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Active Carbon Management: Critical Tools in the Climate Toolbox

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Technologies to capture and store carbon must be part of the arsenal to fight climate change. To deploy them at scale, policymakers should expand federal incentives, increase RD&D for traditional and novel technologies, and expedite permitting and siting of requisite infrastructure.

KEY TAKEAWAYS

- It will be impossible to fully eliminate fossil fuels from the economy by 2050, with models converging on a consensus that the world will likely need to capture between 1 and 10 billion tons of carbon annually.
- Active carbon management technologies will both sequester emissions from hard-to-abate sectors such as heavy transportation, steel, and cement, and draw down historic emissions from the atmosphere.
- In the United States, there has been erratic interest and support for these technologies, but there is now growing recognition that they are necessary to avert the worst effects of climate change.
- Opponents make misleading claims that active carbon management technologies are too expensive, not ready, and environmentally unjust. This undermines the technologies' potential to reduce emissions and spur economic growth.
- The federal government should increase policy support for active carbon management through expanded tax credits, expedited infrastructure permitting and siting, and increased RD&D support.

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INTRODUCTION

Global greenhouse gas (GHG) emissions continue to rise. To alter this menacing trajectory, emissions-reducing technologies, such as wind, solar, hydro, and nuclear power, must be deployed rapidly around the world. However, the continued improvement and deployment of these and related technologies are not likely to be enough to bend the global emissions curve within a meaningful timeframe. Key sectors will continue to find it very hard, if not impossible, to abate their emissions without active carbon management technologies, such as carbon capture and sequestration (CCS) and direct air capture (DAC).

Some voices in the global climate debate insist, largely on ideological grounds, that fossil fuel use must be eliminated entirely. That reasoning is foolhardy and counterproductive to the goal of reducing the risks from climate change. Emissions, rather than the fuels themselves, are what cause global warming, and the development of active carbon management technologies is not a distraction from the fight against climate change, but essential to it. If active carbon management technologies are taken off the table or even slowed in their deployment and development, global emissions-reduction strategies will only become more difficult and expensive, limiting our chances at successfully keeping emissions within the bounds of global carbon budgets.

The critics are right that most active carbon management technologies are not yet ready to meet the challenge of averting billions of tons (gigatons) of carbon dioxide (CO_2) emissions per year. The technical, financial, policy, and regulatory hurdles these technologies face remain steep. Far from abandoning these technologies, policymakers and societal leaders should intensify the push to develop and deploy them, broadening the range of potential pathways toward a low-carbon future. Active carbon management technologies must both be deployed this decade to tackle emission-point sources while the groundwork is being laid for future drawdowns of atmospheric CO_2 concentrations from the ambient air and used to offset emissions from hard-to-abate sectors. But these outcomes will only be achieved with robust public, private, and international support.

Far from abandoning active carbon management technologies, policymakers and societal leaders should intensify the push to develop and deploy them, broadening the range of potential decarbonization pathways.

Active carbon management technologies can enable the continued use of fossil fuels, which provide 80 percent of primary energy demand today.[1] This report investigates the critical role active carbon management technologies, specifically CCS and DAC, could play over the next three decades, and describes innovation policies that could turn that promise into reality. The report begins with an overview of the technologies and their potential contributions. The subsequent section shows that global climate and energy models converge in showing that active carbon management is vital to achieve global climate goals and failing to invest in these technologies today will lead to costlier and more-polluting outcomes by mid-century. The next section traces the history and outlook of U.S. active carbon management policy, which has developed in fits and starts over the last two decades but is experiencing a resurgence of interest and support. The report then addresses misleading claims made by those opposed to these technologies, and concludes with policy recommendations that would enable active carbon management to mature and achieve the scale necessary to fight climate change.

ACTIVE CARBON MANAGEMENT: TECHNOLOGY OVERVIEW AND SCOPE

Carbon is a relatively abundant element on Earth. It is present in the Earth's crust, oceans, and atmosphere; it is the foundation of all life. Flows of carbon within and between the land, sea, sky, and biota comprise the global carbon cycle. Human activity since the Industrial Revolution, especially fossil fuel combustion and deforestation, has altered this cycle, most notably by raising the concentration of CO_2 in the atmosphere.[2] Carbon management seeks to intentionally influence the carbon cycle to halt and eventually reverse the dangerous rise of heat-trapping CO_2. Carbon management reduces the flow of CO_2 emissions into the atmospheric carbon reservoir and draws down the stock of CO_2 already present.

Figure 1 divides carbon management techniques into two broad categories: natural and active carbon management. Natural carbon management seeks to add to the estimated 65,000 gigatons (GT) of carbon that are stored in a semipermanent state in natural sinks.[3] Well-established biological techniques include afforestation and reforestation, soil and agricultural sequestration, biochar, and ocean fertilization, while geological techniques under development include enhanced mineralization, which combines natural carbon sequestration capacity of certain minerals with human intervention and engineering to process and crush reactive minerals.

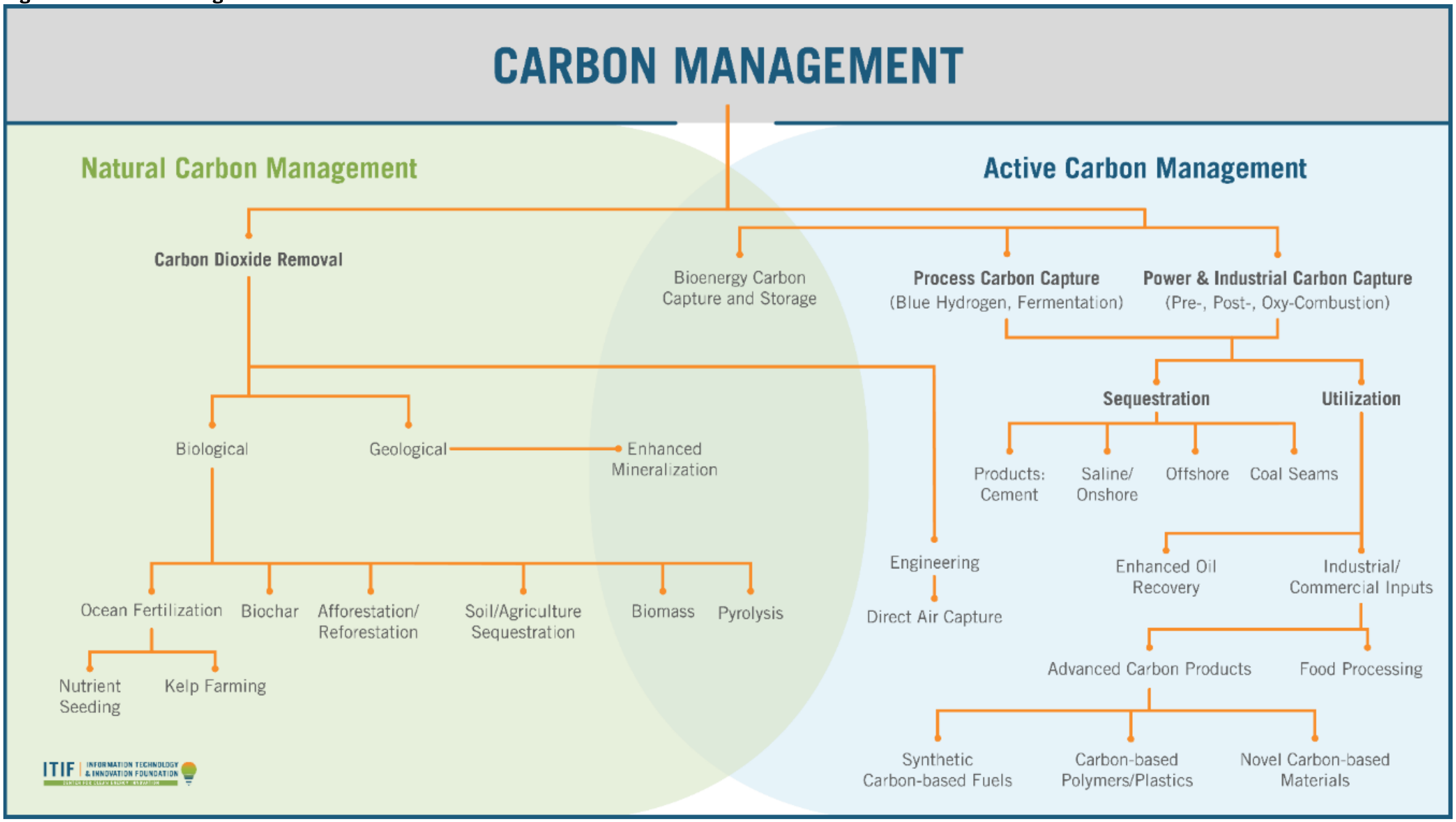
Active carbon management applies engineering techniques to capture CO_2 from emissions at point sources such as factories and power plants, or by removing it from the atmosphere, and then sequestering it deep underground or in products.

Natural carbon management is a valuable and important component of a climate strategy, but alone it is unlikely to be sufficient to stop the rise in atmospheric CO_2. For one thing, it is slow. Forests take years to reach maturity. Young forests sequester carbon faster than older ones but hold less carbon overall, requiring increasing afforestation rates. Forests also have significant land-use and water requirements, such that a new forest the size of Texas would have to be planted every year and grown to maturity in order to fully sequester annual global emissions.[4] Natural carbon sinks are not necessarily permanent, either. Wildfires, for instance, re-release captured carbon. An estimated 153,000 acres of forests grown to offset carbon emissions went up in smoke in the western United States in 2021.[5]

Active carbon management, by contrast, applies engineering techniques to capture CO_2 from emissions at point sources such as factories and power plants, or by removing it from the atmosphere, and then sequestering it deep underground or in products. Underground reservoirs are far less likely to re-release carbon than are forests, grasslands, and soils. Active carbon management also takes much less land, water, and other resources than does natural carbon management, thereby avoiding competition with urban development and agricultural needs. Moreover, active carbon management can be developed and deployed faster than planting forests and protecting them until they mature. Figure 1 highlights the two active carbon management techniques we expect will play the most significant roles between now and 2050: CCS and DAC. Carbon capture and sequestration (or storage) prevents emissions from entering the atmosphere in the first place, reducing the flow of carbon. DAC of CO_2, by contrast, directly reduces the stock of carbon in the atmosphere. CCS and DAC can both be coupled with carbon capture and utilization (CCU), in which captured carbon is used for industrial and commercial purposes.

