U.S. DEPARTMENT OF ENERGY

Pathways to Commercial Liftoff: Carbon Management



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Comments

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Authors

Authors of the Carbon Management Pathway to Commercial Liftoff:

Loan Programs Office: Ramsey Fahs

Fossil Energy and Carbon Management: Rory Jacobson

Office of Clean Energy Demonstrations: Andrew Gilbert, Dan Yawitz, Catherine Clark, Jill Capotosto,

Office of Policy: Colin Cunliff, Brandon McMurtry

Argonne National Labs: Uisung Lee

Cross-cutting Department of Energy leadership for the Pathways to Commercial Liftoff effort:

Office of Clean Energy Demonstrations: David Crane, Kelly Cummins, Melissa Klembara

Office of Technology Transitions: Vanessa Chan, Lucia Tian

Loan Programs Office: Jigar Shah, Jonah Wagner

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Office of Clean Energy Demonstrations: Andrew Dawson, Katrina Pielli, Allison Finder, Liz Moore

Office of Technology Transitions: Erik Hadland, Stephen Hendrickson, Hannah Murdoch, Katheryn (Kate) Scott

Loan Programs Office: Chris Creed, Carolyn Davidson, Matt Kittell, Julie Kozeracki, Leslie Rich, Harry Warren

Office of Policy: Carla Frisch, Steve Capanna, Neelesh Nerurkar, Elke Hodson, Paul Donohoo-Vallett, Marie Fiori

Office of Fossil Energy and Carbon Management: Brad Crabtree, Jennifer Wilcox, Noah Deich, Emily Grubert, Lynn Brickett, Anhar Karimjee, John Litynski, Sarah Leung, Amishi Claros, Traci Rodosta, Jeffrey Hoffmann, Jose Benitez, Tony Feric, Lisa Grogan-McCulloch, Vanessa Núñez-López, Devinn Lambert, Caleb Woodall

Office of the Secretary: Kate Gordon

Director of the Office of Economic Impact and Diversity: Shalanda Baker

Office of Energy Jobs: Betony Jones

Office of the General Counsel: Alexandra Klass, Avi Zevin, Ajoke Agboola

Argonne National Laboratory: Aymeric Rousseau

Table of Contents

Executive Summary		1
Chapter 1:	**Introduction and Objectives**	5
Chapter 2:	**Current State – Carbon Management Technologies and Markets**	7
	Section 2.a: Technology landscape	7
	Section 2.a.i Point-source capture	8
	Section 2.a.ii Carbon Dioxide Removal (CDR)	12
	Section 2.a.iii Transport	14
	Section 2.a.iv Storage	16
	Section 2.a.v Enhanced Oil Recovery (EOR) storage	18
	Section 2.a.vi Utilization	18
	Section 2.b Current regulation and policies supporting CCUS and CDR development	19
Chapter 3:	**Pathways to Widespread Deployment**	22
	Section 3.a The pathway to widespread deployment	22
	Section 3.b Implied capital formation	29
	Section 3.c Broader implications	30
	Section 3.c.i Supply chain	31
	Section 3.c.ii Energy and environmental justice	32
Chapter 4:	**Challenges to Commercialization and Potential Solutions**	36
	Section 4.a Overview of challenges and considerations along the value chain	36
	Section 4.b Priority solutions	40
Chapter 5:	**Metrics and Milestones**	42
Chapter 6:	**References**	43

Purpose of this Report

These Commercial Liftoff reports aim to establish a common fact base and ongoing dialogue with the private sector around the path to commercial lift-off for critical clean energy technologies. Their goal is to catalyze more rapid and coordinated action across the full technology value chain.

Executive Summary

Modeling studies suggest reaching U.S. energy transition goals will require capturing and storing 400 to 1,800 million tonnes (MT) of carbon dioxide (CO_2) annually by 2050, through both point-source carbon capture, utilization, and storage (CCUS) and carbon dioxide removal (CDR).[i] Today, the U.S. has over 20 million tonnes per annum (MTPA) of carbon capture capacity, 1–5% of what could be needed by 2050.[1,ii, iii] This scale-up represents a massive investment opportunity of up to ~$100 billion by 2030 and $600 billion by 2050.

America's >20 MTPA of capture capacity already leads the world in carbon management, and the U.S. is an attractive policy and resource environment for further deployment. An increase in the value of the 45Q tax credit—a federal tax credit provided for stored or utilized CO_2—has provided a greater incentive and more certainty to developers and investors and is likely to yield attractive returns for several types of projects.[iv] In addition, recent climate and infrastructure legislation has provided ~$12 billion in funding to support U.S. carbon management projects. The U.S. has excellent geology for storing CO_2, world-class engineering and professional talent, and relatively abundant low-cost zero-carbon energy resources that can power carbon dioxide removal (CDR) projects to maximize net carbon removed.

Many large-scale carbon management projects are already proving financially attractive today with enhancements to the federal 45Q tax credit, and investors have raised billions to take advantage of these opportunities.[v,vi] These investments range from early-stage equity investments in carbon capture technology providers to large-scale private equity-backed investments in CO_2 transport infrastructure.

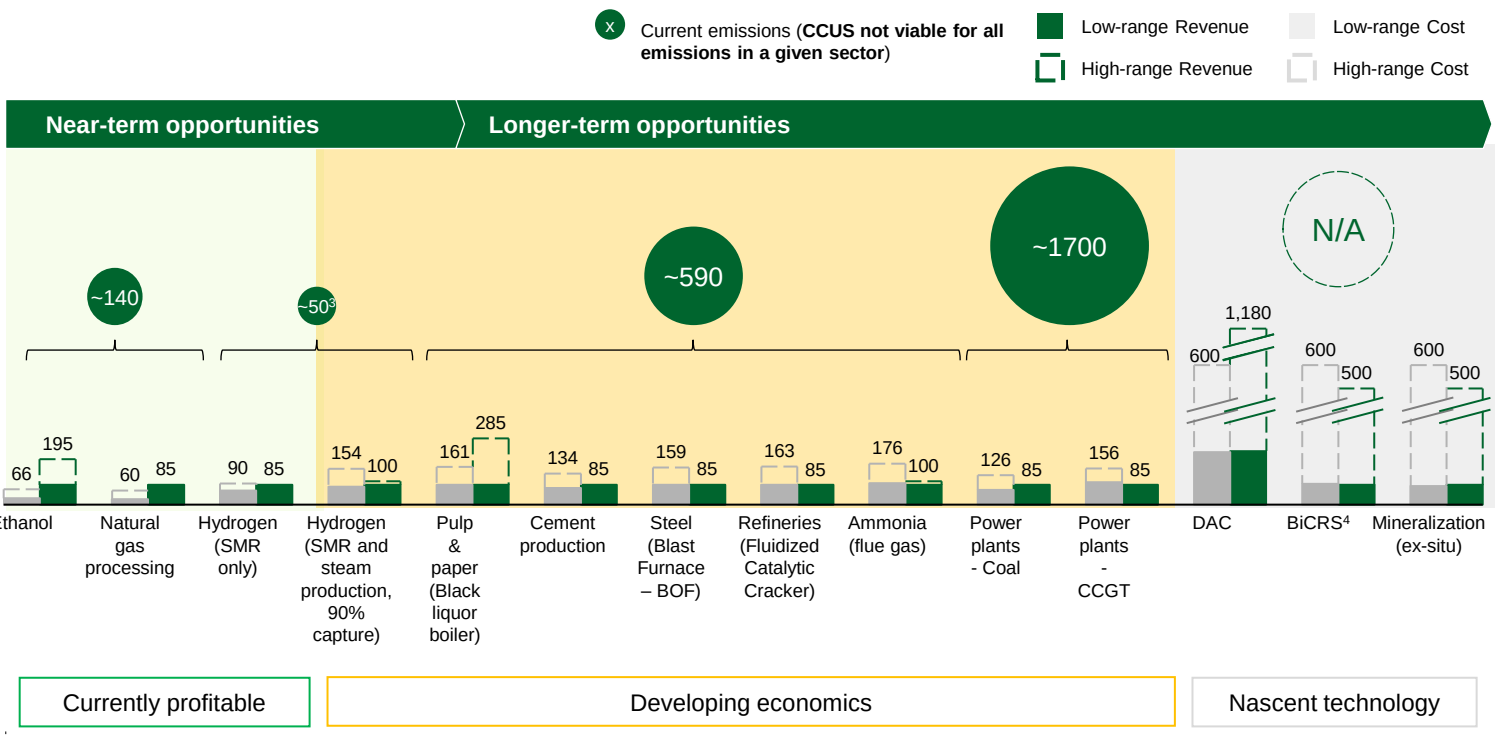
This report outlines the path to meaningful scale in carbon management, which we expect to develop between near-term and longer-term opportunities through 2030 (Figure 1.).[2,3,4]

1. For near-term (through 2030) opportunities, projects in industries with high-purity CO_2 streams (e.g., ethanol, natural gas processing, hydrogen) have the best project economics. Many of these types of projects are in active development or are already in operation. Large-scale transportation and storage infrastructure is likely to emerge to serve these projects. These developments—along with some promising demonstration projects in higher-cost carbon management applications (e.g., steel, cement)—will lay the foundation for more widespread deployment by establishing best-practices in contracting, financing, permitting, community engagement, labor agreements, workforce development, and, in some cases, through building out common carrier transport and storage infrastructure that future projects can use.
2. For longer-term (post-2030) opportunities—industries with lower-purity CO_2 streams and distributed process emissions — project economics must improve to make widescale deployment likely in the absence of other drivers (e.g., regulation). Demonstration projects from now through 2030 can support cost declines—both through learning-by-doing and standardizing project development structures. And increased policy support (either via regulation or incentives) or technology premiums for low-carbon products (e.g., low embodied carbon steel and concrete) would lead to more CCUS and CDR projects.[5] These end-user-backed technology premiums combined with sustained and predictable government support can provide consistent revenue streams as deployment experience reduces costs.

1 Note: Any use of "tonnes" in this report refers to metric tonnes; references to MTPA refer to million tonnes per annum
2 Data in this report for CCUS applications focus only on incremental costs and revenues associated with retrofitting an existing facility with installing and operating carbon capture. They do not reflect the overall economics of a given facility.
3 Near-term and longer-term opportunities refer to an economic analysis of carbon management projects under the current policy and regulatory environment and is not meant as a comment on the technical feasibility of these projects. A wide portfolio of carbon management technologies for a suite of applications are commercially mature and ready to deploy today.
4 We note that the discussion in this paper examines economic break-even points for carbon capture in the absence of regulatory drivers. Any state or federal regulatory actions could dramatically accelerate the business case for profitable investments in carbon management.
5 The Federal Buy Clean Task Force and the First Mover's Coalition are both seeking to provide a clear demand signal for low embodied emissions products

Progress across near-term and longer-term opportunities could create commercial “lift-off” between now and 2030 as project finance mechanisms become de-risked, a robust ecosystem of enabling transport and storage infrastructure matures , state and federal regulatory requirements promote lower-GHG alternatives, and capital markets become comfortable with carbon management projects as an asset class.

Cost[1] and revenue[2] per industry or technology today, $/tonne



Project specific economics dependent on CO_2 capture capacity, utilization, distance to storage and existing equipment

1 Displayed cost estimates based on EFI Foundation capture costs with transport (GCCSI, 2019) and storage (BNEF, 2022) costs of ~$10-40/tonne, except where noted. All in 2022 dollars. All CCUS figures represent retrofits, not new-build facilities. The lower bound costs represents a NOAK plant in a low cost retrofit scenario with low inflation. The higher bound costs represents a FOAK plant in a high cost retrofit scenario with high inflation. The inflation variance on each cost estimate represents the range of cost increases on a generic chemical processing facility due to inflation from 2018 using the Chemical Engineering Plant Cost Index (CEPCI).

2 Revenues based on applicable mix of 45Q tax credit, Low Carbon Fuel Standard, Voluntary Carbon Markets and the 45V tax credit (which cannot be stacked with 45Q). Other sources of revenue (e.g., premium PPAs, EOR) are discussed in more detail in the appendix. Tax credit values do not reflect expected discounts to the face value of the credit associated with tax equity financing or transferability. For retrofits, revenue does not reflect the value of products already sold by the facility (e.g., electricity from an existing power plant)

3 Current hydrogen capacity is likely to grow with the growth of reformation-based capacity and future demand likely

4 Includes BECCS to power, biochar, and bio-oil; Biochar and bio-oil may not be eligible for 45Q

Source: EFI Foundation, “Turning CCS Projects in Heavy Industry & Power into Blue Chip Financial Investments”. Hydrogen SMR-only capture costs from IEA 2019.; Coal and CCGT power plant retrofit cost of capture figures derived from NETL Revision 4a Fossil Baseline study retrofit cases adjusted to 2022 dollars and with 12-year amortization—range represents FOAK with high retrofit factor (high figure) to NOAK with low retrofit factor (low figure). DAC costs from NETL: Direct air capture solvent and sorbent studies; Upper bound of solid sorbent from Climeworks 2018, also cited in “A review of direct air capture (DAC): scaling up commercial technologies and innovating for the future” (McQueen 2021); BiCRS cost estimates from Coalition for Negative Emissions for first-of-a-kind BECCS for power with modified financing costs same as above. Low ranges of purchase of biomass processed feedstock and biomass transport taken from FAO U.S. biomass cost estimates rather than Coalition for Negative Emissions, which has higher estimates applicable to a UK-based plant (“Economic analysis of woody biomass supply chain in Maine (Whalley 2017)) and ICEF “Biomass Carbon Removal and Storage (BiCRS) Roadmap” (2021), Charm Industrial “Carbon Removal: Putting Oil Back Underground” (2021); Mineralization costs from author benchmark cost used in IPCC. Costs for ex situ mineralization with wollastonite, olivine-rich, and serpentine-rich tailings using heat and concentrated CO_2 from Kelemen P, Benson SM, Pilorgé H, Psarras P and Wilcox J (2019) An Overview of the Status and Challenges of CO_2 Storage in Minerals and Geological Formations. Front. Clim. 1:9. doi: 10.3389/fclim.2019.00009; Current emissions from EPA GHGRP FLIGHT database 2019 and includes biogenic CO_2 emissions for pulp and paper (~110 MTPA)
Note: CCUS figures represent incremental costs and revenues associated only with the installation and operation of carbon capture retrofits, not the overall facility economics of the facility in question.
Note: Applications are arranged left-to-right by industry, power, and CDR reflecting the rough CO2 concentration of the CO_2 sources associated with these applications

Figure 1: Concentrated sources of CO_2 (e.g., in ethanol or hydrogen Steam Methane Reformer (SMR) capture facilities) are currently profitable but do not include sufficient emissions reductions alone to achieve net zero goals

The challenges facing widespread deployment of carbon management are real but solvable.

- Estimated project economics for CCUS retrofits on higher-cost-to-capture applications (e.g., cement, and steel) will not lead to widespread deployment without cost or revenue improvements or additional policy.
  - Further demonstration projects in these sectors can enable faster Capital Expenditure (CapEx) cost reductions through commercial standardization, modularization, and technology improvements.[6] **DOE demonstration funding could spur cost improvement in these sectors**.
- In CDR, voluntary carbon markets can be unpredictable and inconsistent, and long-term prices and volumes remain uncertain. Even with high expected growth, voluntary markets may be insufficient to support the scale of deployment required to achieve U.S. net zero goals.
  - Increasing the transparency and certainty of the voluntary and compliance markets for CDR can increase market support. Two factors could create long-term revenue sources: (1) regulations that favor CDR deployment and (2) increased technology premiums for CDR driven by end-user demand. **Project funding and demand-side market support from DOE could help stabilize the market for CDR developers and investors**.
- Across CCUS and certain types of CDR, the need for multi-party agreements (e.g., between emitting facilities, capture providers, transport providers, and storage facilities) and a lack of commercial standardization complicate project development.
  - Potential solutions include creating archetypal, field-tested business models and terms to enable the development and execution of partnerships. **Private sector leadership and DOE-supported "hubs" for direct air capture (DAC) and CCUS** could simplify project development by creating standard commercial arrangements that simplify the development process.[7]
- Permitting dedicated geologic storage projects (e.g., Class VI injection wells) may be seen by developers and investors as a long and uncertain process.
  - Congress provided funding to EPA through the Bipartisan Infrastructure Law (BIL) to support the federal Class VI permitting program as well as to provide grants to states, Tribes, and territories to pursue and implement Class VI primacy applications and programs. **EPA anticipates approximately two years from receipt of completed Class VI applications to issuance of a permit** and has developed a series of tools to help streamline the permitting process.[vii]
- A lack of common-use transport and storage infrastructure could hinder development and may encourage uncoordinated or duplicative source and storage matching.
  - Projects developed today can build out CO_2 transportation networks and storage facilities that can serve as shared infrastructure for future carbon management projects located nearby. **DOE will support development of shared storage facilities and transport infrastructure through Bipartisan Infrastructure Law (BIL) funding**.
- Some groups oppose CCUS projects or policy support for them and others are unfamiliar with the technology.[ix]
  - Addressing these concerns, including environmental justice considerations, requires commitment to responsible carbon management from policymakers and industry to build trust with communities considering carbon management projects. **Developers must anticipate, listen to, and address stakeholder concerns through early, substantive, and transparent engagement on the benefits and risks of these projects**.
  - DOE's Office of Fossil Energy and Carbon Management (FECM) has launched a domestic engagement framework to outline its vision for successful engagement. The framework serves as the guiding principles to ensure that tangible environmental, economic, and social benefits flow to communities. Additionally, DOE has added requirements for carbon management funding opportunity applicants to incorporate community engagement; diversity, equity, inclusion, and accessibility; environmental justice; and quality jobs plans into their applications and project plans.

6 CCUS and certain CDR technologies have significant OpEx expenses (roughly 50% of levelized costs) in the form of energy and material inputs. These persistent OpEx costs make the dramatic total cost declines observed in fuel-free energy technologies like wind and solar unlikely.

7 DAC is one of several CDR pathways discussed further in Chapter 2.

DOE, in partnership with other federal agencies and state and local governments, has tools to address many of these issues and is committed to working with communities and the private sector to build out the nation's carbon management infrastructure and meet the country's climate, economic, and environmental justice goals.

Carbon management is experiencing a once-in-a-generation opportunity given the current policy and market environment. The 45Q tax credit provides certainty and attractive project economics for several project types. Funding for commercial demonstration and deployment projects in BIL and the Inflation Reduction Act (IRA) can spur carbon management projects in industries in which project economics would otherwise still be challenging, providing investors with sector-specific blueprints for project development. Substantial and responsible investment in carbon management deployment over the next decade can prove out business models and generate the community, market, and policy buy-in that carbon management will need to contribute meaningfully to the nation's energy future.

Chapter 1: Introduction & Objectives

The U.S. will likely need to capture and permanently store ~400–1,800 million tonnes of CO_2 annually (MTPA) to meet its net-zero commitments by 2050 (**Figure 2**.).[8] This report provides a pathway for reaching this objective. It focuses on the near-term carbon management project types and business cases that are already attracting investor interest. The report discusses the full carbon management ecosystem, including point-source carbon capture, utilization, and storage (CCUS) and carbon dioxide removal technologies (CDR).

