitutes for fossil fuels. Electrification, where possible, and improved energy efficiency have been able to offset increased activity in each sector (VMT in transportation, economic output in the industrial sector, and floorspace in the buildings sector). But to date, these approaches have been able to achieve only modest emissions reductions. In the electric power sector, a greater number of zero-carbon options exist, including renewables (wind, solar, hydropower, geothermal, and biomass), nuclear power, and carbon capture for fossil fuels. Absent further innovation, electricity generation from zero-carbon sources is not projected to grow fast enough to make a significant dent in emissions.

Despite falling costs for renewables and batteries, total domestic emissions are projected to remain relatively flat through 2050.

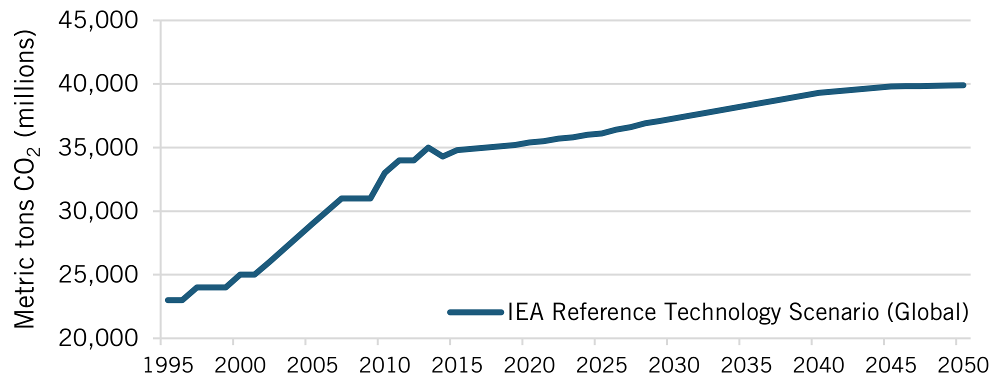
For these reasons, domestic emissions are projected to remain relatively flat, at just over 5,000 million metric tons of carbon dioxide (MMT CO_2) per year through 2050, according to EIA's *Annual Energy Outlook 2018* (figure 4). It is worth noting that EIA does not use static technology costs in its assumptions, but incorporates learning curves for energy technologies into its projections. Because these learning curves are steeper for emerging technologies such as offshore wind, solar photovoltaics (PV), and battery storage, these technologies are projected to see greater future cost reductions than incumbent technologies such as coal and natural gas plants.[33] Yet, despite falling costs for renewables and batteries, total power sector emissions are projected to remain relatively flat.

Figure 4: Projections of U.S. carbon emissions under a Reference Technology Scenario[34]



A similar story plays out at the global level. The International Energy Agency (IEA) has produced a Reference Technology Scenario (RTS) that provides projections of global energy demand and supply. Like EIA's reference projection, the IEA RTS assumes greater cost reductions and performance improvements in clean technologies, as well as commercialization of new clean technologies that are near the end of the innovation pipeline.[35] Additionally, the RTS incorporates the national targets set in the Paris Climate Agreement. Yet, despite falling costs for clean technologies and greater international commitments to address climate change—even if most of these targets are hortative—global emissions are still projected to increase through 2050.

Figure 5: Projections of global carbon emissions under a reference technology scenario[36]



The current suite of clean technologies—even when combined with future cost reductions and proposed climate commitments—are woefully insufficient to drive the significant levels of emissions reductions necessary for carbon neutrality.

Clearly, the current suite of clean technologies—even when combined with future cost reductions and proposed climate commitments—are woefully insufficient to drive the significant levels of emissions reductions necessary for carbon neutrality. Incremental steps—such as increases in vehicle fuel efficiency standards, building codes, and efficiency standards for appliances—may be able to achieve modest emissions reductions in developed countries with low growth in energy demand. But the need to expand access to energy services in the developing world overwhelms improvements in energy efficiency.

AN INNOVATION AGENDA FOR DEEP DECARBONIZATION

Public investment in clean energy innovation is needed to break out of the emissions cul-de-sac. Reducing carbon pollution to net-zero requires a broader set of zero-carbon energy technologies—beyond just wind and solar for electricity generation—that covers all sectors of the economy and is as cheap and efficient as fossil fuels. Generating these technologies requires effective innovation policy. As the last century of technology development has shown, investment and aggressive public policy reforms are key drivers of innovation. From nuclear energy to solar PV to lithium-ion (Li-ion) batteries and solid-state lighting, government innovation policy can have deep impacts supporting the development of low-carbon technologies and fostering a comprehensive energy innovation ecosystem.[37]

Public investment in R&D is an essential part of an effective innovation policy. Option generation is a key part of managing risks, and investing in multiple clean energy buckets guards against the risk of any one technology failing to reach maturity or impact our energy system at a climate-relevant scale. But R&D alone is not enough. Effective clean energy innovation policy requires support across the entire innovation spectrum, from basic science and R&D through testing, demonstration, and smart deployment incentives. Public support is needed to bridge technologies across the "Valleys of Death"—the phases between R&D and prototyping the first generation of a technology, as well as the transition between the first demonstration at scale and commercialization.[38]

The following sections develop an innovation agenda for deep decarbonization. The first section examines the ability of DOE's applied energy RD&D portfolio to accelerate the development of clean energy technologies and bend the current emissions trajectory downward. The second section identifies "hard-to-decarbonize" sectors of the economy for which there are currently few good clean energy substitutes and are underrepresented in the federal energy RD&D portfolio. The final section proposes an innovation agenda that specifically targets these hard-to-decarbonize sectors and introduces the Technology Missions that follow.

BOX 1: ELECTRIFICATION FOR DEEP DECARBONIZATION

Electrification of energy services, in tandem with decarbonization of electricity generation, has emerged as a key element in nearly all deep decarbonization scenarios. The rapid decline in U.S. power sector emissions—and the lack of progress in other sectors—provides an illustrative example. The comparative ease of emissions reductions in the power sector is due, in part, to the wide range of zero-carbon electricity options, including renewable energy (wind, solar, geothermal, and hydropower), nuclear power, and fossil fuels with carbon capture and storage. Electrification is a key part of IEA's Sustainable Development Scenario (SDS), and also features prominently in all U.S. Mid-Century Strategy (MCS) scenarios for deep decarbonization.

The National Renewable Energy Laboratory's (NREL) *Electricity Futures* study finds that electrification of energy services combined with decarbonization of electricity has the potential to reduce U.S. emissions by 74 percent below 2005 levels by 2050. Even in the absence of a decarbonized electricity sector, electrification of energy services alone would result in 41 percent less carbon pollution.

An Innovation Agenda Part 1: The Current Federal Energy RD&D Portfolio

The Federal Government invests in energy RD&D across a range of agencies, including DOE, NSF, DOD, Department of Agriculture (USDA), and others.[39] Most of the basic energy research is funded through NSF or DOE's Office of Science, while the bulk of the energy technology development is centered in DOE's applied energy offices, including the Offices of Energy Efficiency and Renewable Energy (EERE), Fossil Energy (FE), Nuclear Energy (NE), Electricity (OE), and ARPA-E. In fiscal year (FY) 2019, Congress appropriated $5.1 billion to the applied energy programs.[40]

For each of its applied energy technology programs, DOE conducts impact analyses and establishes annual performance targets to guide its R&D investments. As part of the regular budget planning process, each program explores activities that would be possible at a proposed budget level and develops detailed R&D plans as outlined in the president's budget request to Congress.[41]

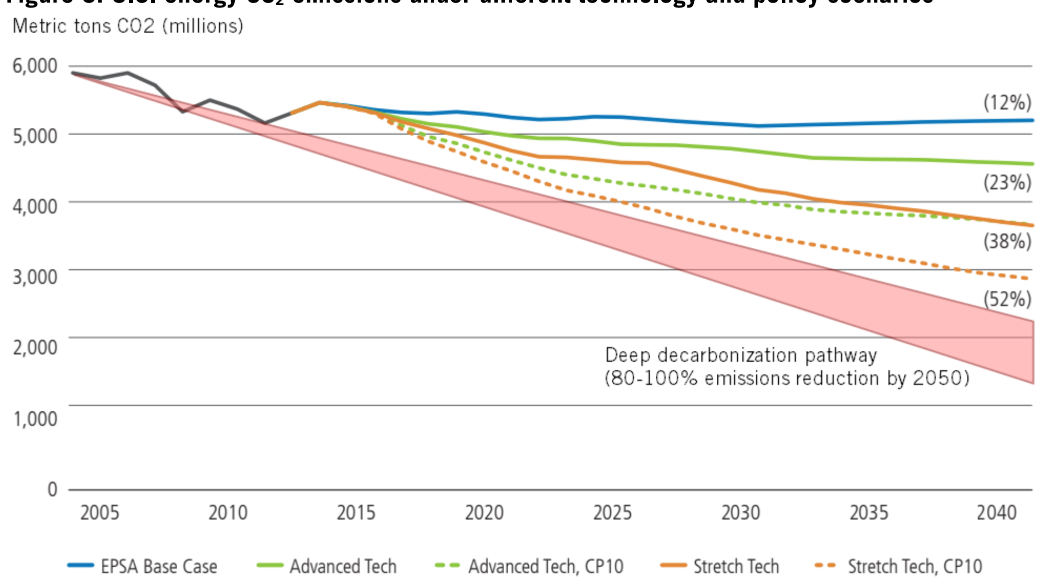
Perhaps the most well-known example is DOE's Sunshot goals, a set of cost targets for solar energy technologies that was chosen to make the average unsubsidized cost of solar energy cheaper than conventional electricity sources. Sunshot's 2030 targets for PV systems range from 3 cents per kilowatt-hour for utility-scale solar to 5 cents per kilowatt-hour for residential rooftop solar.[42] Each year, the solar program evaluates progress toward these goals and links specific elements of the solar energy R&D program to anticipated cost reductions and performance improvements. The other DOE technology offices use a similar approach to set cost and performance targets, and annually report their progress to Congress per the Government Performance and Results Act and other agency directives.[43]

As part of the 2017 *Quadrennial Energy Review* (QER), DOE incorporated all of its energy technology goals into the same energy-economic model used to develop the Reference Technology Scenario projections in EIA's *Annual Energy Outlook*. The analysis examines the potential impacts of DOE's applied energy R&D programs on the U.S. energy system, and provides projections of emissions (and other energy indicators, such as retail electricity prices) for scenarios in which DOE's energy R&D programs hit their performance targets.[44]

By driving down costs and improving the performance of clean energy technologies, DOE's research programs can accelerate clean energy deployment.

The DOE analysis includes three technology scenarios: the "Base Case," which is similar to EIA's Reference Technology Scenario in that it applies a standard technology learning curve but does not account for DOE technology program goals; the "Advanced Technology" case, which assumes all of DOE's energy R&D technology goals are met; and the "Stretch Technology" case with more aggressive technology targets conditioned on a doubling of energy R&D investment (consistent with the U.S. commitment to Mission Innovation). As a proxy for additional policy action, an initial carbon price of $10 per metric ton of CO_2, starting in 2017 and rising by 5 percent per year, was overlaid on top of the Advanced Tech and Stretch Tech cases.

Figure 6: U.S. energy CO_2 emissions under different technology and policy scenarios



Under the Base Case (blue line in figure 6), emissions level off at around 12 percent below 2005 levels by 2040. If DOE achieves its current energy technology cost and performance targets, emissions will decline to 23 percent below 2005 levels (green line). However, achieving even these modest emissions reductions is contingent on sustained funding levels, as projected in 2017. The budgets proposed by the Trump administration in FY2018 and FY2019 would have slashed funding for DOE's program offices, jeopardizing DOE's progress toward their technology performance targets.[45]

More aggressive technology targets consistent with a doubling of investment in applied energy RD&D would reduce emissions by 38 percent (orange line) by 2040. The analysis finds that a combination of carbon pricing and energy RD&D can achieve greater emissions reductions than either approach alone (dotted orange line). The QER study also found that DOE's programs would drive down average residential energy bills for consumers, even in scenarios that include a carbon price.[46]

The projected emissions reductions were not constant across all sectors. DOE's energy RD&D portfolio—assuming it can meet all its technology targets—would have the greatest impact in the electricity sector. In part, this is because more zero-carbon options exist for electricity generation. DOE programs in solar power, wind energy, hydropower, geothermal energy, nuclear energy, and carbon capture for fossil fuels all have the potential to drive down costs and improve the performance of these technologies, which would accelerate deployment of these zero-carbon options. At current budget levels, the effect of meeting DOE's technology targets would result in 40 percent emissions reductions by 2040, while a doubling of investment would lead to 58 percent fewer emissions from electricity generation.

In contrast, other sectors are harder to decarbonize. If DOE meets all its technology targets, direct (non-electricity-related) emissions from energy consumption in buildings would decline by just over 25 percent by 2040. Transportation sector emissions would decline by 15 percent by 2040 (33 percent under the doubling scenario), with projected emissions reductions achieved through improved fuel economy and greater penetration of electric and hydrogen-fueled vehicles. Industrial sector emissions are projected to increase, even if DOE meets its performance targets, due to higher projected energy consumption and growth in the industrial sector.

Clearly, DOE's energy RD&D programs have the potential to bend the emissions curve down from a reference technology scenario. By driving down costs and improving the performance of clean energy technologies, DOE's research programs can accelerate clean energy deployment. DOE's performance targets are also fairly conservative. Out of 64 technology targets reported to Congress between 2012 and 2016, DOE met or exceeded 62.[47]

But gaps still remain, and DOE's applied energy RD&D program by itself—even with a doubling of investment—can not achieve a zero-carbon energy system by mid-century. In order to be on track to reach a deep-decarbonized energy system (80 to 100 percent emissions reduction) by 2050, emissions would have to fall to 1,330–2,260 million metric tons of carbon dioxide emissions by 2040, or 62 to 78 percent below 2005 levels.

