United States Government Accountability Office

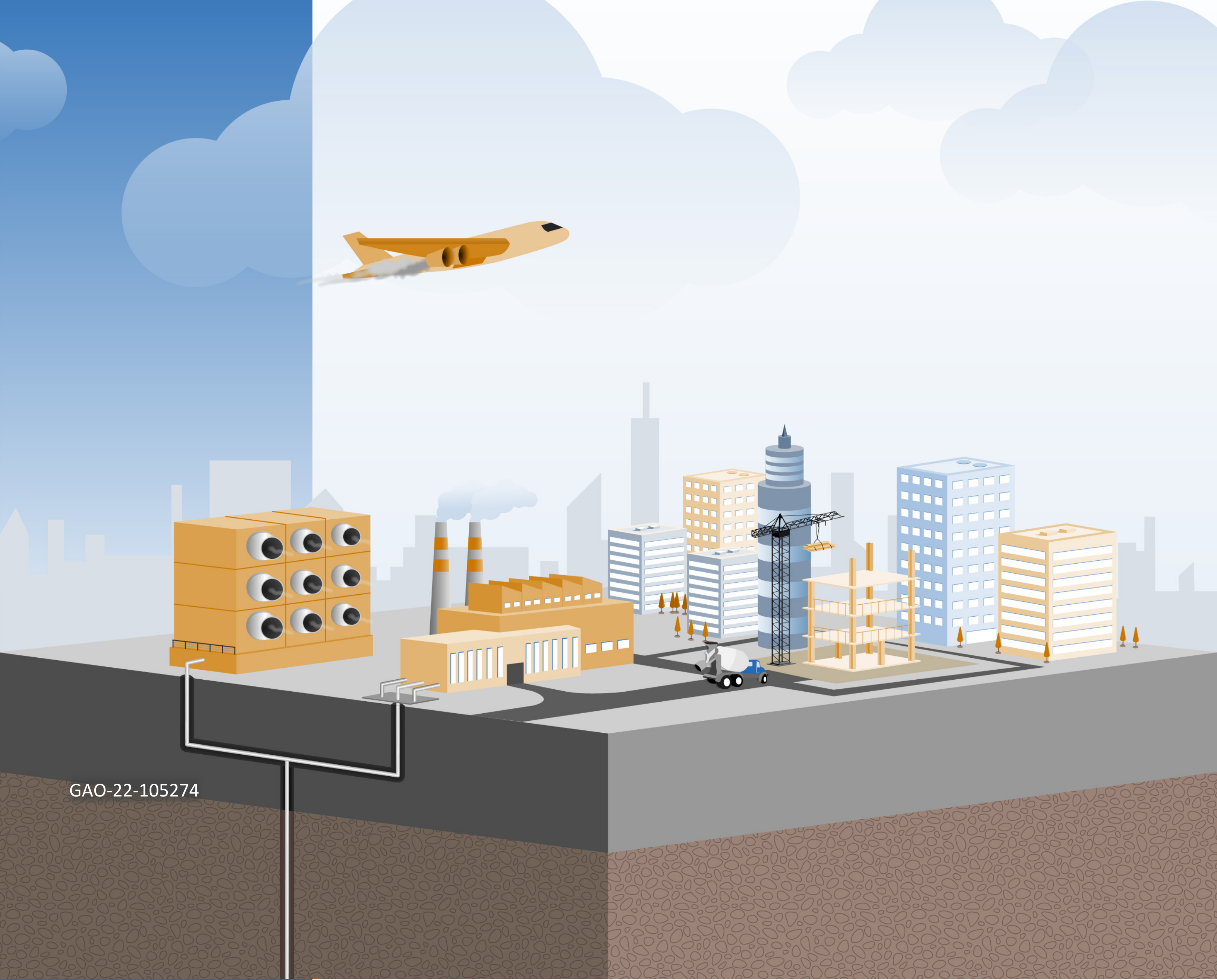
Report to Congressional Addressees

September 2022

TECHNOLOGY ASSESSMENT

Decarbonization

Status, Challenges, and Policy Options for Carbon Capture, Utilization, and Storage



GAO-22-105274

The cover image displays graphical examples of how carbon capture, utilization, and storage may be incorporated into a city, including direct air capture and point-source capture of CO_2 with deep underground storage, as well as use of low-carbon footprint or CO_2-based materials for new building projects and aviation fuel.

Cover source: GAO. | GAO-22-105274

Highlights of GAO-22-105274, a report to congressional addressees

September 2022

TECHNOLOGY ASSESSMENT

Decarbonization

Status, Challenges, and Policy Options for Carbon Capture, Utilization, and Storage

Why GAO did this study

In 2021, CO_2 reached a record high concentration in the Earth's atmosphere for the modern era. Scientific assessments have shown that reducing CO_2 emissions could help mitigate the negative effects of climate change. CCUS is one tool available to help slow, stop, or potentially reverse the rising levels of CO_2 in the atmosphere.

This report discusses (1) the status of available carbon capture technologies; (2) opportunities for using or storing captured CO_2; (3) key challenges that could affect the development, demonstration, and deployment of CCUS technologies; and (4) options policymakers could consider to help address these challenges.

In conducting this assessment, GAO interviewed federal officials, academic researchers, industry organizations, private companies, nongovernmental organizations, technology testing centers, and federal advisory committees; convened an interdisciplinary meeting of 27 experts with assistance from the National Academies of Sciences, Engineering, and Medicine; and reviewed relevant literature. GAO is identifying policy options in this report.

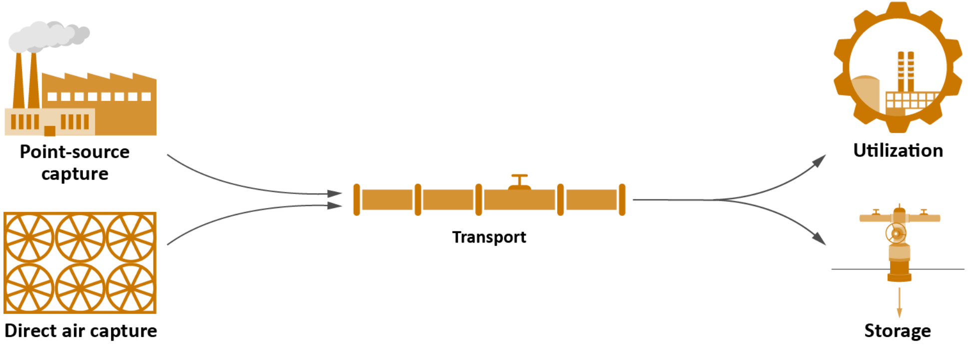
View GAO-22-105274. For more information, contact Karen L. Howard at (202) 512-6888, howardk@gao.gov.

What GAO found

Many technologies for carbon capture, utilization, and storage (CCUS) are ready for wider demonstration or deployment, but multiple challenges limit their use. Carbon capture includes technologies that separate and purify carbon dioxide (CO_2) from a source, which could be an industrial facility (point-source capture) or the atmosphere (direct air capture). Applications of capture technologies at point sources are mature in some sectors (e.g., natural gas processing) but require further demonstration in some of the highest-emitting sectors (e.g., power generation). Direct air capture is not as mature, but has been implemented at pilot scale. Lengthy time to deployment and high costs hinder widespread deployment of both types of carbon capture in the near term.

Technologies for transporting, storing, and directly using captured CO_2 are mature. Companies are beginning to commercialize utilization technologies that convert captured CO_2 into valuable products such as ethanol, sustainable aviation fuel, and mineral aggregates. However, many CO_2-based products are not competitive with conventional products, may be excluded from the market by industry standards, and lack a standardized method for ensuring they effectively reduce CO_2 emissions.

Components of carbon capture, utilization, and storage



Source: GAO. | GAO-22-105274

GAO identified three aspects of CCUS deployment where challenges may arise:

- **Cost.** Deploying CCUS is an added cost to doing business but currently offers few opportunities to generate revenue. Incentives such as federal tax credits help offset the high cost of CCUS for some but not all emitters.
- **Infrastructure development.** More widespread deployment of CCUS would require a build-out of infrastructure for each of its components, including transport and storage. Timing of development, negotiating land access, and proximity of facilities are all challenges affecting this build-out.
- **Community engagement.** Deploying CCUS projects relies on acceptance by and effective engagement with local communities. In the past, unsuccessful community engagement and local opposition have contributed to cancellation or relocation of some CCUS projects, while others were well received.

GAO identified seven policy options that could help address these challenges or enhance the benefits of CCUS technologies. The policy options are possible actions by policymakers, which may include Congress, federal agencies, state and local governments, academic and research institutions, and industry. In addition, policymakers could choose to maintain the status quo, whereby they would not take additional action beyond current efforts. See below for details of the policy options and selected opportunities and considerations.

Policy options to help address challenges or enhance benefits of CCUS technologies, with selected opportunities and considerations

Policy Option	Opportunities	Considerations
Research, development, and demonstration (report p. 20) Policymakers could enhance support for consistent funding of research and development and large-scale demonstrations simultaneously.	• Research and development could reduce cost, resolve issues, mitigate risks, and advance emerging technologies. • Demonstrations could reduce cost and establish the viability of carbon capture by promoting learning-by-doing.	• Stakeholders have different ideas for research and development priorities. • Requires careful oversight of large-scale demonstrations.
Technology-neutral standards (report p. 34) Policymakers could encourage the creation, adoption, or use of technology-neutral standards.	• Could incentivize the development or use of products with the best CO_2 benefits. • Could incentivize manufacture in the U.S.	• Standards development is a resource-intensive and lengthy process. • Could be difficult to compare CO_2 benefits of different products without standardized life cycle assessment.
Standardized life cycle assessment guidelines (report p. 34) Policymakers could support the creation and use of standardized life cycle assessment guidelines to validate CO_2 benefits of CO_2-based products.	• Could improve accuracy of comparisons between various CO_2 utilization pathways or products.	• Standards development and life cycle assessment are resource-intensive and lengthy processes. • Coordination of many stakeholders to establish standardized life cycle assessment guidelines may be challenging.
Framework for land access (report p. 44) Policymakers could support development of legal or regulatory frameworks to manage geologic storage of CO_2 at the state level.	• Legal or regulatory clarity could facilitate deployment of CO_2 storage infrastructure. • Pore-space unitization processes could reduce the time and cost of negotiating land access for storage.	• Individual landowners may oppose losing certain property rights due to pore-space unitization. • CO_2 storage projects may cross state boundaries, requiring coordination.
Strategic siting (report p. 44) Policymakers could facilitate strategic siting of CCUS facilities.	• Could minimize financial and logistical barriers to CCUS development. • Carbon capture and utilization industries may accelerate deployment if access to infrastructure increases.	• Certain geographic regions that are inherently more suited for CCUS could benefit more than others from infrastructure investments. • Some communities may not want CCUS infrastructure for several reasons, including perceptions of environmental and safety risks.
Modify incentives (report p. 55) Policymakers could modify existing incentives to facilitate access for CCUS projects.	• Could increase the number or kinds of facilities that deploy CCUS. • Could incentivize new technology development to reduce costs of capture.	• Modifying tax credits could reduce government tax revenues or increase use of fossil fuels. • Modifying market-based approaches could be subject to uncertainty in carbon prices.
Community engagement (report p. 62) Policymakers could support and encourage proactive community engagement around CCUS deployment.	• Better understanding of public opinion could guide community engagement and decision-making. • Could build local support and reduce delays.	• Well-designed education and public awareness campaigns could be resource-intensive. • May require new funding or reallocation of existing resources to support new efforts.

Source: GAO. | GAO-22-105274

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Abbreviations

CCUS	carbon capture, utilization, and storage
CO_2	carbon dioxide
DOE	U.S. Department of Energy
EPA	U.S. Environmental Protection Agency
IEA	International Energy Agency
LCFS	California's Low Carbon Fuel Standard
PHMSA	Pipeline and Hazardous Materials Safety Administration
RFS	Renewable Fuel Standard
TRL	technology readiness level

U.S. GOVERNMENT ACCOUNTABILITY OFFICE
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Introduction

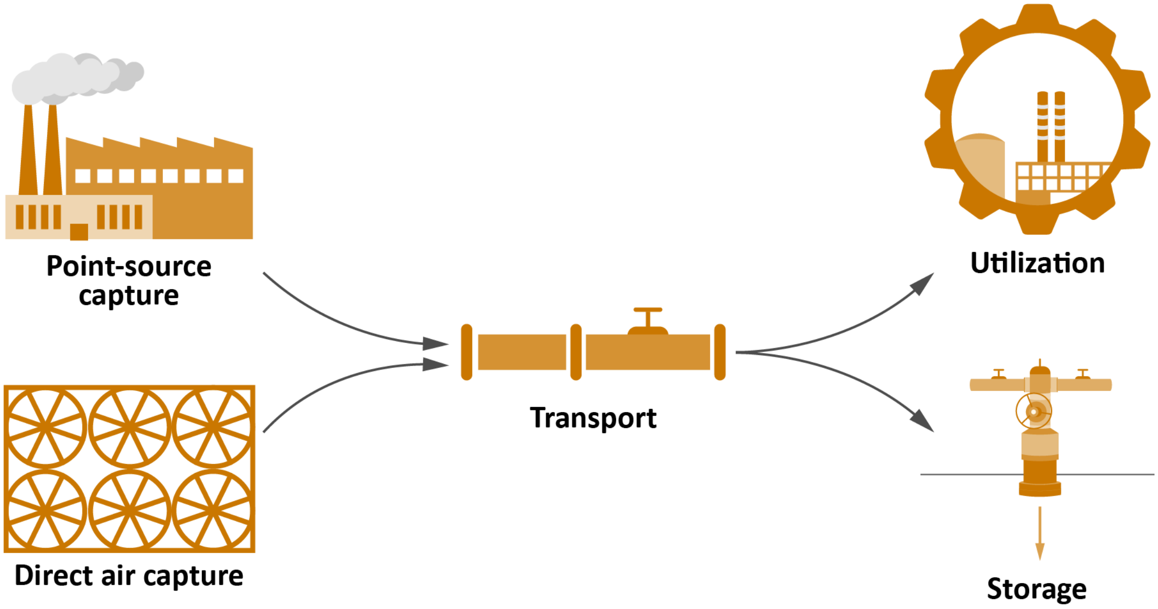
September 29, 2022

Congressional Addressees

In 2021, carbon dioxide (CO_2) reached a record high concentration in the Earth's atmosphere for the modern era, and the concentration has continued to increase in the first half of 2022. The average 2021 concentration was 12.4 percent higher than in 2000. Scientific assessments have shown that reducing CO_2 emissions—the most abundant greenhouse gas emitted through human activities—could help mitigate the negative effects of climate change. Carbon capture, utilization, and storage (CCUS) is one tool available to help slow, stop, or potentially reverse the rising levels of CO_2 in the atmosphere.

CCUS refers to a group of technologies for reducing CO_2 emissions or removing CO_2 from the atmosphere (see fig. 1). *Capture* includes technologies that separate and purify CO_2 from a source, which could be an industrial facility such as a power generation or manufacturing facility (*point-source capture*) or the atmosphere (*direct air capture*). Both point-source capture and direct air capture result in a concentrated stream of CO_2 that can be compressed and transported—typically via pipeline—either for conversion into economically valuable products (*utilization*) or for *storage* in deep underground geologic formations.

Figure 1: Components of carbon capture, utilization, and storage (CCUS)



Source: GAO. | GAO-22-105274

In general, these technologies can reduce CO_2 emissions or remove CO_2 from the atmosphere. This offers the promise of improving the environmental footprint of materials underpinning modern life such as plastics, concrete, and steel. In addition to these environmental benefits, if the CCUS industry grows in the U.S., it could preserve existing jobs and create new ones, and enhance the ability of U.S. companies to sell or export low-carbon products or CCUS technologies as more businesses and nations set greenhouse gas reduction goals.

The U.S. is a global leader in CCUS deployment, with more than 50 percent of the world's capture capacity as of 2021. The maximum capacity of operational U.S. carbon capture and storage facilities is close to 20 million metric tons per year, or about 0.3 percent of U.S. greenhouse gas emissions in 2020.[1] In recent decades, the federal government has provided funding for CCUS research, development, and demonstration projects, among other policy support.[2] For example, GAO previously reported that the Department of Energy (DOE) spent approximately $1.1 billion on nine large carbon capture and storage demonstration projects from 2010 through 2017.[3] In addition, the Energy Act of 2020 authorized $2.6 billion for six demonstration projects through 2025.[4]

We conducted this work under the authority of the Comptroller General to assist Congress with its responsibilities, in light of congressional interest in CCUS technologies. This report discusses (1) the status of available carbon capture technologies; (2) opportunities for using or storing captured CO_2; (3) key challenges that could affect the development, demonstration, and deployment of CCUS technologies; and (4) options policymakers could consider to help address these challenges.[5] The evidence we collected for this review, including peer-reviewed articles and other reports, stakeholder interviews, and an expert meeting all preceded enactment of the Inflation Reduction Act of 2022.[6] Costs discussed in the report are not adjusted for inflation

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[1] This capacity does not include two U.S. carbon capture and storage facilities that have suspended operations, or facilities that sell CO_2 for uses that do not result in geologic storage. A facility may not necessarily operate at its maximum capacity.

[2] For more on the Department of Energy's role in supporting the development of CCUS technologies, see DOE, Office of Fossil Energy and Carbon Management, *Strategic Vision: The Role of Fossil Energy and Carbon Management in Achieving Net-Zero Greenhouse Gas Emissions* (Apr. 5, 2022), accessed Aug. 11, 2022, https://www.energy.gov/fecm/strategic-vision-role-fecm-achieving-net-zero-greenhouse-gas-emissions.

[3] GAO, *Advanced Fossil Energy: Information on DOE-Provided Funding for Research and Development Projects Started from Fiscal Years 2010 through 2017,* GAO-18-619 (Washington, D.C.: Sept. 21, 2018).

[4] Pub. L. No. 116-260, div. Z, § 4002(d)(1)(C), 134 Stat. 1182, 2535 (codified at 42 U.S.C. § 16292(d)(1)(C)). The 2021 Infrastructure Investment and Jobs Act appropriated more than $2.5 billion over fiscal years 2022 through 2025 for these demonstration projects. Pub. L. No. 117-58, div. J, tit. III, 135 Stat. 429, 1377-78 (2021). In addition, the act included multiple other provisions relevant to CCUS, including authorizing funds for front-end engineering and design studies and establishing a program to fund four regional direct air capture hubs, a loan program for CO_2 transport projects, and a program to develop new or expanded large scale CO_2 storage projects.

[5] Policymakers is a broad term including, for example, Congress, federal agencies, state and local governments, academic and research institutions, and industry.

[6] Pub. L. No. 117-169, 136 Stat. 1818.

unless otherwise noted. See appendix I for a full discussion of the objectives, scope, and methodology and appendix II for a list of experts who participated in our meeting.

We conducted our work from May 2021 through September 2022 in accordance with all sections of GAO's Quality Assurance Framework that are relevant to technology assessments. The framework requires that we plan and perform the engagement to obtain sufficient and appropriate evidence to meet our stated objectives and to discuss any limitations to our work. We believe that the information and data obtained, and the analysis conducted, provide a reasonable basis for any findings and conclusions in this product.

1 Why CCUS?

CCUS has the potential to play multiple roles in addressing climate change:

- **Reducing CO_2 emissions from fossil fuel-fired power generation**. Fossil sources accounted for more than 60 percent of U.S. electricity generation in 2021. The major alternatives—such as wind, solar, and nuclear—likely cannot be scaled up quickly enough to replace fossil fuels in the near term. Retaining fossil fuels as part of the energy mix might help preserve jobs and avoid the cost of prematurely retiring fossil fuel facilities and associated infrastructure.
- **Reducing CO_2 emissions from industrial sectors where emissions are difficult or impossible to avoid**. For example, approximately two-thirds of CO_2 emissions from cement production are *process emissions*, which are released by limestone as it is heated rather than by fuel as it burns. Although new cement formulations can reduce process emissions, CCUS is effectively the only option for achieving net-zero emissions in this sector.[7] In another example, manufacture of some products (e.g., steel) requires very high temperatures, which are commonly achieved by burning fossil fuels.
- **Removing CO_2 from the atmosphere**. Because it captures CO_2 from the atmosphere, direct air capture paired with storage or uses that retain CO_2 for decades or more is an example of CO_2 *removal*.[8] CO_2 removal can result in negative emissions. Direct air capture or other removal technologies may be able to help offset emissions from sectors where they are particularly hard to avoid. For example, alternatives to liquid fuels for long-distance air travel—such as batteries for electric planes or hydrogen as a fuel—are not currently feasible on a large scale.

In all of these roles for CCUS, the amount of CO_2 reduced or removed will depend on what happens to the captured CO_2. Geologic storage is generally considered *permanent* (millions of years), as is conversion into certain products, such as concrete. Other CO_2 utilization products only retain CO_2 for amounts of time that may be short (days to years) or moderate (decades to centuries), after which the CO_2 is released to the atmosphere.

Geologic storage is essentially permanent and abundantly available in some regions of the U.S. Because of the relatively smaller scale of opportunities to use CO_2, reports on CCUS deployment expect that more CO_2 will need to be stored than used in the near term to reduce CO_2 emissions.