Within point-source CCUS, this report focuses on retrofits in the following subsectors:

- Ammonia
- Coal power
- Cement
- Chemicals and refining
- Ethanol
- Hydrogen
- Iron and steel
- Natural gas power
- Natural gas processing
- Pulp and paper

Within CDR, this report focuses on:

- Biomass carbon removal and storage (BiCRS)
- Direct air capture (DAC)
- Mineralization

The report also assesses opportunities for CO_2 utilization, including:

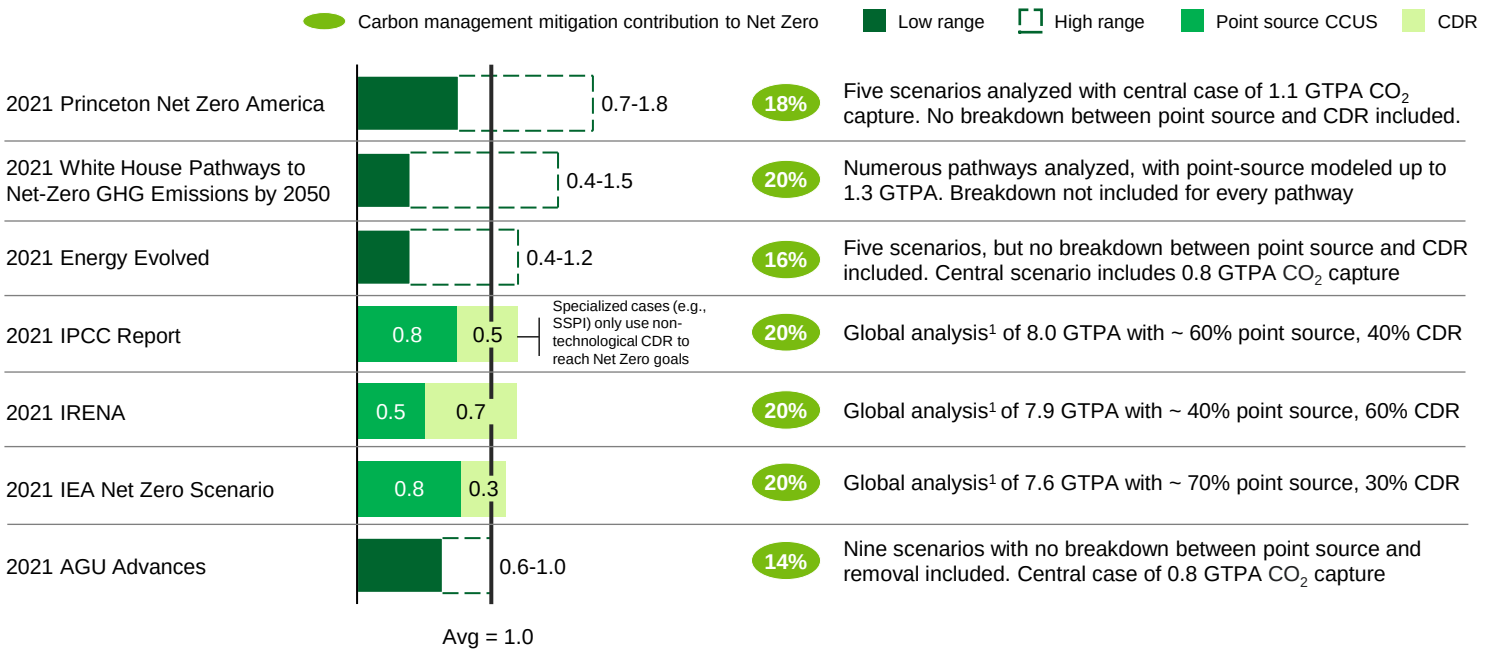
- Building materials
- Plastics
- Synfuels

Finally, this report considers the transport and storage infrastructure that will enable projects to geologically store CO_2 or transport it to a point of use.

Achieving a net-zero economy will require hundreds of billions of dollars of capital investment in carbon management deployments. Policy support—through compliance mechanisms, tax incentives, demonstration funding, procurement, and regulatory requirements—will be key, but the majority of project development and financing will be implemented by the private sector. The analysis in this report provides a primer to investors and others interested in carbon management on the basic economics of certain carbon management project types, the key risks and challenges these projects face, and potential solutions to those challenges.

8 Current range is based on integrated energy modelling as discussed in the "Pathways to Commercial Liftoff: Overview of Societal Considerations and Impacts". Expanded range based on several government and other research reports, including: Princeton's Net Zero America report (2021, the White House Pathways to Net-Zero GHG Emissions by 2050 (2021), The IPCC (2021, IRENA (2021), IEA (2021); Some modelled scenarios estimate figures higher or lower than this range depending on the level of deployment of other decarbonization tools (e.g., renewable electricity, nuclear, reforestation and land use change)

Estimates of U.S. CCUS, CDR[2] required to reach Net Zero by 2050, GTPA CO_2



1 Global estimates were scaled down using the United States share of global CO_2 emissions, currently reported by EPA at 15%. Amounts shown here are indicative and not a prescriptive target as sectoral heterogeneity in the emissions distribution will result in differing requirements for CCUS and CDR

2 It should be noted that CCUS and CDR are not interchangeable and constitute unique sets of technologies. CCUS abates **CO_2** emissions from point sources, while CDR can mitigate difficult to decarbonize sectors (after emissions have been released) or address emissions overshoot

Sources: IPCC 6th Assessment Working Group, 2021; IEA Net Zero Emissions Scenario, 2021; IRENA 1.5 Degree Scenario, 2021; Princeton's Net-Zero America study,2021; Long-Term Strategy of the United States, Pathways to Net-Zero Greenhouse Gas Emissions by 2050, 2021; Evolved Energy Research 350 PPM Pathways for the United States, 2021; Note: Global scenarios in this figure assume U.S. CCUS and CDR deployment will reflect U.S. share of global emissions, though sectoral emissions differences and other factors could drive higher or lower CCUS and CDR adoption relative to global emissions share

Figure 2: A wide range of decarbonization studies find a significant role for both CCUS and CDR to achieve net zero goals by 2050. CCUS and CDR are not interchangeable technologies—CCUS will abate emissions from point sources while CDR can address emissions overshoot or mitigate other difficult to decarbonize sectors.

A portfolio of carbon management technologies for a suite of applications are commercially mature and ready to deploy today. There are several dozen commercial-scale carbon management projects in operation today and well over a hundred are in stages of project development.[xi]

The costs associated with a carbon management project vary based on the type of facility CCUS is applied to or the CDR technology utilized, as well as several regional and facility-specific factors that can drive variation in the cost associated with capturing, transporting, and storing or using a ton of CO_2.[9] Costs for a specific carbon management project could vary even outside of the ranges outlined in this report depending on facility-specific characteristics and energy prices that can have a significant impact on the ultimate cost of deployment.

In this report, "near-term" and "longer-term" opportunities refer to an economic analysis of carbon management projects under the current policy and regulatory environment and is not meant as a comment on the technical feasibility of these projects. A wide portfolio of carbon management technologies for a suite of applications are technically and commercially mature and ready to deploy today.

Moreover, the discussion in this paper examines economic break-even points for carbon capture in the absence of regulatory drivers. Any state or federal regulatory constraints could dramatically accelerate the business case for profitable investments in carbon management. Finally, data in this report for CCUS applications focus only on incremental costs and revenues associated with retrofitting an existing facility with installing and operating carbon capture. They do not reflect the overall economics of a given facility.

9 This report has referenced the National Energy Technologies Lab's (NETL) "Revision 4a" of its "Cost and Performance Baseline for Fossil Energy Plants" for CCUS retrofits in power the Energy Futures Initiative's recent "Turning CCS Projects in Heavy Industry into Blue Chip investments," for CCUS retrofits in industrial applications. NETL has also published recent numbers on CCUS retrofits in industrial applications; see National Energy Technology Laboratory. (2022). Cost of Manufacturing CO_2 from Industrial Sources. This report has also used other estimates from trade groups and, in some cases, individual companies' announced costs and cost targets.

Chapter 2: Current State – Carbon Management Technologies and Markets

Section 2.a: Technology landscape

- The carbon management value chain is broad—featuring different methods and technologies at each stage (i.e., capture, transport, utilization, and storage). Capture represents the majority of costs for most projects, while robust transport and storage or utilization networks are necessary to make projects viable.
- The U.S. leads the world in CCUS capacity (over 20 MTPA), driven by CO_2 from high-purity sources, coupled with incidental geologic storage through enhanced oil recovery (EOR).
- The U.S. has enough geologic storage capacity for trillions of tonnes of CO_2; enough to store the entirety of U.S. emissions for hundreds of years.[xii] Though storage resources are abundant, they must be characterized and developed to become commercially operational, and some in industry point to the permitting process to develop storage sites as a bottleneck to accelerated deployment in the U.S.
- CDR technologies have less commercial deployment experience relative to CCUS, with limited technological CDR capacity in the U.S. today. A recent spate of announced projects and investments could drive cost declines over the next decade.
- CO_2 transport systems to link capture and storage sites require scale-up. Current estimates suggest that 30,000 to 96,000 miles of pipe could be required to meet net zero goals by 2050 (vs. ~5,000 miles of U.S. CO_2 pipelines operating today.)
- Beyond certain niche applications, CO_2 utilization pathways are nascent and currently uneconomic relative to incumbent products. Deployment incentives such as the 45Q tax credit also provide a greater revenue source on a per-tonne basis for dedicated geologic storage relative to utilization.

There are three main parts to the carbon management value chain: CO_2 capture (from both point-sources and the atmosphere), transport, and storage or utilization (**Figure 3**.). Key participants in the value chain include large incumbent firms, startups, companies in emitting industries, EPC firms, CDR credit buyers, and transport and storage providers.[10] A range of other players also interact with and facilitate the carbon management ecosystem, including the communities in which projects operate, the labor force that builds and operates projects, investors, landowners, and voluntary carbon marketplaces.

10 Mostly large amine-capture companies, including oil and gas (e.g., Exxon) and industrial companies (e.g., Mitsubishi); Mostly technology driven start-ups in new capture and removal technologies (e.g., Climeworks)

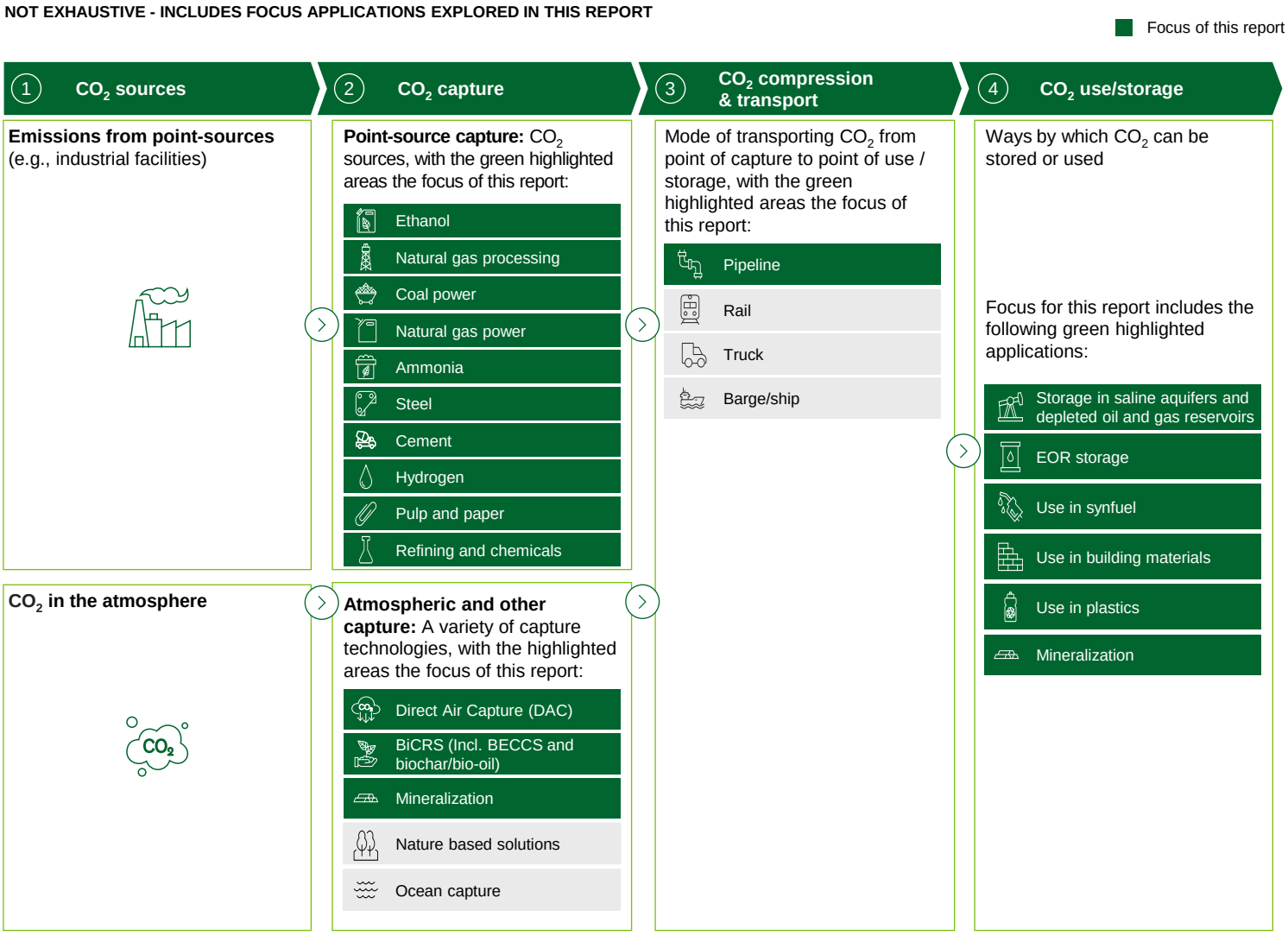
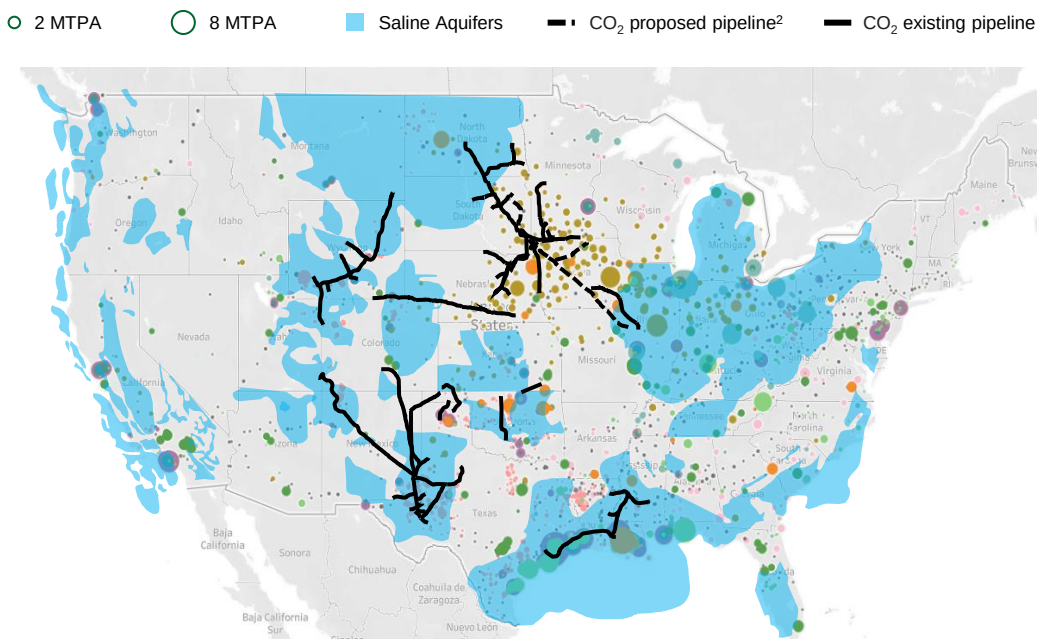


Figure 3: The value chain and applications that are in focus for this analysis are highlighted in green

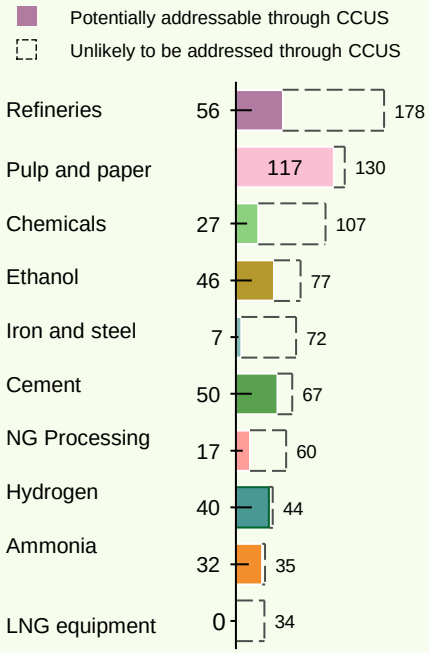
Section 2.a.i Point-source capture

Point-source capture is the separation of CO_2 from an industrial facility or power plant's flue gas, syngas or process stream.[xiii] These sources represent approximately 750 MTPA and 1,700 MTPA of point-source industrial and power emissions in the U.S., though only a subset of these emissions will likely be addressed through carbon management (See Figure 4).[xiv] A significant number of these CO_2 point-sources sit on top of, or are in close proximity to, favorable geology for large-scale carbon storage. Favorable geology includes a combination of geologic sinks with large carbon storage capacity, such as deep saline aquifers, and overlaying confining rock layers for storage permanence. These geologic features require validation through regional characterization work and further site characterization for confirmation on a project-by-project basis.

Map of U.S. point source CO_2 emissions by sector, 2019



Point source CO_2 emissions by sector[1], MTPA



~2,500 facilities

10 sectors

Note: Not all emissions are addressable through carbon capture alone. Plant by plant feasibility studies are required.

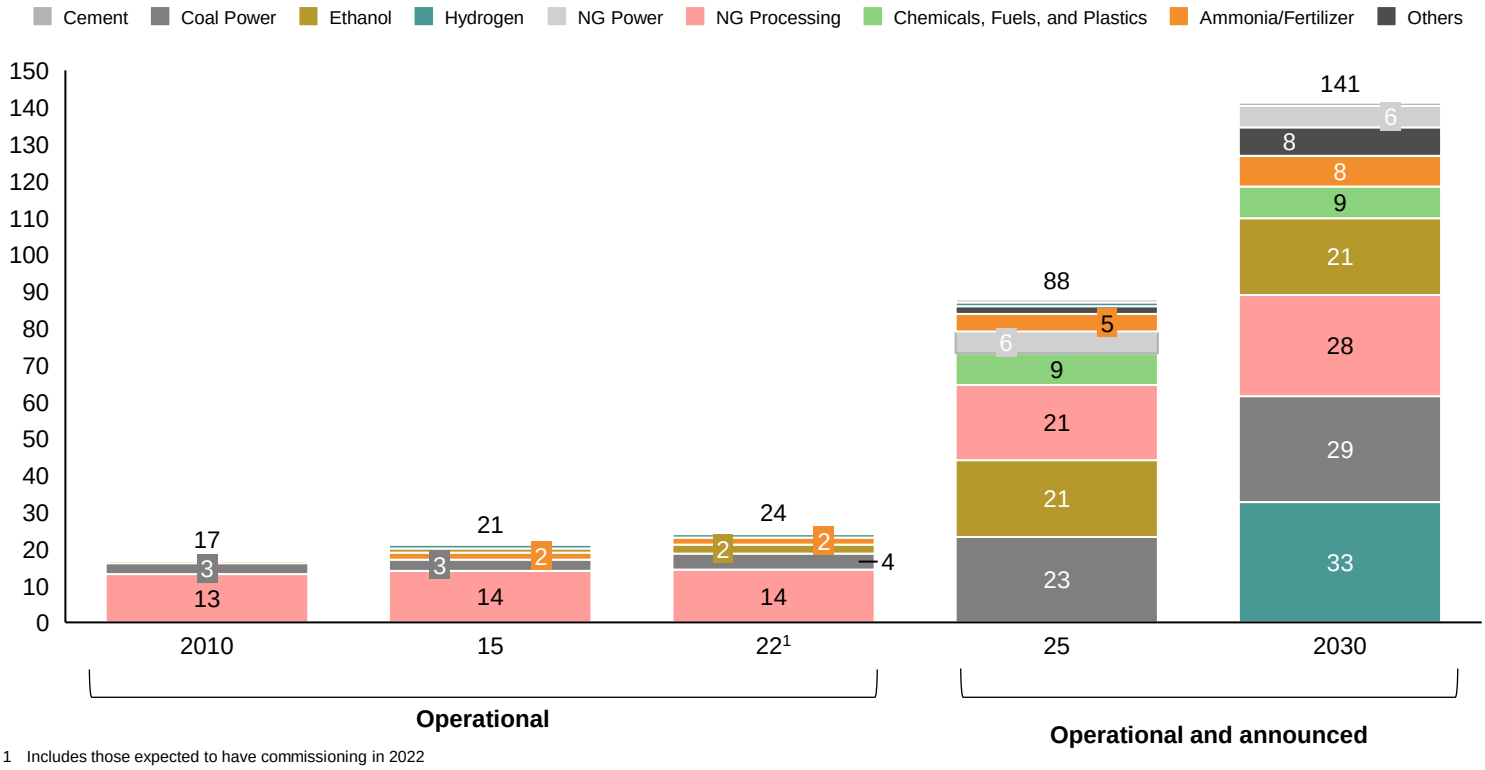
1 High purity and process CO_2 streams are solid, with total CO_2 emissions shown by dotted line. Waste, non-industrial sectors, and some petroleum and NG emissions amounting to ~500 MTPA are not shown on the map and in the MTPA breakdown
2 Includes Summit, Navigator, ADM, and Tallgrass proposed CO_2 pipelines from project websites
3 Exploration of capture on NG transmission and distribution facilities (including LNG terminals) is out of the scope of this report, though there are expected to be CCUS-addressable emissions in that sector

Source: EPA GHGRP FLIGHT database 2019 including biogenic CO_2 for pulp and paper sector, additional public information on smaller point source emitters, and estimated additional emissions from ethanol facilities in EIA ethanol plant database; Summit, Navigator, ADM, and Tallgrass CO_2 pipeline project websites; NatCARB Atlas V Database; Estimates on proportion of CCUS-addressable emissions compiled from EPA FLIGHT database, DOE Industrial Decarbonization Roadmap, and McCoy et. al (2016) for Ethanol, Sagues Et. al (2020) for Pulp and Paper

Figure 4: A substantial number of U.S. industrial point source emissions are within 50 miles of CO_2 transport to saline aquifers that could be suitable for geologic storage. Saline aquifers require characterization work to validate their suitability for commercial storage [xv, xvi]

2022 was a banner year for carbon management project announcements. One industry database is tracking ~140 MTPA in announced projects targeting completion by 2030 (Figure 4). Not every announced project will successfully reach commercial operation date (COD). However, many have line of sight to firm and financeable cashflows, especially when projects tackle low cost-of-capture emissions streams. Many of these projects are backed by experienced investors and management teams.