Difficult-to-Eliminate Emissions, and Gaps in the Energy RD&D Portfolio

The gap between an aggressive energy research and development portfolio and a deep decarbonization pathway points to a set of "hard-to-decarbonize" sectors or technologies that are either not well represented in the federal energy research portfolio or are funded at levels that are insufficient to address the challenge of decarbonizing these sectors. These "difficult-to-eliminate" emissions will require fundamental breakthroughs and investment commensurate to the challenge.

In the electric power sector, many studies have concluded that a 50 to 70 percent reduction in carbon emissions can be achieved with a mix of commercially available technologies—namely, by increasing the share of electricity from natural gas and wind and solar energy, and by maintaining the existing nuclear and hydropower capacity.[48] However, reaching near-zero emissions will require virtually all unabated coal and natural gas plants to be replaced with dispatchable zero-emissions sources that provide the same level of flexibility and essential reliability services as conventional fossil-fuel generation. This gap is sometimes referred to as "highly reliable electricity" or "firm electricity."[49]

"Hard-to-decarbonize" sectors are either not well represented in the federal energy research portfolio or are funded at levels that are insufficient to address the challenge of decarbonizing these sectors.

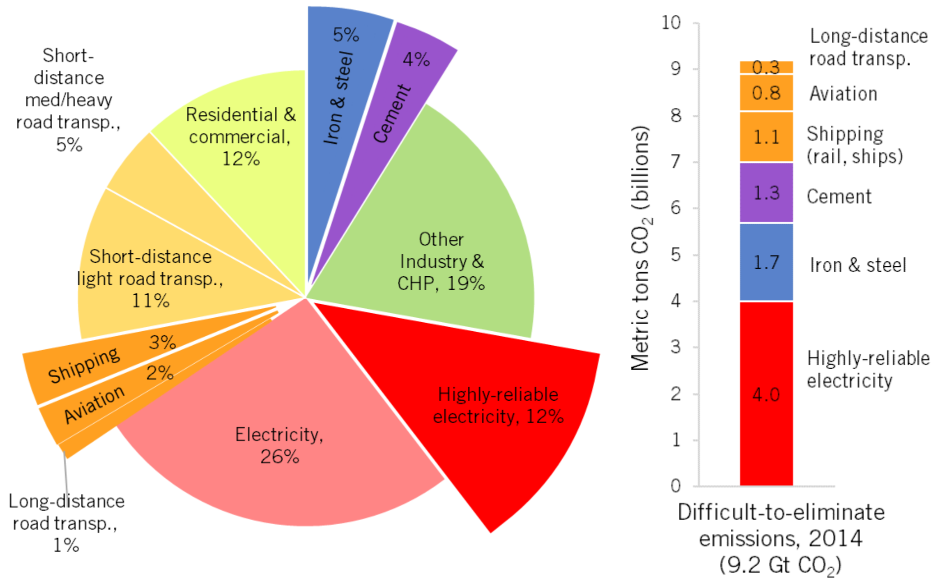
In the three end-use sectors—buildings, transportation, and industry—electrification of energy services, in tandem with decarbonization of electricity, has emerged as a viable pathway for reducing emissions. Of course, the electrification strategy is limited by the ability of the power sector to decarbonize. In addition, some sectors are not amenable to electrification. In the end-use sectors, "difficult-to-eliminate" equates to "hard-to-electrify."

In the transportation sector, batteries are getting cheaper and better, but have not yet achieved the reduced costs and increased performance necessary to enable unsubsidized widespread electrification of passenger vehicles and light-duty trucks. Moreover, the energy density requirements of aviation, shipping, and long-distance road transport make it unlikely batteries will ever be able to replace petroleum-based liquid fuels—and these sectors will need new zero-carbon fuels or other alternatives to reach deep decarbonization.

Similarly, the industrial sector includes two categories of emissions that cannot be eliminated through electrification. "Process" emissions result directly from industrial processes (such as steam methane reforming to make ammonia) and are independent from the source of energy used to drive the process. And the high-temperature heat (i.e., temperatures greater than 750°F) used in many industrial processes is currently provided by fossil fuel combustion and cannot be easily electrified.

A recent study published in *Science* quantifies these "difficult-to-eliminate" emissions. "Highly-reliable electricity" is estimated to account for 4 billion metric tons of carbon dioxide emissions (4 $GtCO_2$) annually. In the industrial sector, iron and steel production and cement production are the two largest sources of process emissions, accounting for 3 billion metric tons of annual carbon dioxide emissions (3 $GtCO_2$). And in the transportation sector, shipping, aviation, and long-distance road transport account for 2.2 billion metric tons annually. Altogether, these sources accounted for 27 percent of global carbon emissions in 2014 (figure 7).

Figure 7: Global "difficult-to-eliminate" carbon emissions from the energy and industrial sectors[50]



Difficult-to-Eliminate Emissions in the Electric Power Sector

The early power sector emissions reductions from the last 10 years are "low-hanging fruit." In the United States, these emissions reductions have come from the replacement of the oldest, least-efficient coal plants—the average age of a coal plant retiring in 2015 was 54 years old—with natural gas and renewable energy, primarily variable generation from wind and solar. But there are limits to this approach. A natural gas combined-cycle plant, for example, emits about 0.89 pounds (405 grams) of carbon dioxide per kilowatt-hour of electricity.[51]

Similarly, greater penetration of variable generation from wind and solar power may result in near-term emission reductions (though their impact may be muted by early retirements of zero-carbon generation from nuclear plants). But there are significant limits to the amount of variable generation the grid can accommodate at reasonable cost.

Nearly all deep decarbonization studies identify the need for "firm" low-carbon dispatchable generation—also referred to as "highly reliable" generation—to balance both variability in demand and variable output from wind and solar. This includes generation technologies that can be counted on to meet demand as needed, in all seasons and over long durations, including flexible nuclear power plants, hydropower plants with high-capacity reservoirs, flexible coal and natural gas plants equipped with carbon capture, geothermal power, and biomass- and biogas-fueled power plants.[52]

The need for firm generation stems from the requirement that modern electricity systems be able to supply electricity with high reliability—which depends on both resource adequacy and operational reliability. Resource adequacy refers to the ability of the power generation system to meet peak electricity demand plus a reserve margin. Operating reliability is defined as "the ability of the electric system to withstand sudden disturbances to system stability or unanticipated loss of system components," and requires a suite of essential reliability services including frequency response, voltage support, and ramping.[53] To meet these requirements, electricity supply must be able to respond dynamically to ensure instantaneous matching with demand. Systems with high penetrations of variable generation that is uncorrelated with demand, such as wind and solar, provide challenges for managing system reliability and typically require some level of firm generation to provide essential reliability services.[54]

Batteries combined with variable generation may be able to help manage shorter-term imbalances on hourly and sub-hourly scales. They are already providing primary frequency response—one of the components of frequency support, an essential reliability service—in many parts of the United States. And battery + renewable systems may be able to store electricity for up to a few hours and dispatch during times of peak demand. But battery storage technologies (with current Li-ion batteries) are unlikely to manage the large seasonal variations in generation from wind and solar.

Electricity system costs rise dramatically in scenarios with limited availability of firm low-carbon resources such as nuclear energy and fossil fuel with CCS.

In addition to technical feasibility, many studies have used energy-economic system models to look at least-cost electricity systems under different carbon constraints and technology scenarios. A diverse portfolio that includes firm low-carbon resources such as nuclear and fossil with carbon capture and storage (CCS) can significantly reduce the cost and technical challenges of deep decarbonization.[55]

The converse is also true: System costs rise dramatically in scenarios with limited availability of firm low-carbon resources that rely primarily on variable renewable energy and battery storage. At higher penetration levels, the marginal energy and capacity substitution value of variable generation and batteries declines rapidly—and significantly more than 1 megawatt of combined variable generation and battery storage is required to replace 1 megawatt of firm low-carbon generation. One literature review of 30 deep decarbonization studies found that systems that rely exclusively on renewables and batteries in very low-carbon scenarios require a total installed capacity that is three to five times the total installed capacity in scenarios with firm low-carbon generation.[56] A recent analysis of more than 900 decarbonization scenarios found that the total installed generation and storage capacity in zero-carbon scenarios would be five to eight times peak electricity demand.[57]

These findings all point to the need for some amount of "highly-reliable" firm low-carbon generation.

Scale of difficult-to-eliminate emissions in the electricity sector: The *Science* study on net-zero energy systems estimated global emissions from highly-reliable electricity to account for roughly 4,000 million metric tons of carbon dioxide emissions in 2014, or about 33 percent of total electricity emissions. Applying their approach to the U.S.

electricity system results in about 1,200 million metric tons of difficult-to-eliminate carbon dioxide emissions from the power sector.

Possible solutions: Flexible nuclear power, hydropower plants with high-capacity reservoirs, flexible coal and natural gas plants equipped with carbon capture, geothermal power, and biomass- and biogas-fueled power plants can all provide firm low-carbon electricity. Hydropower, geothermal, and biomass for power provide flexible, dispatchable zero-carbon electricity today. But hydropower and geothermal are limited by geographic constraints and have limits on the total capacity that can be installed using current technologies. And a large-scale reliance on biomass for power generation competes with other land uses, including agriculture, as well as the use of biomass for energy in the transportation and industrial sectors.[58] Nuclear power that is operated flexibly, fossil fuel plants equipped with carbon capture, and long-duration grid storage that can manage seasonal variability are all potential solutions.

Difficult-to-Eliminate Emissions in the Transportation Sector

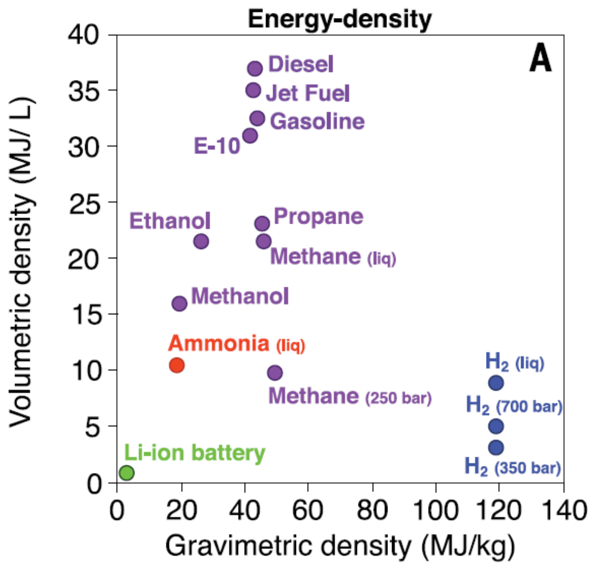
In the transportation sector, there are few good carbon-neutral alternatives to conventional fossil fuels. The attributes of petroleum-based liquid fuels (e.g., gasoline, diesel, jet fuel) make them well-suited to the needs of transportation. In particular, low transmission and distribution costs (e.g., via pipelines) and fast refueling lend themselves to an easy-to-use distributed fueling infrastructure. And the high energy density is hard to replicate with other alternatives.

Electricity is emerging as a promising substitute for petroleum fuels. When coupled with decarbonization of electricity, electrification of vehicles could deliver deep emissions reductions.[59] As the cost and performance of Li-ion batteries continue to improve, electric vehicles are projected to capture growing shares of the market for passenger vehicles. The annualized total cost of ownership for passenger cars and other light-duty vehicles is projected to reach cost parity with conventional internal combustion engine vehicles between 2020 and 2030.[60] Several automakers—including GM, Toyota, and Volvo—have announced plans to electrify their entire fleet of offerings by the mid-2020s.[61] As batteries become better—cheaper and more energy dense—applications will also open up in the medium- and heavy-duty vehicle sectors, though electrification is anticipated to occur more gradually in these sectors.[62]

However, full electrification of road transport still faces significant challenges, including the high upfront costs of batteries and lack of charging infrastructure. This transition could be eased by new technologies, including faster charging devices and cheaper batteries with a larger range. Under current market trends and with current technologies, electric vehicles are projected to capture 19 percent of market share in the United States by 2050, which highlights the magnitude of the challenge of full electrification.[63]

Additionally, batteries will not be able to replace internal combustion engines in all transportation sectors. Petroleum-based fuels have both high volumetric energy density (energy per volume) and high gravimetric energy density (energy per weight), both of which are important for transporting large volumes of goods or numbers of people. The Li-ion batteries that enable electrification of passenger vehicles are several orders of magnitude away from matching the energy density of current liquid fuels (figure 8) and are unlikely to ever meet the performance requirements for aviation, shipping, and long-distance road transport.

Figure 8: Volumetric and gravimetric energy density of transportation fuels



Scale of difficult-to-eliminate emissions in the transportation sector: Aviation, the fastest growing source of transportation-related emissions, currently accounts for 2 percent (800 million metric tons CO_2) of global energy-related carbon dioxide emissions and 5 percent (240 million metric tons CO_2) of U.S. energy-related emissions.[64] Shipping accounts for 3 percent (1,100 million metric tons CO_2) of global emissions and 2 percent (110 million metric tons CO_2) of U.S. emissions. And long-distance road transport is estimated to account for less than 1 percent (300 million metric tons CO_2) of global emissions and about 1 percent (60 million metric tons CO_2) of U.S. emissions.