However, there are multiple benefits to CO_2 utilization that complement storage. First, it is

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[7] Net-zero means reducing greenhouse gas emissions to as close to zero as possible, with any remaining emissions offset elsewhere (i.e., through CO_2 removal).

[8] In addition to CCUS-based removal (e.g., direct air capture, bioenergy with carbon capture and storage), CO_2 removal can use nature-based approaches such as reforestation or soil management. These approaches are outside the scope of this review.

a more market-driven approach to handling captured CO_2 than storage and can yield revenue to help offset capture costs. Second, CO_2 can be an alternative to fossil fuels as a carbon source for certain products, such as aviation fuel and some commodity chemicals. Recycling captured CO_2 to make these products presents an opportunity to reduce their CO_2 emissions. Third, CO_2 utilization may be perceived more positively than CO_2 storage, which may increase public support.

2 Carbon Capture

Many carbon capture technologies are mature, but they have not reached widespread deployment because of high costs and the long timeline for implementation, among other challenges. Some industrial sectors have been capturing CO_2 for decades; however, costs limit the application of capture in some industrial sectors, and more specific challenges are limiting in other sectors. Direct air capture, which has been implemented at pilot scale, is a newer concept than capturing CO_2 from point sources. Direct air capture currently incurs higher cost than point-source capture and is more technically difficult because the atmosphere has a much lower CO_2 concentration than industrial waste gas.

2.1 Status of carbon capture technology

2.1.1 Capture systems

Many carbon capture technologies are ready for wider demonstration and deployment. A carbon capture system includes different components necessary to capture CO_2 from stationary industrial sources (point-source capture) or air (direct air capture) (see app. III for more detail). Most systems include gas separation technologies to isolate CO_2 from a mixture of gases.

Point-source capture includes several approaches to capturing CO_2 from combustion of fossil fuels and biomass. Other approaches apply to capture of process emissions (Table 1).

Table 1: Approaches for capturing carbon dioxide (CO_2) from point sources

Emissions source	Capture approach
CO_2 from combustion of fossil fuels and biomass	**Pre-combustion capture** applies steam, oxygen, and pressure in a series of reactions to convert fossil fuels into hydrogen and CO_2. These gases are then separated, the CO_2 is stored or used, and the hydrogen is burned to generate electricity without CO_2 emissions.
	Post-combustion capture removes CO_2 from flue gas, which is a mixture of waste gases, produced by burning fuels in air.
	Oxyfuel combustion burns fuel in high-purity oxygen. This results in a flue gas that is mainly water vapor and CO_2, which makes it easier to separate CO_2.
CO_2 from process emissions	**Other approaches** include direct separation in cement manufacturing, which heats limestone indirectly to allow easy capture of CO_2 from process emissions.

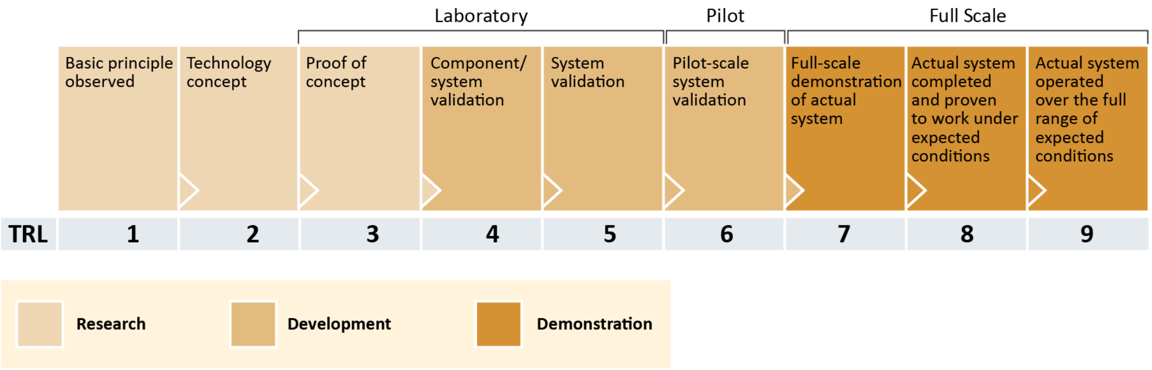
Source: GAO analysis of scientific literature and agency documentation. | GAO-22-105274

Direct air capture separates CO_2 from ambient air. Because it is not tied to an emission source, it can be deployed at a wide range of locations.

Carbon capture systems are relatively mature technologies as measured by technology readiness level (TRL), with some systems already deployed.[9] Figure 2 is a schematic of the nine TRLs. (See app. IV for DOE's definition and description of each TRL.)

Within each category of carbon capture system, the TRL may vary by industrial sector. For example, pre-combustion systems have been demonstrated at TRL 9 for the hydrogen production industry, meaning actual systems have been proven in successful operations. But for coal-fired power generation, pre-combustion capture is considered TRL 7, meaning prototypes have been demonstrated in a relevant environment. Table 2 shows the TRLs, strengths, and limitations of different carbon capture systems.

Figure 2: Example schematic of technology readiness levels



Source: GAO summary of information from Department of Energy, Global CCS Institute, and National Academies of Sciences, Engineering, and Medicine. | GAO-22-105274

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[9] TRLs are a scale of nine levels used to measure a technology's progress, starting with paper studies of a basic concept and ending with a technology that has proven itself in actual use in the product's operational environment. The TRL of a capture system is determined by the lowest TRL of its critical components. GAO, *Technology Readiness Assessment Guide: Best Practices for Evaluating the Readiness of Technology for Use in Acquisition Programs and Projects*, GAO-20-48G (Washington, D.C.: Jan. 7, 2020), 4.

Table 2: Assessment of carbon capture systems

Carbon capture system	Highest technology readiness level reported	Strengths	Limitations
Point-source capture			
Post-combustion	9	Equipment can be retrofitted to existing facilities that still have long lifetimes. Most mature system.	Gas streams with low carbon dioxide (CO_2) concentrations require high energy input for separation. Less cost effective on smaller scale.
Pre-combustion	9[a]	Gas streams have higher pressure and CO_2 concentration than post-combustion flue gases, resulting in easier CO_2 separation.	Higher capital costs than post-combustion systems. Limited applications in some sectors.
Oxyfuel combustion	7	Suitable for retrofitting in existing coal-fired power facilities of various scales. Reduced amount of nitrogen oxides (which are air pollutants) compared to traditional combustion systems.	High energy consumption to produce nearly pure oxygen.
Direct air capture	7	Can capture emissions from small emitters. Equipment can be located at or near storage site, thereby eliminating or reducing transport costs.	High energy requirement. Low-carbon source of energy required to ensure net removal of CO_2.

Source: GAO analysis of peer-reviewed articles, other literature, and agency websites. | GAO-22-105274

[a] TRL level of a capture system varies by sector. For example, the pre-combustion system has reached TRL 9 for hydrogen production but has only reached TRL 7 for use with coal-fired power generation.

2.1.2 Gas separation technologies

In most applications, a critical component of the capture system is the technology to separate CO_2 from other gases. There are multiple categories of gas separation technologies (see table 3 and app. III). The technologies within each category have different levels of maturity, strengths, and limitations, which make some more suitable for certain applications than others. For example, sorbent-based separation is particularly suited for direct air capture because of its efficacy in separating dilute gas mixtures and it can be regenerated with low heat. Although some industrial sectors are using the most mature technologies commercially or applying them in full-scale demonstrations, researchers are developing less mature technologies in parallel to enhance performance and lower costs.

Table 3: Assessment of key gas separation technologies

Gas separation technologies	Technology readiness level	Strengths	Limitations
Solvent-based	2-9	Most mature technology	High energy requirement Some solvents degrade, which can be costly and generate waste and emissions of degradation compounds
Sorbent-based	1-9	Functional under a wide temperature range	Low selectivity in some sorbents Low to moderate stability through regeneration cycles, which can increase costs and generate waste
Membranes	2-9	Compact and modular Easy operation	High manufacturing cost Difficult to achieve high carbon dioxide (CO_2) recovery rate and high purity simultaneously
Cryogenics	3-6	High capture efficiency	High energy requirement

Source: GAO analysis of peer-reviewed articles and agency websites. | GAO-22-105274

2.2 Current deployment of carbon capture

2.2.1 Point-source capture

Carbon capture technologies have not reached widespread deployment. There are many large point sources that could use CO_2 capture, such as power generation facilities, ethanol biorefineries, and several types of manufacturing facilities; however, only 12 facilities that combine commercial-scale carbon capture and storage were operating in the U.S. as of 2021, according to the Global CCS Institute.[10] Two additional facilities in the U.S. captured and stored CO_2 briefly, (one from 2013 to 2018 and the other from 2017 to 2020) but suspended those operations.

Globally, the total capacity of the operational carbon capture and storage facilities more than doubled from 2010 to 2021, increasing from 13.3 million metric tons of CO_2 per year to 36.6 million over that period (fig. 3). However, this capacity represents 0.1 percent of estimated human-caused CO_2 emissions in 2021. Although CO_2 separation or capture is used in some industrial sectors (e.g., bioethanol production, natural gas processing, and fertilizer production), most of those facilities currently either vent the CO_2 into the atmosphere or sell it for use that does not permanently store or retain the CO_2 for a long period.

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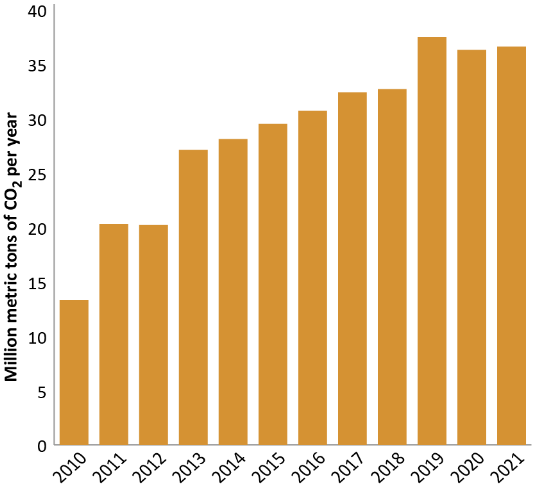
[10] This accounted for almost half of the 27 facilities worldwide. The Global CCS Institute reports the number of facilities that both capture CO_2 and store it geologically. Global CCS Institute, *Global Status of CCS 2021: CCS Accelerating to Net Zero* (Melbourne, Australia: 2021).

Figure 3: **Global capacity of point-source carbon capture and storage facilities**



Source: Global CCS Institute (2021) *Global Status of CCS*. | GAO-22-105274

The highest CO_2 emitting sectors are not likely to deploy carbon capture widely without further demonstration. Although two commercial-scale coal-fired power facilities are retrofitted with carbon capture (TRL 9), the technology has not been demonstrated to that level for natural gas-fired facilities.

Integrating carbon capture technologies into industrial facilities is easier in sectors in which facilities have one (as opposed to multiple) sources of emissions, and waste gas streams with higher concentration and purity of CO_2. In the following four vignettes we highlight some of the sector-specific factors that influence implementation of carbon capture in selected sectors.

Table 4: **Ease of capture for carbon dioxide (CO_2) sources from selected industrial sectors**[a]

Sector	Annual U.S. emissions (million metric tons per year)	CO_2 concentration in gas stream (percent CO_2)	Number of CO_2 emission sources in a facility
Power generation	1,500	1-15	1->3
Cement	66	1-33	1-2
Iron and steel	62	8-27	≥3
Bioethanol[b]	45	≥95	1

Legend: light color = easy; dark color = difficult

Source: GAO analysis of peer-reviewed and other literature, agency websites, and stakeholders. | GAO-22-105274

[a] Integrating carbon capture technologies into industrial facilities is easier in sectors in which industrial facilities have one source of emission, and waste gas streams with higher concentrations of CO_2.

[b] Values in this row refer only to emissions from the fermentation process.

Power Generation

Source: hansenn/stock.adobe.com

The electric power sector is one of the two largest emitters of CO_2 in the U.S., accounting for about 30 percent of CO_2 emissions, according to U.S. Environmental Protection Agency (EPA) estimates. In 2021, 38 percent of U.S. electricity was generated from natural gas and 22 percent from coal. Carbon capture technologies can be included in new power generation facilities or retrofitted to existing ones.

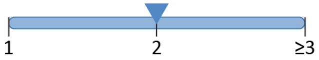
Annual emissions in the U.S.:

1.5 billion metric tons of CO_2

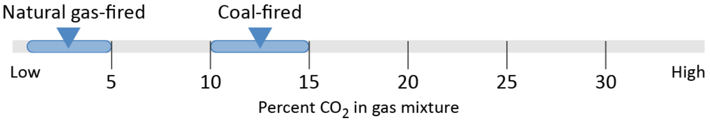
(of direct emissions from fuel combustion)

Factors that influence ease and cost of carbon capture:

▶ Number of capture sources (1 = Easy; Multiple = Difficult):



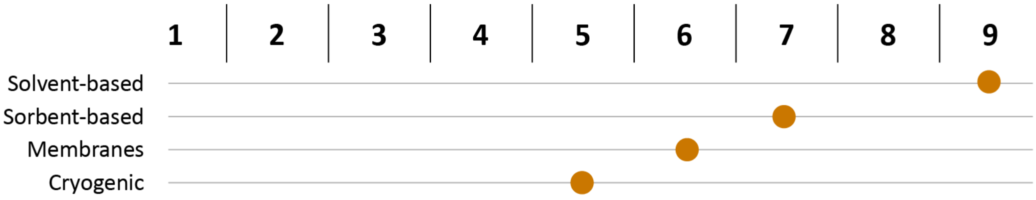
▶ CO_2 concentration (High = Easy; Low = Difficult):



Capture system(s):

Post-combustion, pre-combustion, and oxyfuel combustion.

Technology readiness level of applying selected separation technologies in this sector:



Estimated cost of capture:

$40-$290

per metric ton of CO_2. Estimated costs vary by fuel type and facility configuration.

Source: GAO analysis of agency website, peer-reviewed articles, and other literature. | GAO-22-105274

Examples of demonstration and deployment

From 1991 to 2005, Northeast Energy Associates operated a natural gas-fired power generation facility with carbon capture in Bellingham, MA. The captured CO_2 was used in the food and beverage industry. The Boundary Dam Power Station in Saskatchewan, Canada, was the first coal-fired power facility to implement carbon capture successfully. Operational since 2014, the facility can capture up to 1 million metric tons of CO_2 per year for enhanced oil recovery and geologic storage.

Operational in 2017, the Petra Nova project in Thompson, Texas, was designed to capture at least 90 percent of the CO_2 emissions from a 240-megawatt equivalent flue gas slipstream at the W.A. Parish Electric Generating Station and to store up to 1.4 million metric tons of CO_2 annually. The captured CO_2 was compressed and transported through an 80-mile pipeline for enhanced oil recovery, which is a process that uses gases such as CO_2 to push additional oil out of an oil field once much of the easy-to-produce oil has already been recovered. The facility paused operations in May 2020 because low oil prices reduced the profitability of using captured CO_2 for enhanced oil recovery.

Challenges

- Design and integration of carbon capture technologies can vary based on configuration of the power generation facility and fuel source. The most mature technology (solvent-based system using amine) has only been deployed in a subset of possible configurations of coal-fired power generation facilities.
- Retrofitting a power generation facility with carbon capture can be more difficult with facilities that are older, smaller, or have little available space.
- High capital costs for carbon capture equipment.

Cement


Source: Franco Nadalin/stock.adobe.com

The process of manufacturing cement from limestone releases large quantities of CO_2, known as process emissions. Cement manufacturing also relies heavily on coal for heat, resulting in additional emissions. Aside from using carbon capture technologies, there are few opportunities to reduce these emissions. Some studies suggest carbon capture technologies could reduce emissions from cement manufacturing by 25 to 48 percent.

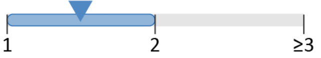
Annual emissions in the U.S.:

66 **million metric tons of CO_2**

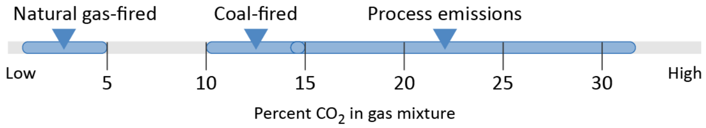
(of direct emissions from fuel combustion and process emissions)

Factors that influence ease and cost of carbon capture:

▶ Number of capture sources (1 = Easy; Multiple = Difficult):



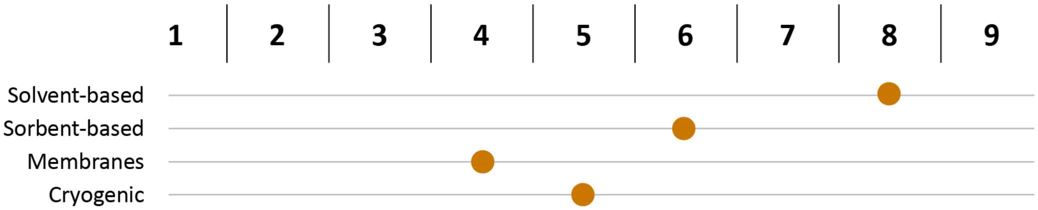
▶ CO_2 concentration (High = Easy; Low = Difficult):



Capture system(s):

Post-combustion, oxyfuel combustion, and direct separations

Technology readiness level of applying selected separation technologies in this sector:



Estimated cost of capture:

$45-$120

per metric ton of CO_2

Source: GAO analysis of agency website, peer-reviewed articles, and other literature. | GAO-22-105274

Examples of demonstration and deployment

According to Global CCS Institute, there were no commercial cement manufacturing facilities integrated with carbon capture and storage as of 2021. Since 2015, Carbonfree Chemicals has been operating a pilot-scale demonstration at a cement manufacturing facility in San Antonio, Texas. The company uses captured CO_2 to manufacture products such as baking soda, bleach, and hydrochloric acid. The technology has a capacity to capture 75,000 metric tons of CO_2 from the facility, which reported around 500,000 metric tons of CO_2 emissions in 2020.

In December 2020, HeidelbergCement announced its plan to install full-scale carbon capture at its Norcem cement manufacturing facility in Brevik, Norway. Capture is expected to begin in 2024 and to enable capture of up to 400,000 metric tons of CO_2 per year. Captured CO_2 will be transported by ship for temporary storage and then by pipeline to a subsea formation in the North Sea.

Challenges

- Carbon capture in cement manufacturing has not been demonstrated at a commercial scale.
- U.S. cement manufacturers have limited ability to pass costs to consumers because cement manufacturing is highly competitive.

Iron and Steel

Source:kasarp/stock.adobe.com

The United States is the world's fourth largest producer of steel. Iron and steel manufacturing is energy intensive and emits large amounts of CO_2. Although the iron and steel industry made strides in reducing CO_2 emissions by improving energy efficiency in recent decades, additional major improvements are not technically possible. Carbon capture, utilization, and storage (CCUS) technologies can further reduce the carbon footprint of iron and steel manufacturing.

Annual emissions in the U.S.:

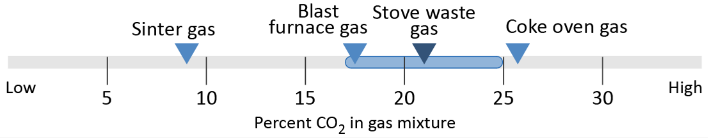
62 million metric tons of CO_2

(of direct emissions from fuel combustion and process emissions)

Factors that influence ease and cost of carbon capture:

▶ Number of capture sources (1 = Easy; Multiple = Difficult):

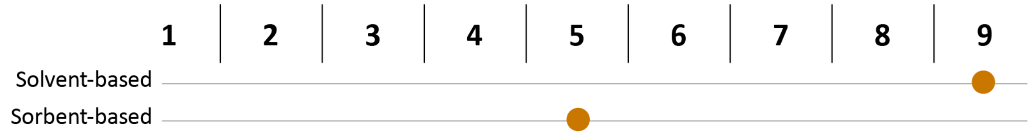
▶ CO_2 concentration (High = Easy; Low = Difficult):



Capture system(s):

Post-combustion, oxyfuel combustion, and capture of process emissions.

Technology readiness level of applying selected separation technologies in this sector:



Estimated cost of capture:

$40-$130

per metric ton of CO_2

Source: GAO analysis of agency website, peer-reviewed articles, and other literature. | GAO-22-105274

Examples of demonstration and deployment

The first and only commercial carbon capture and storage project in the iron and steel industry is the Al Reyadah project in Abu Dhabi, United Arab Emirates. It has been in operation since November 2016 and captures up to 800,000 metric tons of CO_2 per year of emissions from the direct reduced iron reactor (which removes oxygen from iron ore or other iron bearing material). The captured CO_2 is used for enhanced oil recovery, which is a process that uses gases such as CO_2 to push additional oil out of an oil field once much of the easy-to-produce oil has already been recovered.

Although carbon capture has been deployed in the production of direct reduced iron (an intermediate product of steelmaking), applications to other pathways of iron and steelmaking have not been demonstrated at the same technology readiness level.