U.S. point source CCUS capture capacity by year, MTPA



1 Includes those expected to have commissioning in 2022

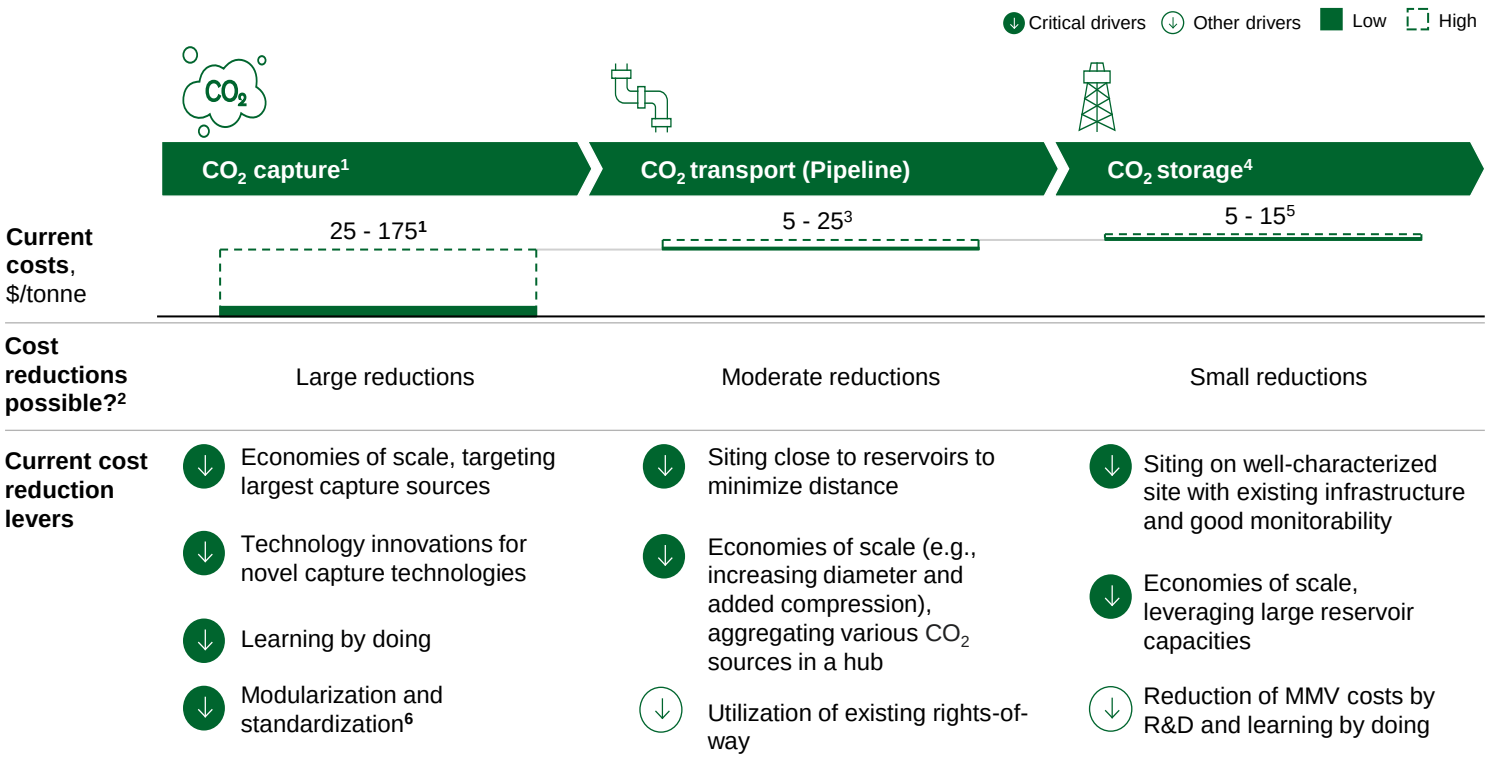
Source: Bloomberg New Energy Finance, "2022 CCUS Market Outlook"

Figure 5: The U.S. has over 20 MTPA of operational point source CCUS capacity, with an announced project pipeline of ~140 MTPA as of Dec 2022

The cost of CCUS retrofits depends heavily on the plant in question. In general, the cost of CO_2 capture is inversely proportional to the CO_2 purity of the emission stream. But even within the same industry, several factors meaningfully impact the cost of capture, including facility design,[11] separation technology used in the capture process, local energy prices, emissions volumes, flue gas temperature and pressure, and the presence of emissions stream contaminants. Because of these project-specific factors, estimates can vary widely for current and projected costs.[12] In general, capture costs are the most expensive component in the CCUS value chain, but economies of scale, learning by doing, modularization and standardization, and novel capture technologies could all yield significant cost improvements. (Figure 6)

11 Including whether a facility must add multiple capture units or can use a single capture unit

12 Some major differences between sources include financing assumptions, first-of-a-kind (FOAK) versus nth-of-a-kind (NOAK) projections, and assumed CO_2 purity of the exhaust stream. While estimated costs may vary between sources, the order of low- to high-cost-of-capture industries tends to be the same across the literature.



1 Refers to CO_2 capture broadly across sectors examined in this report (see Figure 1); Costs drawn from EFI Foundation, "Turning CCS Projects in Heavy Industry & Power into Blue Chip Financial Investments"
2 Generalized across sectors. Individual sectors will have sector-specific cost reductions
3 Approximate costs based on published studies by the European Zero Emission Technology and Innovation Platform, the National Petroleum Council, and GCCSI process simulation for a 30 year asset life. All costs have been converted to a U.S. Gulf Coast basis. Lower end of pipeline cost assumes 20 MTPA, 180 km onshore pipeline. Upper end of pipeline cost assumes 1 MTPA, 300 km onshore pipeline.
4 Utilization routes also exist including, but not limited to, conversion of CO_2 into synfuels or plastics and utilization of CO_2 in EOR and building materials
5 Figure represents a levelized cost of site screening, site selection, permitting & construction, operations, and site closure and post-injection site care
6 Modularization will be a more critical driver for certain technology types than for others
Note: Supply chain risk and technical risk across the CCS value chain has been found to be low (DOE CCS Supply Chain Deep Dive Assessment)
Source: Capture costs from EFI Foundation, "Turning CCS Projects in Heavy Industry & Power into Blue Chip Financial Investments"; Transport costs from Global CCS Institute, "Technology Readiness and Costs of CCS'; Storage costs from BNEF

Figure 6: Capture drives the majority of unit costs for CCUS and represents the majority of cost reduction potential

Costs and characteristics also vary significantly by capture technology. Amine-based chemical absorption processes are the most common and mature capture technology. Other capture technologies (e.g., advanced solvents, membranes, cryogenic, water lean solvents, and solid sorbents) and alternate processes (e.g., Oxy-combustion, the Allam cycle) are in development and may realize future cost advantages.[13,xix]

In amine-based processes, flue gas passes through an amine solvent, which binds the CO_2 molecule. This CO_2-rich solvent is heated in a regeneration unit to release the CO_2 from the solvent. The purified CO_2 stream is compressed and transported for storage or end-use and the released solvents are recycled to again capture CO_2 from flue gas. Modularizing CCUS equipment for amine solvents can speed deployment by minimizing upfront engineering design requirements and by leveraging a simplified production process.[xx]

As the cost of capture falls—either through experience and standardization in project development and finance or efficiency improvements in already commercial technologies —point-source emissions become more economically viable to capture.

13 For example, membrane separation uses a polymeric or inorganic substance with high CO_2 selectivity and has been deployed commercially in syngas and biogas. Physical adsorption uses a solid material to capture CO_2 and then increases temperature or pressure to release the adsorbed **CO_2**. Cryogenic carbon capture involves cooling the gas stream to produce solid CO_2 that can then be separated from the rest of the gas, pressurized, and brought back into the liquid phase.

Section 2.a.ii Carbon Dioxide Removal (CDR)

CDR refers to a wide spectrum of activities that remove carbon dioxide from the atmosphere. These can range from planting trees that take in CO_2 as they grow to direct air capture (DAC) facilities that function like CCUS but treat ambient air instead of flue gas. The permanence of different CDR approaches vary widely: while trees may offer centuries of durable storage under some conditions, they are subject to risks of reversal, such as infections, infestations, wildfires, and logging; whereas geologic storage is expected to last >10,000 years.[xxi] This section focuses on the higher-permanence removals with more established (but still nascent) approaches for monitoring, reporting, and verification (MRV) of removals.

Credits for emissions stored by CDR technologies can be sold in the voluntary carbon markets (VCM) to help companies or other institutions reach their emissions reductions goals. Companies can subtract these removal credits against any emissions they do not reduce directly. With ~40 pilot-scale projects and ~100 thousand tonnes per year (KTPA) of global capacity, technological CDR has seen limited commercial deployment to-date (**Figure 7**.).[xxii] Many planned projects are DAC demonstrations prompted by BIL funding, IRA incentives, and the willingness of a few credit buyers to pay high prices.

Many researchers expect policies such as a carbon tax, large-scale government procurement of CDR, or regulatory mandates will be needed to reach relevant scale. The FY2023 Congressional Omnibus budget report directs DOE to "establish a competitive purchasing pilot program for the purchase of carbon dioxide removed from the atmosphere."[xxiii]

The levelized costs of the CDR approaches discussed in this report are generally higher than for point-source CCUS, due to the relatively dilute concentration of atmospheric CO_2.[14] Investments in R&D, scale-up, and operational efficiencies are needed to lower costs and provide certainty for CDR technology and project developers (Figure 8). Determining the precise climate benefits of some CDR technologies can be challenging. Lifecycle assessment (LCA) and MRV of removals of various CDR technologies will require further validation and standardization to ensure proper measurement of removed carbon.

Direct air capture (DAC)

The DAC process intakes or passively exposes air, which reacts in a contactor to bind CO_2. The CO_2 is then separated from the DAC equipment, compressed, transported, and stored or used. The capture agent is then regenerated, usually with heat, which requires a significant energy supply, before it is then recycled for additional capture. Today, solid sorbent and liquid solvent technologies have seen the most demonstration activity, though both approaches are still nascent. While liquid solvents are expected to be lower-cost today compared to solid sorbents, it is uncertain which technology will be lower-cost as more projects develop.[15,xxiv] Other regeneration processes and capture materials (e.g., electric- and moisture-swing solid sorbents, and membrane processes) are also emerging, with some potentially overlapping with enhanced mineralization (see below)[16].

Biomass with Carbon Removal and Storage (BiCRS)

BiCRS refers to using biomass (i.e., plant matter) as a capture vehicle since plants take in CO_2 as they grow.[17] Like other CDR approaches, BiCRS is in its nascency. The two most prominent BiCRS processes so far are BECCS (bioenergy + carbon capture, utilization, and storage) and biochar/bio-oil. Biomass-to-hydrogen presents another BiCRS pathway and can include biomass gasification or fast pyrolysis to produce hydrogen with capture and storage, potentially resulting in net-CO_2 removal on a lifecycle basis, depending on the feedstock production and processing emissions.[xxv] BECCS refers to using biomass to produce heat, power, fuels, or other products and then capturing and using or storing the point-source emissions. Biochar and bio-oil are carbon-rich solids and liquids that are produced by decomposing biomass at high temperatures (i.e., pyrolysis.) While bio-oil with geological storage has high durability, biochar's storage durability is more uncertain, and depends on use case and elemental composition.[xxvi] Availability and sourcing of low-GHG biomass or biomass that yields a net-GHG reduction are key challenges for BiCRS scale-up.

14 The CO_2 -purity of the flue gas stream is representative of those from power plants and industrial installations (IPCC AR6 WGIII 12.3.1.1 [2022]).
15 Liquid solvent costs are currently estimated to be ~$170–250 per tonne CO_2 compared to solid sorbent costs of ~$365–740 per tonne CO_2; 2050 cost estimates are ~$70–125 and ~$65–145 per tonne CO_2, respectively (Coalition for Negative Emissions)
16 For example, some technologies utilize limestone-based solids to adsorb CO_2 from air and regenerate. In general, DAC will refer to technology-based CO_2 capture from air, even if the sorbent is similar to those used in ex-situ enhanced mineralization
17 BiCRS does not include so-called "nature-based solutions" like afforestation or reforestation

Mineralization (also known as enhanced mineralization)

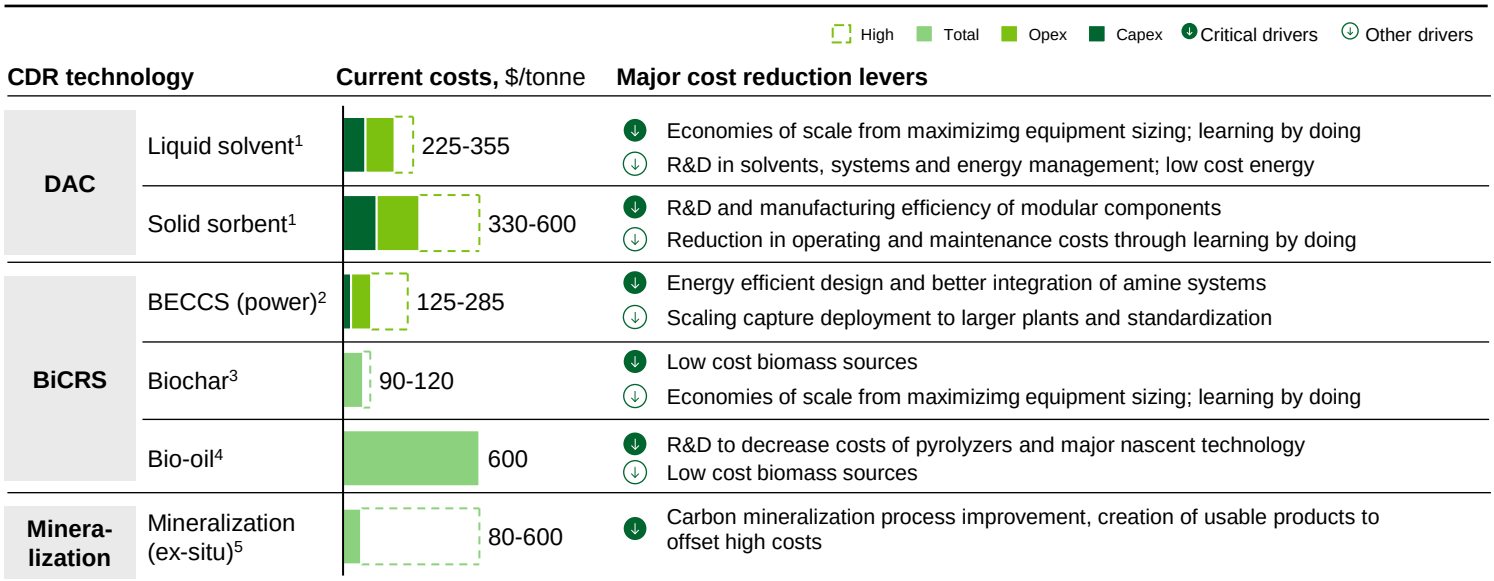
Mineralization is a natural process where CO_2 reacts with an alkaline feedstock (e.g., containing Ca^{2+} or Mg^{2+}) to produce a carbonate, creating a stable, solid mineral. Potential feedstocks could be alkalinity-rich geologic formations (e.g., basalt and peridotite) or in alkaline industrial wastes (e.g., mining wastes, steelmaking slag). The mineralization process has three primary variations: (1) in-situ, where CO_2-rich fluids are injected into subsurface alkaline minerals, (2) ex-situ, whereby alkaline feedstocks are reacted with CO_2 in reactors at high temperature and/or pressure, and (3) surficial, in which alkaline material is reacted with CO_2 at ambient conditions or via sparging of high-purity CO_2 at low pressure.[xxvii] In-situ mineralization can be paired with DAC for permanent storage. Certain components of mineralization can also be used in DAC technologies and there is some uncertainty in technology classification. For example, some technology developers are commercializing passive mineralization DAC technologies that repeatedly produce calcium carbonate by exposing calcium oxide to atmospheric CO_2 then employ renewable heat to produce a high purity CO_2 stream and a regenerated calcium oxide that can again capture CO_2.[xxviii]

			Current capacity[7]		**Announced capacity (as of Sept 2022)[6,7]**	
	CDR technology	**Permanence,** years	**# of projects**	**Total capacity,** TPA CO_2	**# of projects**	**Total capacity,** TPA CO_2
DAC	DAC[1]	>10,000	3	~5K	~70+	77 M
BiCRS	BECCS[2]	>10,000	1	~4K	12+	25M
	Biochar/ bio-oil	Uncertain; depends on use-case, production process; and other factors, but centuries[3]	~35[4]	~65K	~40	1.9M+
	Biomass-to-hydrogen[5]	>10,000 with geological storage	N/A	Limited publicly available information	3	~8 M
Minera-lization	Mineralization (ex-situ)	>10,000	N/A	Lab and pilot scale	N/A	Earlier scale projects

1 DAC announced projects include 1PointFive's 70 1 MTPA DAC facilities by 2035 and CarbonCapture's 5 MTPA Project Bison by 2030
2 BECCS announcements include 15 Mt of biogenic CO_2 from heat and power plants, five cement plants with plans to integrate biomass feedstock in the clinker production process and retrofit CCUS, and two hydrogen facilities to run partly or fully on biomass
3 Biochar permanency estimates are in the decades to centuries timescale (IPCC AR6 WGIII (2022)). Biochar may sequester an estimated 37% after 1000 years with estimated permanence ranging from a few decades to several centuries (Fuss 2018)). Biochar as a soil amendment may sequester carbon for anywhere from ~8–3,500 years ("A Systematic Review of Biochar Research, with a Focus on Its Stability in situ and Its Promise as a Climate Mitigation Strategy" (Gurwick 2013)). Bio-oil carbon could be sequestered for >1,000 years in depleted oil wells ("Pyrogenic carbon capture and storage" (Schmidt 2018), "Biogeochemical potential of biomass pyrolysis systems for limiting global warming to 1.5°C" (Werner 2018))
4 Primarily biochar incumbents who have not historically focused on carbon credit production
5 Routes include gasification and fast pyrolysis to H2. Planned projects include Chevron and Clean Energy Systems biomass to H2 plants
6 Announced project timeline varies between 2024 to 2035
7 Capacity is subject to LCA assumptions on net-GHG emissions and will differ by CDR technology pathway and specific technologies
Source: CDR company websites, "Direct Air Capture 2022" (IEA 2022, public announcements as of July 2022); LNNL: Getting to Neutral: Options for Negative Carbon Emissions in California (2020)

Figure 7: The removal capacity of technological approaches to CDR is expected to increase 100x with announced capacity

Current costs and major cost levers by CDR technology, $/tonne CO_2 captured

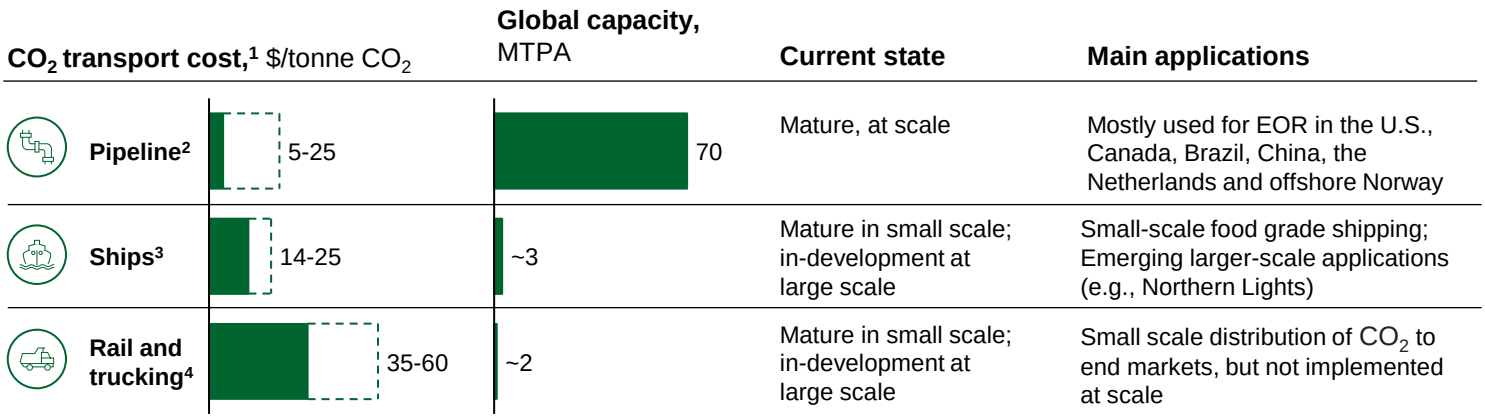


1 Costs from NETL: Direct air capture solvent and sorbent studies; Upper bound of solid sorbent from Climeworks 2018, also cited in "A review of direct air capture (DAC): scaling up commercial technologies and innovating for the future" (McQueen 2021)
2 Cost estimates from Coalition for Negative Emissions for first-of-a-kind BECCS for power with modified financing costs same as above. Low ranges of purchase of biomass processed feedstock and biomass transport taken from FAO U.S. biomass cost estimates rather than Coalition for Negative Emissions, which has higher estimates applicable to a UK-based plant ("Economic analysis of woody biomass supply chain in Maine (Whalley 2017))
3 ICEF "Biomass Carbon Removal and Storage (BiCRS) Roadmap" (2021)
4 Cost for FOAK plant producing bio-oil from cellulosic biomass heated to 500C without oxygen. From Charm Industrial "Carbon Removal: Putting Oil Back Underground" (2021)
5 Costs for ex situ mineralization with wollastonite, olivine-rich, and serpentine-rich tailings using heat and concentrated CO_2 from Kelemen P, Benson SM, Pilorgé H, Psarras P and Wilcox J (2019) An Overview of the Status and Challenges of CO_2 Storage in Minerals and Geological Formations. Front. Clim. 1:9. doi: 10.3389/fclim.2019.00009

Figure 8: Select CDR technologies' costs are currently high but can be lowered through economies of scale, modularization and other levers

Section 2.a.iii Transport

Transport networks connect capture sites with final storage or utilization sites. CO_2 will likely continue to be transported primarily by pipeline for large volumes; rail, trucks, ships, and barges may also be used for specific applications, albeit at a higher cost versus large-scale pipeline transport (**Figure 9**.).