Possible solutions: Biofuels such as corn ethanol and biodiesel are currently the only options for reducing the carbon intensity in hard-to-decarbonize transportation sectors due to their similarity to fossil fuels and relatively high energy density. However, lifecycle emissions from biofuels—which account for the fertilizer, energy, and other inputs needed to grow, harvest, and convert biomass into fuel—are significant, and the use of biofuels will not be sufficient to achieve a zero-carbon transportation system.[65]

Use of carbon capture, utilization, and storage (CCUS) technologies with biofuels production would reduce the carbon intensity of biofuels. The conversion of biomass into fuels (e.g., the fermentation of corn to produce ethanol) releases high-concentration streams of carbon dioxide as a byproduct, thus potentially making the biofuels industry an early adopter of CCUS.[66]

Carbon-neutral fuels that could potentially replace fossil fuels include hydrogen, ammonia, and synthetic hydrocarbons. However, all options face significant cost and performance barriers—and are far from commercial. Developing these options will require significant investment across the full innovation spectrum, from basic science research to technology development and commercialization.

Difficult-to-Eliminate Emissions in the Industrial Sector

The industrial sector is generally recognized as more challenging to decarbonize than the transportation and buildings sectors. There are two major obstacles to achieving a carbon-neutral industrial sector:

- **Process/feedstock emissions** result directly from industrial processes and are independent of the source of energy used to drive the process. For example, the calcination of limestone to make cement produces carbon dioxide as a byproduct. Similarly, ammonia production, which uses natural gas as a feedstock, results in direct emissions of CO_2. These emissions can only be reduced by changing feedstocks or processes, and cannot be eliminated by switching to low-carbon energy sources.

- **High-temperature heat** used in many industrial processes is primarily generated by combusting fossil fuels. Calcination of limestone to make cement (~2,500°F), melting iron ore to produce steel (~2,200°F), and steam cracking to produce ethylene (~1,500°F)—a key feedstock for plastics and other petrochemicals—all use fossil fuel combustion to generate high temperatures.[67] Most emphasis on electrification of heat has focused on lower-temperature applications, such as washing and sterilizing, which require temperatures of less than 750°F.[68] Electrification of high-temperature heat poses cost and technical barriers, and may require significant changes to industrial processes.

"Difficult-to-eliminate" emissions in the industrial sector include process emissions from chemical transformations and emissions from high-temperature heat.

Scale of difficult-to-eliminate emissions in the industrial sector: There is no standard approach for identifying "difficult-to-eliminate" emissions, and the lack of data and large number of industrial processes makes a full accounting challenging. Cement (3 $GtCO_2$) and iron and steel production (2.9 $GtCO_2$) are the largest sources of industrial carbon dioxide, followed by ammonia (0.5 $GtCO_2$) and ethylene (0.2 $GtCO_2$).[69] Global emissions from these sectors alone have surpassed total annual U.S. carbon emissions, and demand for these products is projected to grow, especially in the developing world.

The *Science* study identified 1.7 $GtCO_2$ from iron and steel production and 1.3 $GtCO_2$ from cement production as "difficult-to-eliminate" because these emissions resulted from the processes or feedstocks used in production. However, this estimate likely undercounts difficult-to-eliminate emissions because the study does not include emissions from high-temperature process heat or emissions from other sectors.

In the United States, the five largest sources of process CO_2 emissions—including the production of iron and steel, cement, petrochemicals, lime, and ammonia—accounted for 135 million metric tons of CO_2 emissions in 2016, or 82 percent of total domestic process emissions.[70] The five largest energy-consuming industries—refining, bulk chemicals, iron and steel, mining, and food products—accounted for 830 million metric tons of CO_2 in 2016, or about 60 percent of total industrial energy-related carbon emissions; however, it's not clear how much of this is related to high-temperature heat.[71]

Possible solutions: Capturing the carbon emitted from industrial processes may be the only option for process/feedstock emissions. High-temperature heat could be provided by the replacement of fossil fuels with biomass. Additionally, some advanced nuclear concepts operate at higher temperatures than the current light-water reactor designs, and could be used as a source of process heat. Electric arc furnaces can provide process heat for some kinds of steel. Hydrogen produced from electrolysis using zero-carbon electricity, or other carbon-neutral fuels, could also be combusted to generate high-temperature heat. With the exception of biomass combustion for heat, all options are far from commercial and require substantial RD&D to drive down costs.

The three "hard-to-decarbonize" sectors—highly reliable electricity, hard-to-electrify transportation, and industrial process emissions and high-temperature heat—are not sufficiently represented in the federal energy RD&D programs.

An Innovation Agenda Part 2: Technology Missions for Hard-to-Decarbonize Sectors

The three "hard-to-decarbonize" sectors—highly reliable electricity, hard-to-electrify transportation (aviation, shipping, and long-distance road transport), and industrial process emissions and high-temperature heat—are not sufficiently represented in the federal energy RD&D programs, and constitute gaps in the federal clean energy innovation agenda.

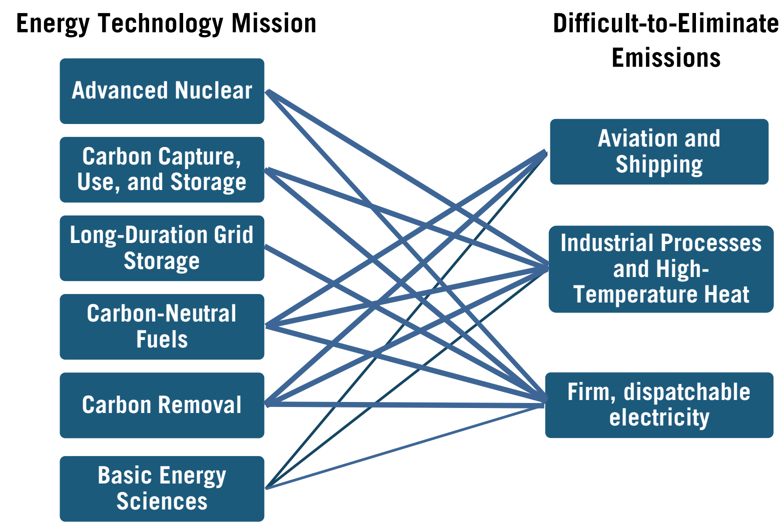
This paper proposes five "Technology Missions" to fill these gaps. In many cases, a single technology solution can address more than one set of difficult-to-decarbonize sectors.

- **Advanced nuclear energy** that is flexibly operated can provide firm, dispatchable low-carbon electricity; and many advanced nuclear concepts can also provide high-temperature process heat for water desalination, hydrogen production, and other industrial processes.
- **Carbon capture, utilization, and storage (CCUS)** can reduce emissions from coal and natural gas power plants, providing a source of low-carbon firm, dispatchable electricity. CCUS can also capture hard-to-decarbonize process emissions in the industrial sector, as well as biofuel process emissions in the transportation sector.
- **Long-duration grid storage** that can store large quantities of electricity on seasonal timescales could enable greater penetration of variable renewables (wind and solar) to provide zero-carbon firm electricity year-round.
- **Carbon-neutral fuels** such as hydrogen, ammonia, and synthetic hydrocarbons could enable decarbonization of aviation, shipping, and long-distance transport—and also provide high-temperature heat for the industrial sector, or long-duration grid storage.
- **Carbon dioxide removal (CDR)** technologies the remove CO_2 directly from the atmosphere and result in net-negative emissions provide insurance against the possibility that the world may not be able to reduce carbon pollution fast enough to avoid dangerous levels of warming.

Each technology mission requires fundamental breakthroughs in basic energy sciences—and the energy innovation agenda should address the entire innovation ecosystem, from basic research through technology development and commercialization. This paper proposes an additional Technology Mission, connecting **basic energy science** research with the four others listed above.

Figure 9 displays the six Technology Missions (left column) mapped to the three difficult-to-decarbonize sectors (right column). These Missions are described in more detail in the following sections.

Figure 9: In most cases, each Technology Mission can address more than one set of difficult-to-eliminate emissions



INNOVATION GAP: ADVANCED NUCLEAR ENERGY

With 98 commercial reactors, the United States has the largest nuclear energy industry in the world after taking the early lead in the development and deployment of nuclear technologies. Nuclear power accounts for 20 percent of U.S. electricity generation and produces more carbon-free electricity than hydropower, wind, and solar combined.[72]

However, the development of nuclear technologies has stagnated, and the domestic nuclear industry has not grown in decades—as only two reactors have come online in the last 25 years. Two new advanced light-water reactors are under construction at the Vogtle facility in Georgia and are scheduled to begin operating by 2022. However, construction of the Vogtle reactors has been subject to delays and cost overruns, with two identical reactors in South Carolina being cancelled due to rising construction costs.[73]

Many existing reactors have been unable to recover their costs in competitive markets, in part because the markets do not value the carbon-free attribute of electricity generated from nuclear plants. Seven reactors have retired since 2013, and 12 more have submitted plans to retire by 2025, potentially resulting in the loss of 11.7 gigawatts (GW) of carbon-free electricity between now and 2025.[74] The rising costs of new nuclear plants combined with the wave of recent and planned retirements of existing plants has led some analysts to refer to nuclear power as “the vanishing low-carbon wedge.”[75]

New Nuclear Reactors Face Significant Challenges

The main barrier to new nuclear power is high construction costs.[76] Nuclear plants are currently built and operated as large ~1 GW “baseload” power plants. The large size of these plants requires a high capital investment and limits the locations such plants can be sited. Additionally, much of the construction and design is site-specific, meaning construction of new nuclear power plants has not seen the “nth-of-a-kind” cost reductions from economies of replication that most technologies see with greater levels of deployment.

Disposal of used nuclear fuel also poses challenges to the long-term viability of nuclear power. The United States is home to more than 78,000 tons of used nuclear fuel, most of which is kept in cooling ponds or in dry-cask storage on reactor sites. The Nuclear Waste Policy Act of 1987 directs the Department of Energy (DOE) to design and construct a geologic repository at Yucca Mountain in Nevada for permanent disposal of used nuclear fuel. However, the site has not opened, and no used nuclear fuel has yet been delivered to Yucca for disposal. In 2012, a bipartisan Blue Ribbon Commission on the future of nuclear power developed a new waste management strategy and made a number of recommendations for a geologic repository; however, the recommendations have yet to be enacted by Congress.[77]

The rising costs of new nuclear plants combined with the wave of recent and planned retirements of existing plants has led some analysts to refer to nuclear power as “the vanishing low-carbon wedge.”

Innovation Is Needed to Address these Challenges

Innovation in nuclear technologies can address many of the challenges the current generation of nuclear power plants faces. Most new nuclear concepts are small modular reactors (SMRs) of less than 300 megawatts (MW) in capacity.[78] The term “modular” encompasses a shift away from primarily field construction of site-specific plant designs to a more serial manufacturing of standardized plants. Design standardization and factory production would enable nuclear plants to take advantage of the manufacturing sector’s high productivity and ability to reduce costs over time.[79] And because of their smaller size, SMRs offer a lower initial capital investment, greater scalability, and siting flexibility.[80] MIT’s *Future of Nuclear Energy* study found that design standardization—such as with SMRs—is essential to reducing capital costs of new nuclear plants.[81]

SMRs can be based on either existing light-water reactor (LWR) technologies—which use water as a moderator and coolant—or next-generation advanced nuclear designs. Many advanced nuclear technologies offer the promise of superior performance in addition to lower costs. Some of these designs would operate at higher temperatures, which would improve the efficiency of conversion of thermal energy to electricity and also enable nuclear reactors to provide high-temperature heat for many industrial processes. Some designs could operate for decades without refueling, which would reduce the volume of spent nuclear fuel requiring disposal. Many also incorporate passive or “walk-away” safety features that do not require a human operator or external electric power supply in order to bring the reactor to a safe shutdown state in the event of an emergency.

Table 1: Advanced (Non-light-water) reactor concepts[82]

Advanced Reactor Concept	Neutron Spectrum (Fast/Thermal)	Coolant	Temperature (Degrees C)
Gas-cooled fast reactor (GFR)	Fast	Helium	850
Lead-cooled fast reactor (LFR)	Fast	Lead-Bismuth Eutectic	550–800
Molten salt reactor (MSR)	Thermal or Fast	Fluoride Salts	700–1,000
Sodium-cooled fast reactor (SFR)	Fast	Sodium	550
Supercritical water-cooled reactor (SCWR)	Thermal or Fast	Water	510–550
High-temperature gas-cooled reactor (HTGR)	Thermal	Helium	1,000

The Generation IV International Forum has identified six main types of advanced reactors (table 1). One prominent design that has been supported by DOE is the high-temperature gas-cooled reactor (HTGR), which uses graphite as a moderator and helium as a coolant. The use of helium rather than water as a coolant enables substantially higher temperatures than current LWR technologies, yielding thermal efficiencies as high as 50 percent compared with the 32–34 percent efficiency of current LWRs. HTGRs also incorporate many passive safety features.[83]

BOX 2: NUCLEAR ENERGY IN DEEP DECARBONIZATION SCENARIOS

Nuclear energy fills an essential role as a carbon-free dispatchable energy technology in most deep decarbonization pathways. The International Energy Agency (IEA) estimates that nuclear energy currently results in avoided emissions of about 1.3 to 2.6 gigatonnes of carbon dioxide ($GtCO_2$) every year, assuming it replaces either gas- or coal-fired generation. Since 1980, nuclear power has led to cumulative emissions reductions of over 60 gigatonnes of CO_2.[84] In IEA's Sustainable Development Scenario, the share of global electricity production from nuclear power rises from 10.3 percent in 2017 to 14.9 percent in 2040, requiring nuclear capacity to more than double from 419 GW in 2017 to 720 GW in 2040. Growth in nuclear power accounts for 6 percent of the emissions reductions needed in the electric power sector.[85]

Domestically, nuclear power continues to be significant source of carbon-free electricity in most of the *U.S. Mid-Century Strategy for Deep Decarbonization* (MCS) scenarios, which are designed to reduce U.S. emissions by 80 percent below 2005 levels by 2050. The need for nuclear power increases in MCS scenarios in which other technologies—such as carbon capture, utilization, and storage (CCUS) or bioenergy—fail to reach technical maturity and achieve commercial-scale deployment. For example, the "No-CCUS" scenario requires 60 percent more generation from nuclear energy than the reference Benchmark Scenario, with annual capacity additions of 6 GW between now and 2050.[86]

Four of the advanced reactor designs are "fast reactors" (also called "fast neutron reactors") that do not use a moderator to slow down neutrons from the fission reactions. Fast reactors can use liquid metal, gas, or molten salt as a coolant, and typically burn nuclear fuel more efficiently than conventional LWR reactors, resulting in lower amounts of waste. Some previous efforts to develop advanced nuclear reactor concepts have focused on large, gigawatt-scale reactor designs, similar to today's nuclear power plants. However, such efforts would likely be plagued by the same challenges—long construction times, high capital costs, and site-specific design and construction—facing LWR-based technologies. Newer advanced reactor designs have focused primarily on SMRs.