Figure 1 also includes hybrid active/natural carbon management techniques worthy of further exploration. Bioenergy with carbon capture and storage (BECCS), for instance, uses the natural process of capturing carbon by growing fuel crops while at the same time capturing emissions when the fuel is consumed to generate electricity and heat.[6] Biomass pyrolysis relies on natural photosynthetic capture, but then treats biomass with high heat and pressure in an oxygen-poor environment, creating a carbon-rich tar-like substance that can be sequestered underground or used.[7] These hybrid carbon management techniques share both the strengths and weaknesses of natural carbon management techniques, notably relatively low energy requirements to capture ambient CO_2, along with extensive land-use and resource requirements and vulnerability to risks such as wildfire and drought.

Figure 1: Carbon management framework



Carbon Capture and Sequestration

CCS can be applied to concentrated or diluted streams of emissions from power plants and industrial facilities. In power plants, these streams flow through smokestacks from the generating units, whereas in industrial facilities they may arise from multiple, diffuse on-site sources. CCS systems can be retrofitted onto existing plants or built into new facilities.

There are three major types of CCS for power plants: post-, pre-, and oxy-combustion. Post-combustion CCS uses scrubbers and chemical systems to separate CO_2 from other gases, such as nitrous oxides, sulfur oxides, and particulate matter in the waste stream after the fossil fuel has been burned. Once other gases are scrubbed, amine-based (ammonia-derived) liquid solvents or solid sorbents chemically react and bind with the CO_2 in large vertical reaction chambers. The CO_2 is released in a pure stream when the materials that capture it are exposed to high temperatures and pressure. The solvents or sorbents are then recycled and returned to the capture stage for reuse. Post-combustion CCS increases the overall energy load of a fossil fuel power plant by as much as 20 percent. It is more energy intensive than pre-combustion CCS because the CO_2 is more dilute (roughly 4 percent of waste gases by volume in advanced natural gas combined-cycle power plants and 12 to 15 percent in coal power plants) and is mixed with a number of other gases.[8]

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Pre-combustion CCS, also referred to as gasification, begins when coal or natural gas is placed in a high heat and pressure environment and partially oxidized to form a synthetic gas composed of hydrogen, carbon monoxide, and CO_2. These components are then separated, with the hydrogen burned to generate electricity or heat. The CO_2 stream resulting from this separation is highly concentrated, which means less energy is required to capture it.[9]

Oxy-combustion CCS involves the combustion of fossil fuels in a pure oxygen environment, rather than with air. This method leaves a waste stream with a high concentration of CO_2.[10] Because no other gases are present during combustion, oxy-combustion eliminates almost all other non-CO_2 co-pollutants, such as nitrogen oxides and sulfur dioxides. Oxy-combustion requires the extra step of pure oxygen production. But even with that addition, oxy-combustion is more efficient and imposes a lower energy burden than the other two methods do.

CCS can be applied to a wide array of industrial applications, as many industrial processes require combustion to generate heat and use the same types of CCS systems that are applied to power plants. Some industrial facilities also emit CO_2 that arises from chemical processes. For example, "blue" hydrogen relies on CCS in its production and is expected to make up roughly 20 to 40 percent of global hydrogen demand by 2050.[11] (Low-carbon hydrogen, whatever its "color," is likely to play a central role in the future economy, due to its versatility across sectors ranging from steel to long-haul transportation to energy storage.)[12] Blue hydrogen production begins with a fossil fuel feedstock and applies high heat and pressure to crack off the hydrocarbon molecules. CO_2 is a byproduct of this method. While it is simply released into the atmosphere by hydrogen producers today, it can be captured relatively easily due to its high concentration.[13]

The capture stage is the most capital-intensive, technologically complex, and energy-intensive stage of the CCS process, representing up to 70 to 90 percent of total project costs for retrofits.[14] Variation in CO_2 concentrations during capture make an enormous difference in the cost of CCS. Applied to ethanol plants, where CO_2 is emitted in a nearly pure stream during fermentation, the cost is estimated to range from $26–$36 per ton, whereas the cost for post-combustion CCS on a power plant is more than $100 per ton.[15] In addition, CCS projects benefit from economies of scale whereby costs decline per ton of captured CO_2 as the size of the projects increases.

Carbon dioxide can be sequestered permanently underground or sold and used in industrial applications. Unless it is used at the same site where it is produced, the purified CO_2 must be compressed and transported, usually via pipeline or rail. If being sequestered, it is injected in a supercritical, liquid-like state into deep saline reservoirs or coal seams. Although the volume of suitable CO_2 sequestration sites is equivalent to many hundreds of years of global emissions, they are not dispersed equally across geographic areas. In the United States, for example, most are located off the coasts and in the interior of the country. CCS facilities are likely be located close to sequestration sites because it is costly to transport compressed CO_2 over long distances. Once pumped underground, the CO_2 must be monitored to verify that it is not leaking into the atmosphere or surrounding water tables. Geological research suggests that once it is properly injected, CO_2 will remain sequestered for thousands of years.[16] The transportation, sequestration, and monitoring adds roughly $3–$23 per ton to the cost of CCS, depending on the location, size, and depth of the sequestration sites.[17]

Utilization of captured CO_2 is an alternative to sequestration. To date, the most common uses of captured CO_2 are to increase oilfield production through enhanced oil recovery (EOR) and in food processing.[18] EOR sequesters the CO_2 underground while providing a revenue stream that can make such projects economical, but it also increases oil production, reducing the overall climate benefits of CCS. Research into new uses of CO_2 as an input in other sectors such as plastics, fertilizer, synthetic aviation fuels, and building materials is ongoing with a hope that commercializing these products will increase demand for active carbon management.

Only one large-scale power-sector CCS project is operating at present, a post-combustion CCS system at the 115 megawatt (MW) SaskPower Boundary Dam plant near Estevan, Saskatchewan, Canada, which opened in 2014.[19] However, over 100 CCS power plant projects, both post- and oxy-combustion facilities, are in either early or advanced project development globally, with a potential capture capacity of 100 million tons of CO_2 per year.[20] The frustrating track record of CCS in the power sector is counterbalanced by industrial applications, with as many as 25 CCS systems globally capturing 40 million tons of CO_2 annually. In 2021, industrial projects capable of sequestering an additional 70 million tons were announced, including several large-scale blue hydrogen projects, such as a $4.5 billion Air Products project in Louisiana.[21]

A handful of large, established industrial and oil and gas companies, including Mitsubishi Heavy Industries, Fluor, Equinor, ExxonMobil, Chevron, and Shell, dominate the CCS business. Many of these companies recently announced a plan to establish a CCS Innovation Zone in the Gulf of Mexico to scale capture technologies to 50 million tons annually by 2030.[22] Net Power, a young company with an innovative design that uses captured CO_2 rather than steam to move a turbine and generate electricity is piloting a 50 MW oxy-combustion facility. Other firms are working on blue hydrogen production, new uses for captured carbon, and modular CCS design and applications across various end uses.

Direct Air Capture

Whereas CCS captures CO_2 from waste streams, DAC captures emissions from the ambient air, with the goal of reducing the concentration of atmospheric CO_2. Rising concentrations of atmospheric CO_2 are large enough to drive climate change; however, they are small in absolute terms at just over 400 parts per million or 0.04 percent. DAC has long been in use on a small scale in specialized industrial applications and to make the air breathable in submarines and spacecraft.

DAC systems use giant arrays of industrial fans to move ambient air through a honeycomb PVC material coated in a liquid or solid sorbent, similar to that used in CCS. As the air passes over the surface, CO_2 binds with the sorbent and is then exposed to high heat and pressure to split off the pure CO_2 as the sorbents are recycled. The process is energy intensive because the very low concentration of CO_2 in the ambient air means large volumes of air must be moved through the system.

In addition to thermal and electric energy needs, DAC requires water and land. Liquid solvent technology uses roughly one to seven tons of water per ton of CO_2 captured, while solid sorbents need somewhat less. DAC land-use requirements range between 100 and 420 acres of land per million tons of CO_2 captured, depending on the source of electricity.[23] Modular DAC designs help minimize land use through unit stacking.

While DAC costs about $250–$600 per ton of CO_2 captured today, a group of engineering and technology experts have estimated that, with strong policy support and rapid growth in deployment, the cost could decline to $100 per ton by 2030.

The critical factor in determining the overall climate benefit of DAC is the energy sources it uses. DAC facilities must be sited near low-cost and plentiful low-carbon electricity and heat if it is to have a chance of drawing down atmospheric CO_2.[24] However, unlike CCS, where siting must consider the market for power or industrial products, DAC can be deliberately sited atop sequestration reservoirs as long as the location has ample electricity, heat, water, and land.

Pairing DAC with low-carbon nuclear electricity would reduce land-use and energy requirements relative to renewable resources. Nuclear power would also provide continuous energy as well as heat, unlike renewables, which are intermittent and less well suited to supplying heat. Natural gas systems equipped with CCS have similar characteristics, which led Carbon Engineering, a DAC company established in 2009, to adopt this approach.