1 Cost ranges approximate based on published studies; costs a strong function of distance and pressure at which CO_2 is transported
2 Approximate costs based on published studies by the European Zero Emission Technology and Innovation Platform, the National Petroleum Council, and GCCSI process simulation for a 30-year asset life. All costs have been converted to a U.S. Gulf Coast basis. Lower end of pipeline cost assumes 20 MTPA, 180 km onshore pipeline. Upper end of pipeline cost assumes 1 MTPA, 300 km onshore pipeline.
3 Approximate cost based on 20 MTPA at a distance of 180 km on the low-end and 2.5MTPA capacity at 1,500 km on the high end. All costs have been converted to US Gulf Coast basis.
4 Low end represents liquid CO_2 transport via rail for 250 km, high-end represents adsorbed CO_2 transported 300 km via truck

Source: Global CCS Institute, Perez et al. (2012), Technic-Economical Evaluation of CO_2 Transport in an Adsorbed Phase, Low Carbon Economy

Figure 9: Pipelines are currently the most used, least expensive, and most mature CO_2 transportation technology, but other modes will be used for certain applications

CO_2 Pipelines

CO_2 pipelines are the most mature, and often the most cost-effective CO_2 transport technology for high volumes (~$5–25 per tonne[18]) and will likely form the backbone of CO_2 transport networks. The U.S. has more than 80% of the world's CO_2 pipelines, with a network spanning roughly 5,000 miles, mostly for enhanced oil recovery (EOR).[xxix] Since existing pipelines largely connect naturally existing CO_2 domes with active oil fields, new pipeline routes will be needed to link emissions sources to geological storage.[19] CO_2 pipelines near the Gulf of Mexico and other areas can be repurposed to deliver captured CO_2 emissions instead of geologic CO_2 sourced from natural domes. Recently, new pipeline projects in the Midwest are seeking to aggregate small, discrete sources of low-cost CO_2 from ethanol plants. [20,xxx]

Today, pipeline siting is largely regulated at the state level. States approve any required permits and any use of eminent domain to acquire the necessary rights of way (RoW) for pipeline development. Two federal bodies that could be equipped to exercise jurisdiction over siting—the Federal Energy Regulatory Commission (FERC) and the Surface Transportation Board (STB) —have not currently been delegated jurisdiction over siting of CO_2 pipelines by Congress, leaving authority to states.[xxxi] The DOT's Pipeline and Hazardous Materials Safety Administration (PHMSA) regulates CO_2 pipeline safety and is currently updating its regulations in the wake of a 2020 CO_2 pipeline rupture.[xxxii]

Some ongoing CO_2 pipeline developments have faced objections from some landowners along their proposed routes. These landowners have raised concerns about compensation, safety, and other impacts (e.g., crop productivity). Developers have attempted to address these concerns and meaningful two-way engagement with host communities can help address or mitigate these issues. Some pipeline companies have publicly explored the possibility of classifying CO_2 pipelines as common carriers, which carry eminent domain rights and certain service provision requirements in some jurisdictions.[21,xxxiii]

Other CO_2 transport methods

Building out pipeline networks is a critical enabler for U.S. carbon management markets, as CO_2 transport by rail and truck are generally more expensive ($35–60 per tonne[22]). Still, rail, truck, and shipping may be important for certain applications in areas where pipeline access is not feasible.

CO_2 transport by ship requires a loading facility and temporary storage on land. [23,xxxiv] This method is currently used on a small scale in Europe for food-quality CO_2. Expanded shipping could enable offshore hub-and-spoke storage networks, especially in global hubs that are anchored near shipping channels or ports (e.g., the Northern Lights project in Europe).[24] Forecasts predict the future load size will vary between 2,000–50,000 tonnes of CO_2 per shipment, leveraging liquified natural gas (LNG) experience and infrastructure.[xxxv]

18 Depending on pipeline width, distance, land ownership and compensation, as well as other maintenance and construction considerations.
19 CO_2 domes are naturally occurring CO_2 reservoirs intentionally produced to be sent to oilfields or for other CO_2 uses
20 Proposed projects by Summit, Navigator and ADM-Wolf would each carry ~10+ MTPA. Emerging projects (e.g., Tallgrass) are also proposing the conversion of natural gas pipelines to CO_2, which could potentially use some of the 320,000 miles of natural gas transmission and distribution across the U.S.
21 Common carrier is used to define pipeline that services any third party under a standard set of terms, rather than a pipeline that is for private use or only serves select parties; Eminent domain refers to the government's ability to convert private property into public use, compensating the owner at fair market value (e.g., rights of way [RoWs] to allow the construction of pipelines); Common carrier transportation
22 These costs are offered as approximate averages and individual project economics will depend on the distance to accessible transport networks (waterways or railways), the distance to storage or conversion sites, and the capacity of the transporting vehicle (and accordingly number of trips required).
23 This process is like those seen in LNG projects, which may indicate a similar scale-up potential and trajectory
24 Liquid CO_2 carriers, with 1,000-2,000 tonnes per ship, transported from large point sources to coastal distribution terminals

Section 2.a.iv Storage

The U.S. has abundant storage resources that are more than sufficient to meet carbon management needs. There are three primary options for the long-term storage of captured CO_2: geologic saline aquifer storage, depleted oil and gas reservoirs, or mineralization (e.g., in ultramafic and mafic rocks such as basalt).

Table 1:

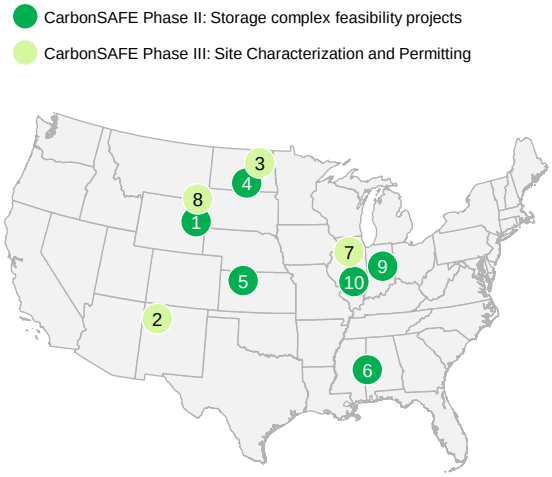
North America has significant CO_2 geologic storage resources, estimated to be sufficient to reach its net zero goals.[xxxvi]

Storage option	Storage potential, billion tonnes		
	Low	Medium	High
Saline aquifers [xxxvii]	**2,379**	**8,328**	**21,633**
Depleted oil and gas reservoirs [xxxviii]	**186**	**205**	**232**
Mineralization	**Global estimates: 2,500–25,000 billion tonnes** [xxxix]		

Project developers and other industry experts believe that most of the CO_2 stored in the U.S. will use saline aquifers. This choice is driven by the large potential capacity across both onshore and offshore saline aquifers and strong public and investor acceptance and toward storage using saline aquifers relative to other options. Capacity estimates are shown in Table 1.

North America possesses ~2,400–21,000 billion tonnes of CO_2 storage resources—enough to store hundreds or thousands of years of captured CO_2 emissions.[25] Saline aquifers are widely dispersed across the U.S., though specific sites require characterization and other development work to better understand their potential commercial attractiveness.

Geologic storage site development supported through DOE's CarbonSAFE initiative



1 Commercial-scale carbon storage complex feasibility study at Dry Fork Station, Wyoming **University of Wyoming**

2 **San Juan Basin CarbonSAFE:** Ensuring safe subsurface storage of CO_2 in saline reservoir, **New Mexico Institute of Mining and Technology**

3 **North Dakota CarbonSAFE Phase III:** Site Characterization and Permitting **University of North Dakota Energy and Environmental Research center (EERC)**

4 North Dakota integrated carbon storage complex feasibility study **The Energy and Environmental Research Center**

5 **Integrated Midcontinent Stacked Carbon Storage Hub**: Storage complex feasibility assessment **Batelle Memorial Institute**

6 Establishing an early CO_2 storage complex in Kemper County, Mississippi: Project ECO2S **Southern States Energy Board**

7 Illinois Storage Corridor **The Board of Trustees of the University of Illinois**

8 Accelerating CCUS at Dry Fork Station, Wyoming **University of Wyoming**

9 Wabash carbon SAFE **University of Illinois**

10 CarbonSAFE Illinois Macon Country **University of Illinois**

Source: Extracted from NETL website - https://netl.doe.gov/carbon-management/carbon-storage/carbonsafe

Figure 10: DOE helped develop multiple CCUS sites through the CarbonSAFE storage site characterization and CO_2 capture assessment projects

25 NETL and DOE: Carbon Atlas V—estimates range from 2,379–21,633 billion metric tonnes. The highest scenarios for carbon management project the U.S. injecting ~1.8 billion metric tonnes annually.

Establishing storage resources for development requires drilling exploration wells, taking seismic imaging data of the reservoir and performing engineering studies. These steps cost millions of dollars and take 1–3 years to complete.[26] DOE's CarbonSAFE Initiative seeks to accelerate this process by supporting the exploration of storage sites across at least seven regions within the U.S. Ten sites with at least 50 MT of capacity have undergone either feasibility or characterization studies (**Figure 10**.).

The CarbonSAFE program is set to expand significantly with $2.5 billion in additional funding for storage projects from the Bipartisan Infrastructure Law.[xl] Further characterization by other developers, often with DOE funding, has demonstrated an additional potential of at least 300 MT from at least 11 sites.[27,xli] Additionally, DOE's Regional Carbon Sequestration Partnerships include 7 regions across the U.S. and facilitate characterization, validation, and development phases. The Partnerships have produced the National Carbon Storage Atlases, contributed to a series of Best Practice Manuals on sequestration approaches, and collectively enabled over 12MT of CO_2 storage.[xlii] Projects funded through Bipartisan Infrastructure Law Programs could unlock more than 350 MT of additional storage capacity, although not all will be commercially attractive to develop.[xliii] More of these sites are required to satisfy the 400-1,800 MTPA capacity necessary for a net-zero economy.[xliv,28]

There is no shortage in physical storage resources, but permitting timelines for storage sites are frequently mentioned as a potential bottleneck by investors and developers. Storage wells are permitted through the Underground Injection Control Program's (UIC) Class VI requirements administered by EPA or implemented by approved "primacy" states, territories, or tribes. The UIC program is designed to ensure that injected CO_2 does not impact underground sources of drinking water or otherwise impact human health and the environment.[29,xlv] EPA has approved six Class VI wells so far, two of which are in operation. For the first four Class VI wells, EPA issued the permits within two years; The permits for the remaining two wells took between 3 and 6 years.[30] EPA has publicly announced that, moving forward, it will strive to permit wells in two years and EPA has developed a series of tools to help streamline the permitting process.[xlvi,xlvii]

EPA can approve States, tribes or territories to be the primary implementation authority for Class VI well permitting responsibilities; approved states are commonly referred to as "primacy states" The two wells in North Dakota permitted under Class VI primacy took 8–10 months.[31,xlvii] Wyoming also has primacy and has two active Class VI permit applications. Texas, Louisiana, Arizona, and West Virginia are currently in the Class VI pre-application or application process to receive primacy from EPA.[xlixF] Pennsylvania is also planning to apply for Class VI primacy. EPA expects to complete its evaluation of Louisiana's Class VI applications and request public comment on this evaluation in May 2023.[li]

As a result of BIL funding, EPA recently announced a grant program for states, Tribes, and territories to defray expenses related to establishing and operating a Class VI UIC program. As a condition of receiving funding for new Class VI programs, states must incorporate Environmental Justice and equity considerations into their state permitting programs.[lii]

Currently, four operational sites—with total initial capacity of ~30 MT—have received Class VI permits in North Dakota and Illinois.[32] Over 60 Class VI applications are currently pending at EPA with additional applications submitted in states with primacy.[liii] Pending applications could expand capacity by 80 MT or more. [33]

In some states, developers face legal ambiguity around pore space ownership (i.e., who owns the space where CO_2 is injected), requiring additional and early due diligence.[liv] In states without comprehensive pore space regulations, the lack of legal precedent or clear law creates uncertainty regarding ownership and its impact on future legal challenges.[lv] Most commonly, this is an issue of split estates on lands where the surface right owner does not also own the mineral right and the primacy of mineral rights relative to pore space rights are unsettled.[lvi] This is also an issue that needs to be addressed with respect to federal lands, particularly in regions where mineral rights are owned by the federal government, but the surface right owner or lease may be different. In 2022, the Bureau of Land Management issued an instruction memorandum clarifying RoWs for geologic sequestration of CO_2.[lvii] In 2021, the BIL provided the Bureau of Ocean Energy Management with the authority to grant leases, RoWs, and easements for the subsurface storage of CO_2.[lviii]

26 Varies by developer and reservoir. 2022 CCUS Institute Report
27 Storage potential is impacted by geological features (e.g., thickness, boundaries and porosity), rock quality (e.g., permeability, pressure), and other factors (e.g., depth, local seismicity, previous drilling, passage through freshwater aquifers [especially single-source USDWs], and pipeline right of way).
28 Assuming 25 years of capture and storage lifetime
29 It includes requirements for site characterization, well construction, operation, monitoring, financial responsibility (including during post-injection care) and reporting / record-keeping
30 Factors specific to each individual application can significantly impact how long it will take to issue a permit. Individual site conditions, community feedback, and the completeness or quality of the application may require additional time. For example, EPA may notify applicants of deficiencies in the application or make Requests for Additional Information. The responsiveness and completeness of applicants' responses will ultimately dictate the permitting timeline.
31 Differing definitions of application submission and approval between state and EPA Class VI processes make direct comparisons difficult.
32 One other site (FutureGen) received Class VI approval, but did not proceed
33 Based on the Class IV Wells Permitted by EPA, the DMR and the Wyoming DEQ

Section 2.a.v Enhanced Oil Recovery (EOR) storage

Historically, captured CO_2 has been primarily injected in oil fields for EOR. CO_2-EOR, injecting from both naturally occurring and anthropogenic sources, was responsible for producing roughly 300,000 barrels of oil per day in the US in 2019.[34,lix] Nearly all of the injected CO_2 ultimately remains geologically stored underground while the oil in the reservoir is displaced and extracted for refining.[lx] Currently, the majority of the CO_2 supply for EOR operations is taken from naturally occurring reservoirs, such as CO_2 domes.[lxi,lxii,lxiii] As industrial and atmospheric capture capacity expands, captured CO_2 that would have gone into the atmosphere could displace naturally occurring CO_2 in EOR operations. Using anthropogenic emissions for EOR can produce oil with lower lifecycle carbon emissions because of the carbon initially stored to produce it. LCA performance will vary over the lifetime of a well and between wells based on well-specific practices and characteristics, but some propose a rule of thumb of ~40% lower lifecycle carbon emissions per barrel of oil produced.[lxiv,lxv]

Section 2.a.vi Utilization

Carbon utilization describes the creation of commercial products or commodities for consumption through the conversion or permanent containment of captured carbon with either CO_2 or carbon monoxide (CO) as feedstocks. In some cases, conversion can serve as an alternative to geologic storage for captured CO_2, adding additional capacity and economic value and often replacing incumbent materials which are more emissions-intensive (**Table 2**.).[35]

NOT EXHAUSTIVE

Utilization Case	Key technologies
1 **Building materials**	• **CO_2-cured cement**: injects CO_2 into fresh ready-mix cement or in pre-cast concrete • **CO_2-based aggregates**: metal oxides are extracted and carbonated using CO_2 from flue gas, and deposited onto a substrate creating aggregate that is composed of carbonates • **Clinker replacement:** substitution of limestone with alkaline materials like fly ash followed by carbonation with CO_2
2 **Plastics, chemicals, & new materials**	• **CO_2-derived polyethylene carbonates (PEC)** polyols for heat insulation foams, transparent polycarbonate and polyurethane plastics • **CO_2-derived polypropylene carbonate (PPC)** and polyethylene carbonates (PEC) polyols for polyurethane plastics
3 **Fuels**	• **Electrolysis**: CO_2 and water converted to syngas through co- electrolysis to produce synthetic fuel (e.g., diesel) through further processes (e.g., Fischer–Tropsch processes) • **Thermo-catalysis**: liquid fuels (gasoline, diesel etc.) are synthesized from CO_2 and hydrogen • **Fischer-Tropsch:** Conversion of syngas into liquid hydrocarbons through a catalytic chemical reaction • **CO conversion:** Non-Fischer-Tropsch conversion of gases containing CO into liquid fuels and chemicals

Table 2: CO_2 can be converted to new materials like building materials, plastics, and synfuels

34 This process has mostly been used in the Permian basin, largely due to favorable geology and accessible, natural sources of CO_2 (NETL: CO_2 Enhanced Oil Recovery: Untapped Domestic Energy Supply and Long-Term Carbon Storage Solution).
35 If utilization results in re-release of CO_2 (e.g., in beverages or fuels) then there is no direct abatement potential.

CO_2 demand for utilization, excluding urea production, was ~20-30 MTPA globally in 2019.[lxvi] However, new commercial pathways have emerged that use conversion to create fuels, chemicals, and building materials. For many utilization applications, economics are highly uncertain and will depend on customer willingness to pay above the subsidized cost to produce. Carbon utilization processes vary in technology readiness, market dynamics, and potential for long-term CO_2 storage permanence. For example, building materials produced via CO_2 mineralization present the potential for permanent CO_2 storage, while producing jet fuel via Fischer-Tropsch synthesis or CO conversion would have no long-term carbon storage potential (as CO_2 is produced and re-emitted upon fuel combustion). However, the emissions abatement from displacement of incumbent fossil-based jet fuel is sufficiently high to present an argument for continued development of these carbon conversion pathways.[lxvii]

At scale, utilization is expected to account for only a fraction of the total carbon emissions captured—the rest must be stored. While small relative to storage, North America's CO_2 demand for utilization is projected to grow to ~40 MTPA by 2030 and ~100–250 MTPA by 2050.[36,lxviii] DOE has supported a diverse portfolio of carbon conversion processes, including catalytic conversion of carbon oxides to fuels and chemicals, uptake in algae and bioproducts, and mineralization for production of inorganic materials. [lxvix]

Section 2.b Current regulation and policies supporting CCUS and CDR development

Several policies support the buildout of CCUS and CDR infrastructure in the U.S.