Challenges

- U.S. iron and steel manufacturers have limited ability to pass the cost of carbon capture to consumers because prices are set by the global market.
- Integrating carbon capture into production processes is complex because facilities have multiple sources of emissions with different CO_2 concentrations.
- Design and integration of carbon capture technologies depends on the production processes used, and the most mature technology (solvent-based system using amine) has only been deployed in the iron-making process.
- High capital costs of carbon capture equipment.

Bioethanol

Source: photogrfx/stock.adobe.com

CO_2 is a byproduct of ethanol production from sugar-based or starch-based feedstocks. Produced during fermentation of sugars, the resulting CO_2 has high purity and requires little processing before it can be used or stored in geologic formations. Commercial technologies to capture CO_2 emissions from the fermentation process are available and have been used for many years.

Annual emissions in the U.S.:

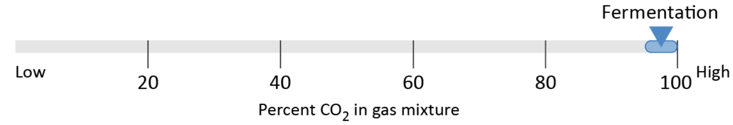
45 million metric tons of CO_2

from fermentation (excluding CO_2 from combustion sources)

Factors that influence ease and cost of carbon capture:

- Number of capture sources (1 = Easy; Multiple = Difficult):

- CO_2 concentration (High = Easy; Low = Difficult):



Capture system(s): Capture of process emissions.

Technology readiness level:

Separation technologies: Not necessary due to the high purity of the CO_2 waste stream.

Estimated cost of capture:

$0-$35

per metric ton of CO_2

Source: GAO analysis of agency website, peer-reviewed articles, and other literature. | GAO-22-105274

Examples of demonstration and deployment

According to Global CCS Institute, there were three commercial ethanol biorefineries integrated with carbon capture and storage and 34 in advanced development in the U.S. in 2021. Arkalon, in Liberal, Kansas, was the first commercial ethanol biorefinery integrated with carbon capture and storage in the U.S. and has been operational since 2009. The facility captures up to 290,000 metric tons of CO_2 per year for enhanced oil recovery. Since then, the number of ethanol biorefineries that are capturing CO_2 has increased, but most captured CO_2 is not stored geologically. As of 2021, about 50 out of 207 ethanol biorefineries in the U.S. are capturing CO_2 for sale in the food-grade CO_2 market.

In 2021, Archer Daniels Midland and the University of Illinois successfully completed the Illinois Basin - Decatur Project, which captures CO_2 from an ethanol biorefinery for geologic storage. The project included the design, construction, and demonstration of a dehydration and compression facility to capture CO_2 resulting from processing corn into ethanol. The CO_2 is then injected at a nearby site for geological storage.

Summit Agricultural Group and Navigator CO_2 Ventures have each launched a large-scale carbon capture and storage project that involves ethanol biorefineries and other facilities in the Midwest. CO_2 captured as a result of these projects will be stored geologically in North Dakota and south-central Illinois, respectively.

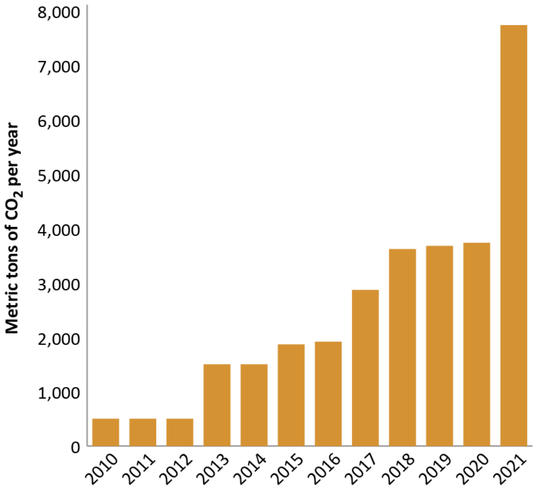
Challenges

- Many ethanol biorefineries in the Midwest are not near CO_2 storage sites.
- Identifying partners for transport, storage, or use of CO_2 may be challenging.

2.2.2 Direct air capture

Direct air capture is a newer system, introduced as an approach to climate mitigation in the late 1990s. Existing projects use a handful of gas separation technologies to capture CO_2. Direct air capture has been implemented at pilot scale, with 18 facilities operating worldwide as of April 2022. The total capacity of operational facilities has increased from less than 1,000 metric tons of CO_2 per year in 2010 to almost 8,000 metric tons in 2021 (fig. 4).

Figure 4: Capacity of direct air capture facilities



Source: International Energy Agency (IEA, 2022). *Direct Air Capture: A Key Technology for Net Zero.* All rights reserved. | GAO-22-105274

As of August 2022, the largest direct air capture facility has the capacity to capture 4,000 metric tons of CO_2 per year. By comparison, the facility with the highest capacity to capture and store CO_2 from a point source can capture up to 7 million metric tons of CO_2 per year.

Direct air capture has higher energy requirements and costs than point-source capture because the concentration of CO_2 in ambient air is relatively low (around 0.041 percent, whereas industrial flue gases are between 1 and 33 percent CO_2). Unless direct air capture is powered by low-carbon energy (e.g., nuclear, wind, solar), the CO_2 emitted from energy use may exceed the CO_2 captured by the system. According to the research literature, life cycle assessment is key to understanding whether direct air capture systems result in CO_2 benefits. Life cycle assessment is a systematic tool that allows for analysis of CO_2 emissions of a system in its entire life cycle and assessment of its impact to the environment.[11]

Opportunities to improve direct air capture systems include identifying materials that can be reused for thousands of cycles of air capture, optimizing processes, and avoiding conditions that accelerate material degradation. These improvements could reduce the cost of direct air capture, which is currently the most costly capture system per ton of CO_2.

2.3 Key challenges to widespread deployment

The long timeline to retrofit carbon capture technologies or develop new facilities, and high costs, among other challenges, could

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[11] K.-M. Lee and A. Inaba, *Life Cycle Assessment: Best Practices of ISO 14040 Series* (Suwon Korea, Asia-Pacific Economic Cooperation: 2004).

hinder widespread deployment in the near term.

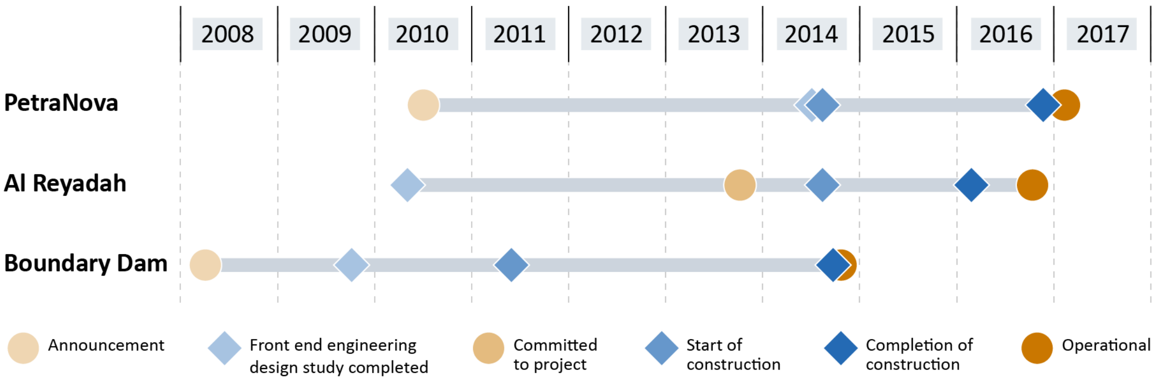
2.3.1 Lengthy time to deployment

The long timeline for deployment poses a challenge for both point-source capture and direct air capture projects to obtain investment and financing because policies and market conditions could change during or after deployment to negatively affect the return on investment. Chapter 5 provides further analysis of economic incentives.

Point-source capture

For sectors such as power generation, iron and steel manufacturing, and cement manufacturing, integration of carbon capture takes time because of the complexities described above. Our review of the timelines for three large-scale point-source demonstration projects (Boundary Dam and PetraNova for coal-fired power generation and Al Reyadah for iron and steel manufacturing) shows that it took 6 to 7 years from the time that a project was announced to when it became operational (fig. 5).[12]

Figure 5: **Timeline for point-source carbon capture and storage demonstration projects**



Source: GAO analysis of agency and university websites, stakeholder report and presentation slides, and literature. | GAO-22-105274

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[12] These are first-of-a-kind projects.

Although the U.S. is considered to be a leader in CCUS deployment, there are nevertheless few carbon capture and storage projects that are completed or under construction in high CO_2-emitting sectors. Although there are additional demonstrations in early and advanced development (see table 5), historically a number of projects in these stages have not reached completion.

Direct air capture

Direct air capture readiness timelines are less certain. It is difficult to project when direct air capture will be ready for widespread deployment given it is currently at TRL 7. Moving from a full-scale prototypical system to an actual system that works in its final form and under expected conditions could take years.

Table 5: Large-scale point-source carbon capture and storage projects planned in selected sectors

Sector	Early development		Advanced development		Under construction		Completed	
	Worldwide	U.S. only	Worldwide	U.S. only	Worldwide	U.S. only	Worldwide	U.S. only
Power generation	15	3	9	8	2	1	2	1
Iron and steel manufacturing	1	0	0	0	0	0	1	0
Cement manufacturing	2	1	0	0	1	0	0	0

Source: Global CCS Institute. | GAO-22-105274

2.3.2 High capital and operating costs

Cost is a key challenge to widespread deployment of point-source carbon capture in some industrial sectors and of direct air capture systems. High upfront capital costs deter investments. Capital costs of integrating carbon capture systems into some of the high-CO_2 emitting sectors (see table 6) are often cited as a challenge to deployment.

For point-source capture, the total costs of capturing one metric ton of CO_2 (including capital and operating costs) are estimated to be from $40 to $290 for some high emitting sectors (fig. 6).[13] In sectors where CO_2 separation is part of the industrial process (e.g., bioethanol production), costs are lower, ranging from $0 to $35 per metric ton. For direct air capture, most sources we reviewed estimated costs to be $100 to $600 per metric ton, with one source estimating the upper bound to be $1,200.[14] In addition to the initial CO_2 concentration in the gas stream, other variables affecting cost include facility size (with lower cost per ton at larger facilities), flow rate of the gas stream, and CO_2 separation technology.

Table 6: Estimated capital costs for commercial-scale carbon capture

Capture type	Sector	Estimated capital cost (millions of dollars)
Point-source capture	Natural gas processing	17-28
	Bioethanol production	21-36
	Ammonia production	24-41
	Cement manufacturing	150-250
	Iron and steel manufacturing	800-1,300
	Power generation	400-1,500
Direct air capture		780-1,100

Source: GAO summary of peer-reviewed article and other literature. | GAO-22-105274

Note: Point-source estimates are from National Petroleum Council, *Meeting the Dual Challenge: A Roadmap to At-Scale Deployment of Carbon Capture, Use, and Storage* (Washington, D.C.: National Petroleum Council, 2019). Direct air capture estimates are from D. W. Keith et al., “A Process for Capturing CO_2 from the Atmosphere,” *Joule*, vol. 2 (2018): 1573.

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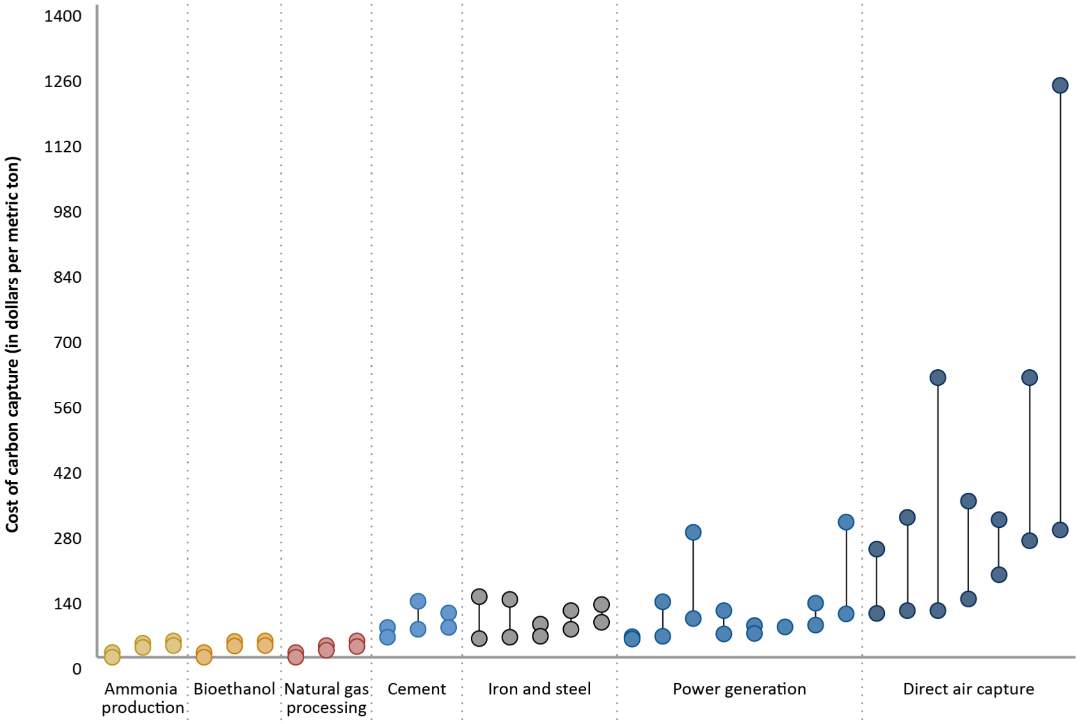
[13] The wide ranges of cost estimates reflect differences in assumptions made in various sources and the ranges of economic parameters applied such as facility size, asset life, and tax rate.

[14] A. Kiani, K. Jiang, and P. Feron, "Techno-Economic Assessment for CO_2 Capture from Air Using a Conventional Liquid-Based Absorption Process,” *Frontiers in Energy Research,* vol. 8, article 92 (2020).

Figure 6: Estimated costs to capture one metric ton of carbon dioxide (CO_2) by sector



Source: GAO analysis of peer-reviewed articles and other literature. | GAO-22-105274

Note: Each range represents estimates from a single source.

Given the total costs of installing and operating carbon capture, research literature and a stakeholder group estimated that these technologies may increase the cost of related products by 10 to 90 percent. Some stakeholders raised the concern that they cannot pass the additional costs to consumers, since they have to compete globally with products made without carbon capture. There is not always a clear business case or profit model to integrate carbon capture into industrial facilities or remove CO_2 from the atmosphere.

Research and development is under way to reduce cost by improving performance, optimizing the carbon capture process, and developing alternatives that are cheaper and more efficient than current mature technologies. Research and development can also help policymakers anticipate and mitigate environmental concerns as the technologies scale up.

Demonstrations are another key way to reduce costs, as well as technical and financial uncertainties. For new technology that is advancing to commercial maturity, it is generally accepted that the first-of-a-kind commercial facility costs significantly more to build than subsequent facilities and provides limited information on operating, maintenance, and cost issues under a narrow set of conditions. “Learning-by-doing” at commercial scale under real-world conditions helps identify risks across a full range of conditions, optimize the system, reduce costs, and develop viable business models. The text box below describes two key attributes of successful carbon capture demonstrations. In addition, chapter 5 provides further analysis of economic incentives.

Technology readiness and revenue credibility of carbon capture demonstrations

Although demonstration facilities play a critical role in technology development, they cost a lot more than bench and pilot projects. Assessments of past demonstration projects suggest that selecting projects that have high technology readiness level and credible revenue streams could reduce the likelihood of spending significant funds on unsuccessful projects.[a,b]

Technology readiness has been suggested as the reason for the failure of the Kemper project. Although the carbon capture technology chosen was mature, the project sought to use a first-of-its-kind gasification technology for power generation.[a,b] The FutureGen 2.0 initiative was intended to be the world's first full-scale oxyfuel-combustion coal-fired power generation facility, but it was terminated before construction began. Oxyfuel-combustion systems have been demonstrated up to TRL 7; in contrast, the three successfully completed carbon capture and storage demonstrations funded by the Department of Energy (DOE) used more mature technologies.

Demonstration projects with credible revenue streams and less reliance on incentives are more likely to succeed, according to Abdullah et al.[a] We previously found that three out of eight projects in DOE's Clean Coal Power Initiative withdrew from participating because they determined that continued participation was not economically viable.[c] One project specifically cited a lack of legislative and regulatory support for cost recovery that it had expected at the time of its original application to DOE, reflecting the effect of credibility of incentives. The Petra Nova project, which was successfully completed, ceased operation in 2020 because its expected revenue stream from carbon dioxide (CO_2) sales dwindled when low oil prices reduced the demand for CO_2 for enhanced oil recovery.

[a] A. Abdullah et al., "Explaining Successful and Failed Investments in U.S. Carbon Capture and Storage Using Empirical and Expert Assessments," *Environmental Research Letters*, vol. 16 (2021): 014036.

[b] H. Herzog, *Lessons Learned from CCS Demonstration and Large Pilot Projects* (Cambridge, Mass.: Massachusetts Institute of Technology, 2016).

[c] GAO, Carbon Capture and Storage: Actions Needed to Improve DOE Management of Demonstration Projects, GAO-22-105111 (Washington, D.C.: Dec. 20, 2021).

Source: GAO analysis of cited literature. | GAO-22-105274

2.4 Policy options

Research, development, and demonstration. Policymakers could take steps to enhance support for consistent funding of research and development and large-scale demonstrations simultaneously.

This policy option could help address the current high costs of implementing point-source or direct air capture systems.

Opportunities	Considerations
Research and development could reduce cost by improving performance, optimizing the carbon capture process, and developing alternatives that are cheaper and more efficient than current mature technologies. It could resolve issues identified in demonstrations and mitigate risks in a timely manner, and can advance emerging technologies. Demonstrations could reduce cost by promoting learning-by-doing for various industrial sectors and for direct air capture. In addition, it could establish the viability of carbon capture and increase investors' confidence.	Stakeholders have different ideas for research and development priorities. Requires careful oversight of large-scale demonstration projects to reduce the likelihood of large expenditures on projects that may be unlikely to succeed.

Source: GAO. | GAO-22-105274

3 Utilization of Captured CO_2

Using CO_2 for products or services is not a new idea. Many technologies that directly use CO_2 are mature and have been used for decades, and newer technologies that convert CO_2 into products are available or in development. CO_2-based products include building materials that offer permanent CO_2 storage and fuels that have large CO_2 utilization potentials. However, production costs and restrictive standards limit the viability of many CO_2-based products in the market. Furthermore, there is no agreed-upon framework for determining whether a given CO_2-based product has the intended effect of mitigating CO_2 emissions.

3.1 Status of CO_2 utilization technology

Worldwide, over 230 million metric tons of CO_2 are currently used or converted to valuable products every year.[15] Figure 7 shows that CO_2 utilization pathways can be sorted into two broad categories: conversion, in which CO_2 is chemically altered, and nonconversion, in which it is not. With the exception of urea production, conversion pathways represent a small fraction of current CO_2 consumption. However, they are a growing area of interest for researchers and industry. According to one research firm, the market for CO_2-based products could grow from less than $1 billion currently to $70 billion by 2030.[16] Most nonconversion pathways, including enhanced oil recovery, are mature and widely used, but outside the scope of this report.[17]

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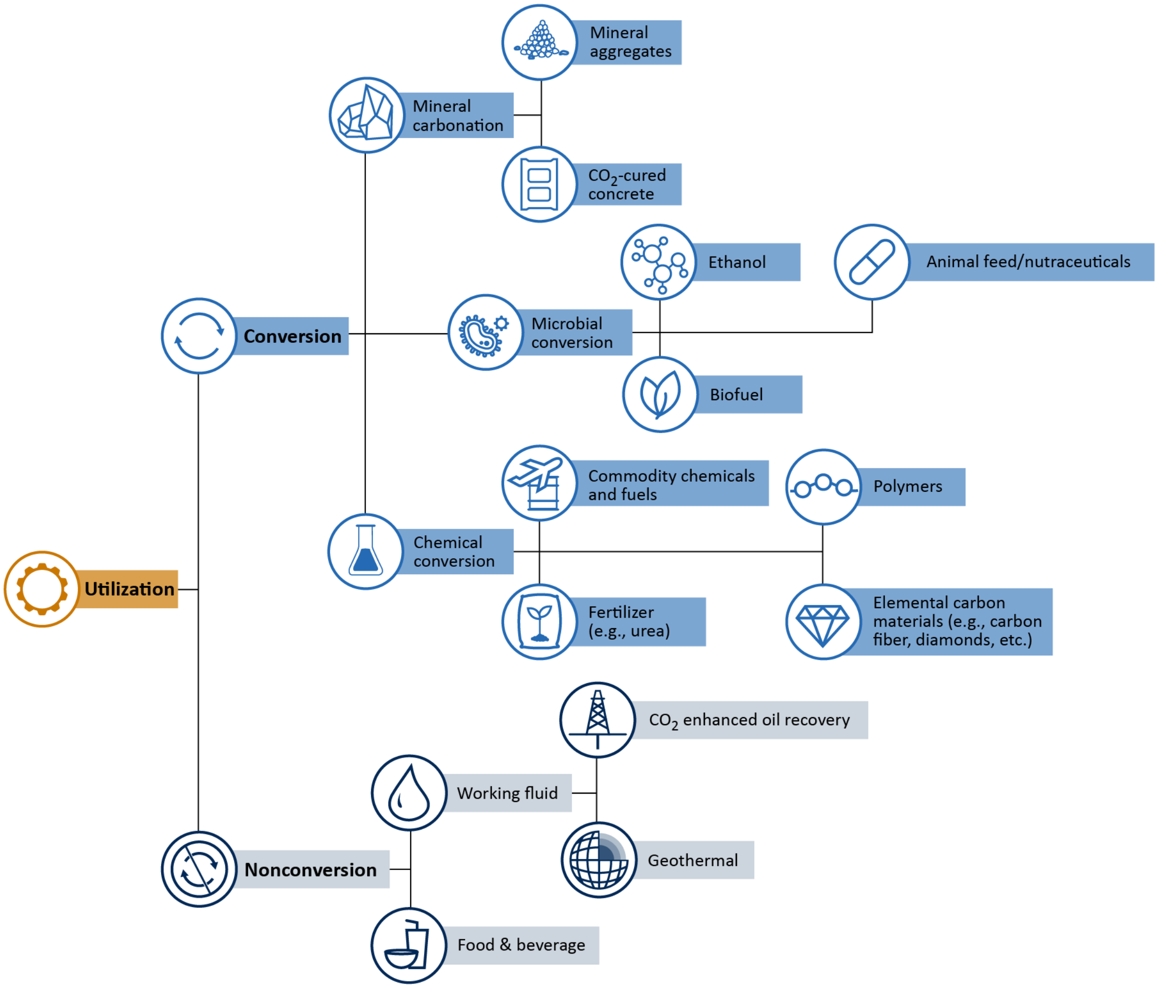
[15] International Energy Agency (IEA), *Putting CO_2 to Use: Creating Value from Emissions* (France: IEA Publications, 2019), 6. Currently, the two largest users of CO_2 are the fertilizer industry for urea production (57 percent), and the oil sector for enhanced oil recovery (34 percent). Enhanced oil recovery via gas injection uses gases such as CO_2 to push additional oil out of an oil field once much of the easy-to-produce oil has already been recovered. Other users of CO_2 include the food and beverage industry, metal fabrication, and greenhouses (to stimulate plant growth).