Innovation in systems integration can also help nuclear plants (both existing and new) provide greater flexibility, as well as other energy services. On the operational side, innovations and changes in regulatory policies and market design could enable nuclear power to provide greater flexibility to the grid—e.g., by varying output, or providing frequency regulation or operating reserves—which would also reduce curtailment from variable renewable sources such as wind and solar. Alternatively, tighter integration with other energy services could allow fixed electricity generation from a nuclear plant to be diverted to hydrogen production, water desalination, or energy storage as an alternative to energy delivery to the grid. [87] And many advanced reactor concepts could provide process heat for industrial applications for which there are few zero-carbon options.[88]

The United States lags other nations—notably Russia and China—in the development of advanced nuclear reactors. Recent actions in Congress and by the Administration aim to jumpstart innovation in advanced nuclear technologies.

An Advanced Nuclear Energy Technology Mission

The United States has been investing in advanced nuclear technologies for decades, but this investment has not translated into a new generation of low-cost nuclear power. Most of the nuclear energy research and development (R&D) investment has occurred through DOE's Office of Nuclear Energy (NE). A recent analysis of NE's budget going back two decades to 1998 found shifting priorities, inconsistent funding, and a focus on incumbent technologies have resulted in few advances. And even if the program had been well-designed, federal investment has been insufficient to demonstrate even a single non-light-water advanced nuclear reactor technology.[89]

Recent action in Congress and by the Administration aims to jumpstart R&D in advanced nuclear technologies. In the last budget cycle, the Administration proposed a new R&D subprogram focused on Advanced (non-light-water) SMRs, to which Congress appropriated $100 million in its FY 2019 budget.[90]

These efforts are laudatory, and Congress and the Administration should sustain these investments in advanced nuclear R&D. However, the United States lags behind other nations—notably Russia and China—in the development of advanced nuclear reactors.[91] And out of a budget of $1.3 billion, DOE-NE still spends only 16 percent on advanced nuclear reactor designs, with the rest going to support incumbent technologies, enabling or cross-cutting technologies, and facilities maintenance.[92] **DOE should restructure NE to prioritize advanced nuclear reactor technologies, and Congress should provide sufficient funding to demonstrate at least one advanced reactor design.**

Other efforts seek to unlock private-sector innovation to spur the development of advanced nuclear technologies. There are currently around 60 companies and research institutions across the country pursuing advanced nuclear reactor concepts.[93] Many of the designs developed by these companies require high-assay, low-enriched uranium (HA-LEU) fuels—fuels that are enriched to slightly higher levels of uranium 235 (U-235) than the current light-water designs.[94] A recent survey found that two-thirds of leading U.S.-based advanced reactor developers rated an "assured supply of High Assay LEU" as either urgent or important. As a result, Congress directed DOE to develop a plan and cost profile for producing HA-LEU in its FY 2019 budget.[95] While it is a good first step, progress will stall if the advanced reactor community does not have a sufficient stockpile of HA-LEU for R&D in the near term. **Congress should direct DOE to establish a strategic reserve of HA-LEU fuel that is compatible with the fueling requirements of advanced reactor concepts.**

Additionally, many advanced reactor designs are fast reactors that do not use a moderator to slow down neutrons. Development of these reactor concepts will require testing of materials and fuel designs in a fast-neutron environment, but the United States currently has no fast-neutron research facilities that would enable developers to test their designs. In contrast, Russia has two operating commercial-scale fast reactors, and China launched a pilot-scale fast reactor for research and testing in 2011. In September 2018 Congress passed the Nuclear Energy Innovation Capabilities Act to develop domestic fast-reactor research facilities on par with international facilities. The act directs DOE to assess the need for a Versatile Test Reactor (VTR) user facility that would enable testing in fast-neutron environments.[96] And in FY 2019, Congress appropriated $65 million toward the design and construction of a VTR.[97] **Congress should follow through on its early support for the VTR, and commit to its construction to enable testing of materials and fuel designs in a fast-neutron environment.**[98]

The use of nuclear energy to provide other energy services (than electricity) such as district heating for buildings, industrial process heat, or hydrogen or other carbon-neutral fuels production will require additional innovation and tighter integration with energy end uses.[99] **DOE should expand R&D into other applications for nuclear energy, including district heating in buildings, desalination, petroleum refining, hydrogen and ammonia production, and other industrial process heat applications.**

Research into advanced nuclear concepts should embrace the entire innovation spectrum, from fundamental research through commercialization. DOE's Office of Basic Energy Sciences (BES) already conducts basic research in coolants, advanced fuels, and materials design for the extreme environments of nuclear reactors.[100] DOE should expand the linkages between basic science research in BES and the applied research, development, and demonstration (RD&D) in other federal agencies, and **BES should establish integrated Energy Frontier Research Centers (EFRCs) to pursue basic materials research needs related to advanced nuclear reactor designs.**

INNOVATION GAP: CARBON CAPTURE, UTILIZATION, AND STORAGE (CCUS)

By capturing the carbon pollution from fossil fuel combustion for subsequent use or sequestration, carbon capture, utilization, and storage (CCUS) technologies have the ability to turn fossil fuels into low-carbon energy sources, enabling the continued use of cheap fossil energy, including coal, in a low-carbon energy system, while also expanding the portfolio of climate mitigation options. CCUS is also currently the only option for decarbonizing many industrial processes—such as the production of ethanol, fertilizers, plastics, cement, and steel—for which carbon-neutral alternatives do not exist.

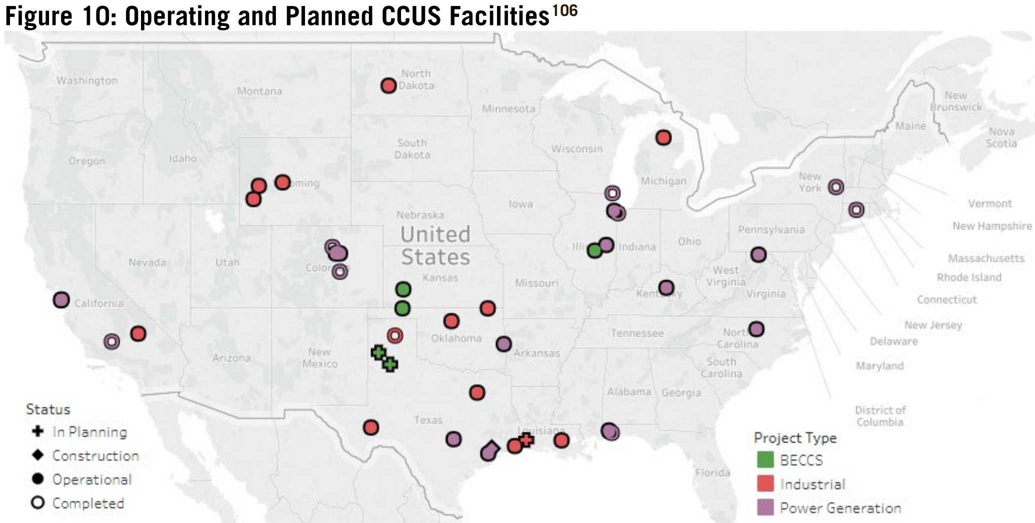
The Intergovernmental Panel on Climate Change (IPCC) has concluded that without CCUS, the costs of climate mitigation could increase by 138 percent, and that maintaining warming below 2°C may not even be possible without the availability of CCUS technologies.[101]

Without carbon capture, utilization, and storage (CCUS) technologies, the costs of climate mitigation could more than double, and maintaining warming below 2°C may not even be possible without the availability of CCUS technologies.

CCUS: On the Cusp of a Breakthrough? Not So Fast

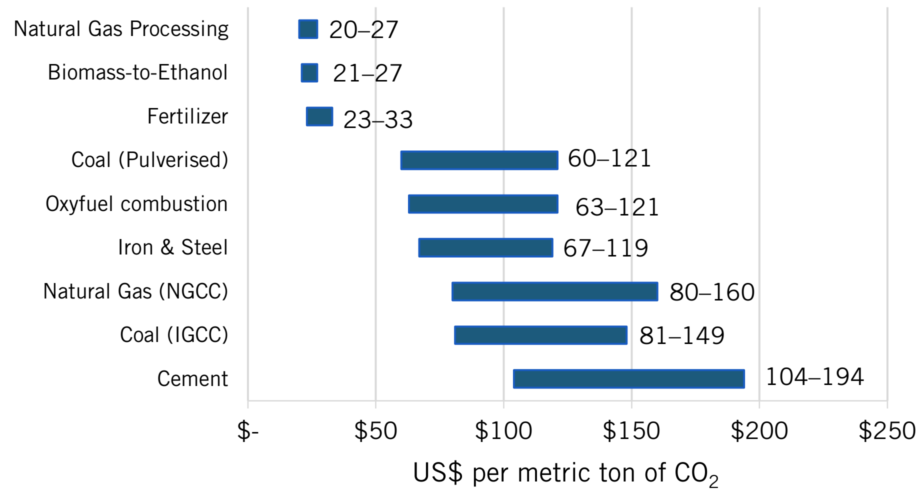
CCUS may be on the cusp of significant new buildouts and cost reductions. DOE's Industrial Carbon Capture and Storage (ICCS) program culminated in the successful launch of CCUS demonstration projects at the Port Arthur fertilizer facility in 2013 and the Archer Daniels Midland ethanol plant in 2017.[102] The world's largest successful post-combustion carbon-capture facility came online at the Petra Nova coal power plant in Texas in 2017.[103] A new pilot-scale natural gas oxy-combustion demonstration began operating at the NET Power facility in Texas in 2018.[104] And in February of 2018, Congress expanded and extended the 45Q tax credit to incentivize greater utilization and storage of captured CO_2.[105]

Figure 10: Operating and Planned CCUS Facilities[106]



Despite this progress, CCUS is "Not on Track" to achieve the scale needed for deep emissions reductions, according to the International Energy Agency.[107] Even with the 45Q tax credit, current state-of-the-art technologies for capturing and storing carbon pollution are still too expensive to spur widespread deployment in the largest emitting sectors, particularly power plants and cement and steel production.

Figure 11: Costs of capture, compression, and transportation from different sources[108]



The biggest barrier to deployment is cost. In general, the cost of carbon capture scales with the dilution of carbon dioxide in the waste stream. Some industrial sources produce near-pure CO_2. For example, the fermentation of corn to produce ethanol releases high-purity (~99 percent) CO_2 which can be captured, dehydrated, and pressurized for transport to a site for use or storage at a cost of $21 to $27 per metric ton of CO_2 (figure 11). In natural gas processing, carbon dioxide is coproduced with natural gas and must be removed from the CO_2-natural gas mixture prior to transmission in natural gas pipelines. Niche industrial sectors such as these are "low-hanging fruit," and provide opportunities for early deployment of CCUS. But the scale of emissions from these sectors (45 million metric tons of CO_2 per year in the case of the domestic ethanol industry) is too low to make much of a dent in global emissions.[109]

Power plants and major industrial sources yield more dilute waste streams or have other process or integration challenges that make CCUS more expensive, requiring additional R&D to drive down carbon capture costs. Carbon dioxide makes up only 12–15 percent of the flue gas from a coal-fired power plant, and only 3–4 percent from natural gas plants.[110] In 2017, coal and natural gas power plants accounted for 1,710 million metric tons of CO_2 ($MtCO_2$) emissions domestically, and 12,840 $MtCO_2$ worldwide.[111] In the industrial sector, worldwide production of cement (3,000 $MtCO_2$) and steel (2,900 $MtCO_2$) together emitted 5,900 million metrics tons of carbon dioxide in 2014, more than the entire U.S. energy sector.[112] Costs will have to decline further in order for CCUS to be adopted at climate-relevant scales.[113]

BOX 3: CCUS IN DEEP DECARBONIZATION SCENARIOS

CCUS technologies are essential in the transition to a low-carbon economy, accounting for 12 percent of cumulative emissions reductions by 2050 in the International Energy Agency's (IEA's) 2°C Scenario. In the power sector, fossil-fuel generation with CCUS is projected to account for 52 billion metric tons of captured CO_2 by 2050, requiring 850 GW of fossil power equipped with CCUS worldwide by mid-century.[114] Another 29 billion metric tons of captured CO_2 would come from industrial sectors where there are currently limited or no alternatives for achieving deep emission reductions, including cement and steel production.