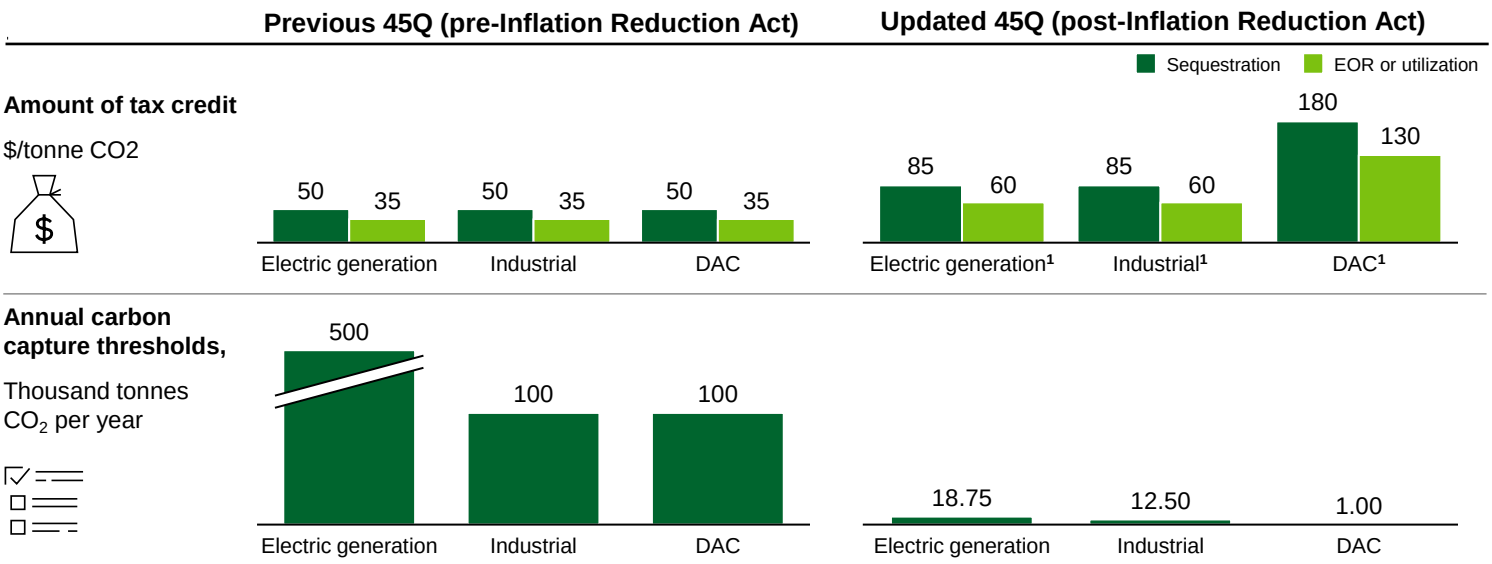
Inflation Reduction Act (IRA) – 45Q

The 45Q tax credit is the largest and most certain incentive for carbon management in the world. By setting a reliable value for geologically stored or utilized carbon, the 45Q credit provides a consistent, performance-based revenue source that developers can use to evaluate potential projects. As amended by the IRA, the 45Q credit pays $85 per ton[37]; requires that qualified projects commence construction by the end of 2032; and allows the taxpayer to claim the credit for 12 years once a project is placed in service (Figure 11). If a CCUS developer can capture and store carbon for under $85 per tonne on an all-in, levelized basis over 12 years, then the project is financially feasible.[38]

Several other tax credits could support deployment of CCUS, including the 45V tax credit for clean hydrogen production and the 40B and 45Z tax credits for sustainable aviation fuels and low-carbon transportation fuels. 45Y and 48E tax credits are applicable for electricity generating facilities with lifecycle greenhouse gas emissions rates of zero or less. Projects cannot "stack" 45Q with 45V, 40B, 45Z, 45Y, or 48E credits.

The IRA also provides $5.8B to support advanced industrial decarbonization deployment, which could include carbon management projects in the industrial sector.

36 Full range from the Princeton Net Zero Americas report is 100-700 MTPA by 2050
37 $85/ton for sequestration subject to certain labor requirements. If CO_2 is utilized, the credit is $60/ton. For DAC projects, 45Q value is $180/ton for sequestration and $130/ton for utilization.
38 Some projects may be eligible for other incentives or revenue streams, including state-level incentives like the California LCFS or the ability to sell a low-carbon product for a premium (e.g., green steel.)



1 If prevailing wage and apprenticeship requirements are met
2 For taxable entities; Tax-exempt entities are eligible to receive direct pay for the full 12 years of the 45Q credit
Source: Inflation Reduction Act 2022

Figure 11: Updates / enhancements to the 45Q tax credit from the IRA provides an enhanced 45Q tax credit for carbon capture

Low Carbon Fuel Standard (LCFS)

Low Carbon Fuel Standard programs are compliance markets that require a reduction in the carbon intensity of transportation fuels that are sold or supplied within a certain geography. State regulatory entities establish declining yearly fuel carbon intensity (CI) requirements. Fuels that exceed this mandated CI generate a credit deficit, while those below the mandated CI generate a credit surplus. As a result, low-carbon fuels (e.g., ethanol produced with CCUS) can receive revenue for credits. Additionally, in the California LCFS market, DAC can generate project-based credits for tonnes captured and stored—even if the capture occurs outside of the LCFS geography. Currently LCFS markets operate in California, Oregon, and Washington; additional states are considering LCFS market adoption. The value for credits in California's LCFS market has been volatile in recent years, ranging from ~$60 to $200 per tonne of CO_2.

Bipartisan Infrastructure Law (BIL)

The BIL provides ~$12 billion in funding for high-potential projects across the carbon management value chain, including funding for demonstration and pilot projects.[lxx] The BIL also includes $8B for Regional Clean Hydrogen Hubs, at least one of which must prioritize projects that use CCUS to generate clean hydrogen and $500M for Industrial Emissions Demonstration Projects that could include carbon management technologies.

- Carbon Capture Demonstration Projects Program ($2.5B)
- Carbon Capture Large-scale Pilot Projects ($937M)
- Carbon Capture Technology Program, Front-End Engineering and Design ($100M)
- Carbon Dioxide Transportation Infrastructure Finance and Innovation ($2.1B)[40]
- Carbon Storage Validation and Testing ($2.5B)
- Carbon Utilization Program ($310M)
- Commercial Direct Air Capture Technologies Prize Competitions ($100M)
- Precommercial Direct Air Capture Technologies Prize Competitions ($15M)
- Regional Direct Air Capture Hubs ($3.5B)

Carbon Negative Shot

The Carbon Negative Shot establishes an objective to advance CDR pathways that will capture and store CO_2 at gigatonne scale for less than $100 per net tonne of CO_2-equivalent within the decade. This effort is part of DOE's Energy Earthshots Initiative, which aims to accelerate breakthroughs of abundant, affordable and reliable clean-energy solutions.

Procurement of Low-Carbon Products or Carbon Utilization Products

Several state and local governments have passed laws that mandate the consideration of the embodied emissions of the products they purchase, including California, New York, and Colorado.[lxxii] Currently, these policies focus mostly on building materials (particularly concrete), and can enable the technological maturation of CO_2 utilization in concrete and aggregates by decreasing the economic challenges to the use of these products. Recently, the Department of Energy released a Notice of Intent to provide grants to state and local governments that will help pay the added cost of procuring carbon utilization products.

40 Funding covers "credit subsidy" associated with a loan, meaning $2.1B in appropriations could translate to $10B+ in loan authority

Chapter 3: Pathways to Widespread Deployment

Key takeaways

- Many carbon management technologies are mature and operating at commercial scale in the U.S. today.
- The carbon management ecosystem will scale between near-term and longer-term opportunities.
  - Initially, a low-cost transport and storage backbone can develop by connecting high-purity CO_2 streams (e.g., ethanol, hydrogen SMR, and natural gas processing). Investors and project developers are working on more than $10B in projects in this space across the carbon management value chain.
  - In parallel, pilots and commercial demonstration projects can help reduce the cost of higher-cost point-source and CDR technologies

- Six main dynamics define the potential build-out of carbon management technologies:
  - Development of low cost-of-capture sectors that are profitable today will aid initial transport and storage build-out
  - Pilot and commercial demonstration projects in lower-purity CCUS applications and CDR will help to decrease costs and establish repeatable commercial arrangements
  - Additional commercial revenue streams, policy incentives, or regulations may be needed to reach the scale of carbon capture required for net-zero by 2050
  - Significant scale-up of carbon-free energy and transmission capacity is needed for DAC and carbon utilization deployment that achieves GHG reductions on a life cycle basis
  - Build-out of transport and storage for CCUS and CDR infrastructure must be swift
  - Financing carbon management projects will depend on a robust tax equity market and implementation of 45Q tax credit “transferability”

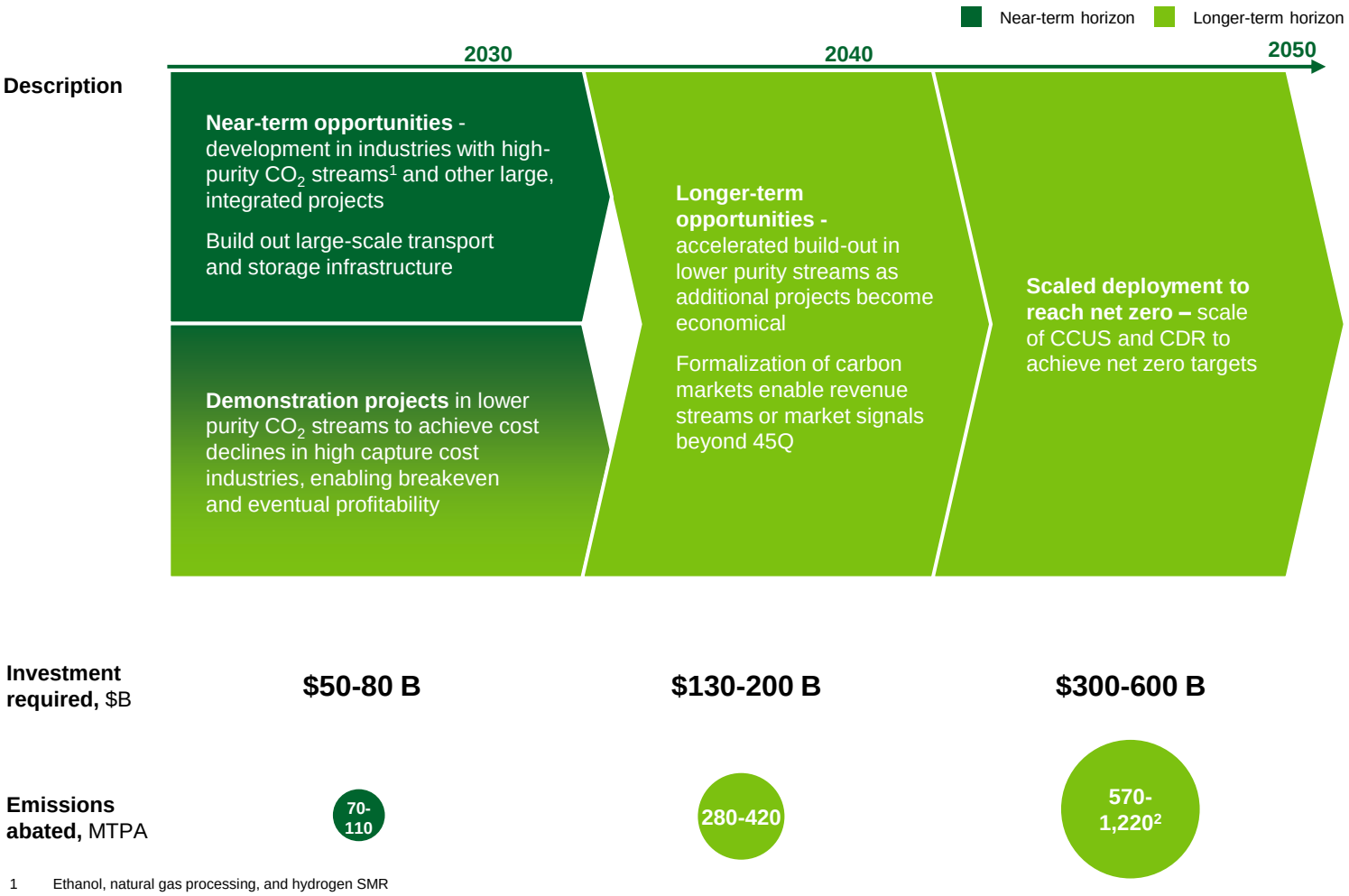
Section 3.a: The pathway to widespread deployment

Carbon management is a mature technology with over 20 MTPA in capture capacity already deployed and operating in the U.S. and several projects in advanced stages of development. This section outlines the path to widespread commercial deployment
at scale.

The carbon management ecosystem is scaling through two overlapping tracks (**Figure 12**):

- In the near-term, industries with high-purity CO_2 streams (e.g., ethanol, hydrogen from steam methane reforming (SMR), and natural gas processing) and other large, integrated projects will lead the way through 2030. These early projects have more favorable economics and can anchor the buildout of large-scale transport and storage infrastructure—laying the foundation for carbon management applications in other industries (e.g., steel, cement).

- Longer-term, industries with lower-purity CO_2 streams will see cost declines supported by pilot and commercial demonstration projects now through the mid-2030s. Demonstration funding and project-specific factors (e.g., proximity to storage, end-customers willingness to pay) will unlock FOAK deployments in many of these sectors prior to 2030.



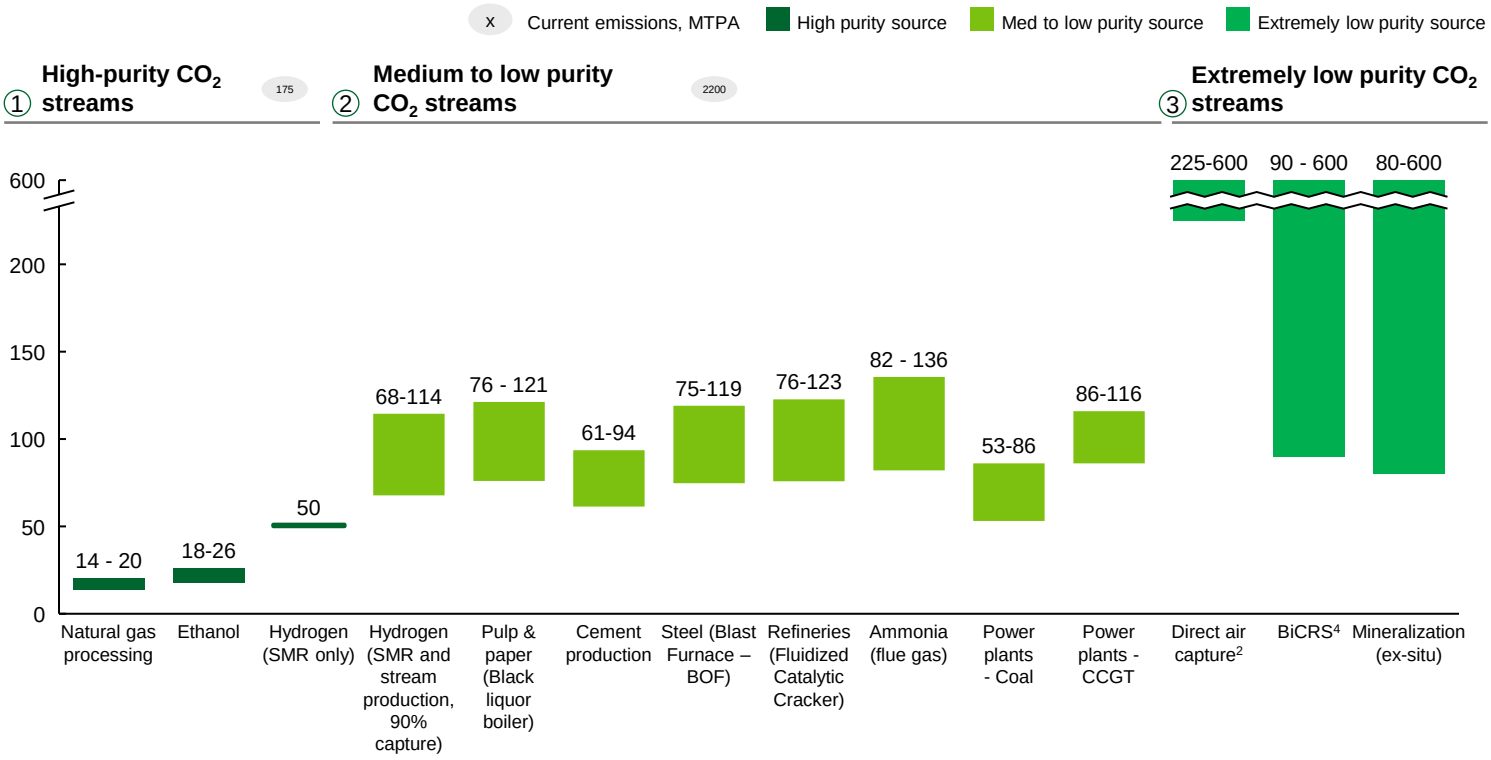
1 Ethanol, natural gas processing, and hydrogen SMR
2 Abated emissions are based on the modeling with the ranges corresponding to net zero and high technology case scenarios. Full range of emissions abated given other reports range from 400-1800 MTPA

Source: Deployment and investment figures in this section are based on modeling conducted for this report by McKinsey & Company in accordance with Government Contract No. DE-AC02-06CH11357 and subcontract 2J-60009. Deployment numbers fall within the general ranges expected from several government and other research reports, including: Princeton's Net Zero America report (2021, the White House Pathways to Net-Zero GHG Emissions by 2050 (2021), The IPCC (2021, IRENA (2021), IEA (2021);)

Figure 12: Near-term opportunities focus on high-purity streams; longer-term opportunities in lower purity streams require demonstration projects [41,lxxii]

41 Net-zero decarbonization scenarios forecast of what it would take to reach net-zero by 2050 under unconstrained renewable and transmission capacity (on the low end) and a technology 'spike' case on the high end where the development of other technologies continues at current momentum and carbon management plays a larger role in decarbonization. Modeling completed for this Pathways effort.

Carbon capture costs[1] excluding storage and transport costs, $/tonne CO_2



1 Displayed cost estimates based on EFI Foundation capture costs with transport (GCCSI, 2019) and storage (BNEF, 2022) costs of ~$10-40/tonne, except where noted. All in 2022 dollars. All CCUS figures represent retrofits, not new-build facilities. The lower bound costs represents a NOAK plant in a low cost retrofit scenario with low inflation. The higher bound costs represents a FOAK plant in a high cost retrofit scenario with high inflation. The inflation variance on each cost estimate represents the range of cost increases on a generic chemical processing facility due to inflation from 2018 using the Chemical Engineering Plant Cost Index (CEPCI).
2 Based on liquid solvent range of $225-355/tonne and solid sorbent range of $330-600/tonne from NETL: Direct air capture solvent and sorbent studies and Climeworks (for solid sorbent)
3 CO_2 concentration is not the only driver of cost in difficult to abate sectors. Multiple units / emissions streams, impurities, and other factors can contribute.
4 Includes BECCS to power, biochar, and bio-oil
Source: EFI Foundation, "Turning CCS Projects in Heavy Industry & Power into Blue Chip Financial Investments". Hydrogen SMR-only capture costs from IEA 2019.; Coal and CCGT power plant retrofit cost of capture figures derived from NETL Revision 4a Fossil Baseline study retrofit cases adjusted to 2022 dollars and with 12-year amortization—range represents FOAK with high retrofit factor (high figure) to NOAK with low retrofit factor (low figure). DAC costs from NETL: Direct air capture solvent and sorbent studies; Upper bound of solid sorbent from Climeworks 2018, also cited in "A review of direct air capture (DAC): scaling up commercial technologies and innovating for the future" (McQueen 2021); BiCRS cost estimates from Coalition for Negative Emissions for first-of-a-kind BECCS for power with modified financing costs same as above. Low ranges of purchase of biomass processed feedstock and biomass transport taken from FAO U.S. biomass cost estimates rather than Coalition for Negative Emissions, which has higher estimates applicable to a UK-based plant ("Economic analysis of woody biomass supply chain in Maine (Whalley 2017)) and ICEF "Biomass Carbon Removal and Storage (BiCRS) Roadmap" (2021), Charm Industrial "Carbon Removal: Putting Oil Back Underground" (2021); Mineralization costs from author benchmark cost used in IPCC. Costs for ex situ mineralization with wollastonite, olivine-rich, and serpentine-rich tailings using heat and concentrated CO_2 from Kelemen P, Benson SM, Pilorgé H, Psarras P and Wilcox J (2019) An Overview of the Status and Challenges of CO_2 Storage in Minerals and Geological Formations. Front. Clim. 1:9. doi: 10.3389/fclim.2019.00009; Current emissions from EPA GHGRP FLIGHT database 2019 and includes biogenic CO_2 emissions for pulp and paper (~110 MTPA)
Note: Applications are arranged left-to-right by industry, power, and CDR reflecting the rough CO_2 concentration of the CO_2 sources associated with these applications

Figure 13: Carbon capture cost is a function of CO_2 concentration and other facility-specific factors

Across both opportunities, 70–110 MTPA of carbon-management capacity is expected by 2030, primarily from the capture of high-purity CO_2 streams and demonstration projects in lower-purity and diffuse steams.[42] High-purity CCUS already has momentum, with developers working on large-scale pipelines to connect ethanol, ammonia, gas processing, and some hydrogen projects that address relatively low cost-of-capture streams. However, some other project types become economic only with additional government support or policy, alternative carbon markets or revenue streams, or cost reduction from demonstration projects (**Figure 14**.). Some particularly attractive projects in the lower-purity industries (e.g., very large emissions sources close to transport and/or storage) are being developed, but broader lift-off could require additional financial or regulatory incentives—and regulatory developments in particular could play a dramatic role in accelerating the pathways described here.