While DAC costs about $250–$600 per ton of CO_2 captured today, a group of engineering and technology experts estimated that, with strong policy support and rapid growth in deployment, the cost could decline to $100 per ton by 2030.[25] At $100 per ton, DAC would be at the upper end of the carbon technology abatement cost curve, but might still be affordable for those required to or interested in offsetting hard-to-abate emissions.

Over the last few years, following decades of public and private investment in early-stage technologies, DAC finally seems ready for takeoff. The first large-scale DAC facility opened in 2021 in Iceland with an annual capture capacity of 4,000 metric tons, followed by a handful of project announcements in the United States. The industry is attracting increasing interest from climate-tech venture capitalists and other investors. Climeworks (Switzerland), Carbon Engineering (Canada), and Global Thermostat (United States) have been developing DAC systems for more than a decade. Numerous start-ups have more recently followed on their heels, seeking to improve existing technology and lower costs or exploring novel approaches to DAC.[26] One company, for example, is working on DAC systems that can be retrofitted onto existing commercial HVAC cooling towers, while another is working on mechanical trees that harness natural breezes to move air over the CO_2 sorbent.[27]

MODELING THE GLOBAL NEED FOR ACTIVE CARBON MANAGEMENT

Fossil fuels have supported global economic growth since the Industrial Revolution.[28] They remain dominant today due to their high energy density, low cost, wide availability, and ease of transportation. These qualities make it likely that much of the world, notably developing regions where total energy use is growing, such as China, India, southeast Asia, and Africa, will continue to rely on them long into the future. As this section shows, many major climate and energy models conclude that it will be impossible to eliminate fossil fuels globally by 2050. Yet, even with a significant amount of fossil fuel use, the world need not necessarily suffer the negative consequences of emissions. If active carbon management technologies are fully developed and deployed, ambitious 2050 climate goals will still be achievable.

Global Climate and Energy Modeling

Modeling is an essential analytical tool for climate and energy policymakers. Climate modeling looks at the climatic consequences of total CO_2 and other GHG emissions. It links emission levels to the probability of heat waves, flooding, and other catastrophic outcomes. Energy modeling details the degree to which emissions can be reduced across economic sectors, bounded by cost, technology, and other constraints.

Climate and energy models have been used for decades, refined as greater computing power and more data became available. The main models converge on a shared finding: The world will need to remove or sequester billions of tons of CO_2 through 2050 and beyond.

These models begin with baseline or business-as-usual scenarios, detailing current climate and energy systems, and rely on historical trends. Given a range of assumptions, variables, and emissions or technology pathways, modelers then assess how to achieve a specific scenario (such as keeping global average temperature rise to below 1.5° Celsius or reducing emissions to net-zero). Such models are not meant to predict the future, but rather provide probable outcomes given specific parameters.

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Table 1: Summary of climate and energy models

Study/Model	Scenarios	Carbon Removal Required	Caveats
IPCC 1.5° Celsius Report	Limiting global warming to 1.5°C above pre-industrial levels	100–1,000 GT total through 2100	• Allows for carbon emissions overshoot (emissions exceed 2050 budget, but come down in subsequent decades through carbon removal) • Relies on BECCS, industrial and power sector CCS, and natural carbon removal
IEA Net-Zero by 2050 (2021)	Net-zero global emissions by 2050	1.7 GT annually by 2030, and 7.6 GT annually by 2050 1 GT of DAC by 2050	• Relies on CCS, BECCS, and DAC to achieve a low-carbon emission pathway
BP Net-Zero report (2020)	Net-zero global emissions by 2050	5.5 GT annually by 2050	• BECCS 1.5 GT of carbon management • CCS/CCUS for industry, power, and hydrogen make up the remainder • Little to no DAC modeled
Shell *Sky* Scenario (2018)	Hold global average temperatures "well below 2°C" and net-zero global emissions by 2070	3.3 GT annually by 2050 and 9.5 GT annually by 2070	• Projects large increase in global energy demand • Little to no DAC modeled
Princeton Net-Zero America Report (2020)	Net-zero economy-wide U.S. by 2050	0.44–0.94 GT annually of CCS by 2040, 0.93–1.65 GT by 2050. 0.01–0.850 GT annually of DAC by 2050	• Fossil fuel demand expected to still make up 24–44% of U.S. energy demand through 2050 • CCS necessary for hard-to-abate industrials, particularly steel, cement, as well as hydrogen for storage • Cheapest total system costs scenario includes highest level of carbon management compared with 100% renewables only

Study/Model	Scenarios	Carbon Removal Required	Caveats
U.S. State Department Pathways to Net-Zero GHG Emissions by 2050 (2021)	Net-zero economy-wide U.S. by 2050	1.0–1.8 GT annually of net carbon removal by 2050	• Model includes both nature-based carbon removal through increased afforestation and restoration and active carbon management, including CCS and DAC • All fossil power plants without CCS phasedown by 2040, with 20–35% of electricity generated from fossil with CCS by 2050

The next sections focus on three of these models in more detail: the Intergovernmental Panel on Climate Change's (IPCC's) *Global Warming of 1.5°C* report, the International Energy Agency's (IEA's) *Net-Zero by 2050* analysis, and the energy giant BP's *Global Energy Outlook*. We chose these studies to provide a range of perspectives on the level of active carbon management necessary to stave off the worst consequences of climate change.

IPCC 1.5° Celsius Report

IPCC is a United Nations body created in 1988 that provides regular assessments of the scientific basis of climate change, its impacts and future risks, and options for adaptation and mitigation. When released in 2018, IPCC's *1.5°C* report was groundbreaking. It projects the possible impacts of global warming of 1.5°C above pre-industrial levels and advanced several emissions-reduction pathways through 2050 and beyond.[29] The report is a dire warning of climate instability if emission increases are not mitigated.

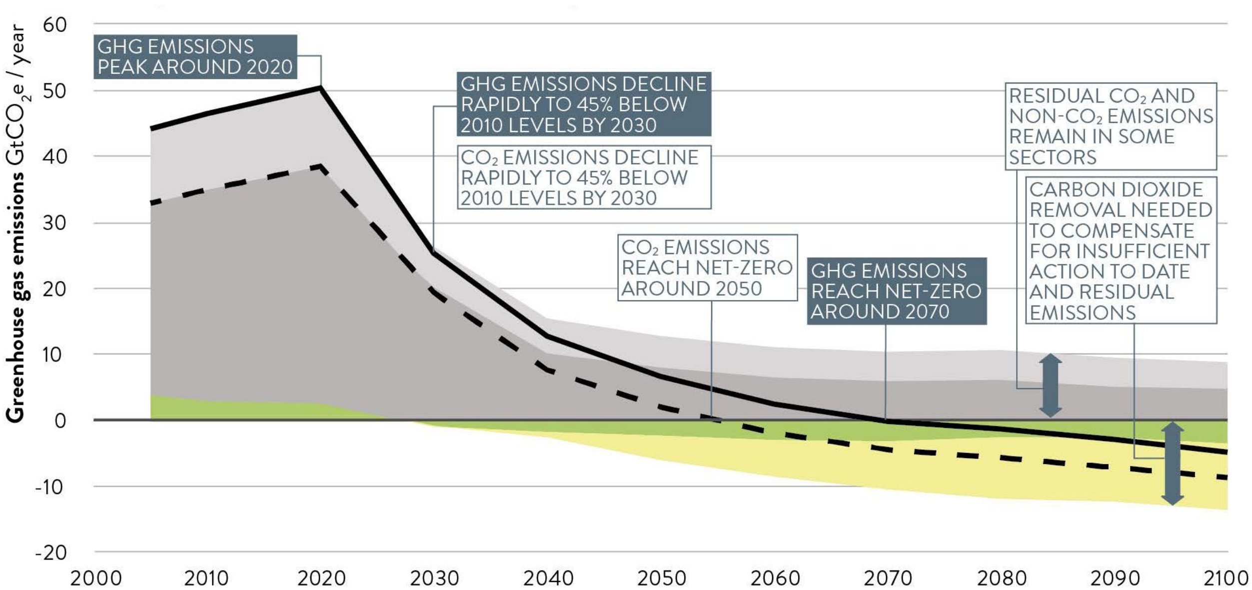
The report estimates that total emissions between now and 2050 must stay between 420 GT and 770 GT CO_2 equivalent to achieve the 1.5°C target. Current net annual global emissions average around 40 GT. Four of the five primary emissions-reduction pathways that would remain within this "carbon budget" depend on active carbon management, largely BECCS and CCS for industrial processes and power plants. The cumulative total of emissions averted or removed would range from 100 to 1,000 GT by 2100.[30]

IPCC's modeling provides two roles for active carbon management. First, it allows emissions to decline more rapidly than otherwise, so the world can stay within or closer to the budget constraint. Second, it provides the means to draw down CO_2 from the atmosphere in scenarios in which emissions overshoot the carbon budget. IPCC finds that overshooting is likely, given the expected growth in the global economy through 2030 and beyond.

A key finding of the report is the "longer the delay in reducing CO_2 emissions toward zero, the larger the likelihood of exceeding 1.5°C, and the heavier the implied reliance on net negative emission after mid-century to return warming to 1.5°C."[31] Ultimately, the IPCC report finds that the global carbon budget can only be achieved in such scenarios if DAC and other carbon removal are deployed on a massive scale.

For example, as seen in the solid line in figure 2, IPCC's analysis shows that in a scenario in which the world overshoots the carbon budget substantially due to sustained and robust economic growth, as much as 8 GT of carbon removal would be needed annually by 2050, and even more through 2100. Removal of CO_2 would be necessary through 2100 to offset both non-CO_2 GHG emissions that remain and to account for insufficient decline in global emissions through mid-century.