CCUS also plays a prominent role in domestic low-carbon scenarios. The *U.S. Mid-Century Strategy* benchmark scenario includes new capacity additions of fossil generation with CCUS at an average rate of more than 10 gigawatts per year between 2036 and 2050.[115]

Innovation Will Be Needed to Reduce Costs Further

DOE is pursuing three different carbon capture approaches: post-combustion, pre-combustion, and oxy-combustion. Post-combustion capture technologies that separate CO_2 from the flue exhaust after combustion are important because they can be used to retrofit existing fossil power plants in a low-carbon world. Pre-combustion technologies separate carbon from the fuel prior to combustion, for example, by gasifying coal to produce a mixture of hydrogen and carbon dioxide, separating the CO_2, and combusting the hydrogen in a combined-cycle electric generator. Oxy-combustion approaches separate oxygen from air and combust the fuel in a pure-oxygen environment, producing higher concentrations of CO_2 in the flue exhaust that facilitates capture. Each approach has potential advantages, but so far only post-combustion capture for coal (Petra Nova) and oxy-combustion for gas (NET Power) have been demonstrated successfully.[116]

Many of the research needs—in advanced solvents, sorbents, and membranes—for carbon capture are crosscutting across all sources and capture processes. However, each source also presents its own unique R&D needs. For example, the flue gas from natural gas power plants contains a higher oxygen content than flue gas from coal combustion, which can lead to faster degradation of the amine solvent in post-combustion capture systems. Additionally, each source has unique integration challenges, requiring demonstration of industry-specific carbon capture technologies at a pilot scale to address the key issues associated with optimizing carbon capture systems for a particular industrial sector.

Geologic storage of carbon dioxide on a large scale presents a variety of technological and societal challenges. The long-term security of sequestration in specific geological formations must be demonstrated to ensure captured carbon dioxide is safely and permanently stored. An equally secure pipeline system for transporting carbon dioxide from power plants and industrial facilities to storage sites must also be constructed.[117]

Turning carbon dioxide into a product that has value is another innovative approach to spurring carbon capture from industrial sources and power plants. Currently, the largest market for CO_2 is in enhanced oil recovery (CO_2-EOR), in which pressurized CO_2 is pumped underground to stimulate oil production from wells that are no longer producing through conventional approaches.[118] Other potential uses include turning captured carbon dioxide into products, such as building materials, plastics, and even fuels (see the section on carbon-neutral fuels).[119] If brought to fruition, these approaches would expand the market for CO_2 and induce greater CO_2 capture. In October 2018, the National Academy of Sciences (NAS) released a study assessing the current status of carbon utilization pathways and developing a detailed R&D agenda for carbon utilization.[120]

A CCUS Technology Mission

CCUS technologies are a potentially important export market for nations that develop cost-effective technologies, which is why many are investing heavily. Half of the world's 18 operating large-scale CCUS facilities are located in the United States, as a consequence of early U.S. investment and leadership in the sector. However, 18 of the 20 large-scale CCUS facilities under construction or development are in other countries, with the majority in China.[121] Mission Innovation—a global initiative to double governments' clean energy R&D investments—has launched an "Innovation Challenge" focused on accelerating innovation in CCUS.[122] And the Clean Energy Ministerial has launched a CCUS initiative to spur private-sector investment and deployment of CCUS technologies around the world.[123]

A robust carbon capture demonstration program would leverage other CCUS incentives such as the 45Q tax credit for carbon storage.

The United States has already invested heavily to develop carbon capture technologies for coal-fired power plants, and these investments are beginning to pay off, with the successful operations of the world's largest post-combustion capture facility at the Petra Nova coal power plant in Texas. However, what works for a coal power plant is not directly portable to a natural gas plant or other industrial sources such as cement and steel production plants. Integrating and optimizing carbon capture technologies with other sources faces technical hurdles unique to each source. DOE has already recommended demonstration of carbon capture at a natural gas power plant, but Congress has yet to fund the proposal. **Congress should direct DOE to establish a carbon capture demonstration program that funds first-of-a-kind demonstration projects for carbon capture at natural gas, steel, concrete, and other large sources of carbon dioxide.**[124] A carbon capture demonstration program would leverage other CCUS incentives such as the 45Q tax credit for carbon storage.

DOE should also expand the Title XVII Loan Program to cover carbon capture at industrial facilities. Making industrial carbon capture facilities eligible for Title XVII loans could help remove barriers associated with financing and high capital costs.[125]

DOE should also continue to develop transformational carbon capture technologies beyond the current amine solvent technologies. However, most of DOE's carbon capture R&D is housed within the Coal CCS & Power Systems program. **DOE should establish a single carbon capture R&D program—outside the coal program office—that includes other carbon sources such as natural gas power plants and industrial sources.**

Carbon utilization—turning carbon dioxide from a waste product into a product of value—is key to expanding the market for carbon dioxide and incenting greater carbon capture. But many potential uses, such as turning captured CO_2 into carbon nanotubes or synthetic hydrocarbon fuels, are far from commercialization. The National Science Foundation (NSF) currently funds 10 projects totaling $3.4 million in carbon dioxide utilization.[126] In FY 2019, DOE increased funding in its applied R&D program for carbon utilization from $12 million to $20 million.[127] And several Advanced Research Projects Agency-Energy (ARPA-E) programs have funded projects that would turn carbon dioxide into fuels or other high-value chemicals.[128] But these levels are insufficient to address the full suite of R&D needs identified in a recent report on carbon utilization by NAS. **DOE and NSF should expand investment in basic and applied R&D and implement the recommendations of the recent National Academies report on carbon utilization.**

Finally, DOE should continue to support R&D in the safe geologic sequestration of carbon in underground saline aquifers and depleted oil and gas fields. **DOE should also expand its storage program to include basalt and other carbon-absorbing formations, and should work with the United States Geological Survey (USGS) to characterize and explore additional storage opportunities.**

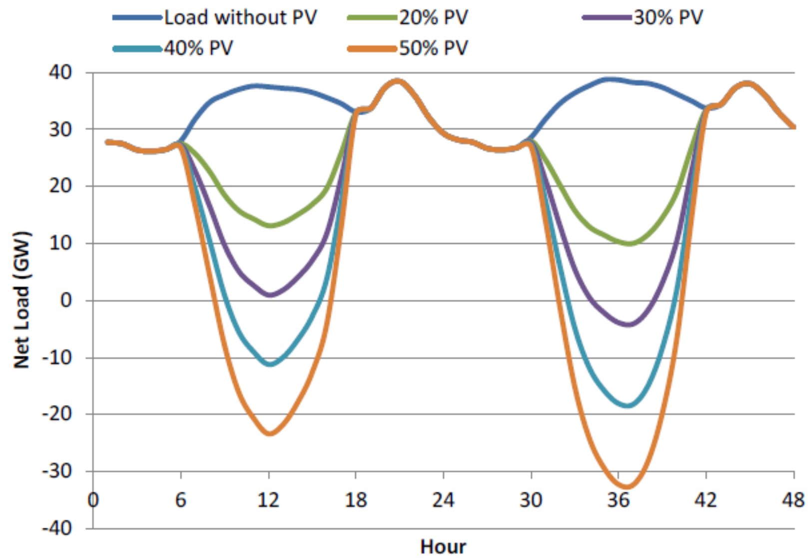
INNOVATION GAP: LONG-DURATION GRID STORAGE

Energy storage may be essential to enabling greater shares of electricity from variable renewable sources such as wind and solar photovoltaics (PV), and the present enthusiasm in the climate and energy communities about systems that combine lithium-ion (Li-ion) batteries with variable renewables is understandable. These batteries can fill in gaps of up to a few hours when the sun is not shining or the wind is not blowing. Additionally, storage can enable fixed generation from inflexible resources such as nuclear to be stored and used when needed. However, because of inherent technological limitations, it is unlikely that Li-ion batteries will ever become good enough or cheap enough to solve the problem of variability for periods of more than a few hours. For renewables to reach penetrations suggested in many deep decarbonization scenarios, electricity systems will need technologies that provide affordable, reliable long-duration storage at grid scale.

Existing Energy Storage Is Insufficient to Support Future Needs

The amount of electricity variable renewables can generate differs greatly from winter to summer, noon to night, and even minute to minute as winds shift or clouds obscure the sun. The larger the share of variable resources on a grid, the more acute the challenge of matching supply with demand becomes. Figure 12 shows the challenges of meeting hourly demand for electricity under increasing penetrations of solar energy for two model spring days in California. As the share of solar power in the state's generation mix rises toward 50 percent (from about 15 percent today), the daily variation in output could become greater than the total load. The net load—the difference between electricity demand and electricity production from variable generation—would become negative under high-penetration scenarios, with as much as 20 to 30 gigawatts of solar energy being curtailed (i.e., discarded) at midday.[129] Energy storage of sufficient duration and capacity would reduce curtailment by storing excess solar energy during the day and providing it to the grid after the sun has set.[130] A similar story plays out for wind power combined with storage.

Figure 12: Modeled load profiles for California during two days in the spring[131]



BOX 4: ENERGY STORAGE IN LOW-CARBON SCENARIOS

IEA's Sustainable Development Scenario requires an additional 80 GW of storage capacity by 2030. The deployment rate in 2017 was insufficient to meet this target, leading to IEA's designation of energy storage as "Not on Track" to meet its sustainability targets.[132] Additional policy support and innovation in storage technologies is required to meet this target. The *U.S. Mid-Century Strategy* also finds that "high penetration of wind and solar power generation in some regions may require investments in storage," although the pathways envisioned in the MCS did not specify energy storage targets.[133]

The two most common technologies used for grid storage today demonstrate the value that storage provides to the grid. Li-ion batteries, akin to those used in cell phones, can hold charges for several hours and can discharge a lot of energy very quickly. Their first major use on the grid in the United States was to provide frequency response on short time scales (on the order of minutes).[134] As costs decline and storage duration extends to the hourly range, paired "storage + solar" systems could soon reach cost parity with natural gas "peaker" plants, which supply power during peak demand when energy prices are high.[135]

Pumped-hydropower storage ("pumped-hydro"), by contrast, can operate on a far longer time scale. As the name suggests, pumped-hydro systems store energy by using electricity to pump water from a lower-elevation reservoir to a higher-elevation reservoir. This energy is transformed back into electricity just as the energy in water behind any other dam would be: by running through turbines. Pumped-hydro systems generally can store far more energy and discharge it in much greater volumes than Li-ion batteries.[136]

However, both technologies have their limits. Li-ion batteries are highly unlikely to become cheap enough and good enough to support long-duration applications that would allow grids with very high renewable penetration to perform as well as today's fossil-fuel-dependent grids. As the authors of an editorial in *Nature Energy* concluded, "a consensus has now formed that lithium-ion batteries will not be able to satisfy the energy storage requirements of the long-term future, and new battery technologies are urgently needed."[137] And further deployment of pumped-hydro systems has halted in recent decades due to geographical limitations and environmental objections. If the trend toward grids that rely more heavily on wind and solar PV continues, energy storage will become increasingly important on all time scales. Indeed, the trend toward renewables will stall if storage systems that allow such grids of the future to perform at least as well and as affordably as today's do not become available.

For renewables to reach penetrations suggested in many deep decarbonization scenarios, electricity systems will need technologies that provide affordable, reliable long-duration storage at grid scale.

Additional Innovation Is Needed to Support Long-Duration Storage

Several technologies have the potential to provide long-duration storage. Pumped-hydro is a mature technology that can store energy for months and deliver electricity economically under many circumstances. However, deployment has stalled for many years, and innovation is required to kick-start it. Other technologies, including flow and liquid-metal batteries, thermal storage, and compressed air, hold the promise of providing long-duration storage, but are not yet mature, much less economically proven. A diverse portfolio of alternatives should be explored in the coming decade so viable options are available when Li-ion batteries reach their limit.[138]

About 21 GW of pumped-hydro capacity are currently operating in the United States. DOE's 2016 *Hydropower Vision* report estimated that more than 35 GW of new pumped-hydro capacity could theoretically be installed by 2050 if innovations in technology, market design, and regulation are realized and environmental objections are mitigated. Undersea and underground designs, for instance, could radically expand the range of pumped-hydro locations while reducing environmental impacts.[139]

Flow batteries and liquid-metal batteries are two non-Li-ion battery technologies with potential grid applications. Flow batteries store energy in two separated tanks of fluid and generate electricity by pumping the fluids together in "stacks," rather than integrating storage and generation in cells such as Li-ion batteries. Flow batteries generally target a sweet spot of five to ten hours' duration. At the low end of this range, flow batteries face growing competition from Li-ion-based systems; the high end falls short of daily or seasonal storage but could fill an important intermediate niche.[140] Liquid-metal batteries can potentially be built on a large scale for grid storage applications of up to 12 hours' duration, and use Earth-abundant, low-cost materials. Both technologies offer potential applications beyond the capability of Li-ion-based systems, but face engineering challenges that will require additional innovation to reach full-scale commercialization.