[16] L. Krishfield et al., *CO_2 Capture & Utilization: The Emergence of a Carbon Economy* (Lux Research, Inc., 2020).

[17] Conversion pathways that are mature and widely used, such as urea production, are also outside the scope of this report.

Figure 7: Carbon dioxide (CO_2) utilization pathways and products



Source: GAO analysis of reports. | GAO-22-105274

3.2 Overview of CO_2 conversion pathways

Although many CO_2 conversion pathways are in early stages of commercialization, they have the potential to use large amounts of CO_2 and generate products with large markets.[18] Table 7 gives an overview of several CO_2 conversion pathways, with their uses, strengths, limitations, and status. (For more details on the conversion processes, see app. V.)

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[18] Though reports often compare potential CO_2 use of products, the amount of CO_2 *used* in a product does not necessarily equal the amount of CO_2 emissions *reduced*. For example, CO_2 conversion pathways that do not use low-carbon energy sources may result in net life-cycle increases in CO_2 emissions instead of reductions.

Table 7: Summary of selected carbon dioxide (CO_2) conversion pathways

Conversion pathway	What it can make	Strengths	Limitations	Status
Mineral carbonation	Mineral aggregates, cured concrete	Permanent CO_2 storage Low energy requirements Can directly use CO_2 waste gas streams	Slow reaction rate Needs careful control of reaction conditions, e.g., pH and water content	Early stages of commercialization to fully commercialized
Hydrogenation	Fuels (e.g., methane, diesel, gasoline, aviation fuel); commodity chemicals (e.g., methanol, ethanol, formic acid)	Produces a large array of products with large market potentials High product yield	Energy intensive; needs low-carbon energy and clean hydrogen to achieve net CO_2 reduction Short CO_2 retention time in products	Methanol and methane are commercialized, many other applications are pilot scale to early stages of commercialization
Electrochemistry	Carbon monoxide, syngas, methanol, formic acid	Produces a large array of products Cost-effective carbon monoxide production	Energy intensive; needs low-carbon energy to achieve net CO_2 reduction Short CO_2 retention time in products	Research phase to early stages of commercialization
Co-polymerization	Polycarbonates, polyols	Moderate CO_2 retention time in products Moderate energy requirements High value materials	Still relies on fossil fuel-based feedstocks Polyol production is small scale compared to conventional More research needed for other polymer types	Fully commercialized
Microbial conversion	Photosynthetic microbes (e.g., algae) can make biofuel, animal feed, nutraceuticals Nonphotosynthetic microbes (e.g., bacteria) can make ethanol, isopropanol, acetone, methane	Photosynthetic microbes can produce high-value products Both microbe types can directly use CO_2 waste gas streams	Photosynthetic: Resource-intensive cultivation and processing Nonphotosynthetic: Needs hydrogen for more carbon-efficient reactions, oxygen can be toxic to some microbes	Some photo-synthetic microbe products and nonphotosynthetic ethanol production are fully commercialized; otherwise, production is research phase to pilot scale

Source: GAO summary of scientific literature. | GAO-22-105274

The conversion pathways described in table 7 are the most mature commercially available conversion technologies. One priority of ongoing research is to improve conversion pathway efficiency, either through process improvements or by developing technologies that combine CO_2 capture and conversion (see text box).

Looking forward: Reactive capture

Reactive capture—the process of capturing CO_2 from a mixed gas stream and converting it directly into a product without further purification—is an emerging area of research that could increase the efficiency and reduce the cost of carbon capture and utilization. It eliminates three intermediate steps: purifying CO_2, compressing it, and regenerating the capture medium (i.e., the solvent or sorbent used for gas separation). Reactive capture also reduces overall transportation costs because no pure CO_2 needs to be transported. Early examples of reactive capture use chemical or microbial processes to make products such as carbon nanotubes and methane. Reactive capture technologies are still relatively immature (TRL 1-3). Further research, development, and demonstration could help address key challenges, such as flue gas impurities and mismatch between the current rate of CO_2 capture and conversion.

Source: GAO summary of Department of Energy workshop. | GAO-22-105274

3.3 CO_2 conversion products

The pathways described above can be used to manufacture a variety of products. We highlight selected examples in four vignettes: synthetic mineral aggregates, CO_2-cured concrete, commodity chemicals and fuels, and polymers. We also summarize emerging elemental carbon materials, such as carbon fiber, in a text box. Table 8 compares these products.

Table 8: Comparison of selected carbon dioxide (CO_2)-based products

Product category	Is the cost to produce the CO_2-based product currently less than the selling price of conventional?	Is CO_2 retained for >100 years?	Could CO_2 utilization potential be >1000 million metric tons by 2050?	Is the maximum TRL ≥ 8?
Synthetic mineral aggregates	X	✓	—	✓
CO_2-cured concrete	✓	✓	✓	✓
Commodity chemicals (methanol)	X	X	X	✓
Fuels	X	X	✓	✓
Polymers	✓	—	X	✓

Legend: ✓ = yes, **X** = no, — = studies are inconsistent

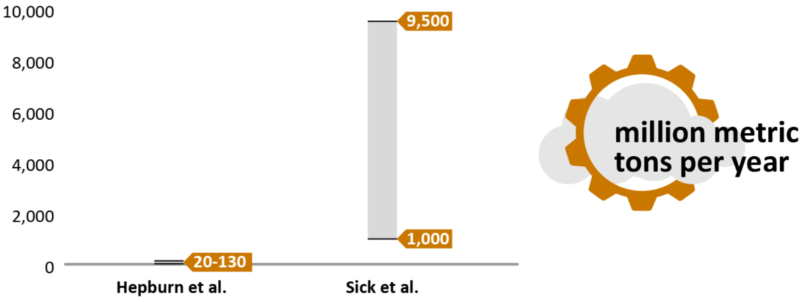
Source: GAO analysis of scientific literature. | GAO-22-105274


Source: JENOCHE/stock.adobe.com

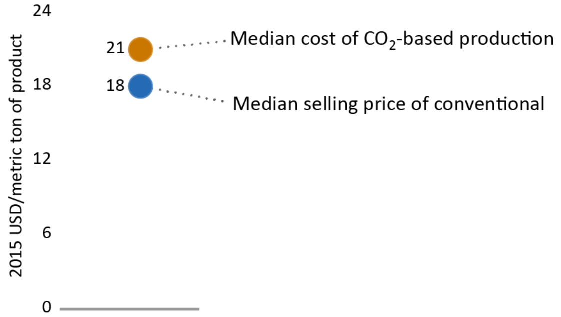
Synthetic Mineral Aggregates

Synthetic mineral aggregates—human-made versions of natural materials such as chalk or limestone— could provide a revenue generating way to store large quantities of CO_2 for millions of years. Most mineral aggregates currently come from mines, and a recent scientific article estimated that the global annual market was 45 billion metric tons in 2020. One primary use is in concrete, which is 60 to 80 percent mineral aggregate. Synthetic aggregates are made by mineral carbonation and can provide essentially permanent storage of CO_2 from either flue gas or pure CO_2 streams. They can also serve as disposal for other industrial wastes, such as fly ash, steel slag, and cement kiln dust.

Potential CO_2 utilization by 2050:



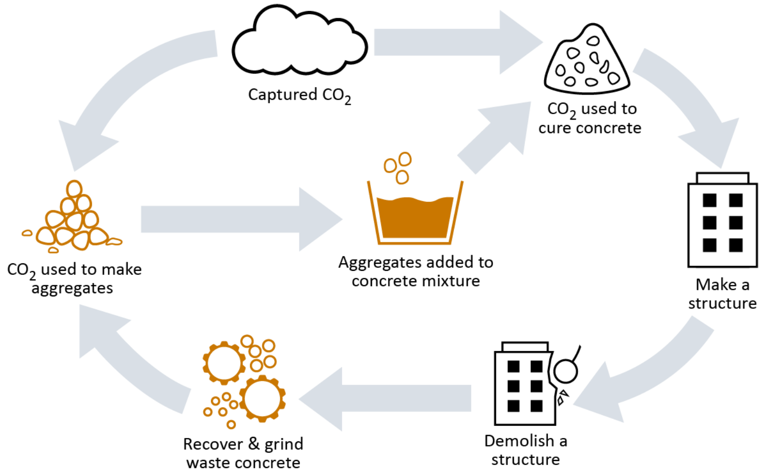
Cost comparison:



Maximum maturity: (TRL)

Source: GAO analysis of C. Hepburn et al., “The Technological and Economic Prospects for CO_2 Utilization and Removal,” *Nature*, vol. 575 (2019); V. Sick, G. Stokes, and F. C. Mason, “CO_2 Utilization and Market Size Projection for CO_2-treated Construction Materials,” *Frontiers in Climate*, vol. 4 (2022). | GAO-22-105274

According to trade groups, a circular economy for concrete is a key step towards CO_2 emissions reduction in the building industry. For example, CO_2 captured from cement manufacturing facilities could create synthetic aggregates or could recarbonate concrete waste for recycled aggregates.



Source: GAO. | GAO-22-105274

Challenges

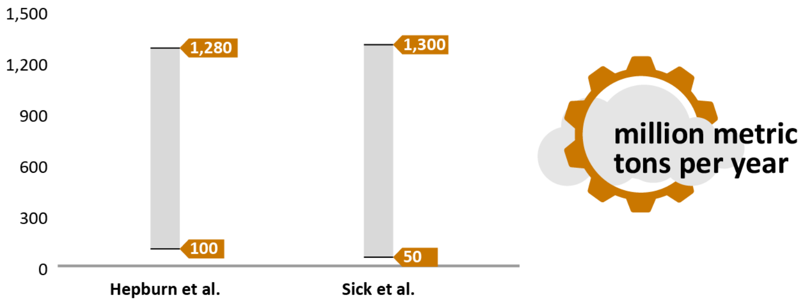
- Availability of the waste materials currently used as feedstocks, such as fly ash or steel slag, may decline if levels of coal mining, coal-fired power generation, or primary steel production decrease.
- May not be cost-competitive with mined or recycled aggregates.
- May not always mitigate more CO_2 emissions than other aggregate types. For example, CO_2 emissions from transporting synthetic aggregates to a construction site might be higher than CO_2 emissions from producing recycled aggregates from construction waste.

Source: onlyyouqj/stock.adobe.com

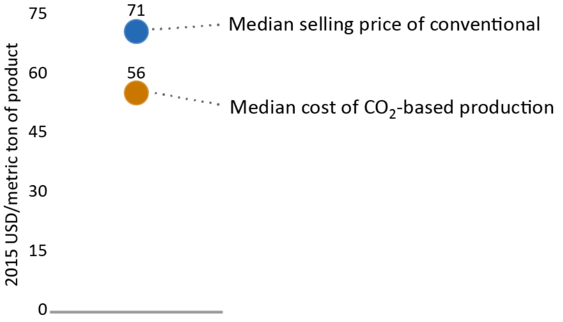
CO_2-Cured Concrete

CO_2-cured concrete retains CO_2 for millions of years and may be price competitive with conventional concrete. Concrete is a mixture of aggregates, cement, and water. The curing process converts cement into interlocking crystals which bind the elements of concrete together. Though CO_2 can be mixed directly with traditional cements in a concrete mixer, fully CO_2-cured concrete uses non-traditional cements that are cured in CO_2 chambers as precast concrete blocks. This process can use flue gas directly, which simplifies both carbon capture and utilization. Furthermore, some demonstrations have shown that CO_2-cured concrete is stronger than traditional concrete.

Potential CO_2 utilization by 2050:



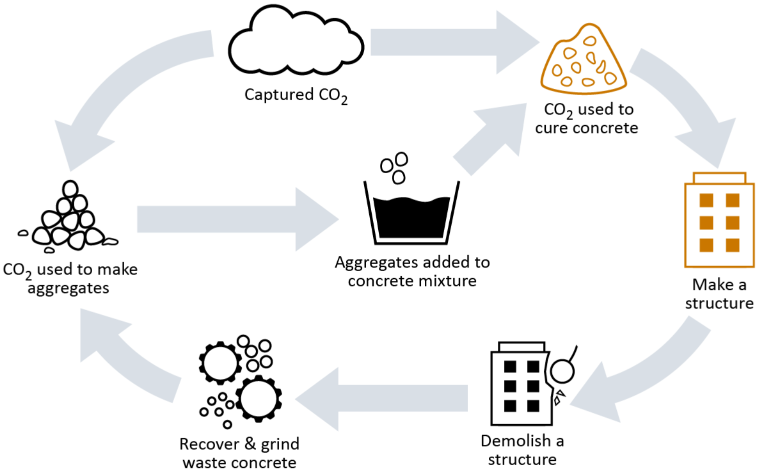
Cost comparison:



Maximum maturity: (TRL)

Source: GAO analysis of C. Hepburn et al., “The Technological and Economic Prospects for CO_2 Utilization and Removal,” *Nature*, vol. 575 (2019); V. Sick, G. Stokes, and F. C. Mason, “CO_2 Utilization and Market Size Projection for CO_2-treated Construction Materials,” *Frontiers in Climate*, vol. 4 (2022). | GAO-22-105274

According to trade groups, a circular economy for concrete is a key step towards CO_2 emissions reduction in the building industry. For example, CO_2 captured from cement manufacturing facilities could cure precast concrete blocks for new buildings or roads.



Source: GAO. | GAO-22-105274

Challenges

- Usually uses nontraditional cements, which may not be allowed under current prescriptive building standards.
- Fully CO_2-cured concrete is currently only available as precast concrete products, which is a small portion of the global concrete market (approximately 30 percent).
- Quantification of CO_2 benefits for CO_2-cured concrete is difficult, and independent life cycle assessments have not confirmed that it results in an overall net reduction in emissions.

Commodity Chemicals and Fuels

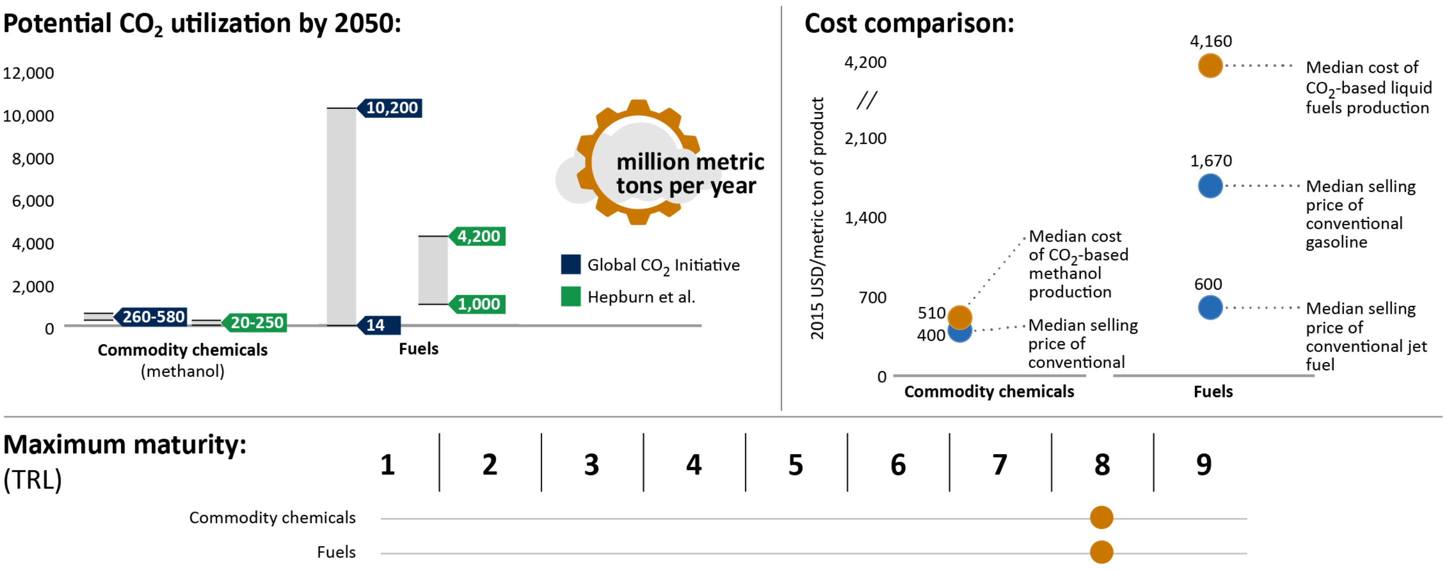
Source: Photoagriculture, Milan/stock.adobe.com

Commodity Chemicals

Certain carbon containing chemicals can be made from captured CO_2 instead of fossil fuels, thereby reducing emissions. Examples of CO_2-based commodity chemicals include urea, methanol, salicylic acid, and ethylene. Alcohols such as methanol or ethanol can be made from CO_2 through either chemical or microbial conversion pathways and then converted into many commodity chemicals using conventional processes. CO_2-based formic acid and methane could also serve as gateways to certain commodity chemicals.

Fuels

Fuels have a large CO_2 utilization potential due to their vast market size, according to multiple estimates. Fuels can either be gases or liquids, including methane, methanol, and gasoline. While energy sources such as electricity or hydrogen fuel cells could decarbonize cars, CO_2-based fuels could be used for sectors that are harder to decarbonize, such as aviation and maritime transportation. CO_2-based fuels are drop-in solutions that have the same energy density as existing fuels and, unlike electricity and hydrogen, do not present a major need for new infrastructure.



Source: GAO analysis of The Global CO_2 Initiative (GCI) and Lux Research, *Implementing CO_2 capture and utilization at scale and speed.* https://dx.doi.org/10.7302/5825; C. Hepburn et al., "The Technological and Economic Prospects for CO_2 Utilization and Removal," *Nature*, vol. 575 (2019). | GAO-22-105274

Note: Estimated cost of CO_2-based production of liquid fuels is determined for a specific process known as Fischer-Tropsch. For more information on this process, see app. V. Commodity chemicals maturity does not include urea or algae-based products.

Challenges

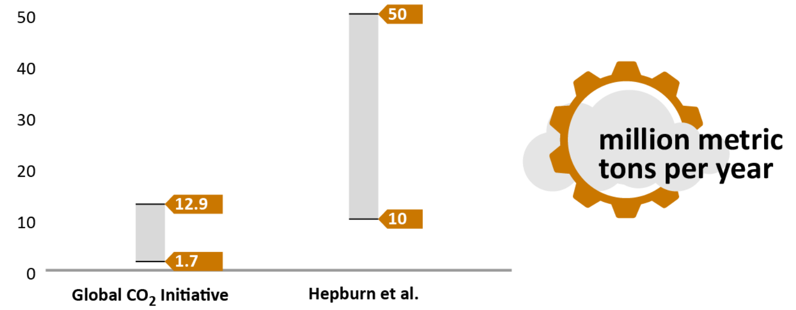
- CO_2 is retained for less than 1 year for fuels and for up to 10 years for most commodity chemicals.
- Greater availability of CO_2-derived chemicals and fuels could lead to increased consumption of those resources, which may divert CO_2 from products with longer retention times, such as building materials.
- The use of CO_2-based methanol as a gateway to other chemicals would require large amounts of additional infrastructure to deliver necessary inputs (e.g., electricity, hydrogen, and CO_2) to produce CO_2-based commodity chemicals at current global scales.
- CO_2-based fuels may not qualify for some incentives, and thus may not be able to compete with other fuels that do.