Figure 2: IPCC 1.5° Celsius pathways[32]



International Energy Agency World Energy Outlook

IEA is an intergovernmental organization of the world's largest energy-using nations. It houses a large energy modeling unit centered on the annual *World Energy Outlook*, which combines supply, demand, and transformation modules to build a detailed overview of global energy and emission trajectories. IEA's 2021 *Net-Zero by 2050* special report builds on this framework. It imposes a net-zero-emissions-by-2050 constraint while simultaneously achieving the UN's Sustainable Development Goals for global economic and human development.

IEA's net-zero emissions (NZE) scenario finds that active carbon management is critical to reduce emissions and remove CO_2 from the atmosphere. Despite enormous growth in low-carbon resources, fossil fuels will still account for one-fifth of global primary energy in 2050. The emissions from these sources must be captured and sequestered or removed from the atmosphere.

IEA projects a total of 7.6 GT of annual CO_2 sequestration and removal from a diverse array of sectors in 2050 (see table 2), the equivalent of more than 20 percent of global energy-related emissions today. In the report's main scenario, CO_2 captured from fossil fuel will total 5.25 GT by 2050, with the industrial applications making up the largest CCS sector (2.6 GT), followed by blue hydrogen production (1.4 GT). IEA projects remaining fossil fuel CCS demand to come from the power sector (0.9 GT) and non-biofuel production such as EOR (0.4 GT). IEA projects a smaller but still significant role for bioenergy CCS applications, largely split between the power (0.6 GT) and biofuels production (0.6 GT) sectors, with only a small role for bioenergy CCS in industrial applications (0.2 GT). Finally, IEA expects almost 1 GT of CO_2 removal through DAC by 2050.

Table 2: Metric tons of carbon captured annually under IEA's net-zero emissions scenario

Active Carbon Removal Process	2020	2030	2050
CO_2 Captured From Fossil Fuel	**39**	**1,338**	**5,245**
Power	3	353	862
Industry	3	360	2,620
Hydrogen Production	3	455	1,353
Non-Biofuel Productions	30	170	410
CO2 Captured From Bioenergy	**1**	**255**	**1,374**
Power	0	90	572
Industry	0	15	178
Biofuels	1	150	624
Direct Air Capture	**0**	**87**	**983**
TOTAL CO_2 CAPTURED	**40**	**1,680**	**7,602**

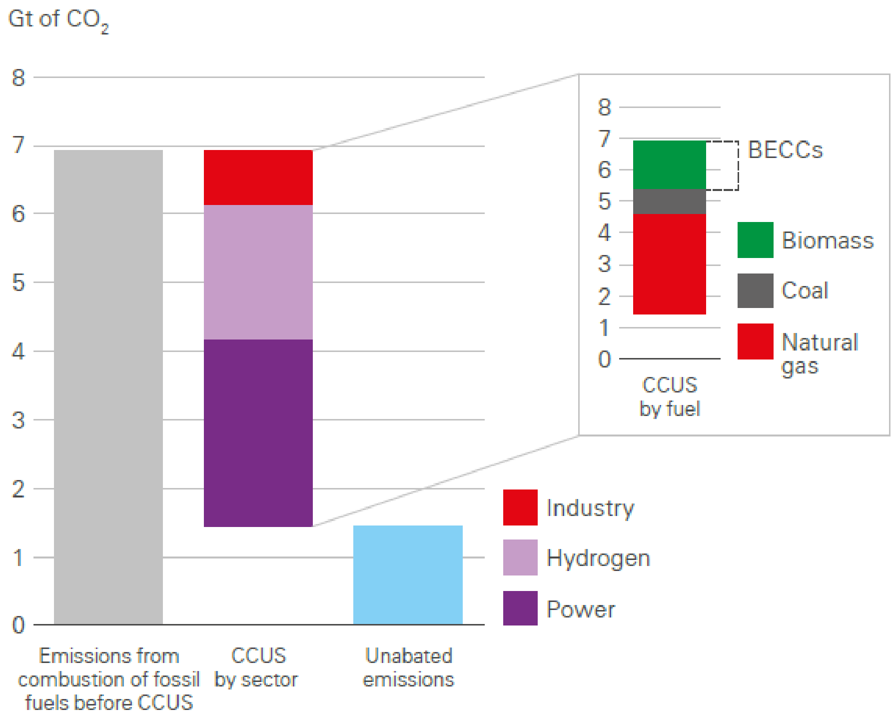
Like IPCC, IEA includes net-zero scenarios that avoid active carbon management. These scenarios are much more expensive, less feasible, and require more land and other resources than those that employ active carbon management do. Around $15 trillion in additional investments for wind, solar, and hydrogen electrolyzer capacity would be needed from an NZE scenario."[Active carbon management] is the only scalable low-emissions option to remove CO_2 from the atmosphere and to almost eliminate emissions from cement production," the report states. "A failure to develop CCUS for fossil fuels could delay or prevent the development of CCUS for process emissions from cement production and carbon removal technologies."[33]

BP's Global Energy Outlook

BP is one of the world's largest oil and gas companies. Its annual *Statistical Review of World Energy* is widely referenced, and BP was a pioneer in scenario planning decades ago. BP's *2020 Global Energy Outlook* includes a "Net-Zero" (by 2050) emissions scenario and a less-ambitious "Rapid" scenario in which emissions fall by roughly two-thirds from 2020.[34] Although these scenarios project rapid declines in demand for fossil fuels, carbon-based energy still makes up more than 20 percent of final energy demand in the Net-Zero scenario and as much as 40 percent in the Rapid scenario. Active carbon management is essential to accommodate this continued use of fossil fuels while keeping a low-emissions pathway possible.

Demand for fossil fuels is driven mainly by natural gas demand in the power and industrial sectors, accounting for a sixth or more of total energy demand by mid-century. The *Net-Zero* scenario projects roughly 5.5 GT per year of carbon sequestration in total. (See figure 3.) "[T]echnologies which capture carbon emissions or extract them from the atmosphere," the report concludes, "are likely to play a material role in a net-zero environment."[35]

Figure 3: CCUS's annual impacts by emissions sector in 2050 in BP's net-zero scenario



Notably, BP's analysis projects that gas with CCS will be a cost-effective and significant resource for electricity generation that will meet demand when renewable resources make up a significant portion of supply, balancing renewables' variability across days, weeks, and seasons. CCS is applied to 90 percent of global gas capacity in the Net-Zero scenario. Blue hydrogen production and industrial applications also rely heavily on CCS. While the scenario does not model DAC, the report notes that it "may play an increasingly important role … offsetting any continuing emission from hard-to-abate sources in the energy system and the wider economy, such as agriculture, as well as any overshoots in the carbon budget."[36]

If the world is to support continued economic and population growth, particularly in the developing world, and meet its emissions-reduction targets through 2050 to ensure a stable climate, then active carbon management must become a viable and affordable suite of solutions for gigatons of emissions.

These three models were developed by different organizations and represent a broad array of models created by other researchers. They yield clear and consistent results. If the world is to support continued economic and population growth, particularly in the developing world, and meet its emissions-reduction targets through 2050, then active carbon management must become a viable and affordable suite of solutions for gigatons of emissions. Fossil fuels will continue to make up a large portion of primary energy demand through 2050. Achieving NZE will be much costlier and perhaps technically impossible without active carbon management solutions.

FEDERAL POLICY FOR ACTIVE CARBON MANAGEMENT

Governments must act now to ensure that active carbon management solutions can achieve their potential in the decades ahead. As the largest historical source of emissions and the world's preeminent nation for science and technology, the United States should take the lead.[37] Federal policy has provided some support for active carbon management through research, development, and demonstration (RD&D) spending and tax credits, policies Congress recently strengthened. However, additional measures must be taken to scale up efforts between now and 2030 and beyond. A comprehensive strategy would include a regulatory framework for expanding the CO_2 pipeline networks, strengthening public confidence in sequestration, and finding new ways to use (rather than store) captured CO_2. This strategy could drive CCS and DAC innovation while simultaneously accelerating deployment in the power, industrial, and commercial sectors and building markets for captured carbon.

Federal Support Through the Trump Administration

Federal support for active carbon management, primarily CCS, has experienced false starts and swings in public interest over the last two decades. The Bush administration initiated programs to retrofit CCS onto existing coal-fired power and industrial plants. The Energy Policy Act of 2005 gave congressional backing to its Clean Coal Power Initiative (CCPI), a public-private cost-sharing collaboration for technology development and demonstration. The Bush administration sought to turn this authorization into expanded funding for CCS RD&D, requesting $650 million for this purpose in its final budget.[38]

However, significantly more funding arrived during the Obama administration with the 2009 American Recovery and Reinvestment Act (ARRA). ARRA allowed DOE to invest roughly $684 million into eight coal-based projects between 2009 and 2017.[39] Only one of these projects proved to be a success, the Petra Nova facility in Texas, and even it was ultimately mothballed when oil prices crashed in 2020. ARRA's $438 million investment in three industrial CCS projects yielded better results. Two of these were ultimately completed and are still in operation. The Obama administration also established an interagency task force to further CCS innovation and deployment by reducing financial and regulatory hurdles and improving coordination.[40] In 2015, the administration sought to add a major regulatory pull to spur investment in CCS with the promulgation of the Clean Power Plan (CPP). The CPP would have required CCS to be applied to all new coal-fired power plants and capture at least 40 percent of CO_2 emissions.[41] But it stalled in the wake of legal challenges and was withdrawn by the Trump administration. Even though the Trump administration touted CCS as "a realistic approach to promote energy innovation," the president's budget attempted to cut appropriations for CCS RD&D by as much as 75 percent.[42] Congress rejected these proposals and increased federal support for DOE's CCS programs throughout the late 2010s.[43]

Tax credits to support CCS for coal-fired power plants date back to 2008, but the Bipartisan Budget Act of 2018 was the first time such support was put in place for the broader CCS and DAC portfolio. Congress increased the credit under section 45Q of the U.S. tax code to $50 per ton of CO_2 permanently sequestered and broadened eligibility considerably for DAC and industrial facilities.[44]

All told, the federal government invested about $7.3 billion in CCS RD&D and projects through annual appropriations from fiscal year 2010 to fiscal year 2021, and ARRA provided an additional $3.4 billion.[45] This policy has yielded modest results so far. Many federally funded CCS projects (especially power plant retrofits) were canceled, including the biggest one, FutureGen. Uptake of 45Q was hampered by unrealistic requirements and a six-year delay in issuing IRS guidance, resulting in only an estimated $600 million in tax credits between fiscal years 2019 and 2023.[46] DAC has been mired in the prototype stage until very recently, with no commercial development.