Thermal storage systems store excess energy in a heat reservoir—typically of molten salt—which can later be released by heating a working fluid that drives a turbine, as in conventional power plants. If the heat reservoir is sufficiently large and adequately insulated, thermal storage can provide long-duration grid storage. At Crescent Dunes in Nevada, for instance, a molten salt-steam system provides 10 hours of storage for a 110 MW concentrating solar power (CSP) plant, enough to supply power to 75,000 homes. However, Crescent Dunes, a first-of-its-kind plant that benefited from a federal loan guarantee, sells power for about twice the price of a natural-gas-fired plant. Further innovation is required to drop this price by another 50 percent or more, and more importantly, to decouple thermal storage from CSP, so that it can be sited independently.[141]

Compressed air energy storage (CAES) uses electricity to run compressors that pack air into a confined space, e.g., a salt dome cavern. The energy is recovered by releasing the pressurized air into turbines, thereby generating electricity. The two commercial grid-scale CAES facilities operating today, in McIntosh, Alabama, and Huntorf, Germany, have storage durations of 26 hours and 2 hours, respectively. In addition to caverns, CAES could be sited in abandoned mines and oil wells, aquifers, and even underwater. A number of start-ups have also sought to build CAES tanks that would free the technology from dependence on geology and geography. Site-dependent costs and revenues, efficient integration of thermal storage, and the cost and durability of tanks for above-ground systems remain significant challenges for this technology.[142]

An Energy Storage Technology Mission

The United States has been and remains a global leader in energy storage science, technology, and innovation. Research at Argonne National Laboratory enabled use of Li-ion batteries in electric vehicles, and the PJM Interconnection pioneered market frameworks that enabled their use in electric grids. The National Aeronautics and Space Administration (NASA) developed flow batteries; MIT researchers invented liquid-metal batteries; and Oak Ridge National Laboratory pioneered thermal storage with molten salt. The Federal Government, in collaboration with other stakeholders, should build on this legacy of leadership to fill the innovation pipeline for long-duration grid storage.

The technologies reviewed in the previous section are at different stages of maturity, but all—even mature technologies such as pumped-hydro—would benefit from continued use-inspired knowledge creation and experimentation. Scientists may also discover new opportunities to develop long-duration grid storage technologies that are not in today's portfolio. Federal investment is crucial to sustain scientific research that can underpin such advances, and federal co-investment is needed to encourage private investors to fund ventures and projects in this field that would otherwise be too risky for them to take on.[143]

Relevant science is supported by several federal agencies, including DOE's Basic Energy Sciences program within the Office of Science (SC), the National Science Foundation, NASA, and the Department of Defense (DOD). This pluralistic funding system, particularly if it expands, would benefit from stronger horizontal linkages for information exchange and coordination, both within DOE and beyond it. **The National Science and Technology Council (NSTC) should establish an interagency working group on long-duration grid storage to perform this function.**

The Joint Center for Energy Storage Research (JCESR), an energy innovation hub supported by the DOE-SC and headquartered at Argonne National Laboratory, integrates battery science, product design, prototyping, and manufacturing process development within a single organization, and represents a model that should be replicated. Research at JCESR has led to three battery and component start-ups, and informs the ongoing work of numerous affiliated battery makers and users. **SC should set up a second hub on the JCESR model to pursue another broad technology field related to long-duration grid storage.**[144]

ARPA-E funds high-risk, high-impact applied research, with an emphasis on proof of concept. It seeks out science and technology "white spaces" that have been neglected by other organizations. A National Academies evaluation found that ARPA-E's funding of energy storage R&D has been "highly productive with respect to accelerating commercialization" of new storage technologies. The applied energy programs within the Office of Electricity (OE) and Energy Efficiency and Renewable Energy (EERE) also support R&D related to long-duration grid storage. A portion of the $25 million annual hydropower R&D budget, for instance, is devoted to closed-loop pumped-hydro designs. However, these amounts are modest relative to the baseload challenge. **DOE's investments in grid storage through the applied energy offices and ARPA-E should be expanded and focused on long-duration challenges.**[145]

R&D is necessary, but not sufficient, for long-duration grid storage technologies to be deployed at scale. Demonstration projects in real-world settings generate valuable information for investors about costs, revenues, and performance, and also allow problems at scale to be identified and solved, so that costs are lower in later installations. **DOE should expand its long-duration grid storage technology demonstration program, and develop pathways from R&D to demonstration for promising grid storage systems.**

The baseload challenge is not confined to the United States, and many countries are pursuing long-duration grid storage technologies. The first liquid-air (a form of CAES) storage facility opened this year in the United Kingdom. China is constructing the world's largest flow battery.[146] International collaboration on long-duration grid storage R&D would allow all countries to contribute to and take advantage of a global pool of knowledge for mutual benefit. **The United States should propose and take leadership of a new innovation challenge on long-duration grid storage within the international Mission Innovation framework.**[147]

Renewables and Li-ion batteries are making important contributions to decarbonizing electricity now, and these contributions will grow much larger. But the stakes in mitigating climate change are enormous—too large to warrant putting all of our technological bets on a restricted range of possible solutions. Long-duration grid storage technologies have the potential to unlock a wider range of decarbonization solutions, perhaps making grids that rely primarily on variable generation feasible. Taking action to explore these opportunities more aggressively today would be a worthwhile diversification to reduce the risk of catastrophic failure tomorrow.

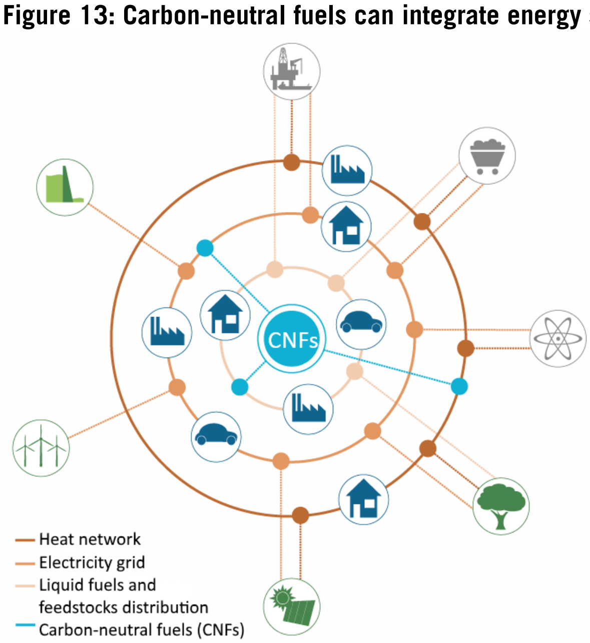
INNOVATION GAP: CARBON-NEUTRAL FUELS

Transportation is one of the most challenging end-use sectors to decarbonize. The high energy density of petroleum-based fuels makes them ideal for vehicles that must carry their own fuel. And the fact that petroleum-based fuels are liquid at normal temperatures and pressures means they can be easily and cheaply distributed from central refineries to distributed fueling stations. Few alternatives that meet the same energy density requirements and low transmission costs without carbon dioxide emissions exist.

The stakes in mitigating climate change are too large to warrant putting all of our technological bets on a restricted range of possible solutions.

The carbon intensity of transportation fuels has barely budged since 2005, with the majority of emissions reductions coming from improvements in fuel economy rather than a decrease in the carbon intensity of fuels. Efficiency is likely to continue to be the driver of emissions reductions in the near term, but will not be able to offset increases in vehicle-miles travelled forever.[148] Ultimately, a zero-carbon transportation system will require carbon-neutral fuels. Electricity from zero-carbon sources stored in batteries is the most promising technology for some transportation subsectors, particularly passenger cars and other light-duty vehicles. But the energy density of lithium-ion (Li-ion) batteries is unlikely to meet the requirements for aviation and long-haul shipping, where constraints on revenue cargo space and payload capacity require energy sources with high volumetric (energy per volume) and gravimetric (energy per weight) density.[149] Energy-dense liquid fuels will continue to be used for many decades. This makes finding carbon-neutral fuels (CNFs) an important and underexplored gap in the federal energy RD&D portfolio.

Figure 13: Carbon-neutral fuels can integrate energy systems across multiple sectors[150]



But CNFs have applications beyond the transportation sector. For example, CNFs generated from excess zero-carbon electricity can provide long-duration electricity storage that can be converted back to electricity as needed. Additionally, CNFs can provide process heat for high-temperature industrial applications. Because of the wide range of end uses, CNFs can facilitate greater integration of energy systems across sectors (figure 13).

The Challenge: Why Current Fuels Are Insufficient to Achieve Carbon-Neutrality

Most of the recent improvements in the carbon intensity of transportation fuels have come from the introduction of biofuels—particularly corn ethanol and biodiesel—into the fuel supply.

Energy-dense liquid fuels will continue to be used for many decades. This makes finding carbon-neutral fuels an important and underexplored gap in the federal energy RD&D portfolio.

However, the ability of corn ethanol and other first-generation biofuels to reduce transportation-sector emissions is limited by scalability and lifecycle emissions. After accounting for the fertilizer, energy, and other inputs needed to grow, harvest, and process corn into ethanol, the Environmental Protection Agency determined that corn ethanol results in 21 percent fewer greenhouse gas emissions than gasoline, on an energy-equivalent basis.[151] Additionally, expanded production of corn ethanol and biodiesel runs into land-use constraints. At current U.S. production levels (about 19 billion gallons per year, or 10 percent of gasoline and 4 percent of diesel), more than 38 million acres of cropland are devoted to ethanol and biodiesel crops. For comparison, this is half the acreage in the United States devoted to food for human consumption.[152]

These factors make it unlikely first-generation biofuels will contribute to future emissions reductions in the transportation sector. Next-generation cellulosic and algae-based biofuels could achieve greater emissions reductions if costs decline to the point they can compete with current fuels. But even these second-generation fuels have non-negligible life-cycle carbon emissions and will not be enough to reach a zero-carbon transportation system.

More Innovation Is Needed to Make CNFs Commercially Viable

Hydrogen, ammonia, and synthetic hydrocarbons are all potentially viable CNFs. Hydrogen-powered fuel cell electric vehicles (FCEVs) are fairly mature, but costs must come down for them to make a significant impact in the passenger vehicles sector. Additional innovation is required to expand the use of hydrogen in aviation and shipping. The use of ammonia and synthetic hydrocarbons in energy systems is at an earlier stage of development and far from commercial viability. A diverse portfolio of CNFs should be explored to hedge against the risk of any one technology failing to reach maturity.

Hydrogen

Hydrogen is a remarkably versatile energy carrier. It can be converted into heat or electricity, either in a gas combustion turbine or in fuel cells, without generating greenhouse gases at the point of use—and has applications across all end-use sectors. In the transportation sector, FCEVs use hydrogen to generate electricity to run their electric drivetrains much like battery-powered electric vehicles. In commercial and residential buildings, as well as in the industrial sector, hydrogen can provide on-site combined heat and power (CHP). And in the electric power sector, hydrogen provides a form of chemical energy storage, using excess carbon-free electricity to generate hydrogen via electrolysis, which can then be stored and reconverted to electricity via fuel cells or turbines when needed in power-to-gas-to-power (P2G2P) systems.[153]

Because of its many uses, hydrogen can also enable the integration of energy systems. Excess electricity can supply hydrogen for non-power applications in buildings, industry, and transportation sectors, providing the opportunity for greater optimization of energy resources across sectors. These attractive features have led many to call for the eventual creation of a "hydrogen economy."[154]

Hydrogen is used on a large scale now—about 55 million metric tons per year—to produce ammonia for fertilizer and to convert heavy petroleum sources into lighter refined fuels.[155] The current state-of-the-art method for hydrogen production is steam methane reforming (SMR), wherein methane is combined with steam under high temperatures and pressures to produce hydrogen, with carbon dioxide as a waste product. Gasification of coal to produce syngas, a mixture of hydrogen, water vapor, carbon dioxide, and carbon monoxide, is another common hydrogen production method. Hydrogen produced from fossil fuels is not carbon neutral, although carbon capture technologies can be added on to SMR and coal-gasification hydrogen production facilities to reduce the carbon intensity of hydrogen production (see the section on CCUS). Carbon-neutral hydrogen can be produced by using either SMR/gasification with carbon capture or carbon-free electricity to split water (electrolysis). Electrolysis accounts for less than 5 percent of global hydrogen production, with the remainder coming from fossil fuels.[156]

Several technical and cost obstacles must be overcome for hydrogen to become a significant resource in a low-carbon energy system. Given the low cost of natural gas, SMR is likely to remain the dominant source of hydrogen production unless the cost of electrolytic hydrogen declines significantly.[157] Compression, transportation, and storage of hydrogen also impose substantial energy costs that are many times higher than for fuels that are liquid at lower pressure, such as gasoline or ammonia. The roundtrip efficiency of P2G2P systems must also increase for hydrogen to contribute to long-duration grid storage.

Ammonia

The second-most manufactured chemical in the world, ammonia is used primarily for fertilizer, with global production volumes of around 160 million tons in 2017.[158] The use of ammonia and ammonia-based fertilizers has been key to enabling greater food production, with an estimated 50 percent of all nitrogen in the average human coming from synthesized ammonia.[159] Ammonia is produced using the Haber-Bosch process, which combines atmospheric nitrogen and industrial hydrogen under high temperatures (~800°F) and high pressures (~100 times atmospheric pressure) in the presence of a catalyst.[160] In the best case, using methane-derived hydrogen and natural gas for energy, ammonia production yields 1.9 metric tons of carbon dioxide per ton of ammonia.[161]

So, the incentive to decarbonize ammonia production already exists due to the large and growing need for ammonia-based fertilizers. But ammonia also has many underexplored potential applications in a future low-carbon energy system.[162] First, ammonia could enable a hydrogen economy by acting as an effective hydrogen carrier. Ammonia is many times less costly to transport and store than hydrogen, and hydrogen can be cheaply "cracked" from ammonia at the point of use. Second, ammonia can be used directly as a fuel in a wide range of applications, including power generation, industrial process heat, building space heating, and as a transportation fuel. Recent work using high temperature solid oxide fuel cells (SOFCs) for electricity generation found comparable power production using ammonia versus using hydrogen as a fuel.[163]

But for ammonia to contribute to a low-carbon energy system, innovation is needed to drive down the cost of carbon-neutral ammonia production. The use of carbon-neutral hydrogen (either from electrolysis or steam methane reforming with carbon capture) will lower the carbon intensity of ammonia production, but the Haber-Bosch process still requires substantial energy inputs. New electro-catalytic, photo-catalytic, and solar thermochemical looping techniques may reduce energy consumption, but this research is still in its early stage.[164] Additionally, the use of ammonia in energy systems such as fuel cells or combustion turbines is far from commercial and has received comparatively little public or private investment.