Polymers

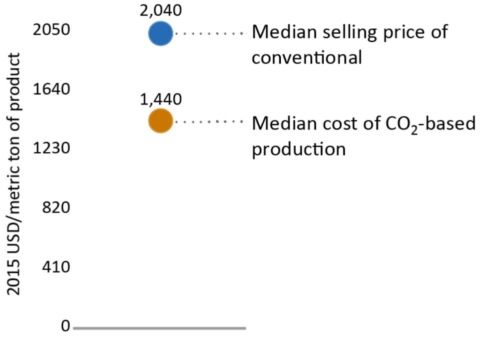
Source: ink drop/stock.adobe.com

CO_2-based polymers are at commercial scale, cost less to make than the selling price of conventional, and can retain CO_2 for tens to hundreds of years. Polymers are the basis of many modern materials, including plastics, foams, and resins. For polymers such as polyols and polycarbonates, it is possible to replace some fossil fuel-based feedstock with CO_2 during manufacture. CO_2-based polyols are currently used in the production of polyurethane, which in turn is used to make products such as foam mattresses, low-impact sports floors, and foams for cars. CO_2-based polycarbonate production is also safer than conventional polycarbonate production because it avoids the use of a toxic chemical.

Potential CO_2 utilization by 2050:



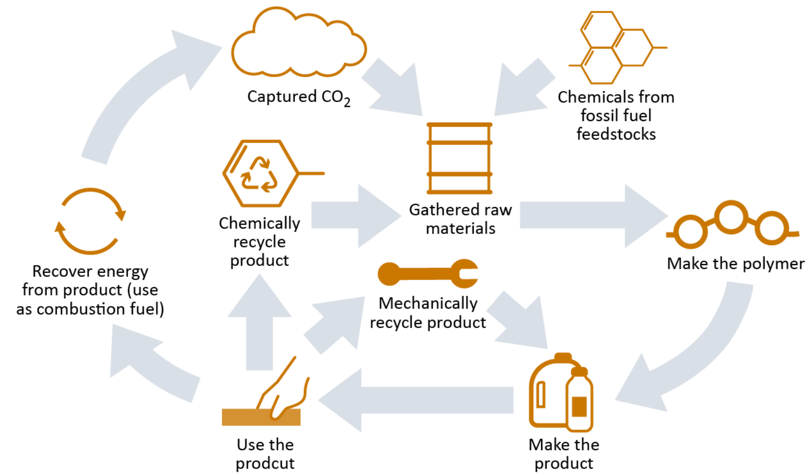
Cost comparison:



Maximum maturity:
(TRL)

Source: GAO analysis of The Global CO_2 Initiative (GCI) and Lux Research, *Implementing CO_2 capture and utilization at scale and speed.* https://dx.doi.org/10.7302/5825; C. Hepburn et al., "The Technological and Economic Prospects for CO_2 Utilization and Removal," *Nature*, vol. 575 (2019); National Academies of Sciences, Engineering, and Medicine, *Gaseous Carbon Waste Streams Utilization: Status and Research Needs* (Washington, D.C.: the National Academies Press, 2019). | GAO-22-105274

There are multiple ways for polymers to be incorporated into a circular economy. In addition to traditional mechanical recycling, plastics could be chemically recycled to recover polymer feedstocks or burned as fuel with the resulting CO_2 captured and reused to make new polymers.



Source: GAO. | GAO-22-105274

Challenges

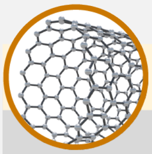
- Production of polycarbonate polyols currently occurs at smaller scale than conventionally produced polymers.
- Though polymers are high value materials, they have smaller market potential than some commodity chemicals or fuels.
- Fossil fuel-based feedstocks would still be needed for 50 to 80 percent of polymer production.
- Other types of nonpolyol CO_2-based polymers are still in the research phase.

Looking forward: Elemental carbon materials

Technologies that convert carbon dioxide (CO_2) to elemental carbon products—such as carbon fiber, carbon nanotubes, and diamonds—are emerging as an area of interest. Some of these products are starting to enter the market, but face technical challenges related to scalability and the use of energy intensive reaction conditions.

Carbon fiber

- **Example applications:** Airplane wings, wind-turbine blades
- **Potential benefits:** Significant potential CO_2 utilization volumes (about 0.1 million metric tons/yr) in building materials
- **Challenges:** Uncertain scale and time to market (10+ years)



Carbon nanotubes

- **Example applications:** Sports gear, water filters, energy storage
- **Potential benefits:** Replacement for nanotubes currently made from fossil fuel-based carbon monoxide
- **Challenges:** Limited applications compared to carbon fibers, small current market size

Diamonds

- **Example applications:** Jewelry, drills
- **Potential benefits:** Can be made with CO_2 from direct air capture and carbon-free energy
- **Challenges:** Energy intensive production

Sources: (text) GAO analysis of scientific literature; (photos left to right): frog, evannovostro, www3D/stock.adobe.com. | GAO-22-105274

Source: GAO analysis of scientific literature. | GAO-22-105274

3.4 Challenges to deployment of CO_2 conversion technologies

We identified three near-term challenges to scaling up technologies for CO_2 conversion: many products are not currently price-competitive, they may not be allowed under current relevant standards, and life cycle assessments are needed to ensure that production results in *reduction* or *avoidance* of CO_2 emissions.

3.4.1 Many products are not price-competitive

Many CO_2-based products are not currently price-competitive with their conventional counterparts in the market. Building materials have low selling prices and low profit margins, which makes it difficult for CO_2-based materials to compete. Although CO_2-cured concrete can have a lower cost of production than the selling price of conventional concrete, the cost of transportation could eliminate any competitive advantage. Some CO_2-based products cost less to produce than the conventional product selling price.[19] However, others such as CO_2-based commodity chemicals and fuels, currently have higher production costs than the selling price of their conventional counterparts.

There are two main factors contributing to the high production costs of CO_2-based

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[19] Polyol polymers, algae-based nutraceuticals, electrochemically produced carbon monoxide, and CO_2-mixed concrete have lower estimated costs of production compared to conventional product selling price.

chemicals and fuels. The first is the need for abundant, inexpensive low-carbon energy for chemical conversion, which can account for 40 to 70 percent of production costs.[20] CO_2 conversion pathways that do not use low-carbon energy sources may result in net life-cycle increases in CO_2 emissions instead of reductions. While reports predict that on-grid renewable energy will be less expensive in the future, other uses of this energy may prove more efficient at CO_2 emissions reduction than CO_2-based chemical production.[21] See the text box for possible ways to address electricity costs for CO_2 conversion technology.

Electricity cost solutions

We identified two possible approaches that may help to reduce the effects of electricity cost on the cost of carbon dioxide (CO_2) chemical conversion. The first is building chemical conversion facilities near a low-carbon electricity source, a low-cost clean source of hydrogen, and an appropriate CO_2 gas stream. A few international facilities producing CO_2-based methanol or methane have had financial success with this approach. The second approach, known as "power-to-X," is to use off-grid renewable energy such as wind or solar to produce resources that store the energy in a more transportable state. These resources could include methane ("power-to-methane" or "power-to-gas") or liquid fuels ("power-to-fuel" or "power-to-liquids"). According to an academic researcher, synthetic liquid fuels could transport more energy through pipelines than a power line while avoiding intermittency issues currently associated with renewable energy.

Source: GAO analysis of scientific literature. | GAO-22-105274

A second reason for the high production costs of chemical conversion technologies is that many conversion pathways require *clean hydrogen* to prevent additional CO_2 emissions. Production of clean hydrogen emits little to no CO_2 but can be expensive. One possible way to address this issue is to integrate chemical conversion technologies into *clean hydrogen hubs* (see text box).

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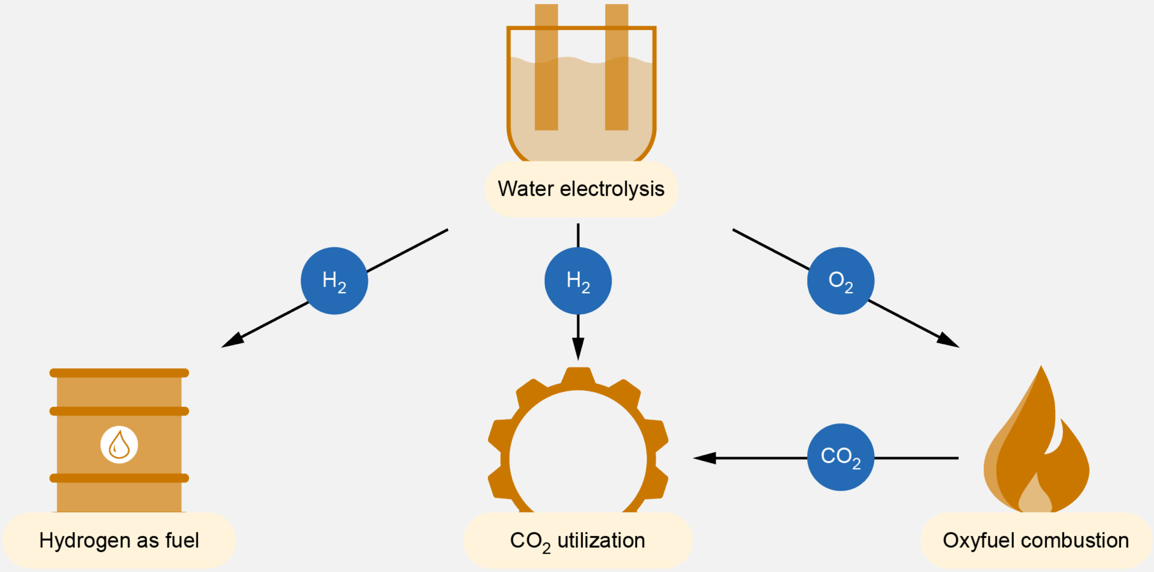
[20] These data are based on actual production of CO_2-based methanol and methane and estimated from a recent study of many other products.

[21] For example, see IEA, *Putting CO_2 to Use*, 44; C. Hepburn et al., "The technological and economic prospects for CO_2 utilization and removal," *Nature*, vol. 575 (2019): 91; and A. Kätelhön et al., "Climate change mitigation potential of carbon capture and utilization in the chemical industry," *PNAS*, vol. 116, no. 23 (2019).

Carbon dioxide (CO_2) conversion and clean hydrogen hubs

The recently enacted Infrastructure Investment and Jobs Act provided $8 billon to support the development of at least four regional clean hydrogen hubs which could be developed into a clean hydrogen network.[a] There are multiple ways CO_2 chemical conversion technologies can be integrated into such hubs. Currently, the most common way to produce hydrogen also emits CO_2. In a clean hydrogen hub, the CO_2 emitted from this process could be captured and combined with the clean hydrogen to produce ethanol, plastics, or sustainable aviation fuel. Another way to generate clean hydrogen—known as water electrolysis—also generates oxygen, which is currently emitted as waste. This process is expensive, but a market for oxygen could provide an additional source of revenue. For example, oxygen from water electrolysis could be used for oxyfuel combustion carbon capture (see ch. 2). Figure 8 illustrates the integration between hydrogen production, carbon capture, and CO_2 conversion that could exist at a clean hydrogen hub.

Figure 8: Example of a clean hydrogen hub integrated with carbon dioxide (CO_2) conversion



Source: GAO. | GAO-22-105274

[a] Infrastructure Investment and Jobs Act, Pub. L. No. 117-58, § 40314, div. J, tit. III,135 Stat.429, 1008-10, 1378 (2021).

Source: GAO analysis of interviews and scientific literature. | GAO-22-105274

One way to offset high production costs is to guarantee a market through preferences for CO_2-based products. Several countries, most recently including the U.S. with the Inflation Reduction Act of 2022, have created such preferences through their public procurement policies.[22] Because the U.S. federal government is often involved with large infrastructure projects, implementation of public procurement policies for CO_2-based products could help create a large market for building materials that have verified lower life-cycle CO_2 emissions than conventional

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[22] Pub. L. No. 117-169, §§ 60503, 60506, 136 Stat. 1818, 2083, 2085-86. Section 70006 of the act also authorizes financial assistance under portions of Robert T. Stafford Disaster Relief and Emergency Assistance Act for costs associated with low-carbon materials.

products.[23] Similar policies could be an option for state level infrastructure projects. Furthermore, private companies could also institute their own version of procurement policies through purchase agreements. For example, one U.S.-based airline recently made a formal commitment to purchase 300 million gallons of sustainable aviation fuel made from CO_2 conversion pathways over the next 20 years.

3.4.2 Current standards may exclude CO_2-based products

Products resulting from CO_2 conversion may not be allowed under current common standards. These standards are often *prescriptive*—requiring, for example, that the materials in concrete mixtures be used in specific proportions like a recipe. Concrete may not meet these standards if it is cured using CO_2 instead of water. In contrast, *performance-based standards* are based on the characteristics of building materials, such as compressive strength. Performance standards for concrete exist and may allow for the use of CO_2-based concrete, but are less common because they can be harder to verify.

Similarly, experts told us that existing standards for fuels may not equally incentivize all CO_2 reduction strategies. For example, algal biofuel qualifies as an advanced biofuel under the U.S. Renewable Fuel Standard (RFS), while CO_2-based fuels made from non-biological sources of CO_2 do not.[24] Stakeholders told us that the RFS and an international standard for aviation fuel can be barriers to CO_2-based fuels deployment.[25]

Creation and adoption of technology-neutral standards—standards based on desired outcomes rather than specific metrics or processes—could lead to incentivizing whichever technology results in the best CO_2 benefits with the fewest costs. For example, low-carbon fuel standards can incentivize innovation in alternative fuel development by requiring fuels to meet CO_2 emissions targets in a specific time frame instead of specifying a source material.[26]

3.4.3 Lack of standardized life cycle assessment guidelines

There is a lack of agreed-upon guidelines for determining whether a given CO_2-based product has the intended effect of mitigating CO_2 emissions. Life cycle assessments can serve as a framework to measure the net CO_2 benefits of a conversion process. However, according to the International Energy Agency (IEA), current life cycle assessment guidance from the International Standards Organization (ISO) 14000 series does not adequately account for considerations specific to CO_2 conversion, such as retention of CO_2 within

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[23] The Inflation Reduction Act of 2022 includes an appropriation to the Administrator of the EPA for administrative costs to develop and carry out a program to identify and label construction materials and products that have substantially lower levels of embodied greenhouse gas emissions. § 60116, 136 Stat. at 2077-78.

[24] 42 U.S.C. § 7545(o).

[25] The aviation standard is the International Civil Aviation Organization's Carbon Offsetting and Reduction Scheme for International Aviation, or CORSIA. Currently, only waste CO_2 converted to ethanol by microbial conversion then to aviation fuel ("alcohol-to-jet") qualifies.

[26] The recently enacted Inflation Reduction Act of 2022 establishes tax credits to incentivize production of clean fuels including sustainable aviation fuels with a broader definition than the RFS. § 13203, 136 Stat. at 1932-35. The tax credit is not a mandatory standard.

the product.[27] Some organizations have proposed updated life cycle assessment guidelines for CO_2 utilization, but they have not yet been widely adopted.

The wide variety of CO_2-based products on the market makes it challenging to establish a common method of analyzing life cycle emissions. In addition, it is not clear how to estimate the resulting emissions reduction because it is also difficult to estimate CO_2 emissions for the conventional products that would be replaced.[28] Without clear guidance addressing these points of variability, determination of emissions reduction will be conducted on a subjective, case-by-case basis by (or on behalf of) the company seeking a life cycle assessment of their product.

Reports and experts have described several desirable characteristics of a standardized life cycle assessment process. They include transparency, clear sets of assumptions on input data, clear system boundaries, and a clear comparative reference for each product type.

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[27] Some current life cycle assessment guidelines prescribe the use of a constant 100-year period for determining CO_2 emissions. While this would not affect products such as CO_2-based building materials that store CO_2 for millions of years, products that retain CO_2 for less than 100 years, such as CO_2-based alcohols and fuels would need to account for the release of the CO_2 back into the atmosphere.

[28] For example, methanol is currently produced from a range of pathways, including natural gas reforming and coal gasification, which have different levels of associated CO_2 emissions.

3.5 Policy options

Technology-neutral standards. Policymakers could encourage the creation, adoption, or use of technology-neutral standards (e.g., performance based building standards, low-carbon fuel standards).

This policy option could address the exclusion of CO_2-based products by current standards.

Potential implementation approaches:

For building materials, encourage the use of performance-based standards in construction.

For fuels, encourage the creation of state or federal standards based on the desired outcome (CO_2 emissions reduction) rather than feedstock, technology, or other contributing factors.

Opportunities	Considerations
By rewarding outcomes instead of specific technologies, technology-neutral standards could incentivize the development or use of products with the best CO_2 benefits. Could incentivize manufacture in the U.S. instead of abroad. For building materials, federally acknowledged performance-based standards could assist state agencies in charge of implementation.	Standards development is a resource-intensive and lengthy process. Without standardized life cycle assessments, it could be difficult to compare net CO_2 benefits of different products. To ensure performance-based standards are met, materials need to be assessed, which is more complicated than following a prescribed recipe. Predictive models may be necessary to determine the performance of CO_2-based materials in the far-term.

Standardized life cycle assessment guidelines. Policymakers could support the creation and use of standardized life cycle assessment guidelines to validate CO_2 benefits of CO_2-based products.

This policy option could address the lack of standardized life cycle assessment guidelines.

Opportunities	Considerations
Could improve accuracy of comparisons between various CO_2 utilization pathways or products.	Standards development and life cycle assessment are resource-intensive and lengthy processes. Coordination of many stakeholders to establish standardized life cycle assessment guidelines may be challenging. As many CO_2-based products are globally traded, it may be necessary but challenging to reach a global consensus on optimal life cycle assessment guidelines.

Source: GAO. | GAO-22-105274

4 Transport, Storage, and Infrastructure

CCUS is a complex process with multiple interdependent components: a system of systems. Carbon capture does not reduce emissions or remove CO_2 if it is vented back into the atmosphere rather than stored or used. Although many of the necessary technologies are mature, including those for transporting and storing CO_2, the CCUS industry is in its infancy. Scale-up would require an increase in capture, pipeline, and storage infrastructure—each of which can take years to develop. Several intertwining challenges can affect the cost and feasibility of this scale-up, including timing, negotiating with landowners for access, and the proximity of capture facilities to storage sites.

4.1 Transport

Pipelines are the most common and least expensive way to transport large volumes of CO_2, but the majority of current infrastructure supports enhanced oil recovery using CO_2 from underground, not from carbon capture.[29] As of 2020, the U.S. had over 5,000 miles of CO_2 pipeline, according to the most recent data from the Pipeline and Hazardous Materials Safety Administration (PHMSA). To achieve widespread deployment of CCUS, several reports indicate that the U.S. would need tens of thousands of additional miles of CO_2 pipeline infrastructure.[30] Although these pipelines are a mature technology and have been used safely at a commercial-scale in the U.S. since 1972, a recent accident prompted PHMSA to announce new measures to strengthen its safety oversight of CO_2 pipelines.[31] Figure 9 shows the current locations of CO_2 pipelines in the U.S. and example estimates of future pipeline needs.

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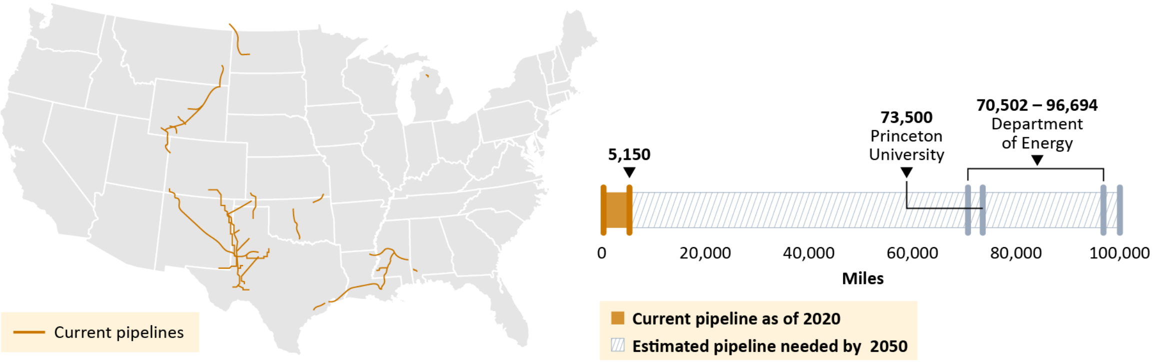
[29] Other methods of transporting CO_2, such as by truck, rail or ship, may be viable for small volumes or short distances. Transporting large volumes of CO_2 by truck or rail is not economical. Transportation by ship is not widely deployed, but is more economical than pipelines for transporting small volumes across large bodies of water.