2020–2021: A Turning Point for RD&D

Over the last three years, the weaknesses of past federal policies and the growing urgency of climate innovation have combined to excite bipartisan interest in active carbon management. More than 50 bills that would advance a national strategy have been introduced into Congress during that time.[47] The ferment culminated in the passage of the Energy Act of 2020 (EA 2020) and the Infrastructure Investment and Jobs Act of 2021 (IIJA), which supercharged federal investment in this field. The enhanced public support has been met with increased commercial interest, with over 50 CCS and a handful of small-scale DAC projects announced in the United States in 2021.[48]

EA 2020 set the tone by expanding the authorization of DOE's Office of Fossil Energy to include carbon management, prompting the Biden administration to rename it the Office of Fossil Energy and Carbon Management (FECM). The IIJA followed through by appropriating an estimated $12.5 billion over five years for CCS, DAC, and pipelines.[49] (See table 3.) The overall investment substantially exceeds prior federal support for these technologies to date.[50]

Table 3: Active carbon management programs funded by the Industrial Investment and Jobs Act of 2021

Program	Appropriations	Notes
Carbon Capture Technology Program (§40303)	$100 million	Funding for front-end engineering and design studies to support CO_2 transport infrastructure
Carbon Capture Transportation Infrastructure Program (§40304)	$2.1 billion	Based largely on language found in the bipartisan SCALE Act, provides support for CO_2 transportation and pipeline infrastructure through grants, loan guarantees, and speedy permitting
Carbon Storage Validation and Testing (§40305)	$2.5 billion	Authorizes funds for the Large-Scale Carbon Storage Commercialization Project by the DOE, providing funding for the development of new or expanded commercial carbon sequestration projects and CO_2 transport infrastructure
Secure Geologic Storage Permitting (§40306)	$75 million	Provides $25 million in funding to speed EPA permitting of CO_2 wells, alongside $50 million for state CO_2 well permitting and monitoring
Direct Air Capture Hubs (§40308)	$3.5 billion	Funding to support up to four regional DAC hubs with the capacity to sequester or utilize up to 1 million metric tons of CO_2 annually
Carbon Capture Pilot and Demonstration Program (§41004)	$3.47 billion	Funding for large pilot projects that scale technology for commercial applications
Direct Air Capture Technologies Prize Competition (§41005)	$115 million	Provides $15 million in funding for precommercial and $100 million for commercial DAC technologies

Program	Appropriations	Notes
Industrial Emissions Demonstration Projects (§41008)	$500 million	Funding to support CCS projects that reduce non-power sector emissions from industrial applications

The industrial sector is the source of about 30 percent of United States' emissions. The IIJA renewed federal support for industrial CCS applications, including in the cement, steel, and fertilizer industries. Industrial decarbonization is an extremely complex challenge, given the diverse uses of fossil fuels and process emissions resulting from chemical reactions in this sector. DOE has already begun to respond to this congressional imperative, such as the October 2021 announcement of $45 million in funding for 12 pilot-stage industrial CCS projects. The White House announced additional measures in February 2022.[51]

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The IIJA created a new program to establish four DAC demonstration hubs. Public-private partnerships will build these hubs across diverse sectors and regional environments. The hub approach allows for economies of scale that lower costs by utilizing shared infrastructure.[52] A DAC hub in the Gulf of Mexico, for example, could take advantage of existing CO_2 pipelines, oil and gas workforce expertise, and easy access to geological sequestration sites. The hubs should drive domestic DAC manufacturing as well. The program could lay the foundation for the United States to become a DAC technology exporter to both developing and developed nations alike.

DOE is taking on the numerous technical and financial challenges of large-scale carbon storage through its Carbon Storage Assurance Facility Enterprise (CarbonSAFE) Initiative, which aims to scope, permit, build, and operate several multimillion-ton sites located at industrial facilities by 2026. CarbonSAFE is working to identify RD&D knowledge gaps and develop necessary technologies at scale while building expertise in commercial-scale project selection, development, modeling, and monitoring. It has funded several front-end feasibility studies to date.[53]

The IIJA updated financing and payment criteria used by DOE's Loan Programs Office (LPO) to make it easier for CCS and DAC projects to benefit from LPO's lower-cost capital, flexible financing, and technical expertise. Under the 2005 Energy Policy Act, LPO already had the authority to distribute up to $8.5 billion in loan guarantees to eligible advanced fossil energy projects but had not used much of it.[54] LPO revamped its processes, inducing a surge in applications topping $53 billion in total, and began to expand into new areas, making its first conditional commitment during the Biden administration to a methane pyrolysis plant to be built by Monolith.[55]

Building on EA 2020 and the IIJA, DOE announced a Carbon Negative Shot Initiative in November 2021 to lower the cost of carbon removal to $100 per ton and sequester one billion tons of emissions by 2050. This initiative is being led by FECM and includes efforts to scale technology, reduce costs, improve sectoral knowledge sharing, and spur innovation through project development and deployment.[56]

The Next Frontier of CO_2 Storage: Under the Sea

The next frontier of CO_2 storage will be under the world's oceans, where gigatons of cheap and accessible storage space can be found. One study estimates that meeting a 2° Celsius target would require more than 10,000 offshore CO_2 injection wells globally by 2050.[57] The United States' outer continental shelf represents a particularly appealing location, as its geology affords ample opportunity for CO_2 storage. IEA reports that the United States' theoretical offshore CO_2 storage potential is over 250 GT.[58]

Offshore CO_2 storage has important advantages over onshore storage from a regulatory perspective. Most federal and state drilling regulations are in place to ensure safe access to drinking water. These concerns are not present for offshore injection wells, as no freshwater aquifers would be impacted. Whereas a driller may need a half dozen permits from state and federal agencies to drill a Class VI well onshore, the only regulator of drilling beneath federal waters is the United States Department of Interior's Bureau of Ocean Energy Management (BOEM).

While these procedural advantages may speed the development of offshore CO_2 storage, it is still a relatively new area for both industry and government. Only a handful of offshore storage sites are operating globally, mostly in the North Sea.[59] The federal government has yet to issue much guidance for this kind of development, and it does not yet run an offshore leasing program for this purpose. Once large-scale project proposals come forth, the federal government will need to vet and approve them quickly to help the industry scale. The IIJA did amend the Outer Continental Shelf Lands Act, authorizing the U.S. Department of the Interior (DOI) to promulgate offshore storage guidance and regulation within the coming year.

If economically and safely developed, offshore CO_2 storage offers opportunities to utilize existing human and infrastructure capital invested in carbon-intensive production. The Gulf of Mexico is home to one of the world's most advanced offshore oil and gas industries, which could be reoriented to negate the emissions it has contributed to over many years.

Carbon Utilization, Accounting, Pricing, and Regulation

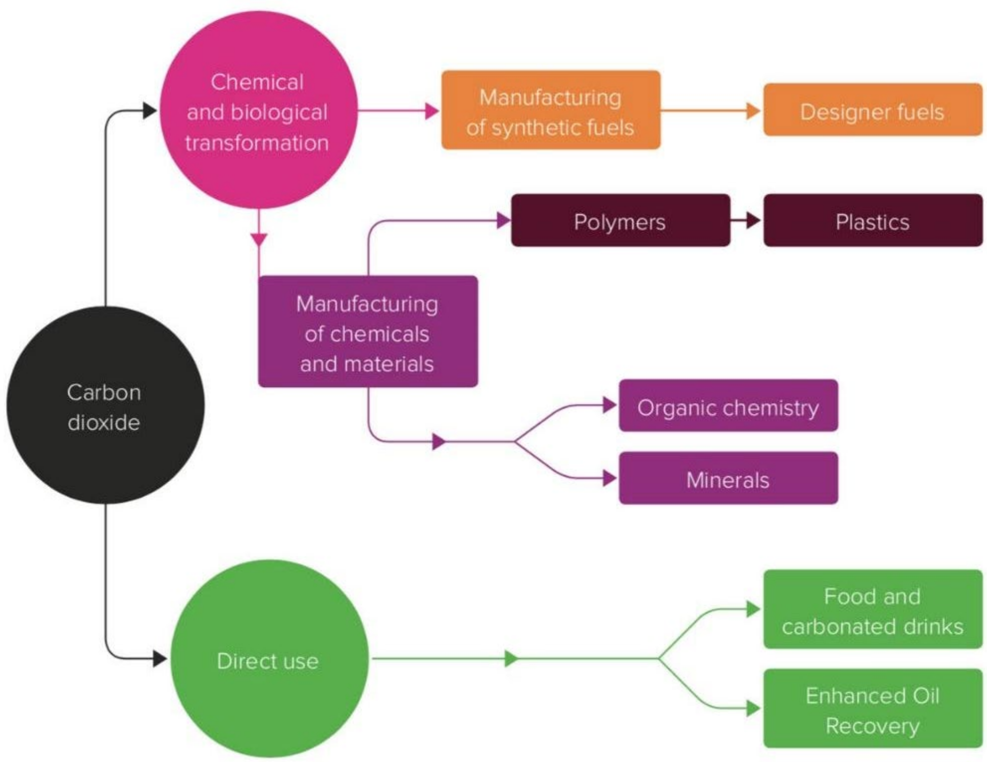
Federal RD&D, tax, procurement, and regulatory policies for active carbon management are moving forward, albeit at different rates. They have the potential to jump-start the industry and dramatically lower the costs of CCS and DAC. However, the industry's ultimate success in reaching gigaton scale will require the development of a carbon market that does not depend on large federal subsidies.