Synthetic Fuels

Synthetic fuels could play a significant role in a circular carbon economy, wherein individual carbon dioxide molecules are "recycled" between the atmosphere and fuels. This can only be done when the feedstocks and energy used to convert carbon into synthetic fuels is generated from carbon-free sources.[165] Synthetic fuels provide a couple key benefits: They can expand the market for carbon dioxide, which would incent greater carbon capture (see the CCUS section), and displace conventional fossil fuels in aviation and other subsectors that require high energy density fuels.

Synthetic fuels can be made today by first converting CO_2 into carbon monoxide (CO), and then combining CO with hydrogen using the Fischer-Tropsch process to make a variety of liquid fuels, such as synthetic gasoline, synthetic diesel fuel, alcohols, and dimethyl ether. However, the Fischer-Tropsch process is capital-intensive and requires massive energy inputs and sustainably produced hydrogen. Recent attention has focused on direct conversion of CO_2 and water into hydrocarbons, using renewable or nuclear electricity (rather than heat) to drive the process.

Synthetic fuels are at an earlier stage of development than hydrogen and ammonia, and are far from commercially viable. The National Academies recently released a report on carbon utilization that identifies the research needs for synthetic fuels.

A Technology Mission for Carbon-Neutral Fuels

The United States has long been the world leader in the development and deployment of hydrogen FCEVs, with nearly 4,500 in operation as of 2017. However, U.S. investment in hydrogen research has declined in recent years, and the United States is set to be overtaken in the emerging hydrogen economy as other nations such as Japan and France set ambitious targets for hydrogen production and use.[166]

The Federal Government should continue to invest in hydrogen and other carbon-neutral fuels across the entire innovation spectrum, from basic research through commercialization, and from fuel production to consumption.

The Joint Center for Artificial Photosynthesis (JCAP), an energy innovation hub supported by the DOE Office of Science (SC) and led by the California Institute of Technology (Caltech) and its lead partner Lawrence Berkeley National Laboratory, was established in 2010 to produce synthetic fuels from sunlight, water, and carbon dioxide. Since its inception, the hub has filed over 50 invention disclosures and applications, and continues to be a model that should be replicated for other carbon-neutral fuels, including hydrogen and ammonia.[167] **SC should establish a new innovation hub, in the model of JCAP, that is focused on novel, low-cost methods of hydrogen and ammonia production that do not use fossil fuels as a feedstock.**

The United States is set to be overtaken in the emerging hydrogen economy as other nations such as Japan and France set ambitious targets for hydrogen production and use.

Applied research on synthetic hydrocarbon production is centered on the carbon utilization programs within the Coal CCS & Power Systems program office (see the section on CCUS). However, at $20 million in FY 2019, funding for CO_2-to-fuels research is far below the level needed to address all research needs. **DOE should expand research on carbon dioxide-to-fuels pathways that incorporates recommendations from the recent National Academies report on carbon utilization.[168]**

Most research into the use of hydrogen in energy systems has focused on passenger vehicles and other light-duty transport. However, costs for battery electric vehicles (BEV) are declining faster than for fuel-cell vehicles, and BEVs appear to be a better match for use in these sectors. **Federal investment in end uses of hydrogen should refocus on those transportation subsectors—including aviation and shipping—for which batteries are ill-suited. Additionally, R&D should expand to include potential applications in other sectors, such as combustion of hydrogen for process heat in the industrial sector.**

ARPA-E's REFUEL program funds high-risk, high-impact research in both the production of carbon-neutral liquid fuels (including ammonia and synthetic hydrocarbons) and their conversion to electricity or hydrogen.[169] However, ARPA-E's investment is too small to explore the full range of applications, such as the use of ammonia in hard-to-decarbonize transportation sectors like shipping, or in industrial sectors. **ARPA-E's investment in CNFs should be expanded to address a wider range of energy applications. Additionally, DOE should establish a new applied energy R&D program in ammonia and other carbon-neutral fuels to research applications of CNFs in providing energy services, including in the transportation and industrial sectors.**

INNOVATION GAP: CARBON DIOXIDE REMOVAL (CDR) TECHNOLOGIES

Despite our best efforts, the world may not be able to reduce carbon pollution fast enough or at sufficient scale to avoid dangerous levels of warming—prompting the need for technologies that can remove carbon from the atmosphere.[170] However, no carbon dioxide removal (CDR) technologies—also referred to as negative emissions technologies (NET)—have been deployed at a scale that can meaningfully address the magnitude of global climate pollution. And little is known about the viability and scalability of rapid deployment. Federal investment in research, development, demonstration, and commercialization of CDR technologies is urgently needed to create new options for reducing carbon pollution.

Removing Carbon from the Air to Restore the Natural Balance of Carbon Levels

CDR includes a suite of technologies and approaches that remove carbon dioxide from the ambient atmosphere for subsequent storage or use. Many land-use approaches such as reforestation and afforestation have long been included in traditional mitigation efforts; however, these approaches run into competition for land use (e.g., for agriculture) and face barriers to deployment at the needed scales. Technological approaches are relatively immature but have the potential to permanently sequester atmospheric CO_2, on the order of billions of metric tons annually.[171]

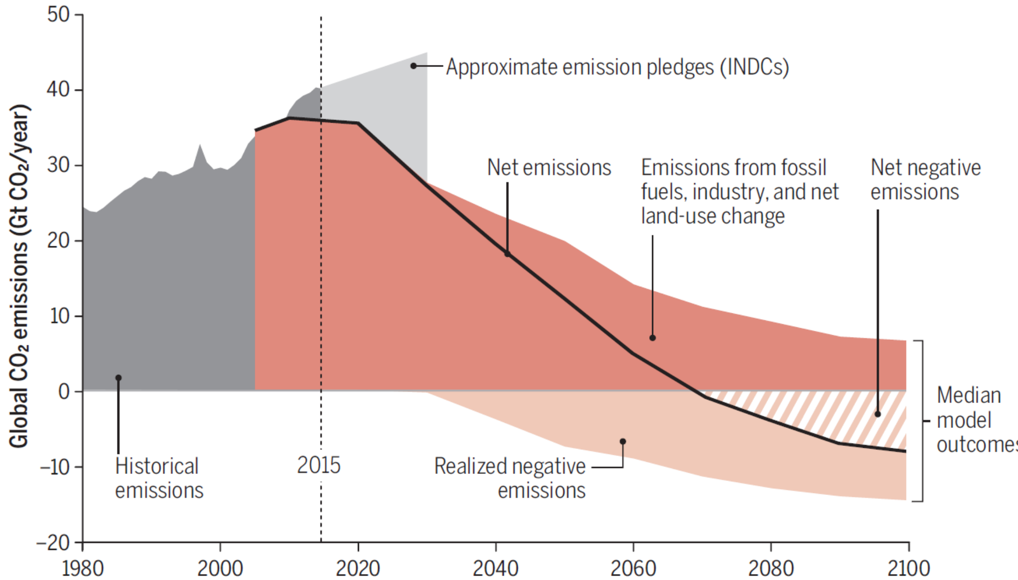
Scientists and climate advocates are increasingly coming to view carbon removal as an essential but overlooked element of a deep decarbonization strategy.

Scientists and climate advocates are increasingly coming to view carbon removal as an essential but overlooked element of a deep decarbonization strategy, and many energy-climate models find it impossible to achieve a 2°C (3.6°F) target without relying on CDR technologies.[172] Carbon removal hedges against two key risks that are common to all deep decarbonization pathways: the risk of a carbon budget overshoot, and the need to counter emissions from "difficult-to-decarbonize" sectors.

First, a carbon budget overshoot would occur if emissions do not decline quickly enough to avoid unacceptable and severe climate impacts. Several factors could contribute to a carbon budget overshoot: Clean energy technologies may not advance as quickly as needed. Countries may not set sufficiently aggressive mitigation targets. Failure to reduce emissions rapidly enough would require net emissions to become negative before the end of the century (black line in figure 14).

Second, even the most optimistic technology scenarios still include emissions from "difficult-to-decarbonize" sectors—such as aviation, long-haul shipping, cement, and steel—for which there are few carbon-neutral options on the horizon (dark-pink-shaded area in figure 14). Mitigating emissions from these sectors will either require significant technological breakthroughs or some way of offsetting emissions from these sectors. Additionally, many incumbent technologies and infrastructures have long life spans—a new home built today will still exist in 2050.[173] CDR technologies help smooth the transition to a low-carbon economy by averting the need for accelerated stock turnover in sectors where such turnover would be prohibitively expensive.

Figure 14: Carbon dioxide removal (CDR) technologies are likely essential to achieving deep decarbonized systems[174]



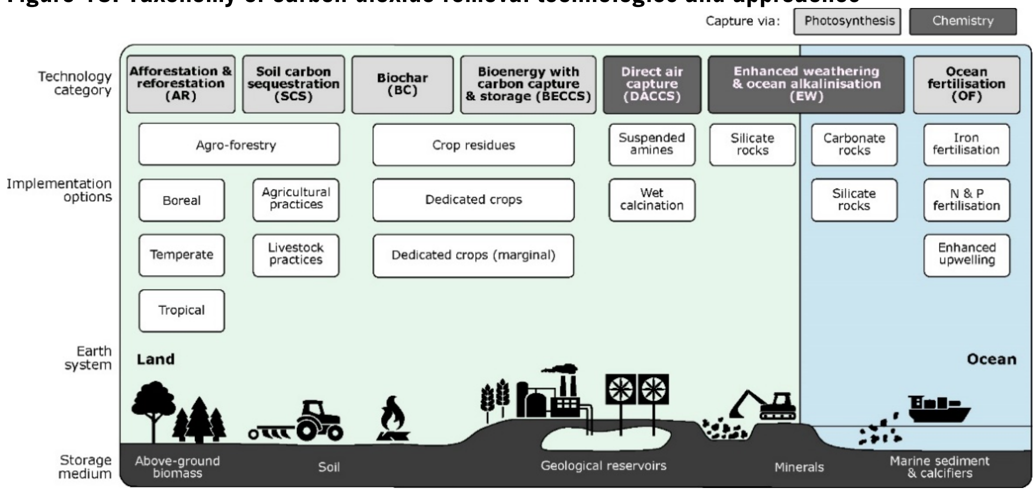
Additionally, CDR technologies help manage risks in our understanding of the climate system and our ability to manage and adapt to the impacts of climate change. Although the notion of a carbon budget provides a simple way to track mitigation efforts, the complexity of energy-climate systems makes it impossible to assign a specific budget to a given temperature increase. The current carbon budget may lead to unacceptably high damages, including greater-than-anticipated sea-level rise or more frequent extreme weather. Carbon removal hedges against the risk of climate impacts being greater than anticipated.

More Innovation Is Needed to Bring CDR to Maturity

Technological approaches to carbon removal have only recently emerged as the subject of climate mitigation research, with the number of publications and technologies regarding carbon removal growing rapidly since the early 2000s.[175] The increased attention to CDR technologies parallels the growing recognition that the world may only be a few decades away from blowing past the carbon budget consistent with a 2°C target. However, research to date has been confined mostly to academic studies and modeling, with limited public support—either domestically or internationally—to develop the technologies that climate models say are needed to achieve deep decarbonization.

Figure 15 provides a taxonomy of biological and technological carbon removal approaches, distinguished by their carbon capture method (photosynthetic or chemical) and carbon storage medium. Bioenergy with carbon capture and storage (BECCS) is one promising approach to achieving negative emissions because of its ability both to produce energy and sequester carbon. BECCS is the process by which biomass such as wood or switchgrass is converted to heat, electricity, or liquid or gas fuel, followed by carbon capture and storage (CCS). The carbon capture process is similar to the capture process from coal- and natural gas-fired power plants (see the section on CCUS). Deployment on a large scale runs into land-use and other resource constraints, e.g., competition with agriculture for land, water, and fertilizer. Additional research is needed to address sustainability concerns and to identify energy crops with lower resource requirements.[176]

Figure 15: Taxonomy of carbon dioxide removal technologies and approaches[177]



Direct air capture (DAC) of carbon dioxide is another nascent CDR technology with a large potential for carbon removal. DAC is not a new technology, as small systems have been installed in submarines, space applications, and other closed environments to prevent CO_2 buildup from exhalation. Although not traditionally a factor for these small, niche applications, cost is the key hurdle in scaling up DAC systems to climate-relevant scales—with current cost estimates ranging from \$100 to \$600 per metric ton of CO_2 captured.[178]

Other innovative carbon removal approaches include carbon mineralization—trapping carbon dioxide in solid mineral carbonates, which can be used in building materials—as well as biotechnology approaches to enhance soil carbon, which can improve soil quality and boost crop yields. Most proposed CDR approaches have the potential for widespread deployment on a scale relevant for climate mitigation, but many face significant knowledge and technical gaps that will require substantial investment in R&D.