[30] E. Larson et al., *Net-Zero America: Potential Pathways, Infrastructure, and Impacts, Final Report* (Princeton, N.J.: Princeton University, Oct. 29, 2021); Great Plains Institute, *Transport Infrastructure for Carbon Capture and Storage* (June 2020); Department of Energy, *Carbon Capture, Transport, & Storage – Supply Chain Deep Dive Assessment* (Feb. 24, 2022).

[31] In 2020, a landslide near Satartia, Mississippi ruptured a CO_2 pipeline. Two hundred nearby residents were evacuated and 45 were hospitalized. PHMSA, *Failure Investigation Report – Denbury Gulf Coast Pipelines LLC Pipeline Rupture/Natural Force Damage* (Washington, D.C.: May 26, 2022).

Figure 9: Current and estimated carbon dioxide (CO_2) pipelines in the U.S. by 2050



Source: GAO analysis of Department of Energy and Princeton University data. | GAO-22-105274

CO_2 pipeline transportation costs will generally decrease as the capacity of the pipeline increases. According to a 2020 report, transporting CO_2 through a network of large, shared pipelines would be less expensive per ton than transporting it through many smaller pipelines that connect individual facilities to storage opportunities.[32]

CO_2 pipeline infrastructure can take years to develop. States regulate the siting of pipelines on nonfederal lands, and their requirements for siting approval vary. When a proposed CO_2 pipeline crosses federal land, it triggers a National Environmental Policy Act review, which prolongs the development process.[33]

4.2 Storage

The U.S. has abundant potential geologic storage opportunities for CO_2, but in some regions this potential storage may not be practical to develop for various reasons, including technical limitations and lack of economic viability. Developing these storage sites can take several years and millions of dollars per site. Saline formations account for more than 95 percent of potential storage, according to DOE. Depleted oil and gas reservoirs are less abundant but are already well understood.[34] (See fig. 10 for a map of potential storage opportunities.)

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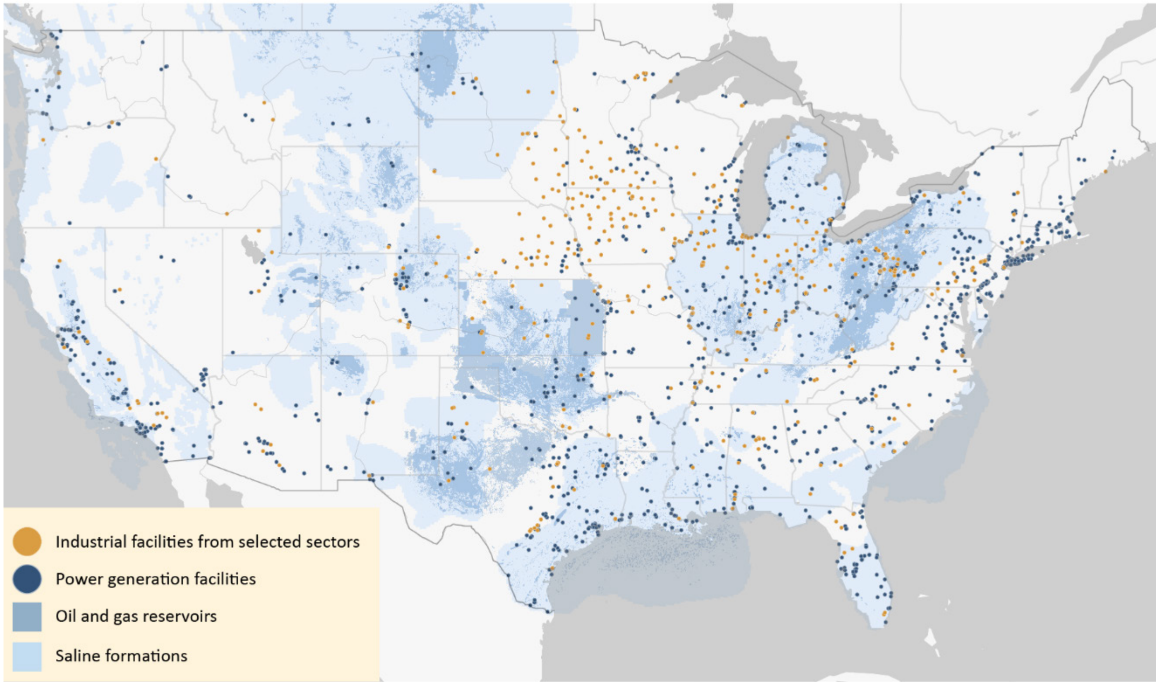
[32] Great Plains Institute, *Transport Infrastructure for Carbon Capture and Storage*.

[33] On February 16, 2022, the Council on Environmental Quality issued interim guidance encouraging agencies to facilitate efficient, orderly, and responsible deployment of CCUS projects, including developing programmatic reviews under the National Environmental Policy Act of 1969. Carbon Capture, Utilization, and Sequestration Guidance, 87 Fed. Reg. 8808 (Feb. 16, 2022).

[34] Other geologic options, such as shales, coal beds, and basalts may offer additional opportunities but have not been extensively developed.

Figure 10: Potential storage and emitting facilities from selected industrial sectors



Sources: National Energy Technology Laboratory (storage); Environmental Protection Agency (facilities); Esri, HERE, Garmin, FAO, NOAA, USGS, © OpenStreetMap contributors, and the GIS User Community (map). | GAO-22-105274

Note: Industrial facilities shown on this map are from the cement, iron and steel, and bioethanol production industries.

CO_2 storage in these formations is generally considered to be safe and secure when a storage facility is carefully sited and operated. Naturally occurring CO_2 has remained trapped underground for millions of years. Industrial-scale projects have successfully injected or stored CO_2 underground in geologic formations since the 1970s. Combined experience from successful commercial and research projects and naturally trapped CO_2 provide evidence that underground geologic storage of CO_2 can be safe, secure, and permanent, according to the National Energy Technology Laboratory.[35]

The IEA estimates that more than half of onshore storage in the U.S. costs less than $10 per ton of CO_2, but storage costs can vary significantly (see fig. 11). Cost depends on the location and characteristics of each storage site, including the number of wells needed, the depth of the underground storage formation, and what the land around the storage site is already used for.

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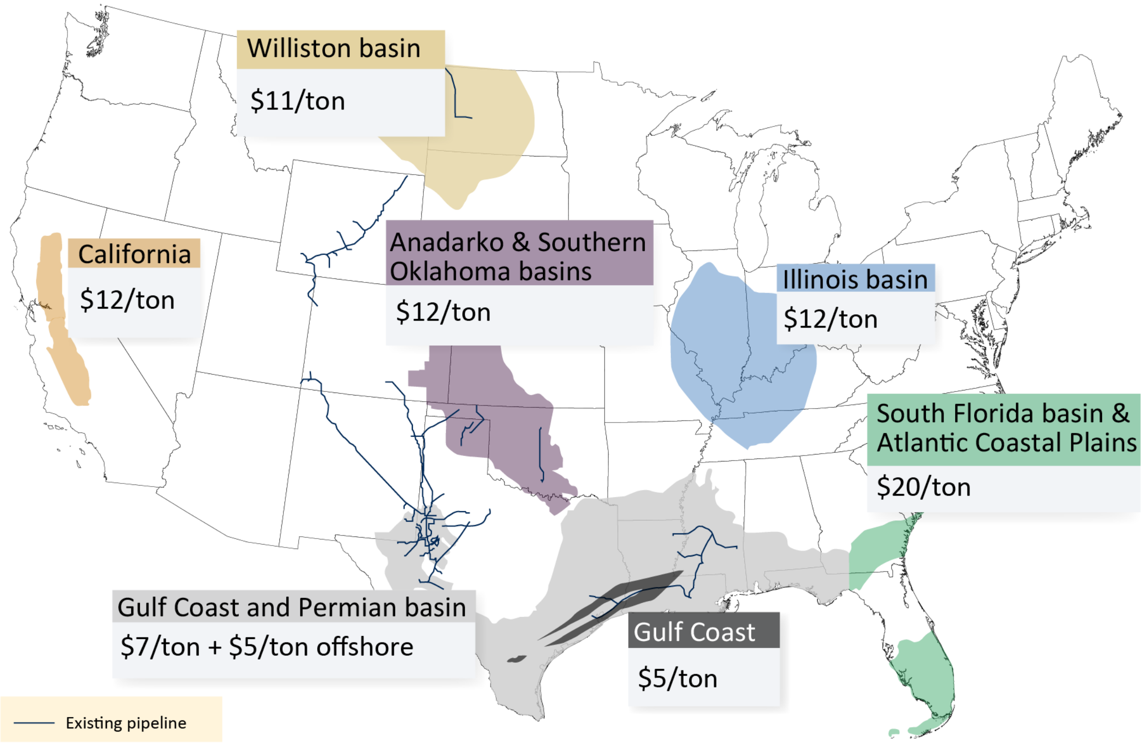
[35] T. Warner et al., *Overview of Potential Failure Modes and Effects Associated with CO_2 Injection and Storage Operations in Saline Formations,* DOE/NETL-2020/2634, (Pittsburgh, Pa.: National Energy Technology Laboratory, Oct. 16, 2020).

Figure 11: Estimated storage costs per ton of carbon dioxide (CO_2) in seven U.S. regions



Source: Princeton University, *Net-Zero America: Potential Pathways, Infrastructure, and Impacts, Final Report* (2021). | GAO-22-105274

Projects seeking to inject CO_2 into formations for permanent storage are subject to EPA's Class VI Rule and must obtain a Class VI permit.[36] Although some stakeholders expressed concern over the time it took past developers to receive a Class VI permit, others told us that this timeline will improve now that the Infrastructure Investment and Jobs Act has authorized additional funding for EPA permitting of Class VI wells and a grant program for state enforcement.[37] As of 2022, EPA had issued permits for two active Class VI injection wells, which took at least 3 years per permit. Interest in permits has increased, with 25 permit applications pending as of August 2022. EPA officials told us they are streamlining the permitting process. While there are many factors that influence permitting timeframes, EPA officials anticipate that prospective owners or operators submitting complete Class VI applications will be issued permits in approximately 2 years.[38]

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[36] Class VI wells are used to inject CO_2 into deep rock formations for long-term storage. The Class VI injection well classification was established by the Federal Requirements under the Underground Injection Control Program for Carbon Dioxide (CO_2), 75 Fed. Reg. 77230 (Dec. 10, 2010), referred to as the Class VI Rule, which established requirements to protect underground sources of drinking water from long-term storage of CO_2. These include requirements for siting, constructing, operating, testing, monitoring, and closing an injection site.

[37] Infrastructure Investment and Jobs Act, Pub. L. No. 117-58, § 40306, 135 Stat. 429, 1002 (2021).

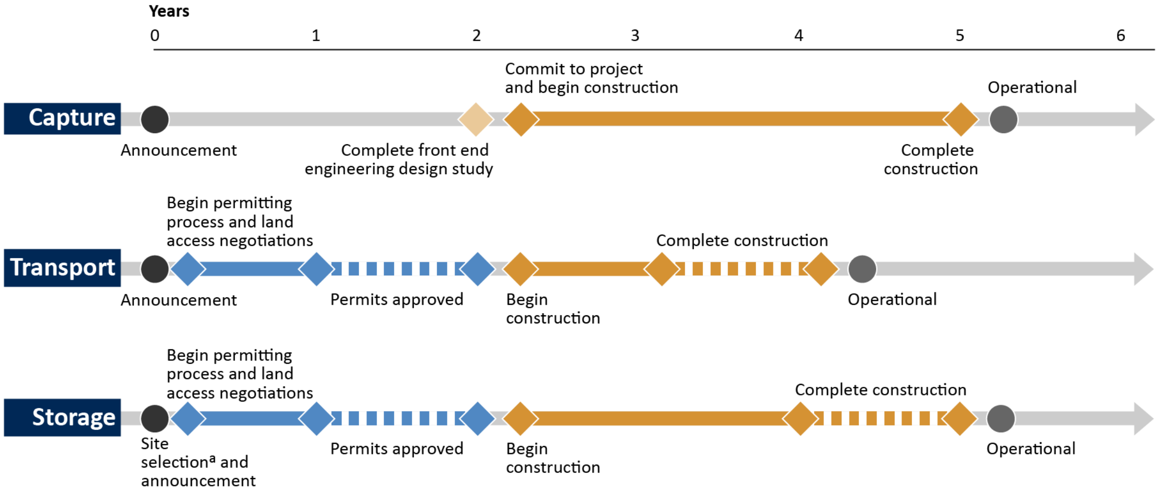
[38] States may apply for primary enforcement authority, or primacy, for the Class VI well program. North Dakota and Wyoming have primacy for Class VI wells as of August 2022. After being granted primacy in 2018, North Dakota issued two

4.3 Challenges affecting infrastructure development

4.3.1 Timing of development

Developing the necessary infrastructure presents a chicken-and-egg problem: CO_2-emitting industries hesitate to deploy capture technologies if there is no infrastructure to transport and store the captured CO_2, but development of such infrastructure is risky if industry is not already capturing CO_2. It can take years to plan, permit, and build infrastructure for capturing, transporting, and storing CO_2 (see fig. 12). Developing this infrastructure in parallel rather than in sequence could accelerate deployment of the CCUS industry as a whole, according to stakeholders.

Figure 12: Optimistic timeline to develop and deploy carbon dioxide (CO_2) capture, transport, and storage infrastructure



Source: GAO analysis of stakeholder interviews, expert discussions, and reports. | GAO-22-105274

[a]Site screening, selection, and characterization can take more than 4 years.

Class VI permits, which took less than 1 year each. However, we did not examine whether Class VI primacy could expedite the permitting process more generally.

4.3.2 Negotiating private land access

Generally, developers must negotiate land access for both transportation and storage infrastructure, which can be costly. Transport and storage developers may have to negotiate with hundreds to thousands of land owners, depending on location and the distance between the capture and storage sites.[39] These negotiations can be complicated for storage developers in states that have not explicitly defined who owns the underground pore space where CO_2 is injected. The majority of states do not have a regulatory framework for geologic CO_2 storage.[40] Fewer than half have defined pore-space rights. Furthermore, only a few allow unitization for CO_2 storage—a process that allows operators to proceed with injection after reaching agreement with a minimum percentage of owners, rather than all landowners. Industry stakeholders and an expert said that unitization is a key tool for developing CO_2 storage projects in large areas, using the underground pore space efficiently, and ensuring that landowners benefit in an equitable way.

4.3.3 Proximity of capture facilities to storage sites

The distance between capture facilities and storage sites affects the cost and feasibility of transporting CO_2. Transportation costs are lower when capture facilities are co-located with storage. The majority of point-source emitters in the U.S. are within 30 miles of a potential geologic storage site according to IEA; however, not every potential site will be technically or commercially feasible. In such cases, emitters may need to pay more to transport CO_2 longer distances to storage sites that have already been established. A 2021 report estimated that with wider deployment, the majority of combined U.S. transport and storage costs by 2050 could be $40 or less per ton of $CO_{2,}$ with an average cost of $17-23 per ton of CO_2 (see fig. 13).[41]

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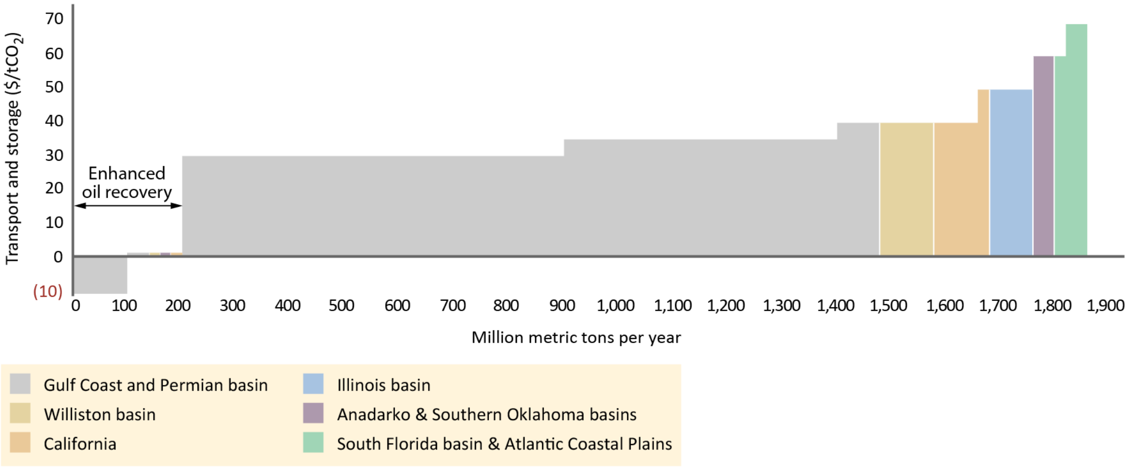
[39] Developing CCUS projects on public land could reduce negotiations. In February of 2022, the White House issued a press release listing actions to support CCUS deployment including the Department of the Interior working to establish safeguards for geologic sequestration on federally managed lands. In June of 2022, Interior issued an Instruction Memorandum conveying policy and direction for authorizing rights-of-way to use public lands for CCUS projects. This included authorizing the use of pore space managed by the Bureau of Land Management, even when the surface facilities are owned by a separate entity.

[40] R. L. Gresham and O. L. Anderson, "Legal and Commercial Models for Pore-Space Access and Use for Geologic CO_2 Sequestration," *University of Pittsburgh Law Review*, vol. 72 (2011); T. Gray, "A 2015 Analysis and Update on U.S. Pore Space Law – The Necessity of Proceeding Cautiously with Respect to the 'Stick' Known as Pore Space," *1 Oil and Gas, Natural Resources, and Energy Journal,* vol. 277 (2015); and Global CCS Institute, *Brief – Pore Space Rights – U.S. Overview* (May 2022).

[41] Larson et al., *Net-Zero America*.

Figure 13: Combined carbon dioxide (CO_2) transport and storage costs in the U.S.



Source: Princeton University, *Net-Zero America: Potential Pathways, Infrastructure, and Impacts, Final Report* (2021). | GAO-22-105274

4.4 Shared infrastructure

Shared infrastructure can help lower costs and provide additional benefits.[42] CCUS pipeline networks are an example of shared infrastructure that connect emitters that are geographically dispersed or far away from potential geologic storage sites. According to the IEA, 15 percent of point-source emissions in the U.S. come from sources that are not near a potential geologic storage site. These emitters could reduce their CO_2 transport costs by using networks of shared, larger pipelines (see fig. 14 for a summary of CO_2 pipeline networks).

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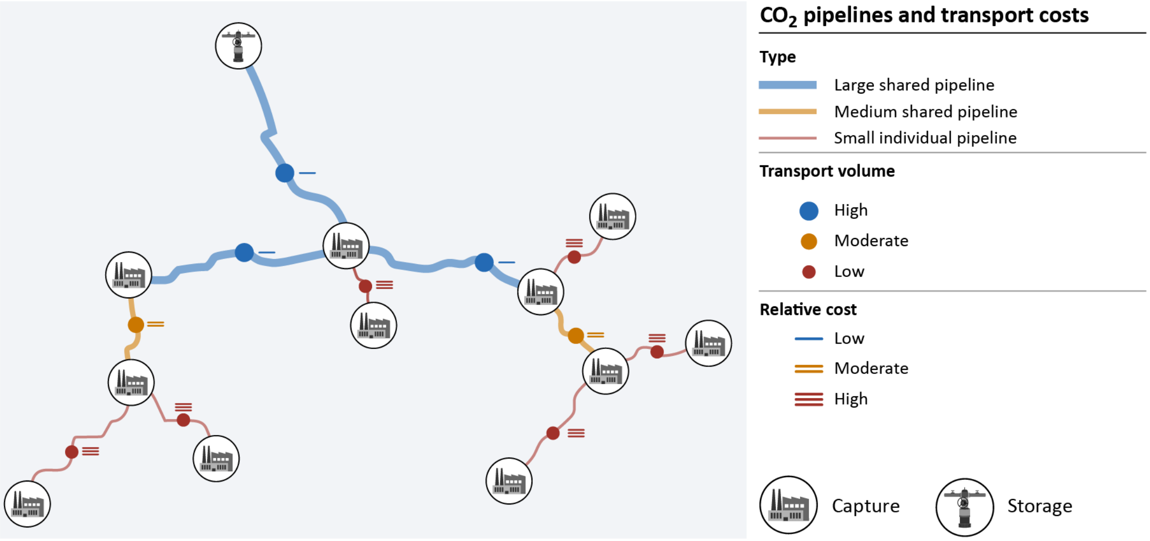
[42] Shared infrastructure can also present challenges. For example, shutting down or restricting shared pipeline operation would affect multiple emitters, according to agency officials.