CO_2 is sold today for uses such as EOR and food processing. These sources of demand are nowhere near large enough to accommodate the plentiful supply that a robust active carbon management industry would generate. In addition, EOR is a highly volatile financing mechanism, as its value fluctuates with oil and natural gas prices. The largest power-sector CCS project in the United States, Petra Nova in Texas, was mothballed in 2020 when gasoline prices fell due to the COVID-19 pandemic, and the cost of capturing CO_2 was greater than the marginal economic benefit of selling it for EOR.[60] To date, even with crude oil prices over $100 per barrel, this facility remains inoperative.

New technologies and applications would further grow the market for CO_2 as a valuable industrial input. Figure 4 shows two major pathways for carbon utilization. Today, most uses are direct; CO_2 is simply recycled as is. The direct pathway can be expanded to include building materials. CarbonCure Technologies, which won $7.5 million from the XPrize Foundation in April 2021, for example, injects captured CO_2 into cement during the mixing process. This process not only finds useful commercial applications for captured CO_2 in concrete, but also provides a long-term and low-cost sequestration solution.[61]

Indirect CO_2 utilization pathways split the carbon from oxygen and recombine it with hydrogen and other elements to make fuels, chemicals, and materials. (See figure 4.) One future pathway would use carbon from captured CO_2 with blue or green hydrogen to form carbon-neutral jet fuel. Alternatively, captured CO_2 could be used to spur rapid algae growth, which could then be refined into biofuels. Structural materials made from advanced carbon fibers and carbon nanotubes could be substitutes for steel.[62]

Figure 4: Uses of carbon dioxide[63]



A handful of U.S. companies are pursuing a variety of tantalizing possibilities. LanzaTech, one of the best-known companies in the CO_2 utilization arena, is using gas fermentation processes to turn captured carbon into biofuels, bioplastics, and bio-composite materials and polymers.[64] Federal agencies such as Advanced Research Projects Agency–Energy (ARPA-E) should expand their support for carbon utilization entrepreneurs seeking to find novel means of commercializing captured carbon.[65]

On the demand side, some private investors are rewarding firms that reduce their emissions. So-called ESG (environmental, social, governance) funds, which have received massive inflows of capital in recent years, focus on such criteria, along with financial performance. Investment strategies such as these depend on a robust and credible carbon accounting system. A ton of carbon captured by one technology or company must be confidently equated to a ton captured elsewhere. Investors must be sure that storage is indeed permanent.

Some corporations interested in bolstering a low-carbon image and furthering corporate climate objectives are investing in carbon removal technologies as well, even at the price of paying a substantial "green" premium. Technology companies such as Stripe, Meta (formerly Facebook), Alphabet (Google's parent company), and Shopify, for example, recently announced a $925 million carbon removal initiative that aims to increase corporate demand while developing criteria to vet projects and credits.[66] This financing mechanism is an innovative way to grow both the demand and supply of removal technologies while driving unit costs lower.

Although carbon utilization and climate-conscious investing are valuable steps toward creating a carbon removal market, carbon removal subsidies or regulation must supplement them. CCS innovation policies will reduce, but will not eliminate, the green premium for many low-carbon products. No matter how cheap DAC becomes, it will cost money. Markets for captured carbon are thus highly unlikely to be commensurate with the total amount of CO_2 that must be removed. Governments will have to continue to fund carbon removal, paying a bounty for every ton. Just like public sewers, which are funded by taxpayers, carbon removal will have to be subsidized by governments because waste disposal is never free.[67] This could be funded through a carbon-free, carbon-based import tariff, or some other energy or environmental tax. Using the waste analogy, municipal garbage collection will always dwarf the market for recyclable materials, but both are necessary to manage waste effectively. Innovations that lower the costs of active carbon management, however, will make such comprehensive policies less expensive and more politically feasible.

REBUTTING MISLEADING CLAIMS ABOUT ACTIVE CARBON MANAGEMENT

Despite a broad expert consensus that active carbon management is essential to achieve climate goals, it still provokes intense opposition in some quarters. For CCS and DAC technologies to play vital roles in the energy and climate transition, the public must come to see them as just as necessary to the low-carbon future as wind turbines and solar panels. While well-grounded concerns such as the threat of methane leakage from natural gas production, transportation, and use should be acknowledged and addressed, misleading claims must be rebutted.

One of the most prominent deceptive objections is that active carbon management is a distraction that diverts vital investments away from more immediate emissions-reduction priorities. A second claim is that it is too expensive. Third, environmental justice groups often oppose these technologies because they may prolong the life of old facilities that pollute the air in disadvantaged communities or will require new infrastructure that may be placed near these communities. What underlies much opposition to active carbon management technologies is an opposition to the "oil age," a type of industrial development and living made possible by the discovery and widespread use of oil.

Claim 1: Active Carbon Management Is a Diversion

For many opponents of active carbon management, the enemy is fossil fuel use rather than the emissions that result from it. They worry that any attention paid to it will divert efforts from alternative pathways to decarbonization that do not rely on fossil fuels. A closely related argument posits that active carbon management creates a moral hazard that excuses the unabated use of fossil fuels on the premise that emissions can be cleaned up later.[68] Our analysis shows that CCS and DAC are not distractions on the pathway to a low-carbon future, but rather vital companion technologies that will help achieve that future while allowing for continued global economic development.

Ambitious decarbonization scenarios in these models find that fossil fuels will continue to supply a large fraction of the world's energy needs through 2050.[69] The global energy system is so enormous, complex, and important that it will be essentially impossible to fully eliminate in just 30 years the 80 percent share met today by fossil fuels. Some sources of emissions will be too costly or technically infeasible to substitute with alternatives. They will need to be abated with CCS or offset with DAC. Moreover, if the world overshoots the carbon budget, only DAC will remove historical emissions to restore an acceptable level of atmospheric CO_2.

A good example of these dynamics is the development of firm power resources that will work alongside variable renewables to reduce annual emissions without compromising reliability. Reliable power will become increasingly important as cars, homes, and industries rely more heavily on the grid in the coming years. But grids with high penetrations of variable renewables will require significant flexibility to accommodate their swings in supply on hourly, daily, and seasonal timescales. Natural gas provides this flexibility in many locations today. Although bigger and smarter grids and energy storage can enhance reliability as well, CCS-equipped fossil power plants will be a key option for balancing, frequency regulation, and other reliability services, especially when other resources are prohibitively expensive or simply unavailable.[70]

It will be essentially impossible to eliminate in just 30 years the 80 percent share of global energy met today by fossil fuels. Some sources of emissions will be too costly or technically infeasible to substitute with alternatives. They will need to be abated with CCS or offset with DAC.

Active carbon management will be particularly important to ensure that the demand for energy in the developing world is met at a reasonable cost. Global average per capita energy use is a tiny fraction of the United States' national per capita energy demand. Citizens of developing nations desire increased access to the goods and services enjoyed by the world's wealthiest inhabitants, and their governments will respond to meet those needs.[71] While the development pathways of these nations need not be as profligate as were those of the developed world, energy use in developing nations is certain to grow. Unless low-cost-climate-solution options are available, these nations will undoubtedly prioritize economic development over emissions reduction. Active carbon management allows for the continued reliance on fossil resources without abandoning emissions-reduction goals. CCS and DAC complement other low-carbon strategies and may enable equitable, climate-friendly development.

Active carbon management is already imperative in the developing world because its energy-using infrastructure is very young. Given the high costs of power systems and industrial plants, shutting down these assets and stranding investments in them is unlikely to be an acceptable choice. For example, in China, the average coal-fired blast furnace for steel production is less than 15 years old.[72] Such assets typically have a useful life of over 50 years, and they will continue to be around through 2050. Efforts to reduce or eliminate emissions from these facilities must rely on CCS or DAC.

Claim 2: Active Carbon Management Is Too Expensive

Opponents of active carbon management technologies argue that these technologies are more expensive than renewables and will never cost-effectively scale to meet emissions-reduction targets.[73] For example, the Center for International Environmental Law stated, "CCS technology entrenches reliance on fossil fuels rather than accelerating the needed transition to cheaper and cleaner renewable energy."[74] Again, this shows the true focus of many environmental groups: getting rid of fossil fuels rather than CO_2 emission. The stark fact is these fuels are not going away for a long time.

The claim that active carbon management technologies are too expensive to meaningfully reduce global emissions is misguided. The comparison to today's costs is sloppy, and the assessment of future prospects is excessively pessimistic. Comparing CCS and DAC to renewables is an apples-to-oranges comparison. It is certainly true that renewables generally have a lower levelized cost of energy (LCOE), but this metric alone is not adequate for comparison, as renewables are intermittent power resources. Fossil-fuel power plants with CCS are firm power-generating resources. Industrial and other applications of CCS avert emissions. DAC removes CO_2 from the air. These are different services. LCOE does not account for grid services firm resources provide, nor does it account for CCS's abatement of industrial or other emissions or DAC's capability to offset emissions elsewhere in the economy that would otherwise be infeasible to abate.