A Carbon Dioxide Removal Technology Mission

A carbon removal technology mission would harness U.S. strengths in science and engineering, and provide an opportunity for the United States to lead the world in the emerging carbon removal sector. In October 2018, the National Academy of Sciences (NAS) released a detailed roadmap supporting innovation in carbon removal technologies and identifying R&D needs. Many other scientific and advisory bodies have also recommended greater investment in carbon removal research, reflecting a growing consensus that carbon removal technologies are important for national goals in economic growth and environmental stewardship.[179]

Bipartisan Congressional support for carbon removal is growing. In the February 2018 budget agreement, Congress extended and expanded the 45Q tax credits for carbon storage

BOX 5: CARBON REMOVAL IN ENERGY-CLIMATE MODELS

CDR technologies are increasingly relied on in integrated energy-climate assessment models to achieve deep decarbonization—and this reliance is robust across different energy-climate models, as well as assumptions about population growth, economic growth, technology availability, and other inputs. In the Fifth Assessment Report on climate change, IPCC assessed 900 mitigation scenarios across 30 energy-climate models. Out of the 116 scenarios consistent with warming below 2°C, 101 (87 percent) use carbon removal approaches in the second half of the century, with average net carbon removal exceeding 12 billion metric tons annually by 2100.[180]

to include direct air capture. Both the USE IT Act in the Senate and the Fossil Energy R&D Act introduced in the House would establish R&D programs for carbon removal, though neither legislation would fund R&D at the level proposed by the NAS report—or fund the full suite of carbon removal technologies.[181]

The National Academies report found that direct air capture and carbon mineralization have nearly unlimited carbon removal potential and fewer potential negative environmental impacts than other approaches, but are limited by high costs and technical feasibility. Investment in carbon removal technologies should span the entire innovation spectrum, from fundamental research to commercialization.

- **DOE's Office of Science (SC) should establish a new energy innovation hub that addresses the basic science needs for carbon removal pathways, including direct air capture and carbon mineralization.**

- **DOE should establish an applied RD&D program that implements the recommendations of the National Academies report and prioritizes pilot-scale demonstrations of direct air capture.**

Land-based approaches to carbon removal—including BECCS, afforestation and reforestation, biochar and soil carbon sequestration, and changes in forest management and agricultural practices—are viable today at relatively low costs, but have limited scalability due to competition for land and concerns about environmental impacts. **Federal agencies should research ways to increase the carbon removal capacity and mitigate environmental impacts of land-based approaches.**

The full set of R&D needs spans basic energy science to applied research to technology commercialization and deployment—and the technical capabilities to address carbon removal research needs are distributed across multiple agencies, especially DOE, EPA, DOI, USGS, and NSF. **Federal policymakers should establish an interagency working group with the National Science and Technology Council (NSTC) to coordinate federal research and facilitate information exchange.**

INNOVATION GAP: BASIC ENERGY RESEARCH

All of the technologies previously described would benefit from more fundamental breakthroughs in catalysts or materials discovery, and require better control and understanding of structures and functions at atomic—and even subatomic—scales. The innovation agenda for deep decarbonization should embrace the entire innovation spectrum, from use-inspired basic science to technology development and demonstration to commercialization.

Basic Energy Research Has Already Yielded Huge Gains

Federal investment in science and basic energy research is behind many of the transformational energy technologies that are currently disrupting today's energy systems. Basic research to commercial application can take decades, and many of the technologies that are now emerging owe their existence to breakthroughs in fundamental science and materials research that occurred decades ago.

The innovation agenda for deep decarbonization should embrace the entire innovation spectrum, from use-inspired basic science to technology development and demonstration to commercialization.

Basic research in subsurface fluid flow and high-strength materials by DOE in the early 1980s resulted in advancements in hydraulic fracturing and horizontal drilling that enabled the shale-gas boom of the mid-2000s that continues to reshape U.S. electricity markets.[182] Similarly, the discovery of quantum dots—small semiconductor particles a few billionths of a meter across that allow for conversion of blue light into other colors—were critical to the development of cheap, efficient light-emitting diodes (LEDs) that now account for 13 percent of all new lighting.[183]

Advancing from basic research to commercialization of new technologies can take decades, often with surprising twists. The discovery in 1986 of high-temperature superconductors led to a burst of research at DOD, DOE, NSF, NASA, and NIST, both in applications of superconductivity as well as basic science to explain the phenomena and develop new superconducting materials. Decades later, superconductors now have applications in offshore wind, electric grid fail-safe devices, and MRIs for medical imaging. Superconducting filters that process signals thousands of times faster than conventional electronics and without energy loss have now been installed in more than 10,000 mobile communications towers.[184]

In the United States, most of the basic energy research is funded through the DOE's Basic Energy Sciences program or NSF. The basic research funded through these programs has translated into tremendous economic gains, and the return on investment in fundamental research has paid for itself many times over. BES recently produced a retrospective report highlighting the return on investment in fundamental energy research over the last 40 years.[185] The report identifies some of the groundbreaking discoveries made as a result of federal funding that—years, and often decades, later—have resulted in the commercialization of new technologies that shape the way we produce and consume energy.

Greater Investment in Basic Clean Energy Research Will Accelerate Next-Generation Energy Technologies

Investment in basic science research can take decades to come to fruition, and often does so in surprising ways. The energy system of the future will look dramatically different from today's energy system. Just as the basic science research conducted decades ago is beginning to transform our energy systems of today, investment in basic science today is needed to seed new technologies and create new options for the energy systems of the future.

In 2007, DOE's Office of Science (SC) produced a landmark report that identified "Grand Challenges" for controlling matter and energy down to atomic scales—and even down to the quantum level of electrons—which were used to guide department research in basic energy science. These grand challenges in energy science were chosen based on their potential to spark revolutionary changes in technologies that could meet the nation's most pressing energy needs; and the report was used to guide DOE research in basic energy science in subsequent years.[186]

Since then, advances in energy science, a changing energy landscape, and order-of-magnitude improvements in computing and experimental tools prompted DOE's Basic Energy Science Advisory Committee (BESAC) to assess progress toward meeting these challenges and identify new opportunities to advance energy science. In 2015, BESAC produced a new roadmap identifying five Transformational Opportunities in advanced energy science: i) mastering hierarchical architectures and beyond-equilibrium matter; ii) understanding the critical roles of heterogeneity, interfaces, and disorder; iii) harnessing coherence in light and matter; iv) advancing models, mathematics, algorithms, data, and computing; and v) exploiting transformative advances in imaging capabilities across multiple scales.[187]

The BESAC report sparked a series of workshops to identify basic research needs in a range of cutting-edge basic energy sciences—including energy storage, quantum materials, catalysts, nuclear energy science, and the energy-water nexus.

Advanced Catalysts and Materials That Can Withstand Extreme Environments

Catalytic materials are key to the production of fuels and chemicals—currently, over 80 percent of all chemical products and carbon-based fuels are made using catalysts in at least one of the processing steps.[188] Catalysts increase chemical reaction rates without being consumed in the reaction. In addition to petrochemicals production, catalysts can be used to transform biomass into chemicals and fuels, or convert excess energy from wind and solar into fuels such as hydrogen and ammonia. Catalysts are also key elements of carbon utilization processes that could turn industrial CO_2 waste into high-value products such as fuels and plastics. Advanced catalysts and catalytic processes have the potential to lower energy requirements (a key driver of chemical conversion costs) and the carbon intensity of the fuels and chemicals industries. Better catalysts have been identified as key research needs across a range of advanced energy technologies, including energy storage, ammonia production, fuel cells, and carbon utilization.[189]

Many advanced energy technologies expose materials to high temperatures or extreme environments that challenge the structural and functional integrity of current materials and can lead to performance degradation. One common need across all thermoelectric generation is for materials that can withstand high temperatures, as generation from coal, natural gas, nuclear energy, and concentrating solar power all use turbine generators to convert heat energy into electricity. The efficiency of thermal conversion depends on the temperature of the inlet gas: Higher temperatures lead to higher efficiencies. A 1 percent increase in turbine efficiency in the existing U.S. power-generation fleet would produce enough additional electricity to power 2.4 million U.S. homes and save $800 million per year in energy costs.[190] Advances in materials that can withstand higher temperatures could lead to even greater efficiency improvements.

Molten-salt coolants and fuels, and the design of structural materials able to perform in the extreme environments of advanced nuclear reactors are key materials research needs that can enable advanced nuclear technologies.[191] Similarly, marine and hydrokinetic (MHK) energy conversion technologies operate in high-pressure, corrosive marine environments, and require research into advanced materials capable of operating in these environments.[192]

Quantum Materials

Quantum materials have exotic physical properties arising from the quantum mechanical properties of their constituent electrons. Some quantum materials, such as superconductors, are already making an appearance in commercial technologies, while others, such as topological insulators, have many potential applications.[193]

Superconductivity—the ability of a material to conduct electricity without resistance—was first observed in simple metals at temperatures near absolute zero (-460°F). The high cost of cooling metals to these temperatures prevented the widespread application of superconductors in all but the highest-value applications, such as magnetic resonance imaging (MRI) for medical diagnostics. The discovery of high-temperature superconductors—materials that become superconducting above -320°F, the boiling point of liquid nitrogen—have expanded the potential use of superconductors because of the relatively low cost of producing liquid nitrogen.

Because they can transmit electricity without loss, superconductors have many potential applications in electronics and electricity systems. For example, high-temperature superconductors could be used in very light-weight electrical generators in offshore wind turbines. Despite the need for cooling systems, the smaller size and weight of these generators make them less costly than conventional generators.[194] Room-temperature superconductivity remains the elusive holy grail of quantum materials research, and has the potential to save tens of billions of dollars in electricity transmission and distribution losses.

Topological materials are another category of quantum materials with enormous potential applications in electronics and advanced energy technologies. Topological insulators are electrically insulating in bulk, but have atomically thin conducting surface layers that enable the conduction of electrons without loss of energy, similar to superconductors but potentially at much higher temperatures. Applications could include increased energy efficiency of computing and thermoelectric devices.[195]

User Facilities and Advanced Experimentation Tools

Advanced instrumentation and experimentation methods can probe matter on smaller and smaller time- and length-scales, opening up new domains in materials discovery and characterization, and providing real-time imaging of chemical transformations and quantum processes. Innovations in neutron imaging and x-ray techniques enable 3-D visualization of materials down to sub-nanometer (less than 10^{-9}m) distances and ultrafast time scales on the order of quadrillionths of a second (femtoseconds, 10^{-15} s).

Many of these tools are too expensive for a single university lab or private company to own and operate. Instead, the Federal Government operates large user facilities such as x-ray free electron lasers (XFELs), synchrotron light sources, neutron sources, and nanoscience research facilities that enable academic and industry users to access these advanced tools. X-ray and neutron sources, in particular, are key tools for researching energy storage materials, advanced catalysts, and quantum processes and materials.

Advances in foundational energy science are needed to address the challenges posed by hard-to-decarbonize sectors. The federal government should do more to connect basic science research with technology priorities.

A Basic Energy Research Mission

Advances in foundational energy science are needed to address the challenges posed by difficult-to-decarbonize sectors. But disconnected, curiosity-driven research alone is likely insufficient to meet these challenges. The federal government should do more to connect basic science research with technology priorities.

DOE's Energy Frontier Research Centers (EFRCs), designed during the George W. Bush administration and first funded in 2009, were established to address grand energy challenges and connect basic research with industry needs. EFRCs are multi-disciplinary, multi-institutional partnerships among academic, government, and industry researchers, and are particularly suited to the challenges posed by difficult-to-decarbonize sectors. **DOE should double the number of EFRCs and align their focus with Technology Missions addressing difficult-to-eliminate carbon emissions.**

Congress should provide full funding for the next generation of DOE user facilities, as well as planned upgrades at existing facilities. These facilities are critical to addressing basic research needs in energy storage, advanced catalysts, quantum materials, and other materials-discovery research needs. However, the United States has only one XFEL, four synchrotron x-ray sources, two neutron-scattering sources, and five nanoscale science centers. **DOE should evaluate whether the capacity of existing user facilities is sufficient to accommodate all research applications with scientific merit, and present a plan to Congress for building additional user facilities if warranted.**

In addition, NSF provides integral support for basic energy science. Research projects it supports in chemical, bioengineering, transport systems, materials, and other fields have implications for developing and improving new energy technologies. **Congress should expand NSF funding for energy-related research that advances the science underpinning clean energy technology breakthroughs.**[196]

CONCLUSION

Government energy innovation agendas have the potential to accelerate the clean energy transition and reduce carbon pollution, while also lowering energy costs for consumers. However, current levels of investment in energy RD&D are insufficient to achieve deep emissions reductions by mid-century. Additionally, the energy RD&D portfolio has significant blind spots when it comes to hard-to-decarbonize sectors. The industrial sector, particularly cement and steel, has been largely overlooked in the clean agenda. Most research in aviation and other hard-to-decarbonize transportation sectors has focused on lower-emitting biofuels, but breakthrough research in carbon-neutral fuels will be needed to completely decarbonize these sectors. And even in the electric power sector—where early emissions reductions have been easier to come by—net-zero electricity will require some form of zero-carbon electricity that can be dispatched as needed to manage variability in net load from hourly to seasonal timescales. Reducing carbon pollution from these sectors to zero will require a sustained government commitment and investment commensurate with the challenge posed by these difficult-to-eliminate emissions.

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