42 Low case projecting 40-50% of all ethanol, ammonia, and natural gas processing and accessible H2 install capture, as well as one demonstration project at average plant size in power, refining, cement, steel, DAC, and other CDR. Current emissions from EPA GHGRP FLIGHT database. High case represents 70-80% of ethanol, ammonia and H2, 50% of natural gas processing, ~2 demonstration projects at average plant size in power, refining, cement and steel, and announced capacity of leading DAC player.

Dynamics impacting pathways to commercialization scale

Six dynamics impact the commercialization pathway for carbon management.

Development of low-cost-of-capture sectors that are solidly investable today will aid early infrastructure build-out, but is not sufficient to reach net-zero goals

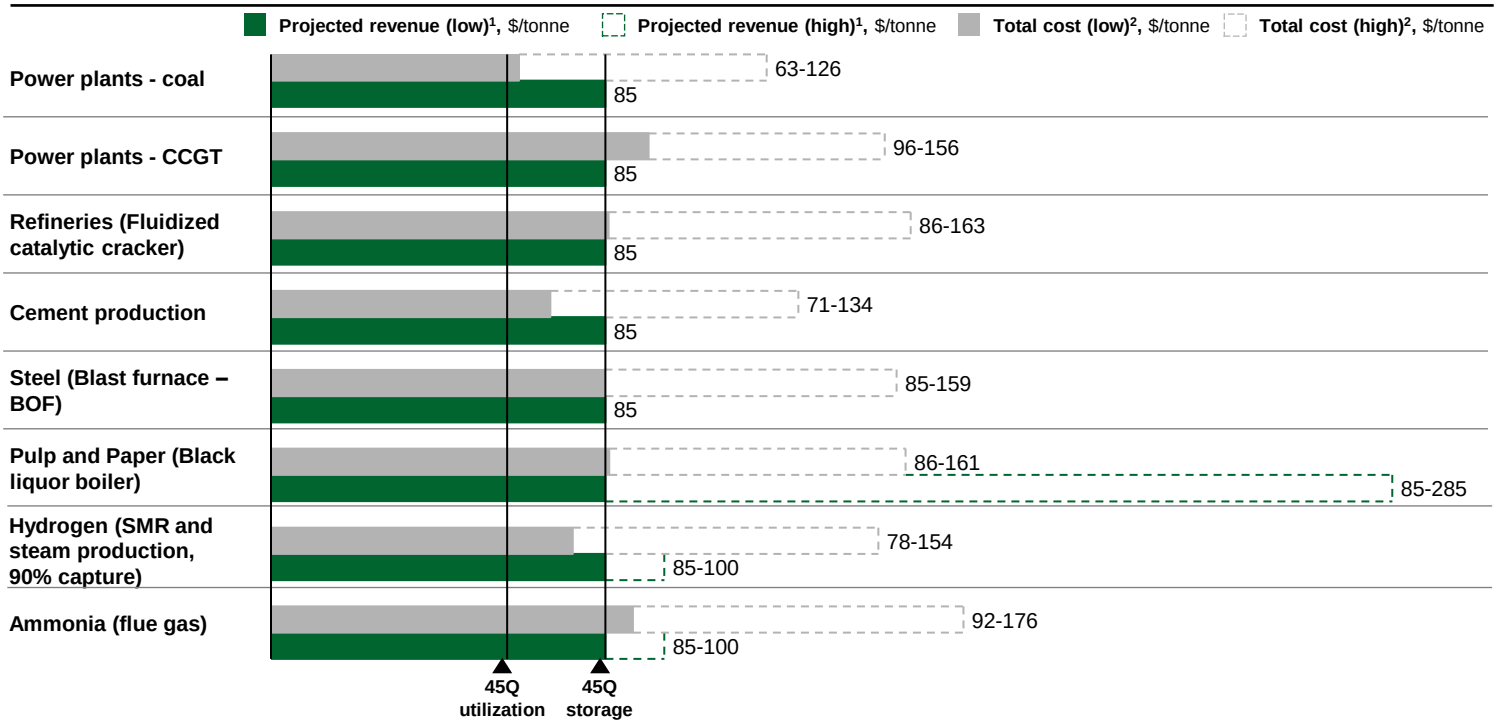
Today, build-out of CCUS is primarily in industries with a low cost of capturing CO_2, typically enabled by high-purity CO_2 streams (e.g., ethanol, natural-gas processing, hydrogen from SMR). Business case modeling suggests that ethanol CCUS projects could see unlevered internal rates of return (IRRs) of 10–15% or more with the enhanced 45Q tax credit from the IRA. Project development in these low cost-of-capture applications is ongoing and accelerating.

Although these projects constitute a fraction of overall carbon management potential, they can jumpstart the build-out of shared transport and storage infrastructure.

Higher cost-of-capture CCUS and CDR may not deploy absent additional drivers, such as regulations

Current average costs are estimated to be close to or above the $85 per tonne CO_2 45Q credit in higher-cost applications (e.g., cement, iron and steel, power including BECCS), and sustained inflation could increase costs further given that the IRA suspends inflation adjustment for 45Q until after 2025. Limited revenue sources for captured CO_2 beyond the 12-year 45Q tax credit window results in carbon management projects that are economically challenged today (**Figure 14**.) Individual project dynamics (e.g., close proximity to storage) are critical, and projects will be sensitive to any cost overruns. Regulations constraining emissions from any of the relevant sectors could shift commercialization significantly. For DAC, the new IRA 45Q tax credit of $180 per tonne is still insufficient without further cost declines or strong markets for carbon removal credits.

Costs and potential revenues for CCUS point source retrofits in higher cost-of-capture applications



1 Revenue includes 45Q for all industries, with a value of $60-85/tonne. Pulp and paper includes potential VCM revenue. Hydrogen revenue includes PTC, estimated to be ~$100/tonne. 2. Industrial applications from EFI Foundation, "Turning CCS Projects in Heavy Industry & Power into Blue Chip Financial Investments" Coal and CCGT power plant retrofit cost of capture figures derived from NETL Revision 4a Fossil Baseline study retrofit cases adjusted to 2022 dollars and with 12-year amortization—range represents FOAK with high retrofit factor (high figure) to NOAK with low retrofit factor (low figure). Transport (GCCSI, 2019) and storage (BNEF, 2022) range from $10-40/tonne

Figure 14: Lower purity point sources require further cost reductions or additional revenue streams

Demonstration and initial commercial projects are critical to achieving cost declines through “learning-by-doing”. Retrofitting CCUS in some contexts can require some facility-specific designs that may not be perfectly transferrable to other facilities. Nevertheless, creation of standard (e.g., starting point) designs, increased modularization, and dissemination of operational learnings will enable cost reductions over time.

Researchers and developers expect cost declines with deployment, though the persistent energy requirements for many carbon management technologies mean that the drastic cost declines observed in no-fuel technologies like wind and solar are unlikely. Researchers have modeled potential CapEx learning rates for DAC of 10-20% (that is, a 10-20% decline in CapEx costs for every cumulative doubling of capacity.)

Developers have set aggressive cost reduction targets. Start-ups have announced pathways to achieve $30-50/tonne cost of capture for industrial sources (from $60-120/tonne today) and DAC developers Carbon Engineering and Climeworks claim a pathway to ~$100/tonne within ten years.[lxxiii,lxxiv,lxxv]

Cost declines in CO_2 transport and storage are achievable through building shared regional pipeline and storage networks but given their relatively small share of total costs for higher cost-of-capture applications these reductions alone may not make retrofit projects profitable in the absence of other drivers.

Additional revenue streams or regulation may be required to reach the scale of carbon capture needed for net-zero by 2050.

If cost declines do not bring levelized costs of carbon management below expected revenues, additional revenue sources or regulation will be needed for carbon management to reach a scale of deployment commensurate with its emissions reduction potential. In many cases, FOAK deployments financed by BIL and IRA will establish baseline costs and subsequent facilities will realize cost reductions as a result of project development, technology, permitting, and community engagement learnings, as well as economies of scale and enabling infrastructure.

While 45Q constitutes the primary incentive for carbon management in the US today and is scheduled to sunset for new projects beginning construction after 2032, industry players across CCUS and CDR expect regulations and private sector action to continue incentivizing or driving growth of carbon management in the future. Mechanisms could include extension of 45Q, regulations such as emissions standards, cap and trade programs or carbon taxes, or support for other revenue streams (e.g., voluntary carbon markets, technology premiums, premium PPAs and revenues from other products.).

Build-out of DAC and CO_2 utilization could be limited if clean energy build-out is constrained.

Today’s DAC technologies require significant energy and heat to operate; current technology requires ~6–8 GJ per tonne CO_2 captured.[lxxvi] With current configurations, thermal energy accounts for ~80% of total energy needs for sorbent-based DAC.[lxxvii] Achieving net-negative emissions, therefore, will require significant clean power and thermal energy for DAC technologies.

Clean energy is also needed for utilization pathways in which CO_2 and CO are converted to other molecules (e.g., synfuels, plastics).[lxxviii] Up to 9,300 TWh per year of additional zero-carbon electricity capacity could be needed to achieve net-zero aviation globally by 2050.[lxxix] This level of generation represents more than double the total annual electricity consumption in the U.S.

Build-out of transport and storage infrastructure for carbon management must be swift.

The build-out of CO_2 transport and storage infrastructure is critical. Currently, the U.S. has ~5,000 miles of operational CO_2 pipelines, largely developed for enhanced oil recovery (EOR). Significant new transport infrastructure that can enable geologic saline aquifer storage will be crucial as the carbon management ecosystem develops. Several studies have attempted to optimize the required pipelines based on varying estimates of CO_2 that will need to be transported. Regardless of the scenario, studies suggest transport capacity must be scaled to 30,000-96,000 miles by 2050 (**Figure 15**.).[lxxx] In addition to expansion in pipeline capacity, other modes of CO_2 transport including barge, ship, train, and trucks are likely to serve an important role in facilitating offshore storage, shorter routes, and collection from multiple proximate facilities.[lxxxi]

Case	Pipeline scenario	Case	Pipeline scenario
Current state (~4,500 miles)		**Net Zero Americas** (~70,000 miles)	
Great Plains Institute (~30,000 miles)		**DOE stress case from Net Zero America** (~96,000 miles)	

Source: NETL Review of CO_2 Pipelines in the United States, Princeton net-zero Americas, Great Plains Institute

Figure 15: Different pipeline network configurations have been proposed by various studies, with 30,000 to 96,000 miles of pipeline expected to be required by 2050

The scale of CCUS deployment will also require significant storage capacity to be developed. The timeline to permit and develop storage capacity must be accelerated to meet the amount of storage needed to support 70–110 MTPA by 2030. More than 50 MTPA of Class VI applications are currently awaiting or under review.[lxxxii] State Class VI primacy and EPA achieving its goal of 2-year processing timelines can alleviate this potential bottleneck.

Project finance will depend on a robust tax equity market and implementation of 45Q "transferability"

Like other clean energy technologies, carbon management projects must use the future delivery of federal tax credits to finance large upfront construction costs. In carbon management's case, these are the 45Q tax credits projects receive from the IRS for each tonne of captured carbon emissions they successfully store or utilize. While 45Q projects developed by for-profit entities can receive direct payment of the face value of the credit for the first five years of project operations, most projects' credits in years 6-12 must be used directly by the project sponsor, monetized via a tax equity investor, or sold to another entity with a tax liability under the new "transferability" provisions in the IRA.[43] Carbon management projects have substantial operational costs and, absent other drivers, projects may not be able to profitably continue operation of capture equipment once they stop receiving 45Q credits after 12 years of operations.[44] As a result, project finance investors in carbon management projects generally must plan to hit their return thresholds within 12 years.

Carbon management projects could pursue financing through tax equity or through traditional project finance. Both approaches face uncertainties that could complicate project development.

43 Not-for-profit entities like rural electric cooperatives can receive direct payment for all 12 years of the credit.
44 Many investors expect further policy support or regulation to come into play as 45Q facilities start reaching the end of this 12-year period, but this support is not certain.

Tax equity is the primary way clean energy developers, especially in wind and solar, have monetized their tax credits if they do not have a sufficient tax liability of their own. Tax equity allows entities with a large tax bill to put up upfront capital in the project in exchange for the right to the tax credits generated. These tax equity investors can then use these tax credits to lower their tax liability. Tax equity requires complex project structuring and developers generally cede a portion of the face value of the credit to their tax equity partner.

Challenges for carbon management projects using tax equity include:

- **The size of the tax equity market is constrained:** Historically, only large financial institutions have had the persistent tax bill and structured finance wherewithal that make tax equity an attractive proposition. The total market for tax equity is ~$20 billion/year and two banks–JP Morgan and Bank of America–account for ~50% of tax equity volumes.[lxxxiii] Future growth of the tax equity market may be constrained. The large number of tax equity-eligible projects seeking to partner with a relatively small number of tax equity investors has led to projects consistently accepting tax equity investment at a significant effective discount to face value.

- **Carbon management projects will compete with other clean energy projects for tax equity investors' interest:** Historically, tax equity investors have focused almost exclusively on wind and solar projects. Wind and solar are well-understood asset classes with reliable tax equity structures that tax equity investors are comfortable with. The expansion of 45Q, the extension of renewable energy credits, and the creation of large new credits like 45V for hydrogen production could create hundreds of billions of dollars in projects seeking tax equity compared to a tax equity market of ~$20 billion/year.

Traditional project finance, in which projects receive debt against expected future cashflows, may become a more viable option for carbon management projects with the passage of the IRA. Tax-exempt entities can receive direct payments for 45Q tax credits, simplifying project finance for these developers dramatically. For non-tax-exempt developers, direct payment is available for the first five years of the project. After year five, the IRA allows for-profit entities to transfer tax credits to taxpayers uninvolved in a project. Projects can sell those credits directly to entities with a tax bill they are trying to minimize. These carbon management projects may seek a loan from commercial banks underwritten by the expected revenues from transferring credits in years 6-12 of project operations.

The scale of traditional project finance for carbon management projects will depend on the extent to which the following challenges related to the transfer of 45Q tax credits can be overcome:

- **Unfamiliar buyers**: The novelty of tax credit transferability means that potential buyers will be unfamiliar with the market. It will take time for CFOs of corporations with tax liabilities, for example, to learn about transferability and get comfortable entering a purchase agreement for tax credits. Potential buyers will likely become more familiar with the transferability market over time.

- **Uncertain value of transferable credits**: Projects will have to sell their tax credits at some discount to their face value (e.g., 90 cents on the dollar) to attract buyers, but it is difficult to determine what this discount will be in years 6-12 of a carbon management project. Corporations are one of the most likely buyers of transferable tax credits, but each individual corporation's tax bill differs significantly from year to year depending on profitability and other factors. This could make it difficult for projects to secure purchasers for their credits in advance, which can make it challenging to receive upfront financing based on these expected revenues.

Carbon management developers with a large tax liability of their own (e.g., some large oil and gas companies) may face less complexity in financing their projects if they expect to be able to use their tax credits directly. But even large companies can lack a consistent enough annual tax liability to be able to rely on direct use of tax credits a project will generate for the 7 years remaining after the 5 years of direct pay for 45Q expires. Project deployments over the next few years, as well as further details on how the transferability mechanism will operate, may surface solutions to some of these financing challenges.

Section 3.b Implied capital formation

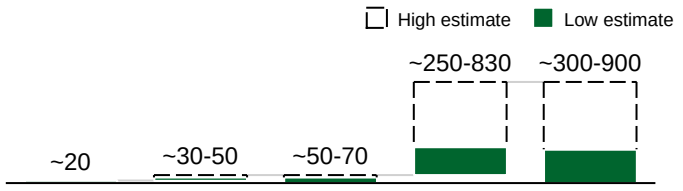
Key takeaways

- The first generation of carbon management projects relied on government funding and corporate investment from large industry players; the level of risk associated with these projects was incompatible with significant debt/equity financing from private equity, institutional investors, or banks
- More recent carbon management projects have begun to attract established infrastructure investors
- The required capital formation for carbon management deployment is significant through 2030 ($50–80B total) and must accelerate afterwards, from ~$10B per year to $20–40B per year to achieve the level of deployment modeling scenarios suggest may be needed to reach net-zero
- This capital acceleration requires significant progress through FOAK and NOAK in each technology and business model to mitigate execution risk and unlock larger pools of lower-cost capital

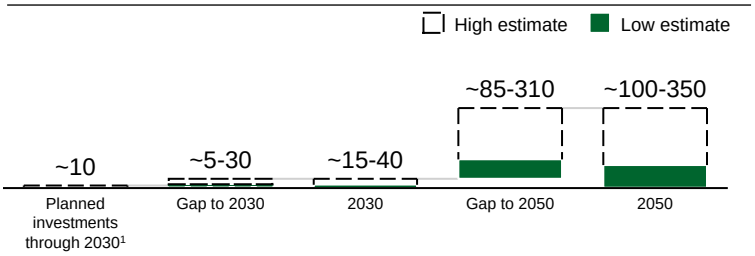
Forecasted investment needs[45]

Scaling CCUS and CDR will require investment along the full value chain, including investment in technology, capture projects, transport, and storage. To reach net-zero by 2050, $50–80B of investment will be needed by 2030 and $300–600B of cumulative investment by 2050.[lxxxiv,45] High technology adoption by 2030 is forecasted in high-purity sources (e.g., ethanol, hydrogen SMR, and gas processing) with multiple large-scale commercial projects in lower-purity industries and among certain CDR technologies. These near-term investments could spur further investment in the sector, with the higher investment levels corresponding to a net-zero emissions scenario with a high-technology uptake. Approximately 10% of this investment need is in the development of transport and storage infrastructure; the remaining investment is required for capture facility build-out.[lxxxv] This level of investment across the value chain represents a significant acceleration relative to the current trajectory (**Figure 16**.).[lxxxvi]

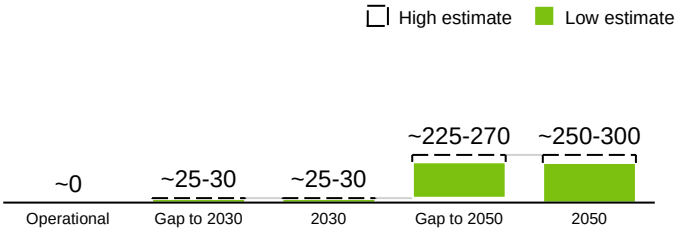
Announced and estimated required CCUS total capacity, MTPA



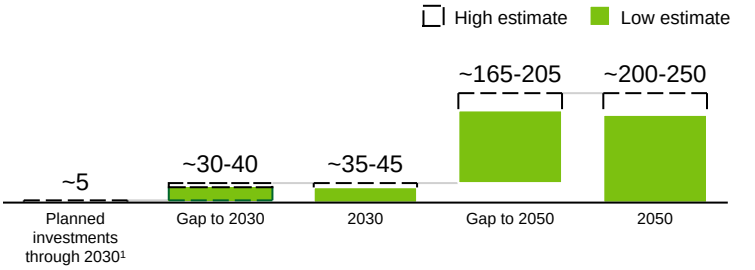
Announced and estimated required CCUS total Capex investment, $B



Announced and estimated required CDR total capacity, MTPA



Announced and estimated required CDR total Capex investment, $B



1 Many projects have not announced investment associated with the project
Source: McKinsey Power Model, Global Energy Perspective 2022, GHG FLIGHT Database 2022, NPC report, Project announcements and press releases, Coalition for Negative Emissions; DAC and BECCS were the only CDR technologies modeled

Figure 16: ~$300-600B investment would be required for a net zero scenario with ~570-1,220 MTPA of CCUS and CDR[47]

45 Deployment and investment figures in this section are based on modeling conducted for this report by McKinsey & Company in accordance with Government Contract No. DE-AC02-06CH11357 and subcontract 2J-60009. Deployment numbers fall within the general ranges expected from several government and other research reports, including: Princeton's Net Zero America report (2021, the White House Pathways to Net-Zero GHG Emissions by 2050 (2021), The IPCC (2021, IRENA (2021), IEA (2021);)
46 Range based on net-zero 2050 – high RE decarbonization scenario and carbon management technology spike scenario
47 Range based on net-zero 2050 – high RE decarbonization scenario and carbon management technology spike scenario

Sources of capital

Carbon management in low cost-of-capture applications is increasingly attracting interest from established infrastructure investors and commercial banks. More than $1 billion has been raised to develop large-scale CO_2 pipelines and capture equipment on ethanol facilities in the Midwest by established private equity and infrastructure investors, including Blackrock, TPG, and CPPIB.[lxxxvii]

First-of-a-kind large-scale direct air capture projects are also seeing interest. A DAC developer raised over $600 million in equity in 2022 and one established oil and gas player plans to self-fund several DAC projects from equity or corporate-backed debt.[lxxxviii, lxxxvix,48] These projects could unlock lower-cost debt financing if they are sufficiently de-risked during development.