Figure 14: Notional representation of pipeline networks



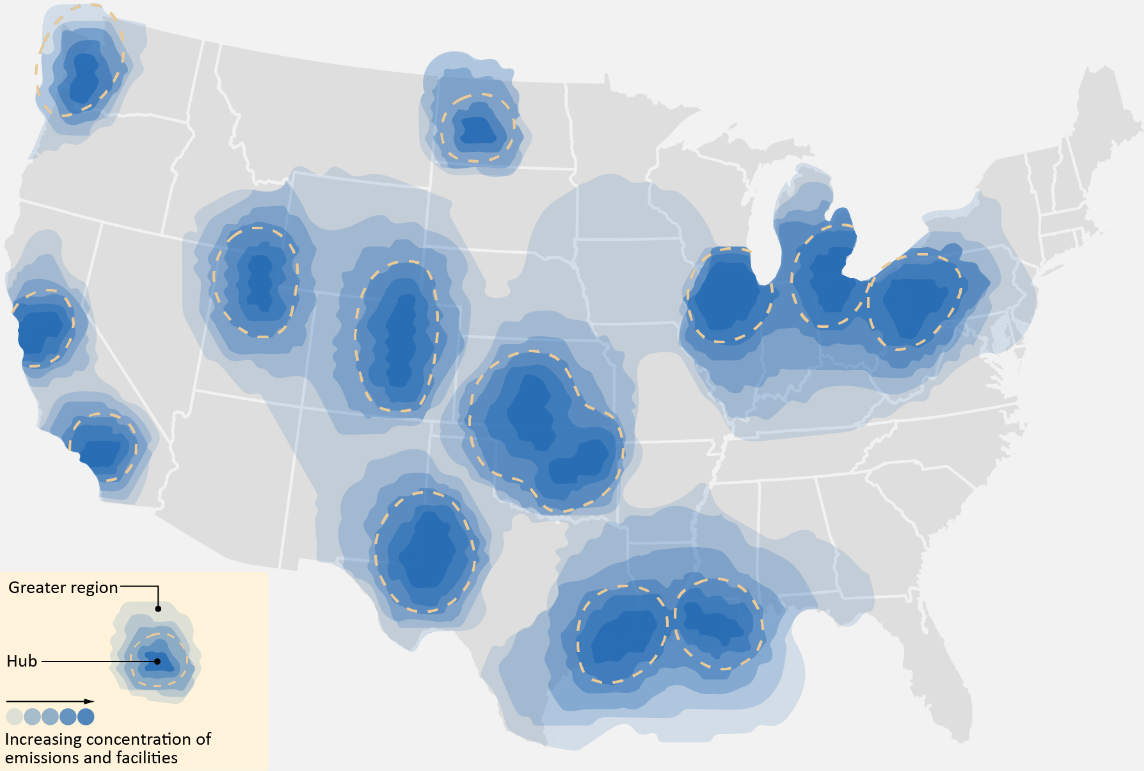
Source: GAO analysis of information from industry and non-governmental reports. | GAO-22-105274

CCUS "hubs" are another example of shared infrastructure that connect the components of the CCUS industry (see text box). They allow emitters that are concentrated near potential geologic storage sites to participate in CCUS without needing to develop their own transport and storage infrastructure, while providing several sources of CO_2 for transport and storage developers.

Hubs

Carbon capture, utilization, and storage (CCUS) hubs include central carbon dioxide (CO_2) collection or distribution points that share common infrastructure. Such hubs could help accelerate widespread deployment of CCUS, according to experts and reports. Some organizations have started identifying regions in the U.S. that could be suitable for hubs.[a] These regions have industrial facilities concentrated near potential geologic storage sites, along with other qualities such as ample energy production and commodity transportation infrastructure. Figure 15 presents an example of potential hub locations from one study.

Figure 15: Potential locations for carbon capture, utilization, and storage (CCUS) hubs



Source: Great Plains Institute, 2021. | GAO-22-105274

Potential benefits of hubs:

- ✓ Allow CCUS projects to share infrastructure and operation costs.
- ✓ Decrease investment risks.
- ✓ Make it easier for small-volume CO_2 capture projects to participate.
- ✓ Streamline planning and regulatory efforts; reduce negotiations with landowners.
- ✓ Minimize infrastructure impacts on the environment and communities.

Potential drawback:

- ✗ Increase project lead time because the development of hubs can be complex.

[a] For example, see: Great Plains Institute, *An Atlas of Carbon and Hydrogen Hubs for United States Decarbonization* (2022); Oil and Gas Climate Initiative, "The CCUS Hub" (launched March 3, 2022), accessed July 27, 2022, https://ccushub.ogci.com/ccus-hub-search/.

Source: GAO analysis of reports. | GAO-22-105274

4.5 Policy options

Framework for land access. Policymakers could support development of legal or regulatory frameworks to manage geologic storage of CO_2 at the state level.

This policy option could help address the challenge of lengthy negotiations for land access.

Potential implementation approaches:

Clarify state pore-space ownership rights.

Consider pore-space unitization processes for geologic storage of CO_2, which would allow storage projects to proceed through agreements with some minimum percentage of landowners.

Opportunities	Considerations
Legal or regulatory clarity could facilitate more rapid deployment of commercial-scale CO_2 storage infrastructure. Pore-space unitization processes for geologic storage of CO_2 could reduce the time and cost of negotiating land access for storage projects.	Individual landowners may oppose losing certain property rights due to pore-space unitization. CO_2 storage projects may cross state boundaries, so legal or regulatory frameworks established at the state level would likely require coordination between states or with federal agencies, which may have different goals or structures.

Strategic siting. Policymakers could facilitate strategic siting of carbon capture, utilization, and storage (CCUS) facilities.

This policy option could help address the challenges affecting infrastructure development.

Opportunities	Considerations
Strategic siting of infrastructure could minimize financial and logistical barriers to CCUS development. Carbon capture and utilization industries could accelerate deployment if access to necessary infrastructure increases.	Certain geographic regions that are inherently more suited for CCUS could benefit more than others from strategic infrastructure investments. Some communities may not want CCUS infrastructure. Project costs and community acceptance can vary depending on the level of involvement of various types of stakeholders in siting (e.g., industry, government, nonprofit).

Source: GAO. | GAO-22-105274

5 Economic Incentives

Little CCUS deployment has taken place to date, in part because it offers few opportunities to generate revenue. Some incentives that do exist, such as federal tax credits, have helped address the high cost of carbon capture in some industries that emit CO_2. The recently enacted Inflation Reduction Act of 2022 modified some existing incentives for CCUS and created new ones.[43] However, if decision makers would like to pursue widespread deployment, additional modifications to other incentives could further improve the economic and financial conditions for CCUS projects.

5.1 Economic and financial conditions for CCUS

For emitting facilities that could use point-source capture, deploying CCUS technology is an added cost to doing business that offers few opportunities to generate offsetting revenue. Currently, there is a small commercial market for CO_2—for example, for enhanced oil recovery, fertilizer production, and the food and beverage industry—and a growing interest in CO_2 conversion. Existing CCUS projects have largely been limited to sectors where the cost of capture was low and the captured CO_2 could be sold for use in enhanced oil recovery. All but one of the 12 operational CCUS projects in the U.S. earn revenue from the sale of CO_2 for enhanced oil recovery. However, current demand is too small to incentivize more widespread deployment of CCUS technologies.

Direct air capture systems are not tied to a facility that produces a conventional product, such as electricity or cement. Companies active in this nascent area are exploring possible revenue streams. These include selling CO_2 removal as a service to businesses or individuals interested in offsetting their emissions, either directly or through voluntary carbon markets, or selling captured CO_2 to utilization companies.

Similarly, there is little incentive to expand transportation and storage of CO_2. Existing CO_2 pipelines in the U.S. were primarily constructed to transport CO_2 for use in enhanced oil recovery; however, the majority of this CO_2 is extracted from underground rather than from carbon capture. Storing CO_2 does not generate revenue without financial drivers.

Table 9 summarizes the costs for carbon capture, transport, and storage per unit of CO_2. For sectors where capture is costly (e.g., power generation, iron and steel manufacturing), the cost of capture is the dominant factor influencing the overall cost of CCUS. For sectors where capture is relatively inexpensive (e.g., bioethanol production), the costs of transport and storage are a greater consideration. CCUS costs would likely decrease with more widespread deployment. The experience of implementing a technology at commercial scale under real-world conditions would help identify risks, optimize the system, and

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[43] E.g., Pub. L. No. 117-169, §§ 13104, 13801, 60503, 136 Stat. 1818, 1924-29, 2003-13, 2083.

develop viable business models. Studies have estimated that learning-by-doing could reduce capture costs. One report estimated learning-by-doing could reduce costs by half by mid-century under certain assumptions.

Table 9: Summary of carbon capture, transport, and storage cost per unit of CO_2

Component	Cost range per metric ton of CO_2	Cost factors
Capture	\$0-\$35 (sectors where CO_2 separation is part of the industrial process) \$40-\$290 (high-emitting point sources) \$100-\$600 (direct air capture)	CO_2 separation technology used Concentration of CO_2 in the gas stream Facility size (larger facilities have lower cost per metric ton) Flow rate of the gas stream
Transport	Less than \$10 to more than \$20	Distance between capture and storage/use sites Pipeline capacity
Storage	\$5-\$20	Location and characteristics of storage site (e.g., depth, number of wells needed)

Source: GAO analysis of peer-reviewed articles and other literature. | GAO-22-105274

Note: Costs are quoted from the literature not adjusted for inflation and are averaged over a project's operational lifetime.

The lack of economic return for many CCUS projects has affected the success of capture facilities and limited their deployment. We recently found that the DOE's investment of \$1.1 billion on nine large CCUS demonstration projects from 2010 to 2017 resulted in varying levels of success.[44] Projects implemented at coal facilities were generally less successful than those at other industrial facilities, largely due to external factors that affected their economic viability.

Other economic disincentives for wider CCUS deployment include risk to early adopters and difficulty attracting private investment. Companies may be reluctant to invest in early CCUS projects because of the possibility that competitors will benefit from the knowledge gained from those projects. Often, the knowledge gained from early research, development, and deployment benefits others and not the implementing company that undertook the greater risk.[45] In addition, CCUS projects often require significant upfront investment, but developers cannot access certain financing instruments that are available to other infrastructure projects. For example, they are not eligible to take tax advantage through Master Limited Partnerships.[46]

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[44] GAO, *Carbon Capture and Storage: Actions Needed to Improve DOE Management of Demonstration Projects,* GAO-22-105111 (Washington, D.C.: Dec. 20, 2021).

[45] National Academies of Sciences, Engineering, and Medicine, *The Power of Change: Innovation for Development and Deployment of Increasingly Clean Electric Power Technologies* (Washington, D.C.: The National Academies Press, 2016).

[46] Master Limited Partnerships are publicly listed limited partnerships focused on natural-resource-related activities that trade on a national securities exchange. They are structured so as not to be subject to corporate taxation.

5.2 Key current incentives

Despite the small market that currently exists for CO_2, several policies and market-based approaches are in place that may help incentivize CCUS deployment (see table 10). These include federal tax credits, state policies such as California's Low Carbon Fuel Standard (LCFS), and voluntary carbon markets. However, multiple factors limit the ability of companies to take full advantage of each of these approaches, according to economic studies, experts, and other stakeholders.

Table 10: Selected current approaches to incentivize CCUS deployment

Approach	Factors affecting access
Internal Revenue Code 45Q (as of the 2018 revision)	Access for smaller facilities, value of the tax credit, claim period, and commence construction date[a]
Internal Revenue Code 48A	Outdated efficiency requirement, limited to coal
California's Low Carbon Fuel Standard (LCFS)	Delay in developing new benchmarks; company's capacity to conduct life cycle assessment
Voluntary carbon market	Low price, lack of verifiable crediting standards on CCUS

Source: GAO analysis of reports, stakeholder interviews, and expert discussions. | GAO-22-105274

[a] Most of these factors were addressed by changes to 45Q and how the credit can be received in the Inflation Reduction Act of 2022, Pub. L. No. 117-169, §§ 13104, 13801, 136 Stat. 1818, 1924-29, 2003-13.

5.2.1 CCUS tax credits

Federal tax credits, including sections 45Q and 48A of the Internal Revenue Code, are financial incentives currently in place that can encourage investment in CCUS projects (see below). These credits can reduce the cost to the developer of investing in a project, but reliance on such credits has limitations.

Section 45Q grants a credit for each metric ton of qualified CO_2 (or other carbon oxide) captured and stored.[47] The 2018 revision increased the dollar amount per metric ton of qualified CO_2, among other changes.[48] For example, for projects with dedicated storage (i.e., not enhanced oil recovery), the credit value in 2020 was $23.82 for equipment placed in service before the revision. The 2020 credit value for these projects was $31.77 for equipment placed in service on or after the revision and was to increase to $50 by 2026, after which it was to be adjusted for inflation. In January 2021, the Internal Revenue Service issued final regulations regarding 45Q, providing clarification on the use of the tax credit. Those changes, along with others, were expected to stimulate additional investments in CCUS projects, and a number of projects have been announced since the Internal Revenue Service issued the final regulations (fig. 16). According to stakeholders, the 2018 changes to 45Q

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[47] 26 U.S.C. § 45Q. The act provides credits for sequestration of any type of carbon oxide, such as carbon monoxide which unlike CO_2 is not a significant greenhouse gas.

[48] Other changes included (1) adding a start-of-construction deadline and 12-year claim period; (2) eliminating the 75 million metric ton cap; (3) allowing the credit for CO_2 utilization in addition to enhanced oil recovery and direct air capture; (4) allowing smaller facilities to claim the credit; and (5) allowing owners of carbon capture equipment to claim tax credits instead of the person capturing the CO_2, which creates flexibility in ownership structures facilitating tax-equity investment. Bipartisan Budget Act of 2018, Pub. L. No. 115-123, § 41119. 132 Stat. 64, 162-68.

generated increased interest in CCUS projects. The Inflation Reduction Act of 2022 further expanded and modified 45Q and how it can be received.[49]

Figure 16: Timeline of changes to section 45Q of the Internal Revenue Code and carbon capture and storage project deployment or announcement

Source: Adapted from Global CCS Institute (2021) *Global Status of CCS*. | GAO 22-105274

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[49] Pub. L. No. 117-169, §§ 13104, 13801, 136 Stat. 1818, 1924-29, 2003-13.

Prior to the 2022 revision of 45Q, the National Petroleum Council estimated that at a level of \$50 per metric ton, the credit could induce the capture of an additional 25 to 40 million metric tons of CO_2 per year in the next 5 to 7 years.[50] The IEA estimated that the credits could stimulate \$1 billion in investments over the next 6 years following its 2018 report and increase global capture capacity by about 10 to 30 million metric tons of CO_2 per year.[51] The effects of the 2022 revision on deployment will not be known for some time, although some organizations have started to model those effects.

However, reliance on tax credits increases government tax expenditures (i.e., revenue losses attributable to provision of a tax credit). For example, according to Department of the Treasury estimates, using the 45Q levels from the 2018 revision the total tax expenditures for 45Q were expected to be approximately \$9.9 billion from 2021 to 2030. Another peer-reviewed study based on the 2018 45Q levels estimated that the expenditures could be \$1 to \$2.3 billion (in 2018 dollars) per year by 2030. These expenditures could be higher with the 2022 increase of 45Q levels, depending on the extent of future CCUS project deployment.

In addition, higher levels of financial incentives might increase extraction and use of fossil fuels if companies use the incentives to expand production. For example, a higher level of 45Q tax credit could reduce the effects of CCUS deployment if the emission-increasing effect of additional production is above the emission-reducing effect from carbon capture.[52]

Several factors affected the applicability of the 2018 revision of the 45Q tax credit, according to literature and stakeholders, most of which were addressed by the Inflation Reduction Act (see table 11).

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[50] National Petroleum Council, “Chapter three - Policy, Regulatory and Legal Enablers,” *Meeting the Dual Challenge: A Roadmap to At-Scale Deployment of Carbon Capture, Use, and Storage* (Washington, D.C.: March 2021).

[51] S. Bennett and T. Stanley, “U.S. Budget Bill May Help Carbon Capture Get Back on Track,” International Energy Agency (Mar. 12, 2018), accessed June 24, 2022, https://www.iea.org/commentaries/us-budget-bill-may-help-carbon-capture-get-back-on-track.

[52] Q. Zhu et al., "Enhancing Policy Realism in Energy System Optimization Models: Politically Feasible Decarbonization Pathways for the United States," *Energy Policy,* vol. 161 (2022): 112754.

Table 11: Selected changes to Internal Revenue Code 45Q in the Inflation Reduction Act of 2022

	2018	Inflation Reduction Act of 2022
Credit value ($ per metric ton)	Geologic storage: Increases from $22.66 to $50 each year from 2016 to 2026, then inflation-adjusted Enhanced oil recovery and other qualified uses: Increases from $12.83 to $35 each year from 2016 to 2026, then inflation-adjusted	Geologic storage: up to $17 *5 ($85) each year from 2016 to 2026, then inflation adjusted Enhanced oil recovery or permanent use: up to $12 *5 ($60) each year from 2016 to 2026, then inflation adjusted Direct air capture with geologic storage or use: up to $36 *5 ($180)
Commence construction date	Before 01/01/2026	Before 01/01/2033
Direct pay[a]	No	Yes
Annual capture requirements		
Power generation facility	At least 500,000 metric tons At least 25,000 for facilities that do not emit more than 500,000 metric tons	At least 18,750 metric tons and 75 percent of baseline carbon oxide production
Direct air capture	At least 100,000 metric tons	At least 1,000 metric tons
Other	At least 25,000 metric tons for facilities that do not emit more than 500,000 metric tons	At least 12,500 metric tons

Source: GAO analysis of section 45Q in the Bipartisan Budget Act of 2018 and the Inflation Reduction Act of 2022. | GAO-22-105274

[a] Direct pay allows taxpayers to elect a cash payment in lieu of tax credit. Under the 2018 revision to the 45Q tax credit, recipients often had to participate in tax equity financing wherein an investor provides capital to a developer in exchange for tax credits. The Inflation Reduction Act of 2022 allows for a method of direct pay. See Pub. L. No. 117-169, § 13801, 136 Stat. 1818, 2003-13.

These factors include the following:

- **Access for smaller facilities.** According to stakeholders and reports, the lack of a direct pay mechanism and the capture requirement in the 2018 revision of 45Q limited access for smaller facilities. 45Q tax credits were non-refundable and direct pay was not included in the 2018 revision. Therefore, smaller facilities may have had difficulty taking advantage of the tax credit if they did not have a large annual tax liability. Smaller facilities could also not access the 2018 revision of 45Q if they did not meet the capture requirement. The Inflation Reduction Act of 2022 allows direct payment for certain 45Q credits and decreased the capture capacity requirement for qualified facilities.[53]

- **Value of the credit.** The 2018 value of the credit helped incentivize CCUS deployment primarily in sectors with low capture costs. For example, one study examined 563 industrial facilities and found that $50 per metric ton of CO_2 would cover the cost of deployment in 24 facilities where capture costs were lowest.[54] At the 2018 level, studies expected CCUS deployment to increase in sectors with lower capture costs (the “low hanging fruit”) but not in more costly sectors, such as power generation. One study projected that the credit level would need to be $66 per metric ton to cover the costs of retrofitting coal facilities and $142 per metric ton to cover the costs for CO_2 capture at certain natural gas-fired power generation facilities.[55] The Inflation Reduction Act of 2022 increased the value of the credit up to $85 per ton for point-source capture facilities that meet certain requirements and up to $180 per ton for direct air capture facilities that meet those requirements.
- **Commence construction deadline.** According to reports, the time between the issuance of the Internal Revenue Service regulations in 2021 and the commence construction deadline of January 1, 2026, in the 2018 revision was insufficient for large CCUS projects. These projects generally require a long lead time for planning, conducting front-end engineering studies, and getting permits. Some past projects have taken longer than 5 years from announcement to beginning operations. The Inflation Reduction Act of 2022 requires construction to commence prior to January 1, 2033.[56]
- **Claim period.** According to stakeholders and experts, the claim period of 12 years for the credit is insufficient to pay back the investment in a CCUS project, given the potential operating lifetime of a facility. One stakeholder group we interviewed said that period could be sufficient to pay back the capital investment, but likely not enough of an incentive for continued operations. For comparison, the global average retirement age of coal-fired power generation facilities is 46 years. Some of the early natural gas processing capture and storage facilities have been operating since the 1970s and 1980s. However, extending the claim period would increase tax expenditures.[57]

Section 48A provides a federal tax credit that is equal to 20 percent of the qualified

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[53] Pub. L. No. 117-169, §§ 13104, 13801, 136 Stat. 1818, 1924-29, 2003-13.

[54] This study examined facilities in the natural gas processing, ethylene oxide, ammonia, ethanol, and hydrogen producing sectors and assumed optimistic geology for storage and a 50-mile transport range when calculating costs. See B. Tarufelli, B. Snyder, and D. Dismukes, “The Potential Impact of the U.S. Carbon Capture and Storage Tax Credit Expansion on the Economic Feasibility of Industrial Carbon Capture and Storage,” *Energy Policy,* vol. 149 (2021): 112064.

[55] J. J. Anderson et al., "A Techno-Economic Assessment of Carbon-Sequestration Tax Incentives in the U.S. Power Sector." *International Journal of Greenhouse Gas Control,* vol. 111 (2021): 103450.