A U.S. grid relying entirely on wind and solar power and battery storage in 2050 would cost some $2 trillion more than a system that draws 20 percent of its power from plants equipped with CCS, according to Princeton University's *Net-Zero America* report.

The value of firm power resources will rise as the penetration of variable resources grows. Most energy models project that renewables will continue to dominate new capacity construction, as they do in many places now, for many years. But as renewables' share of generation rises from 40 or 50 percent to 90 or 100 percent, their economics change. Such systems must be overbuilt, resulting in higher costs and substantial land-use demand. A U.S. grid relying entirely on wind and solar power and battery storage in 2050 would cost some $2 trillion more than a system that draws 20 percent of its power from plants equipped with CCS, according to Princeton University's *Net-Zero America* report.[75]

CCS is likely a cheaper alternative for industrial decarbonization as well. Blue hydrogen derived from natural gas systems equipped with CCS is projected to be more affordable and available in many locations than green hydrogen made with renewable energy for some time to come. Low-carbon hydrogen is required for clean steel-making and many other industries. One analysis finds that replacing the entire annual primary capacity from one large steel plant in the Netherlands with hydrogen would require 6 GW of renewables, equivalent to all the wind power currently installed in the country that made the windmill famous.[76] For cement, which results in roughly 2 percent of annual global emissions, it is unclear if there is any way to eliminate CO_2 emissions other than through active carbon management.

With adequate public and private investment in innovation, the costs of active carbon management will come down, and performance will improve. In industrial applications that handle waste streams with very high concentrations of CO_2, such as in ethanol production, carbon capture costs as little as $26 per ton today.[77] Power sector applications range from $60–$120 per ton, with retrofits being more expensive than new construction.[78] CCS research focuses on improving CO_2 absorption, reducing the energy required to strip CO_2 off and regenerate the sorbent, improving the longevity of the sorbent, and scaling sorbent production capacity. Economies of scale, standardization, and efficiency improvements will also help create a virtuous cycle for CCS as market growth feeds innovation along with public RD&D investment.

DAC is no less critical to achieving a low-carbon economy at an acceptable cost. If deployed at scale, it will serve as the upper limit on the cost of emissions reduction from all sources. For example, the estimated cost of eliminating emissions for an international airline flight is as high as $2,000 per ton of CO_2.[79] If the cost of DAC is less than that, airlines will use DAC instead of trying to eliminate jet exhaust. The same logic applies across other economic sectors, including power, transportation, and hard-to-abate industries. One study finds that "including [active carbon management] technologies in the choice set lowers the cost of electric sector decarbonization, complementing extensive, conventional mitigation as part of cost-minimizing pathways to reach net-zero targets."[80]

DAC is relatively expensive today compared with natural CDR alternatives such as afforestation. All-in costs are estimated to be between $250 and $600 per ton.[81] However, DAC developers see a viable pathway to lower this unit cost to around $100 per ton by 2030, largely through improved sorbent efficiency, low-cost renewable electricity, and improved efficiency and sitting of arrays.[82] If this target is realized, long-distance transportation, global shipping, and other hard-to-abate sectors might well choose to purchase high-quality emissions-reduction credits from DAC developers. Once such revenue streams open up, a virtuous cycle of growth and innovation should follow.

Critics of active carbon management are right that numerous demonstration projects, such as FutureGen, have failed.[83] CCS and DAC are complex systems composed of many intermediate processes, and some first-of-a-kind implementations of such systems are bound to fail. Some of these failures, too, resulted from poor management and political interference and had little to do with technology.[84] Energy innovation takes time and sustained funding. Solar PV, wind turbines, LED lightbulbs, and lithium-ion batteries took 20 to 70 years to go from prototype to just a 1 percent market share.[85] Preemptively excluding active carbon management from further development based on today's costs would be grievously shortsighted.

Claim 3: Active Carbon Management Perpetuates Environmental Injustice

Opponents of active carbon management worry that it will perpetuate environmental injustice in communities that have borne the brunt of air and water pollution from past energy and industrial development. This claim ignores the potential benefits of lowering emissions while keeping important economic assets commercially viable. If active carbon management infrastructure is built responsibly and collaboratively with the communities in which it will be located—to be fair, a big “if”—these communities will reap environmental and economic benefits that enhance environmental justice.

The critics are right that some forms of active carbon management infrastructure, particularly pipelines and storage facilities, are likely to be built alongside existing infrastructure. CCS will likely develop first at facilities such as oil and gas refineries, ethanol and fertilizer plants, and natural gas power plants. DAC, by contrast, can be sited anywhere suitable storage potential and cheap, low-carbon energy are available.

Implementation of CCS will follow in the footsteps of past air pollution control technologies, enhancing their impact for the better. In the United States, control systems required by the Clean Air Act (CAA) and other environmental laws have drastically reduced harmful pollutants such as lead, mercury, sulfur dioxide, and nitrogen dioxide since the 1990s.[86] Post-combustion and oxy-combustion CCS applied to power plants could further reduce these pollutants, while pre-combustion carbon sequestration could eliminate them completely.[87]

The drive to meet 2050 emission targets will bring an estimated $655 billion to $1.3 trillion in investment in active carbon management. This influx will sustain millions of jobs, especially in construction and production trades that pay above-median wages.

CO_2 pipelines have a long history of operating safely in the United States and globally, with no serious injuries or fatalities ever reported.[88] It is not explosive or poisonous, but as noted, CO_2 pipeline regulations must be further fortified to protect the communities they pass through and build public confidence.[89] On the benefit side of the equation, the drive to meet 2050 emission targets will bring an estimated $655 billion to $1.3 trillion in investment in active carbon management. A large portion of this investment could be received by frontline communities that already house energy and industrial infrastructure. This influx will sustain millions of jobs, especially in construction and production trades that pay above-median wages.[90]

Ultimately, any successful active carbon management strategy must gain public and community support. Project developers will need to show that community benefits outweigh costs and do so in ways that build trust. Proactive, collaborative, and conscientious engagement with frontline communities will ultimately dispel the misguided claim that active carbon management is synonymous with environmental injustice.

RECOMMENDATIONS

Federal and Private RD&D

- **Expand federal and private RD&D support for current and novel carbon capture technologies**: While many active carbon management technologies are mature enough to be deployed, potential game-changing technologies, such as advanced solvents and sorbents, warrant continued investment in RD&D. Additional objectives include improving CO_2 absorption, reducing energy and water use, and improving regeneration, all of which will ultimately reduce costs. Next-generation capture technologies may include cryogenic processing (using different freezing points to isolate CO_2), membranes, enzymes, and microbiological or algal-based absorption media.[91] DOE RD&D funding research has focused heavily on power plant applications. Its scope should be expanded into new industrial applications, such as steel and cement.

- **Support innovative new DAC systems**: Mechanical DAC trees, DAC integrated into commercial HVAC systems, offshore wind-powered DAC—these are just some of the next-generation technologies being developed by science-based entrepreneurs in the United States. DAC technology is still in its infancy, and sustained exploration of alternatives and competition among them will help it mature rapidly. A key design feature for DAC is modularity, which would improve project financing and allow projects to be easily scaled in diverse applications and settings.[92]
- **Expand federal funding for carbon utilization RD&D:** Commercial products that use captured carbon will provide additional revenue streams to drive CCS and DAC projects. A 2016 industry study estimates the global potential market revenue for such products could be worth billions by 2030.[93] Beyond EOR and food processing, applications could include building materials such as cement and carpeting tiles, synthetic liquid fuels for maritime and aviation transportation, plastic polymers to replace fossil fuel feedstocks, and even novel carbon-based materials such as carbon nanotubes. While start-ups are active in CCU, federally funded RD&D at national labs and universities is vital to support this emerging industry.

Leveraging Innovation Funding for Expanded Market Development

- **Implement IIJA funding**: The IIJA of 2021 provides over $12.5 billion in funding for CCS and DAC CO_2 pipeline infrastructure, DAC hubs, industrial emissions sequestration, and permanent geological sequestration monitoring and verification. These programs represent substantial investments to spur the domestic active carbon management industry and must be implemented effectively and speedily. Pilot and demonstration projects supported by the IIJA should be diverse in both technology and application but proven enough to feasibly scale. Many should be located in areas with favorable siting and permitting regimes and access to existing infrastructure and potential CO_2 off-takers.
- **Expand federal tax credits**: Federal tax credits for CCS systems will provide vital and certain financial revenue for early project development, as they did for wind and solar. Congress should increase 45Q federal tax credits to $85 per ton for carbon captured and stored from industrial and power plants and $180 per ton for DAC technologies.[94] In addition, the timeline should be expanded beyond the original sunset date of 2026 to at least 2030, while the minimum sequestration requirement for facilities should be revised downward or eliminated altogether. Finally, all 45Q tax credits should have a fully refundable direct-pay option to reduce transaction costs and ease access to federal tax credit financing.[95]
- **Establish a federal fee to fund carbon removal:** Just as society pays for waste management and sewers to safeguard public health, governments will almost certainly have to fund carbon removal over the long term. While government policies today should be focused on lowering the cost of capture as much as possible while building private markets for CCS, CCU, and DAC technologies, it is highly unlikely that it will ever be profitable to remove carbon. If the cost of CO2 removal were to decline to $100 per ton, it would cost each U.S. taxpayer roughly $67 per year to remove 1 billion tons.