However, industry participants have indicated that most CCUS and CDR projects that are economically marginal under the current policy environment could require government funding or strategic balance-sheet investment from large industry players—or a change in the policy environment. These projects have thus far seen less success accessing project equity funding from PE or institutional investors, or project debt from banks.

As previously discussed, carbon management projects could require participation of tax equity investors who constitute a relatively small market (~$20B/year) in the context of total deployment needs and have shown a preference for more established technologies like wind and solar.

Scaling carbon capture beyond 2030 on a path towards what is needed to reach 2050 net zero goals requires investments to be sufficiently de-risked to unlock later-stage, lower-cost capital (e.g., infrastructure funds, institutional funds, and banks). As CCUS and certain CDR technologies move from FOAK to nth-of-a-kind (NOAK), developers and researchers expect technology and execution risks to decrease, and a broader range of investors can move into this growing market.

Section 3.c Broader implications

Key takeaways

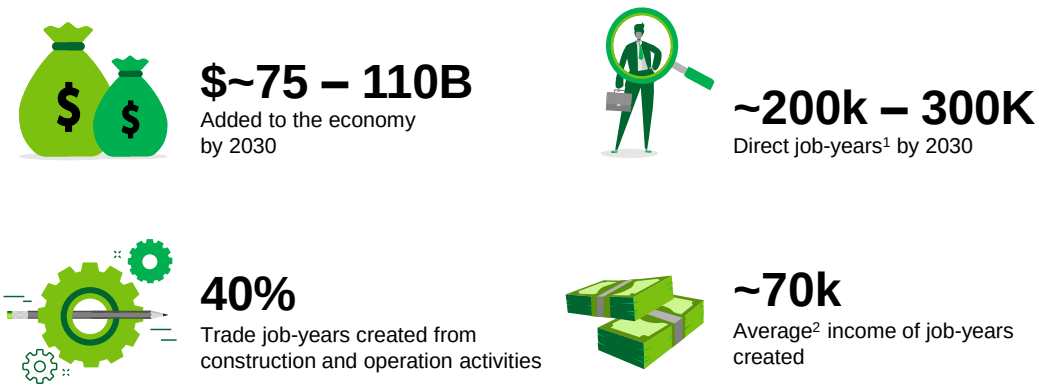
- The materials and human resources required to build CCUS and CDR projects at the scales anticipated will require major investments in supply chain and workforce development. Beyond climate benefits, widespread deployment of CCUS and CDR could:
  - Add ~$600B–1,450B in gross value added to the economy by 2050
  - Support ~3 million cumulative direct job-years by 2050—with more than 70% paying above the median salary.
- Evaluating the appropriateness of carbon management projects will rely on determining whether the project's benefits align with regional needs (employment opportunities, tax revenues, community needs and benefits, air pollution reductions, etc.). Robust and meaningful engagement within communities that may consider hosting CCUS or CDR projects can help to build understanding and align project development with community priorities and needs. Frequent and genuine consultation and engagement with community members and local organizations and stakeholders will be a prerequisite for project success by helping to ensure that projects garner community support by addressing local environmental, economic, and social considerations and then incorporating such considerations into project design.

48 For example, Occidental Petroleum has announced that it will spend at least $1 billion on a DAC facility for a start-up in 2024

Section 3.c.i Supply chain

Common point source amines are commercially available and generally have robust and resilient supply chains that could enable rapid scale up. Some DAC systems may also rely on similar amine-based technologies and could benefit from existing supply chain infrastructure. Because of this maturity, a DOE review found that there is low supply chain risk associated with the main inputs for scale-up.[xc] Other more nascent carbon capture and CDR technologies require different supply chains, but most technologies rely on common inputs that are already widely produced both in the U.S. and globally.

Certain carbon management projects may face fuel or feedstock risk, as in the case of BiCRS projects, which ideally rely on sources of biomass that can provide GHG benefits when used. While the U.S. may be able to produce up to 1 billion tonnes of biomass by 2050, other potentially higher-value applications (e.g., sustainable aviation, biochemicals) could increase feedstock costs for BiCRS technologies.[xci] Coal- or natural gas-powered plants and capture units may also face fuel risk in a scenario in which decarbonization makes these fuel sources less accessible.



1 A job-year is one year of work for one person; a new construction job that lasts five years is five job-years. 2.Weighted average

Source: McKinsey integrated modeling based on inputs from McKinsey Power Model, Global Energy Perspective 2022, GHG Flight Database 2022, Vivid Economics I3M Economic Model and other sources

Deploying carbon management to achieve net zero goals depends on a skilled and trained workforce and can have significant socioeconomic impacts. Widespread deployment of CCUS and CDR has the potential to add value to gross domestic product (GDP), support domestic industries, generate jobs during the construction and operation of plants, and provide economic and environmental benefits to affected communities.[49]

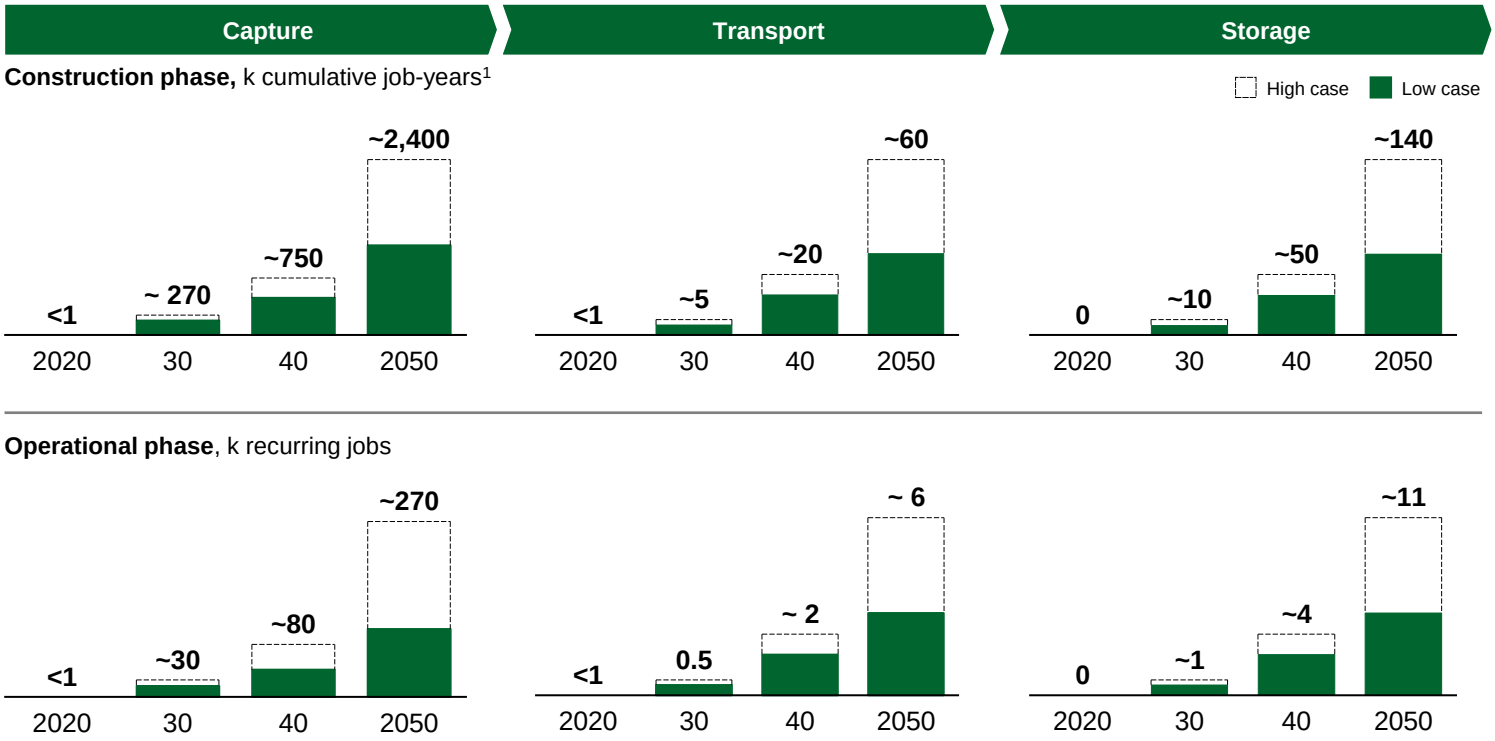
Figure 17: Projected socioeconomic impacts from carbon management build-out

Reaching net-zero by 2050 could require ~$300-600 billion in cumulative capital investment in carbon management. This investment could add ~$500B–1,000B in gross value (GVA) to the economy and require more than 3 million cumulative direct job-years between 2020–2050 (**Figure 18**.).[50] High-paying jobs that offer strong labor protections and training/placement opportunities such as registered apprenticeships and pathways for long-term career growth can strengthen the economy while supporting the energy transition. The "Pathways to Commercial Liftoff: Overview of Societal Considerations and Impacts" provides an in-depth discussion of the significance of these quality jobs characteristics and how they can be achieved.

The majority of direct jobs (~90%) are expected to be in the construction of facilities, which tend to be project-based.[xcii,51] The remaining ~10% of jobs are expected to be tied to ongoing facility operations and maintenance. In terms of value chain, capture could drive 90% of the jobs. Jobs created tend to be skilled and pay above prevailing local median wages.[52] Trades and engineers account for roughly 40% and 15% of direct job creation, respectively.[53]

49 Direct employment benefits estimate the number of jobs supported by capital expenditure. Indirect jobs are jobs supported by the share of capital expenditure directed to spending on goods and services in the wider domestic supply chain.
50 Gross value added (GVA) can be defined as the measure of the value of goods and services produced in an area, industry or sector of an economy. It is comparable to GDP but does not include taxes or subsidies. Modeling based on inputs from McKinsey Power Model, Global Energy Perspective 2022, GHG FLIGHT Database 2022, Vivid Economics I3M Economic Model and other sources. The analysis was performed using the I3M Economic Model using input-output tables developed by IMPLAN. The analysis assumes a 10% share of domestic manufacturing in capital expenditures and an assumption that annual operational expenditures amount to 4.81% of total capital expenditure across all technologies and sectors
51 Because there are likely to be more construction jobs than manufacturing equipment jobs, employment during the construction phase would be skewed to jobs that move from project to project.
52 The actual jobs associated with capital investment in carbon management in any given year will depend on the pace of project development. This number represents an average in a single year; A job-year is defined as one job for one year.
53 Welders, electricians, metal workers, fabricators, installation, maintenance, and repair technicians and other construction and manufacturing trades workers.

Total direct labor pool to achieve ~0.5 to 1.2 GTPA of capture by 2050



1 Low range presents estimate breakdowns from the Carbon Capture Net Zero Scenario. High range presents figures from the Carbon Management technology spike scenario
Source: McKinsey Power Model, Global Energy Perspective 2022, GHG FLIGHT Database 2022, NPC report, Vivid Economics I3M Economic Model

Figure 18. Most job generation originates from construction of CCUS and CDR facilities

Creating jobs does not always translate to filling jobs. The skilled trades and professional roles required for scale-up comprise <5% of the current workforce in those fields. Even so, staffing these roles could be challenging as other decarbonization technologies come online at the same time. This challenge could be particularly acute in the skilled trades (e.g., electrical, plumbing, and mechanical trades). Carbon management efforts should be pursued in collaboration with labor and management groups in the construction, oil, and gas industries. Many of the skills needed to build and operate carbon management plants are similar to those used by workers in existing industries, and this experience can be leveraged to effectively transition these workers into new jobs.

Section 3.c.ii Energy and environmental justice

Carbon management companies and investors play a critical role in determining whether projects support a just and equitable clean energy transition or contribute to existing injustices.[xciii] The "Pathways to Commercial Liftoff: Overview of Societal Considerations and Impacts" covers key energy and environmental justice (EEJ) considerations, recommends specific actions, and provides online resources, while the section below covers EEJ considerations and impacts specific to carbon management.

The energy and environmental justice impacts of carbon management projects, as with any project, depend on what the benefits and harms are, who experiences them, and how the impacts alleviate or compound existing burdens. As with other energy technologies, the way carbon management is deployed can combat or exacerbate existing inequalities, especially if projects are sited in or near existing oil, gas, and chemical facilities, which are disproportionately sited in communities of color and low-income communities that are overburdened by existing infrastructure and underserved by government programs.[xciv,xcv,xcvi,xcvii,xcviii]

Ensuring carbon management projects support energy and environmental justice is critical as a moral imperative—and because project success depends on it.[xcix] Carbon management projects have already experienced community- or organization-led lawsuits or protests.[c,ci,cii,ciii,civ] Public criticism and skepticism around carbon management—which may be rooted in a lack of trust or opposition to project and funding decisions—can also pose severe reputational risks for companies, limiting potential for industry partnership building.[cv] In contrast, well-executed projects with meaningful engagement and well-tailored community benefit plans can build trust and lead to successful deployment of carbon management technologies in the eyes of both developers and communities. Projects can mitigate risks (both to the project and caused by the project) by being aware of potential EEJ impacts, taking proactive steps to maximize project benefits and minimize harms, and engaging in early, frequent, transparent, and two-way dialogue with impacted groups.[cvi]

At the community and stakeholder level, there may be a range of concerns across the carbon management value chain, from capture to transport, storage, and utilization. These include concerns about safety and potential environmental impacts of CO_2 infrastructure and a lack of benefits for local communities. The magnitude and nature of local concerns, and of potential impacts or benefits, vary by project type and technology, as well as local context, requiring that community impact and perceptions be assessed on a project-by-project basis. Another concern among certain stakeholders has been that investment in carbon management technologies may prolong fossil energy production and use. This raises both project-specific risks like the potential for prolonged pollution and health impacts from fossil fuels, as well as broader economic and public policy considerations for fuel use which must both be factored into assessments of whether a carbon management project is appropriate for a given facility and community and within the broader clean energy transition.

EEJ advocates have voiced both concern and hope about the potential impacts of carbon management.[cvii,cviii,cix,cx] DOE has heard these concerns corroborated in listening sessions and requests for information. Commonly discussed concerns include:

Health impacts due to air pollution: Carbon management deployment can have a positive overall effect on local air quality, but realizing potential benefits depends on project design considerations. More research is underway to understand the extent of the benefits and potential harms.[cxi] Developers can and should design CCUS projects that maximize environmental benefits beyond carbon management. If these environmental considerations are identified and prioritized early in the technology selection and community engagement processes, projects are more likely to meet the needs of surrounding communities. Important dynamics include:

- In certain applications, point-source carbon capture can reduce emissions of criteria air pollutants such as sulfur oxides, nitrogen oxides, particulate matter, and hazardous air pollutants such as mercury and hydrogen chloride, relative to non-CCUS operations.[cxii] These benefits may occur as a result of engineering necessity or as a result of major modifications that may trigger New Source Review for National Ambient Air Quality Standards for criteria pollutants.[cxiii]

- Some compounds associated with the capture unit itself (e.g., aerosols such as nitrosamines from solvent-based capture systems) can add new pollutants to a site. Pollution monitoring and control mechanisms for these pollutants are currently standard operating procedure for CCUS facilities employing these capture technologies.[54,cxiv]

- The energy needed to operate the capture unit can introduce additional energy demand and, depending on the energy source, associated pollutants at the point of capture and over the feedstock supply chain. Pollution control equipment could mitigate these risks.

- Carbon capture and use may help reduce emissions in hard-to-abate sectors by creating products from captured carbon emissions that would otherwise require fossil energy extraction and combustion. The emissions impact depends on the carbon source and the degree of fossil fuel displacement.[cxv]

54 The high-range cost numbers referenced in this report include a retrofit factor that accounts for potential incremental capital costs that the retrofitting facility must incur to be able to integrate a capture project.

Safety of CO_2 infrastructure: EEJ advocates have focused on the potential health and safety impacts of CO_2 transport and storage infrastructure.

- CO_2 is inert, an asphyxiant that is heavier than air, colorless, and odorless. Large-scale leaks or ruptures present a public health risk for anyone in the vicinity. A 2020 CO_2 pipeline rupture in Mississippi that hospitalized 45 people has focused attention on the potential safety risks associated with CO_2 pipelines. In response to the Mississippi incident, the Department of Transportation is updating its CO_2 pipeline safety standard regulations and is funding studies to understand the impact of CO_2 pipeline releases and leaks.[cxvi]
- In general, CO_2 pipelines have had a better safety track record than other kinds of pipelines (e.g., natural gas) or other types of large-scale infrastructure such as electric transmission and distribution. According to statistics from the Department of Transportation, there have been no fatalities caused by regulated CO_2 pipelines over the last 20 years. In addition to the hospitalizations from the Mississippi pipeline rupture, there was one other injury from regulated CO_2 pipelines.[cxvii]
- EPA Class VI well permitting is designed to protect underground sources of drinking water as well as mitigate impacts to human health and the environment. Some states are applying for Class VI primacy from EPA to become the primary implementing authority for Class VI projects in their state. Some EEJ advocates fear state primacy will result in fewer opportunities for public comment and reduced consideration of EEJ concerns. It is important to balance the need to expedite permitting process with addressing EEJ concerns. EPA has indicated it will look at states' environmental justice plans when considering Class VI primacy applications.[cxviii]

Cumulative burden on communities: EEJ advocates in some regions may view carbon management projects as inconsistent with local needs.

- There is a basic concern around the potential for utilities to pass the costs of commercial scale demonstrations and early implementation of new technologies onto ratepayers. In many cases, the 45Q credit, other tax incentives, and BIL programs will help to defray costs and insulate ratepayers from the costs of FOAK projects.
- Some EEJ advocates also worry that CCUS projects extend the life of fossil-fuel industrial facilities beyond when they would have otherwise shut down, possibly continuing to harm nearby communities.[cxix] CO_2 pipeline siting is also a contentious issue for some communities. For example, some landowners in the Midwest have voiced opposition to large CO_2 trunkline projects there.

DOE has heard additional concerns from external stakeholders and affected communities relating to carbon management. These groups have expressed concerns that:

- The development of some carbon management projects may provide financial support to companies with poor track records in disadvantaged communities.
- There may be inadequate or unsustained long-term economic benefits to community members after initial project construction.
- Funding carbon management projects may provide continued financial support to fossil fuel companies despite their role in causing the climate crisis and delaying climate action.
- Supporting geologic storage, through EOR, for example, may provide financial incentives to keep extracting oil.[cxxi]
- Carbon management technologies are being deployed with a perceived absence of adequate data about impacts. While a geologic storage permit requires extensive data collection and modeling, there are long-standing feelings of mistrust among frontline communities who feel they are experimented on, and treated as disposable, by government and industry.[cxxii,cxxiii]
- Carbon management projects have insufficient long-term monitoring and accountability once Federal funding ends.
- Carbon management projects have insufficient disaster preparedness, disaster response, and disaster recovery for carbon management project.

There are many ways for projects to maximize benefits and minimize negative impacts in line with EEJ goals and principles, including Project Labor Agreements and Community Benefits Plans.[cxxiv]

The "Pathways to Commercial Liftoff: Overview of Societal Considerations and Impacts" offers specific considerations and actions related to the distribution of impacts (i.e., who experiences benefits and who experiences burdens) and process (i.e., enabling impacted individuals/groups to make decisions about projects that affect them). Third-party researchers have also developed several resources and reports featuring recommendations for CCUS and CDR developers with respect to environmental justice and community engagement.[cxxv,cxxvi,cxxvii]

Chapter 4: Challenges to Commercialization and Potential Solutions

Section 4.a Overview of challenges and considerations along the value chain

Key takeaways

- The U.S. is the most attractive market for investment in carbon management deployment given its policy environment, geologic endowments, experience with carbon management, and talented workforce.
- While significant deployment is expected over the coming decade, some challenges remain to seeing carbon management deployment reach its full potential. These include:

  Economic and commercial factors:

  - Cost uncertainty, as project costs remain high for some types of point-source CCUS applications and early deployments of certain CDR technologies.
  - Demand uncertainty, driven by an absence of compliance markets and limited evidence of bankable revenue streams for low-carbon products and voluntary carbon removals.
  - Lack of commercial standardization for the partnerships and commercial arrangements carbon management projects will require.

  Execution factors:

  - Lead times in permitting storage infrastructure which many developers see as a potentially lengthy and uncertain process.
  - Lack of transport and storage infrastructure in some areas could slow execution of capture projects.
  - Local opposition to project development in some instances.
- Each of these challenges can be overcome through concerted effort from the public sector, private sector, and key stakeholders and communities.
  - BIL and IRA programs and incentives substantially reduce economic challenges for project development and will help to establish enabling carbon transportation and storage infrastructure.
  - BIL investments in geologic storage permitting capacity at the federal and state levels can help increase timeline certainty.
  - FOAK projects supported by BIL and IRA programs can demonstrate and prove investment theses and help to standardize project finance and development processes.
  - Community Benefit Plans executed through BIL and IRA programs will establish best practices for engagement, negotiation, and partnership development.

The U.S. is the world's most attractive destination for deployment of carbon management technology. Stable policy support in the form of 45Q, world-leading existing deployment, favorable geologic resources, and a capable workforce have set the stage for a rapid scale-up in carbon management over the coming decade.

While the field is set to see significant deployment, certain challenges remain to reaching the full scale-up in CCUS and CDR that modeling suggests will be needed to achieve U.S. climate goals for 2050.[55]

Point-source CCUS and CDR have different challenges to overcome. While CCUS projects have been federally supported at commercial scales, support for CDR has largely emphasized research and development until recent IRA tax credit and BIL program developments. The CDR approaches covered in this report are less technologically mature and face a limited demand pool, relative to many CCUS projects which may be financeable today with federal incentives and private sector purchasing power.

Commercial and economic challenges

1. Cost uncertainty for "next generation" CCUS applications and early deployments of DAC, with limited consensus on how costs will decrease over time

The economics of capture for lower purity CO_2 stream have been and will continue to be demonstrated at scale through BIL programs and IRA incentives. Demonstration and commercial deployment of FOAK CCUS projects through BIL cooperative agreements and IRA tax incentives will benchmark real capital and operational costs and help to better inform project finance models. NOAK projects will benefit from some cost reductions as construction and financing of these facilities is derisked.

Technology learnings from the buildout of low-cost-of-capture facilities may not translate to equivalent cost reductions in higher cost-of-capture facilities; higher cost-of-capture applications require specialized equipment (e.g., amine scrubber and regeneration units/reboilers) not seen in facilities where the emissions stream is essentially pure CO_2. Cost reductions that do materialize for CCUS may be limited to CapEx cost reductions as OpEx costs can be driven by fuel inputs and parasitic load.

For certain CDR approaches, current costs are high with additional R&D, piloting, and demonstration required. As such, there is uncertainty around how costs will be reduced, with varying perspectives on the scale and magnitude of learning curves. For example, industry sources project that DAC costs could see overall reductions ranging 20–50% with scale-up to 0.25 billion tonnes per year (GTPA).[56]

A variety of cost reduction strategies are unfolding in the market. Some technologies are attempting to come down the learning curve quickly by deploying relatively small, modular units.[57] Other technologies are planning larger plants (e.g., >1 MTPA) to achieve economies of scale and may face longer learning curves from fewer iteration cycles.[58]

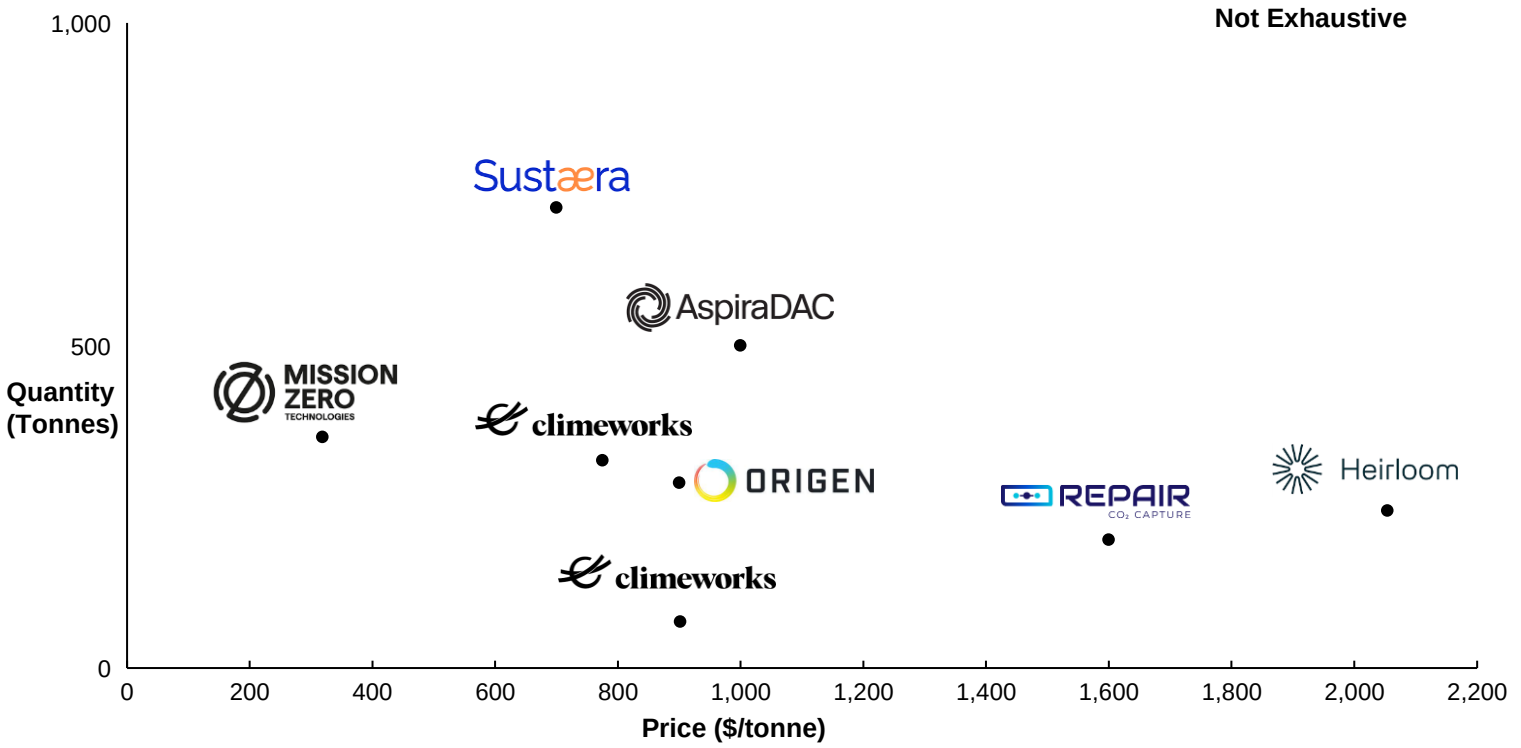
2. Demand uncertainty driven by absence of compliance markets, and nascent markets for low-carbon products and carbon removals

Carbon management projects rely on a limited set of revenue sources to make their business cases work.

CCUS and DAC projects will rely on 45Q as a key revenue source. Even projects that qualify for 45Q may currently require large additional revenue streams from voluntary carbon markets or premiums for low-carbon products to be financially viable.

55 BNEF is tracking ~140 MTPA in announced projects. Historically there has been a significant attrition rate between announced projects and projects reaching completion and commercial operations.
56 See Chapter 2 for a full explanation of cost declines from Coalition of Negative Emissions and Climeworks.
57 See Chapter 2 for cost reduction drivers. For example, a solid-sorbent DAC pathway to reduce costs involves manufacturing a large number of standard units.
58 See Chapter 2 for cost reduction drivers. For example, a liquid-sorbent DAC pathway to reduce costs involves scaling-up process units by the maximum allowable by the design to maximize economies of scale.

Publicly announced DAC VCM commitments with price available, $/tonne CO_2, and volume



1 Heirloom Carbon Technologies encompasses both direct air capture and mineralization technology

Source: Stripe 2020, Spring 2021, and Fall 2021 Climate reports; "Frontier facilitates first carbon removal purchases" (2022)

Figure 19. Current DAC VCM contracts have high prices (>$300/tonne), but are traded at small quantities

VCM credits for CDR are currently being sold at a large price range (Figure 19.). The market, however, is immature and few codified standards define what constitutes a credit. Most credit buyers are also not yet entering long-term (e.g., 10-year) offtake contracts; many investors require these long-term contracts to be in place to consider projects bankable. Most credit agreements to date have been fewer than 10 years for medium volumes (e.g., thousands of tonnes annually), such as Airbus's 100 kTPA offtake agreement for four years. [cxxviii]

Premiums for low-carbon products or compliance mechanisms requiring emissions control are needed to make some CCUS projects financially feasible. Premiums must be firm and bankable to stimulate investment. While low-carbon steel, for instance, can sometimes fetch a premium in the market today, demand signals are generally not yet strong enough to justify large upfront capital expenses.[cxxix]

Captured carbon emissions can be used to create products, generating additional revenue streams. Most carbon utilization pathways attempt to substitute for established, lower-cost, higher-carbon, traditional products. For example, CO_2-to-plastics will likely compete with the established traditional plastics industry. The willingness to pay premiums and the depth of market for premiums on low-carbon products is currently low or unproven.

3. Lack of commercial standardization

CCUS and certain CDR projects often require partnerships between asset owners, investors, capture technology providers, transport, and storage. These partnerships make development more complex than other established clean-energy technologies, such as solar and wind.

There are few models for these types of partnerships. For example, industry players have stated there is a lack of standard pricing around capture, transport, and storage. These agreements are currently negotiated on a bespoke, project-by-project basis, complicating the overall economics of projects and extending the timeline for project development.

Execution challenges

4. Lead-times in permitting storage

Developers and investors worry that what they see as long and uncertain permitting timelines will hinder project development. Storage projects that plan to inject CO_2 permanently into geologic formations face a Class VI well approval process that developers say will require predictable and consistent timelines and appropriate technical assistance. EPA has issued six Class VI permits to date. For the first four Class VI wells, EPA issued the permits within two years; The permits for the remaining two wells took between 3 and 6 years.[59]

EPA has publicly announced that, moving forward, it will strive to permit wells in two years, which is expected to increase confidence among developers and investors.[cxxx,cxxxi] Review and approval timelines are likely to improve as more permits are issued and regulators become familiar with the process. However, storage availability and permitting may be a rate-limiting factor on the pace of deployment, depending on state primacy efforts and EPA resources.[60]

5. Insufficient transport and storage infrastructure

The transport sector faces a "chicken and egg" dilemma: most transport and storage infrastructure is being developed as fit-to-purpose after the capture projects have been identified, but more capture projects would be developed if sufficient transport and storage infrastructure already existed. Congress has provided DOE with funding through both the Carbon Storage Validation and Testing program ($2.5B) and the Carbon Dioxide Transportation Infrastructure Finance and Innovation (CIFIA) program ($2.1B), bipartisan provisions which were expressly developed as an integrated approach to overcoming the chicken and egg infrastructure challenge on a regional hub basis. Together these programs will help to finance common carrier projects that most effectively pair CCUS and CDR technology projects with storage sites through a network of transportation resources. With appropriate coordination of CIFIA and the Large-Scale Carbon Storage Commercialization programs with other BIL programs supporting carbon capture and direct air capture facilities, the impact of 45Q and other tax credits will be enhanced.

6. Potential local opposition and hesitancy to the development of some CCUS projects

Surveys indicate a lack of awareness and familiarity with CCUS and CDR technologies among the American public. For example, a recent survey in the United States showed that only 19% of respondents stated that they had heard about carbon capture and storage. Where CCUS discussion has occurred, questions and concerns about CCUS have been focused on both technical and social topics. A 2009 study of potential pilot sites for California's DOE-funded West Coast Regional Partnership (WESTCARB) in two areas of California found that communities saw risks not just as technical but social, relating to levels of community empowerment and the history of community-industry relations.[cxxxiii] An early collaborative study conducted in the same timeframe by DOE's Regional Carbon Sequestration Partnership (RCSP), which examined five communities, found that "In all cases, social factors, such as existing low socioeconomic status, desire for compensation, benefits to the community and past experience with government were of greater concern than concern about the risks of the technology itself."[cxxxiv] More recently, as the number of announced CCUS projects has grown, some communities have expressed resistance to CCUS deployments.[cxxxv]

59 Factors specific to each individual application can significantly impact how long it will take to issue a permit. Individual site conditions, community feedback, and the completeness or quality of the application may require additional time. For example, EPA may notify applicants of deficiencies in the application or make Requests for Additional Information. The responsiveness and completeness of applicants' responses will ultimately dictate the permitting timeline.

60 For example, public modelling efforts on the impact of the IRA, such as Princeton's Net-Zero America, set the availability of transport and characterization of storage sites as the rate limiter for CDR deployment, with the storage rate bounded by a multiple of current U.S. oil production on a volume-equivalent basis

Pipeline projects may face particular engagement challenges given the sheer number of landowners impacted by a long interstate pipeline. For instance, Summit Carbon Solutions has announced that it has signed more than 1,200 voluntary easements with 700 landowners in the state of Iowa.[cxxxvi] The number of individual negotiations required for this type of project can require a significant amount of time and, if not addressed early in the project, could slow project development.

Considering the lessons learned for CCUS and challenges facing new clean energy infrastructure, it is critical to understand and address the societal considerations and impacts of these projects at local, regional, and global levels. Meaningful public involvement in how carbon management technologies and infrastructure are planned and built is critical. DOE is committed to conducting and supporting meaningful two-way engagement that can help communities and stakeholders become project partners whose ideas and concerns can improve overall outcomes for project developers, while also ensuring that tangible, environmental, economic, and social benefits flow to affected communities.

Section 4.b Priority solutions Key takeaways

While the challenges facing carbon management are significant, they are surmountable with concerted effort (Figure 20.).

Challenges	Solutions
1 Cost uncertainty for "next generation" CCUS applications and early deployments of certain CDR types	Support for early project development in high-cost sectors and DAC can enable faster cost reductions
2 Revenue uncertainty driven by absence of compliance markets, and immature markets for removals	Development of bankable revenue streams for carbon removals and low-carbon products can spur development
3 Lack of commercial standardization (e.g., sequestration agreements)	Creation of archetypal, field-tested business models and terms will enable the development and execution of partnerships
4 Lead-times in permitting storage (e.g., for Class VI injection wells)	Building EPA and State technical and regulatory capacity will increase the efficiency and effectiveness of the Class VI permitting program
5 Lack of transport and storage infrastructure	Initial build-out from large integrated projects and regional aggregations of profitable projects can spur build-out
6 Local opposition to project development in some instances	Capacity building and early, frequent, and transparent engagement between developers and communities can strengthen trust and improve project outcomes

Figure 20: Challenges in carbon management are significant but can be overcome

Support for early project development in high-cost sectors and DAC can enable cost reductions

Support for early project development is needed to reduce technology and execution risks associated with less widely deployed technology in point-source capture and CDR. Grants or cooperative agreements for pilot and demonstration projects can kickstart initial deployment. BIL and IRA contain billions of dollars in funding that could be directed to early deployments of CCUS and CDR. Federal, state, and local regulations could also create greater commercial certainty.

Development of bankable revenue streams for carbon removals and low-carbon products will spur development

Increasing demand for low-carbon products can lead to more bankable revenue streams for projects. For carbon removals, an industry shift from low-cost, low-quality removals to high-quality, high-permanence removals will firm up demand for CDR technologies. According to developers, compliance policies that require companies to reduce emissions or buy carbon removals would improve the economics of these projects significantly.[cxxxvii] Nearer term, advance market commitments such as the Frontier commitment for carbon removal purchases and the First Mover's Coalition commitments for low-carbon products can spur development of bankable revenue streams.

Where price premiums do not emerge, CO_2- and CO-based products will need to rely more on regulation and/or further cost reduction to compete with traditional products. Changes to the regulatory landscape could also significantly alter project economics.

Creation of archetypal, field-tested business models and terms will enable partnerships

Standardized project and financing structures can create significant benefits for CCUS and certain CDR approaches. Incentives from government and efforts by industry to develop hubs or clusters are already spurring partnerships that could drive the kind of commercial standardization that aided the scale-up of wind and solar.[61]

Once partnerships are formed, the publication of project execution best practices, lessons learned, and aggregated partnership terms—particularly from projects that receive government support for FOAK deployments—can act as a blueprint for others.

Building EPA and State technical and regulatory capacity will increase the efficiency and effectiveness of the Class VI permitting program

Recent legislation has provided funding to EPA to build out the Class VI program and process Class VI permitting applications and EPA has developed several tools to help streamline the permitting process.[cxxxviii] In addition to increasing appropriations for the Class VI program, the BIL also provides EPA with additional funds to both build capacity at the federal level and to provide grants to States, Tribes, and Territories seeking to develop, receive, and implement Class VI primacy.[cxxxix] In combination, these additional resources and capacity at the State and Federal level will help to ensure developers receive timely permitting decisions and technical assistance.

Initial large integrated projects and regional aggregations of profitable projects can spur build-out

Development of investable projects is already enabling the build-out of storage facilities and large-scale transport infrastructure that can be used for future carbon management developments.

Development of regional carbon management hubs, supported by DOE's Regional DAC Hubs, Carbon Storage Validation and Testing, and CIFIA programs, can increase shared infrastructure, thus reducing the total amount of transport and storage infrastructure needed for widespread deployment.

Capacity building among both developers and communities will strengthen engagement efforts and improve project outcomes

Ensuring that developers understand the needs of the communities they aspire to work in and that community members are aware of a proposed project's attributes and benefits can lead to more productive dialogue. By empowering and equipping community leaders, stakeholders, labor, and environmental justice advocates with the information and tools needed to effectively negotiate with project developers and regulators, projects are more likely to garner support and deliver tangible, meaningful benefits. Community Benefit Plans required for CCUS and DAC projects financed through BIL programs will help establish best practices, provide communities with the resources to advocate and negotiate, and advance public awareness of carbon management technologies.

61 DOE's Regional Direct Air Capture Hubs, Regional Clean Hydrogen Hubs, Carbon Storage Validation and Testing, and Carbon Dioxide Transportation Infrastructure Finance and Innovation (CIFIA) programs can all contribute to hub / cluster development.

Chapter 5: Metrics and Milestones

Three types of key performance indicators can gauge the progress needed for successful market scale-up of CCUS and CDR technologies:

- **Outcomes** show the relative impact of CCUS and CDR on broader Administration targets (e.g., job creation, emissions reduction)
- **Leading indicators** are early signs of the relative readiness of technologies and markets for at-scale adoption (e.g., early signs indicating CCUS and CDR are "on-track" for net-zero targets); and
- **Lagging indicators** are confirmation of successful scaling and adoption of CCUS and CDR (e.g., evidence and progress toward net-zero targets).

These indicators will be tracked and reported periodically throughout DOE. There are several priority KPIs that will be indicative of successfully tracking toward carbon management deployment in line with a net-zero pathway. [62]

Outcomes show the achieved impact of CCUS and CDR on broader Administration targets

- **CCUS and CDR total installed capture capacity**
- **Tonnes of CO_2 captured each year**
- **Tonnes of CO_2 permanently stored each year**
- **Tonnes of CO_2 utilized each year**

Leading indicators show the ability of carbon management technologies and players to create the pathway needed by 2030 to meet 2050 net-zero goals

- **Project pipeline**
  - **~100 MTPA of CCUS or CDR projects at an advanced stage of development by 2025**
- **Commercial storage**
  - **2 billion tonnes of commercial storage capacity by 2030**

Lagging indicators will be most important for tracking scale-up progress. Additionally, performing retrospectives will help inform future technology commercialization efforts

- **Capacity of operational projects**
  - **~100 MTPA by 2030**
  - **~300 MTPA by 2040**
  - **~800 MTPA by 2050**
- **CDR cost**
  - **$100/net tonne of CO_2 for high-quality carbon dioxide removals by 2030**

62 Goals and metrics draw from DOE FECM's 2022 Strategic Vision, DOE's Carbon Negative Shot, and midpoint rages from modeling studies conducted for this effort

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