- **Establish federal procurement standards for low-carbon industrial products:** Industrial CCS is likely to increase the cost of end products relative to those made without it, especially early in its use. The federal government, as the largest single purchaser of goods in the world, can support CCS and DAC deployment and drive down the "green premium" for low-carbon cement, steel, asphalt, and other products by establishing procurement standards for low-carbon products.[96] Alternatively, "contracts for differences" between federal buyers and clean product manufacturers could cover the green premium.[97] The White House recently established a Buy Clean Task Force, which aims to use federal government procurement authority to purchase low-carbon domestic products and mobilize investments in low-carbon production.[98]
- **Develop federal guidance and standards for sequestered carbon:** EPA Class VI well requirements include stringent reporting, monitoring, and verification, and with proper oversight, there is little risk of carbon leakage once it is sequestered. With the emergence of new and innovative ways to sequester and remove carbon, either from the smokestack or the air, it is critical that there be certification of removal across different technologies. Individuals, corporations, and governments will likely rely on active carbon management to reduce or eliminate residual emissions that cannot be cost-effectively or feasibly addressed. Strong and transparent guidance for carbon sequestration credits is critical to creating robust markets that will lead to capital-intensive investments.[99] All parties must have full confidence that carbon sequestered in every location via any type of carbon management technology is functionally equivalent to any other.
- **Create technology competitions and prizes for industrial CCS applications:** Technology to capture and sequester emissions from the industrial sector, particularly from cement, iron, steel, and aluminum processes, is not well developed. Prizes can spur innovators to tackle well-defined problems with out-of-the-box thinking (such as brining solutions) from outside the sector. The IIJA includes $100 million for a DAC commercial prize competition. Future federal funding should include technology prizes for innovative technologies that successfully capture process emissions from industrial process emissions such as steel and cement.

Sitting and Permitting of CO_2 Infrastructure and Sequestration Sites

- **Streamline federal siting and permitting authorizations and approvals:** Developers of CCS and associated infrastructure projects must be assured that they will not be subject to lengthy permitting hurdles that increase project costs and risks. Certain projects that receive federal funds trigger National Environmental Policy Act (NEPA) reviews, and onshore sequestration sites need EPA injection well certification. Federal reviewing bodies must be fully staffed and funded and have access to appropriate expertise. The USE IT Act established CCS as an applicable sector under the Fixing America's Surface Transportation (FAST-41) Act, which aims to speed the permitting process for large-scale infrastructure projects. The IIJA includes the Federal Permitting Reform and Jobs Act, which removed the FAST-41 sunset and established a two-year permitting target for covered projects. Federal review processes must comply with these targets to provide regulatory certainty to developers. Federal support for the development of model state and municipal ordinances for CCS projects and infrastructure could help speed project development as well. The federal government could consider categorical exclusions under the NEPA for CO_2 pipelines that meet established safety requirements.[100] Finally, agencies could adopt programmatic environmental impact statements, whereby multiple projects can be reviewed in a streamlined and efficient manner, while maintaining review stringency.

- **Develop federal guidelines for co-location of CO_2 pipelines next to other critical infrastructure:** While federal guidance regarding the safe transportation of CO_2 via pipeline exist, the Department of Transportation (which has authority over pipeline safety), should develop guidance for the safe transportation of large quantities of compressed CO_2 along existing rights of way.[101] Transporting CO_2 is different from transporting natural gas or oil because it must be held at much higher pressures and is more corrosive. Federal guidance could speed development and reduce siting costs while ensuring that CO_2 pipelines ae operated at the highest safety standards.
- **Establish a one-stop agency siting and permitting authority for CO_2 pipeline infrastructure:** Currently, federal siting and permitting authority is dispersed among a handful of agencies. Streamlined federal siting and permitting will be crucial to support regional CO_2 pipeline infrastructure. Establishing one federal agency, such as the Department of Transportation, with primary responsibility for managing siting and permitting requirements would help speed up the process, avoiding duplicative federal oversight and providing greater certainty to project developers. Such a change would require congressional authorizing legislation.
- **Design federal offshore sequestration permitting:** DOI should promptly design regulations governing offshore sequestration sites located in federal waters and access to them.[102] DOI should speedily complete all necessary NEPA reviews to enable development of such sites as well, while coordinating a whole-of-government approach to confirm that all agency actions fall under a streamlined NEPA review process. In addition, DOI must develop guidance to facilitate monitoring, verification, and compliance of offshore sequestration.
- **Create a long-term storage monitoring, verification, and insurance program:** Storing hundreds of millions of tons of CO_2 for hundreds of years will require ongoing monitoring and verification.[103] Existing EPA Class VI permitting and the Greenhouse Gas Reporting Program include detailed monitoring and verification standards for long-term geological CO_2 storage. The federal government is the only entity able to monitor these sites for the duration of these projects' lifespans. Congress should also consider establishing a fund to manage the risks of bankruptcy and liability for CCS project developers based on total amount of CO_2 injected per well site. Such a fund might be supported by revenue from a carbon tax or a small injection fee on the CCS and DAC industries.

Environmental Justice and Community Engagement

- **Engage impacted communities from beginning to end of projects**: Active carbon management projects may have significant impacts on the communities in which they are sited.[104] To win acceptance and mitigate concerns and impacts, developers must engage communities from the beginning of the development process, listen to community concerns, and modify projects in response. These best practices to ensure procedural fairness have been learned the hard way from large-scale energy projects over the last two decades, such as offshore wind projects in the northeastern United States. The failure of Cape Wind offshore wind project off the Massachusetts coast shows that the absence of robust public communication, engagement, and responsiveness can result in significant local opposition and expensive lawsuit setbacks. More recent offshore wind projects have benefited from expanded community engagement throughout the process, a showing of direct community benefits, collaboration with impacted communities, and a willingness to change or modify engineering plans and decisions.[105]

- **Locate projects in communities that want them**: Developers of active carbon management projects should seek out communities that are interested in having these investments in their communities. While the economic benefits of these projects may draw community interest, developers should be aware that such benefits alone may not avert all community resistance. Developers should be open and honest about the risks of active carbon management projects and technologies, as well as the benefits.[106] They should share as much data and information as possible with communities and address specific questions and concerns with clarity and openness.
- **Share the costs and benefits**: Widely sharing both the costs and benefits of active carbon management will be critical to build public support for large-scale projects. If the costs of active carbon management technologies are borne only by the communities in which projects are located, community resistance to project development will likely increase as more projects are built. For example, a CCS retrofit on a power plant located in a rural community will raise the cost of electricity generated from that plant. This increased cost must be shared equitably across all members of society who benefit rather than just local ratepayers. Relatedly, communities should not bear the burden of project decommissioning or clean up if sites are abandoned.[107]
- **Build robust federal and state regulatory safeguards:** Strong federal and state regulation is essential to build community support for active carbon management projects and ensure projects are safely operated to maximize their positive climate impact. Robust federal oversight must encompass CO_2 pipelines, compressor stations, storage, and sequestration sites, while state and local governments will also be involved in periodic project inspection and monitoring. Just as most Americans routinely accept the hundreds of thousands of miles of natural gas and oil pipelines that crisscross the nation today, they are likely to accept the CCS and DAC industries and pipelines as well.

Increasing International Cooperation and Deployment

- **Support Mission Innovation's public-private alliances**: Mission Innovation is a global collaborative effort to increase public and private investment in RD&D to make low-carbon technologies affordable, available, and attractive to nations around the world. Active carbon management features prominently in its agenda, including Clean Hydrogen and Carbon Dioxide Removal missions.[108] Continued public support for Mission Innovation will help advance key technologies, diffuse know-how across borders, and spur collaborative private-sector efforts.
- **Develop internationally recognized CCS and DAC standards**: Companies, governments, and individuals interested in offsetting their carbon emissions may decide to purchase credits. Consistent international standards with respect to what constitutes permanent

sequestration will be necessary to allow offset markets and active carbon management project revenue to scale. An industry-wide voluntary effort, similar to efforts to develop high-quality carbon offsets in forestry and agriculture, would be useful to drive these standards.

- **Devise international standards for low-carbon industrial products:** Climate change and trade are increasingly intertwined and contentious international issues. Global cooperation to devise carbon-intensity standards for industrial products such as steel may help spur the adoption of CCS and other low-carbon production technologies. The risk of being put at a competitive disadvantage or even being shut out of markets will create a strong incentive for carbon-intensive producers to reduce emissions.

CONCLUSION

The global carbon cycle can no longer be left to nature alone. Active carbon management must be incorporated into every national and global strategy to tackle climate change. Global energy and climate modelers agree that billions of tons of carbon will need to be captured from point sources or removed from the atmosphere by 2050. However, the technologies necessary to accomplish these ambitious goals will not be available at an affordable cost if policymakers neglect innovation today.

Innovation is neither a black box nor automatic, but rather the result of steady and concerted effort across the public, private, academic, and societal spheres. Active carbon management technologies that are nearing maturity need policy support to scale from demonstration to large-scale commercialization, enabling learning-by-doing to drive down costs and work out remaining technical hurdles. Those that are further away from the market, including many industrial CCS applications and the full suite of DAC possibilities, must be nurtured with both technology-push and demand-pull policies. These next-generation active carbon management technologies will lead to opportunities that are difficult to predict or imagine today.

If the costs of active carbon management fall steadily, a robust commercial industry should emerge, including DAC providers and customers who demand cost-effective carbon removal. As this industry develops, it must listen carefully and respond to environmental justice and other community concerns. Society more broadly must gain confidence that its regulators are protecting public health and safety.

These are exciting times in the fight against climate change. Just a few years ago, few major actors considered NZE to be a worthwhile target, and the scope of action was limited to a handful of technologies in a small number of sectors. Today, the canvass is much broader, and new options to avoid additional emissions and remove past ones are on the horizon. Now is the time to act.

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