[56] Inflation Reduction Act of 2022, Pub. L. No. 117-169, § 13104, 136 Stat. 118, 1924-29.

[57] For example, one study predicted that 45Q expenditures would reach $20 billion per year by 2030 if 45Q were extended to the operational lifetime of CCUS facilities and made available to new construction any time in the future.

investment for certain kinds of coal-fired power generation projects up to $800 million,[58] and 15 or 30 percent for other advanced, coal-fired power generation technologies including CCUS, with limits of $500 million or $1.2 billion respectively. Unlike 45Q, under which credits are claimed each year over a set period, 48A tax credits are available the year qualifying equipment is placed into service.

CCUS project developers also face challenges in using the 48A tax credit, according to several studies.

- **Outdated efficiency requirement.** To be eligible for 48A, advanced coal projects need to meet requirements related to a minimum percentage of total CO_2 emissions level sequestered, efficiency requirements, and certain pollutants. However, existing coal-fired power generation units retrofitted with carbon capture cannot meet the efficiency requirement, because electricity and steam are needed to power the capture equipment requires energy, thus reducing the efficiency below what is required for the credit.
- **Limited to coal.** Section 48A is only available to coal-based projects.

5.2.2 Market-based approaches

Participation in carbon markets, either regulatory or voluntary, is another option for improving the economic viability of CCUS projects. Carbon markets allow investors and companies to offset their emissions by trading carbon credits. Carbon credits are generated from emissions reduction or removal activities, including some CCUS projects, and verified by a government crediting mechanism or an independent standard-setting organization. They can be used to meet the compliance requirements or to meet an organization's pledge to voluntarily reduce emissions.

California's LCFS is an example of a market-based approach that can incentivize carbon capture and storage projects. It has an established market for credits that can be traded to meet California's fuel standards.[59]

According to the California Air Resources Board, the LCFS encourages the use of cleaner, low-carbon transportation fuels in California by using life cycle assessments to estimate carbon intensity standards for fuels, and the standards reduce over time. To meet the fuel standards, fuel producers and providers in California must annually balance the credits from low-carbon fuels with the "deficits" from fossil fuels.[60] Fuels associated with carbon capture and storage (e.g.,

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[58] Integrated gasification combined cycle projects use gas and steam turbines to produce electricity, most commonly using coal as the carbon-based fuel. For more information, see National Energy Technology Lab, "Commercial Power production Based on Gasification," accessed July 22, 2022, https://netl.doe.gov/research/Coal/energy-systems/gasification/gasifipedia/igcc.

[59] States with existing low-carbon fuel standards (also called clean fuel standards) include California, Oregon, and Washington. States that have considered a low-carbon fuel standard include Colorado, New Mexico, and New York.

[60] To achieve the reduction in carbon intensity, fuel providers in California can change production processes to decrease the carbon intensity of fuels they produce, purchase credits from other fuel providers, and use credits generated in previous years, among other options. For more information, see California Air Resources Board, "Low Carbon Fuel Standard," accessed Aug. 15, 2022, https://ww2.arb.ca.gov/our-work/programs/low-carbon-fuel-standard/about.

bioethanol with carbon capture and storage) and sold in California are eligible for these credits. Direct air capture projects anywhere in the world can generate credits. The average price for an LCFS credit was approximately $193 per credit between 2019 and 2021 but declined to $125 in May 2022. LCFS credits can be combined with 45Q, providing an additional incentive for CCUS projects.

Carbon capture and storage companies may have difficulty accessing the LCFS market due to uncertainty in credit prices and capacity constraints of both regulators and companies. According to one expert from our meeting, it can be difficult for companies to get financing based on LCFS because of the variability in prices. The California Air Resources Board had to spend considerable time developing carbon-intensity benchmarks using life cycle assessment. They have also had to redo a lot of the life cycle assessment work submitted by companies, according to an expert. Companies need the capacity to conduct life cycle assessment, ensure third-party verification of carbon capture and storage protocols, and comply with annual reporting requirements.

Voluntary carbon markets can also incentivize CCUS; however, several factors affect the ability of CCUS projects to participate in such markets. Half of the credits came from independent crediting standards organizations in the carbon crediting market in 2020. Price ranges depend on market demand and buyers' preferences for the different types of projects that can generate credits (e.g., reforestation or direct air capture). The value of credits averaged around a few dollars as of 2021 and fluctuates with market conditions. At current prices, selling carbon credits alone is an insufficient incentive to deploy CCUS projects.

Additionally, it is difficult to verify emissions reduction or removal from CCUS projects in voluntary carbon markets due to a lack of standards. According to the experts from our meeting, current carbon crediting standards do not include standards for carbon storage with the exception of using captured CO_2 for enhanced oil recovery. An alliance of organizations is advancing carbon accounting methodologies to enable verification of emissions reduction or removal from CCUS projects in voluntary carbon markets.

5.3 Carbon pricing mechanisms

Carbon pricing is an additional instrument available to incentivize CCUS.[61] Though there is no federal carbon pricing in the U.S., parts

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[61] There are two mechanisms for explicit carbon pricing by government policy: (1) a carbon tax, or (2) a cap-and-trade program. There is an extensive economic literature examining the effects, advantages, limitations, and designs of these two mechanisms. For example, see R. N. Stavins. "The Relative Merits of Carbon Pricing Instruments: Taxes versus Trading," *Review of Environmental Economics and Policy,* vol. 16, no. 1 (2022): 62-82. Prior GAO reports have also described carbon pricing and carbon trading in general. For example, see GAO, *Climate Change: Expert Opinion on the Economics of Policy Options to Address Climate Change*, GAO-08-605 (Washington, D.C.: May 9, 2008).

of the U.S. have carbon pricing through cap-and-trade programs, such as the Regional Greenhouse Gas Initiative in the northeastern U.S., and California's Cap-and-Trade Program. Economic literature indicates that carbon pricing can provide incentives similar to subsidies for CCUS such as 45Q, but could be less costly to the government for the same level of emissions reduction. Carbon pricing is not specific to CCUS, but instead would incentivize emitters to find the most cost-effective approach to reduce emissions, such as switching to low-carbon technology or improving efficiency. It would incentivize CCUS deployment up to the point when the cost of CCUS emissions reduction for one additional ton of CO_2 equals the value of the carbon price for one additional ton of CO_2. In contrast, 45Q incentivizes CCUS deployment at the tax-payers' expense.

However, carbon pricing would likely have other effects, including increasing the cost of carbon-intensive products such as gasoline or electricity. The increased cost could be passed to consumers or could motivate companies to relocate to countries or regions without a carbon price, a phenomenon known as "carbon leakage." For globally traded energy-intensive commodities, leakage could cause emissions to increase in regions or countries without carbon pricing. To reduce leakages, several studies have proposed border carbon adjustments.[62]

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[62] A border carbon adjustment is an environmental trade policy that consists of charges on imports and sometimes rebates on exports that reflect the regulatory costs borne by domestically produced carbon-intensive products but not by the same foreign-produced products. For example, see B. Flannery et al., "Framework Proposal for a US Upstream GHG Tax with WTO-Compliant Border Adjustments: 2020 Update," Resources for the Future (Washington, D.C.: Oct. 2020).

5.4 Policy options

Modify incentives. Policymakers could modify existing incentives to facilitate access for carbon capture, utilization, and storage (CCUS) projects.

This policy option could help improve the economic and financial conditions of CCUS projects by addressing factors that affect access to incentives.

Potential implementation approaches:

Modify 48A tax credits by, for example, adjusting the heat efficiency requirement or extending the credit beyond coal projects.

Support changes to or expansion of existing market-based approaches to facilitate access by CCUS projects.

Opportunities	Considerations
Could increase the number or kinds of sectors or facilities that deploy CCUS technologies.	Modifying tax credits could reduce government tax revenues.
Could incentivize new technology development to reduce costs of CO_2 capture.	Modifying tax credits could increase use of fossil fuels.
Could be a bridge to future carbon pricing policies.	Could be subject to political and regulatory uncertainty.
For market-based approaches, could increase demand for CO_2 emissions reduction and volumes of CO_2 traded in the markets.	For market-based approaches, could be subject to uncertainty in carbon prices.
For market-based approaches, could increase the deployment of CCUS if the value of credit is appropriate.	

Source: GAO. | GAO-22-105274

6 Community Acceptance and Engagement

CCUS, like many technologies, has faced public opposition and is likely to face more in the future.[63] If CCUS is to achieve widespread deployment in the U.S., it will require acceptance by and effective engagement with communities where CCUS projects and related infrastructure are to be located.

Although each community is different, they have historically shared common questions and concerns about CCUS,[64] including:

- How does it work?
- Who pays for it?
- What are the benefits?
- What are the risks?
- Will it impact local property values?
- Who is responsible for underground CO_2?
- Will it benefit the local economy?

6.1 Key factors influencing community acceptance of CCUS

Several factors influence community acceptance of CCUS projects and therefore will likely be important in determining the course of CCUS development and deployment.[65]

Knowledge and awareness

Generally, knowledge and awareness of CCUS can help communities make informed decisions about projects, but recent studies show that the majority of Americans are unfamiliar with CCUS.[66] Successful deployment could require developers, policymakers, or other organizations to provide information to communities as projects develop. Policymakers could help communicate the value of CCUS to public audiences by supporting education, public awareness campaigns, and other outreach efforts.

However, such efforts can benefit from careful planning and execution. The information provided can be inconsistent or overly technical. This can lead to misconceptions about or opposition to projects. In addition, providing information to communities does not always increase support. Rather, some communities may oppose CCUS more after certain information is provided. Near-term public opinion polling

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[63] Examples of technologies that have faced public opposition include genetically modified food crops, pesticides, nuclear energy technologies, and renewable energy technologies.

[64] S. Greenberg et al., *Stakeholder Analysis Report Subtask 3.3 – CarbonSAFE Illinois East Sub-Basin Topical Report 8*, (April 1, 2019).

[65] S. L. Seigo, S. Dohle, and M. Siegrist, "Public Perception of Carbon Capture and Storage (CCS): A Review," *Renewable and Sustainable Energy Reviews*, vol. 38 (2014): 848-863; P. Tcvetkov, A. Cherepovitsyn, and S. Fedoseev, "Public perception of carbon capture and storage: A state-of-the-art review," *Heliyon*, vol. 5 (2019).

[66] S. Pianta, A. Rinscheid, and E. U. Weber, "Carbon Capture and Storage in the United States: Perceptions, Preferences, and Lessons for Policy," *Energy Policy*, vol. 151 (2021): 112149; L. Whitmarsh, D. Xenias, and C. R. Jones, "Framing Effects on Public Support for Carbon Capture and Storage," *Palgrave Communications*, vol. 5 (2019).

in regions of interest for CCUS development could help gauge local priorities and concerns.

Perceived risks and benefits

Communities are more likely to support CCUS projects when developers provide clear and realistic descriptions of the potential risks and benefits of the projects, according to reports. Individual communities and groups within the community will perceive the potential effects of CCUS differently. Developers and outreach coordinators may be better able to engage with communities if they understand how each community views the potential risks and benefits of CCUS.

Social science research studying this topic is ongoing. For example, studies show that people often consider perceived benefits (or perceived lack of benefits) to be more important than perceived risks when forming an opinion of CCUS, according to studies.[67] In particular, communities may perceive local job creation, economic development, regional revitalization, and climate-change mitigation as potential benefits of CCUS (see text box). Perceived risks may include CO_2 leaks, safety risks, and environmental damage. Perceived risks and benefits do not necessarily reflect the realistic risks and benefits of CCUS projects and may instead reflect unaddressed misconceptions.[68] Additional research could help assess broader public attitudes towards CCUS.

Trust

Trust in CCUS project developers, regulators, and other stakeholders is another key variable for acceptance. Prior projects suggest that a community's level of trust that developers and regulators will be honest, fair, and accountable may be more important than understanding technical information about a project. Further, information is more likely to be perceived as trustworthy and objective when it is endorsed by multiple sources. Project developers are perceived as less trustworthy when they are not transparent about decision-making, intentions, and local risks. Trust can be difficult to rebuild after negative experiences between communities and CCUS project stakeholders, or between communities and other related industries.

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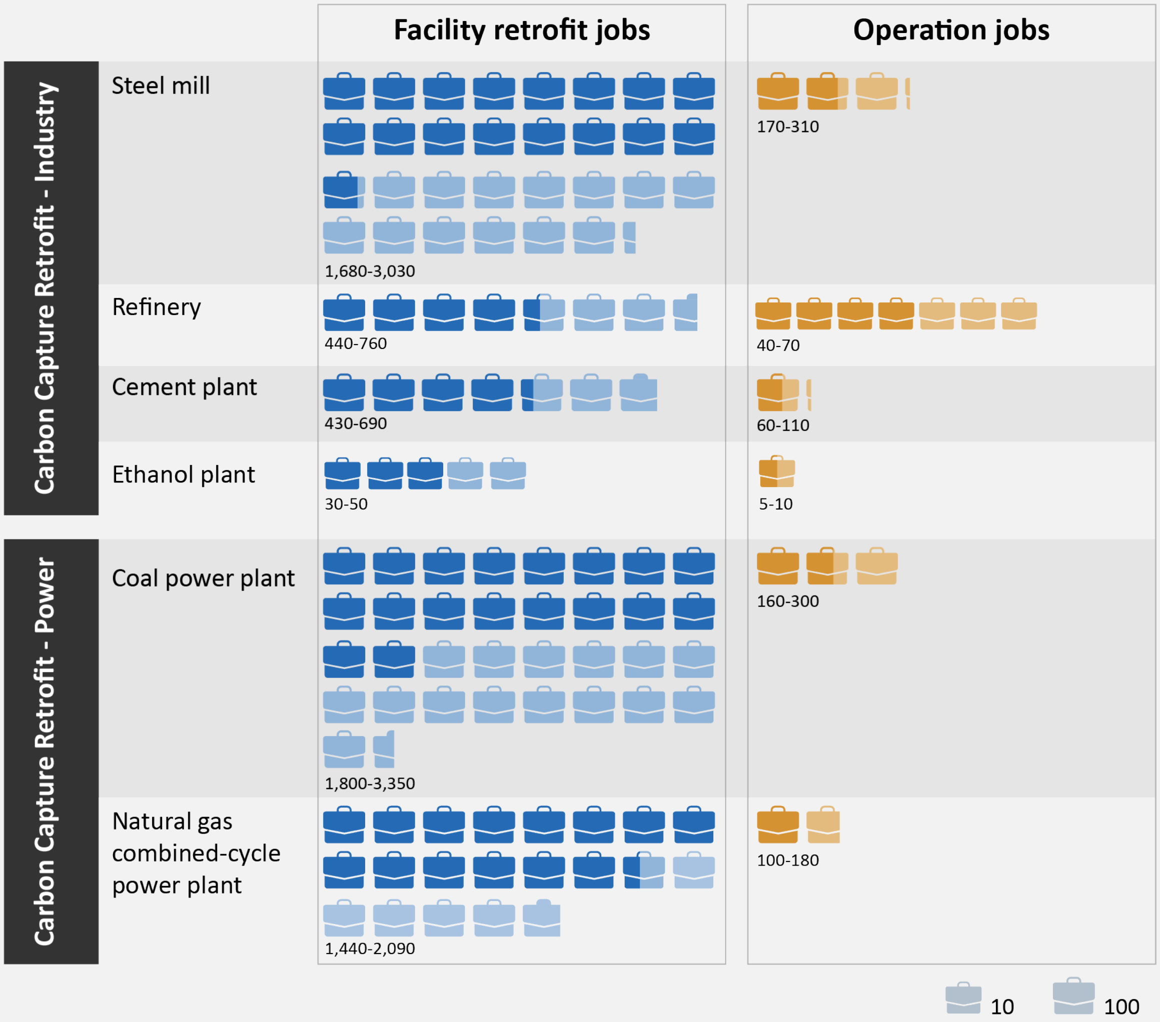
[67] Tcvetkov et al., "Public perception of carbon capture and storage" (2019); W. Leiss and P. Larkin, "Risk communication and public engagement in CCS projects: the foundations of public acceptability," *International Journal of Risk Assessment and Management*, vol. 22 (2019): 384-403.

[68] We did not assess the environmental or safety risks of CCUS projects because they are generally site and project dependent.

Carbon capture, utilization, and storage (CCUS) and the workforce

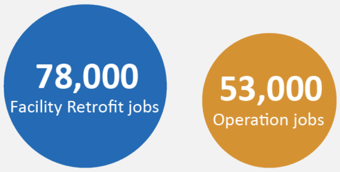
One potential benefit of deploying CCUS is the creation of jobs within communities both for construction and operation of CCUS infrastructure. Generally, hundreds to thousands of workers are involved in constructing and retrofitting CCUS facilities. A 2020 analysis indicated that building and operating a 1 million metric ton direct air capture facility could generate roughly 3,500 jobs in fields such as engineering, construction, and materials manufacturing.[a] Fewer workers are needed to operate CCUS facilities than to build them; however, these jobs are long-lasting and high-paying. CCUS hiring could potentially provide employment to workers from the fossil fuel industry and provide existing industries the opportunity to continue contributing to local economies.

Figure 17: **Job creation from carbon capture facility retrofits in different industries**



Source: GAO analysis of data from the Carbon Capture Coalition. | GAO-22-105274

Investment in CCUS could generate up to 78,000 jobs related to CCUS facility retrofits by 2050 and an additional 53,000 jobs operating those retrofit facilities.



Source: GAO analysis of data from the Rhodium Group. | GAO-22-105274

[a] J. Larsen, W. Herndon, and G. Hiltbrand, *Capturing New Jobs – The Employment Opportunities Associated with Scale-up of Direct Air Capture (DAC) Technology in the US* (Rhodium Group, June 23, 2020).

Source: GAO analysis of non-governmental reports. | GAO-22-105274

The text box provides an example of how these three factors have contributed to opposition to CO_2 pipelines in certain local communities.

Recent community opposition to pipelines

Some local communities oppose carbon dioxide (CO_2) pipeline installation. We reviewed dockets containing public comments related to recent CO_2 pipeline projects. Among the projects we reviewed, the following were common reasons for opposition:

Knowledge and awareness

- Misconceptions about CO_2, such as believing it is explosive.
- Misconceptions about CO_2 storage processes.
- Beliefs that the carbon capture, utilization, and storage (CCUS) process is unproven and unknown.

Perceived risks

- Perceptions that there are substantial safety risks.
- Perceptions of economic losses from damaged land.

Perceived lack of benefits

- Perceptions that CCUS will not benefit local communities.
- Perceptions that CCUS and CO_2 pipelines offer no climate benefits.
- Perceptions that CO_2 pipelines only serve the investor's financial interests.

Trust

- Lack of trust in project developers.

Source: GAO analysis of public docket comments. | GAO-22-105274

6.2 Importance of community engagement

Effective community engagement is a key component of successful CCUS projects, according to stakeholders and reports.[69] Community engagement can take many forms. It may be limited to providing answers to questions, or project developers may listen to community concerns and incorporate them directly into alternative project designs. For example, projects seeking funding for front-end engineering design studies through DOE's Carbon Capture Technology Program must consider community engagement and input in identifying alternative transport route designs, when appropriate. According to an expert, recognizing communities as partners in the success of a project could be a strategy for certain CCUS projects.

There are many ways that community engagement can fail, including when:

- There is little to no community engagement at all.
- Engagement starts too late in project development.
- Communication is not open and factual.
- Communities do not feel their concerns are being addressed.
- Potential risks and benefits are not clearly communicated.
- Potential risks and benefits are not evenly distributed.

One expert stated that some communities, particularly disadvantaged communities, may

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[69] P. Ashworth et al., *Communication, Project Planning and Management for Carbon Capture and Storage Projects: An International Comparison* (CSIRO: 2010); World Resources Institute, *Guidelines for Community Engagement* (2010); NPC, *Meeting the Dual Challenge* (2019).

need additional resources to effectively participate in community engagement.

There are several examples of projects that have successfully engaged with their local communities; however, there are also multiple examples of unsuccessful community engagement and local opposition contributing to the cancellation, relocation, or delay of capture or storage projects in the U.S. We describe five selected projects below and summarize community engagement practices they did or did not employ in table 12.

Jamestown, New York

Jamestown is the largest city in Chautauqua County. It serves as an industrial, commercial, financial, and recreational hub for southwest New York.

In 2004, developers proposed replacing an existing coal-fired power generation facility with a new one in Jamestown, New York. As a response to community criticism, the project was changed to include a carbon capture and storage demonstration project in 2007. The project was eventually cancelled around 2012 after failing several times to secure DOE funding. Local activists and a coalition of environmental groups undertook years of community organizing in opposition. Many groups that opposed the project said they did not oppose carbon capture and storage technology, but opposed this project because they believed it would increase local electricity costs.

Carson, California

Carson is an urban, heavily industrialized city in Los Angeles County. The location of this proposed power generation facility was adjacent to predominately minority and low-income neighborhoods.

In 2006, developers proposed a coal-fired power generation facility with carbon capture and storage in Carson, California. This project was cancelled in 2009 due to unsuitable storage site conditions. Prior to cancellation, the project faced opposition from nine local and state environmental organizations and became a rallying point in a contentious debate over a short-lived state bill to regulate carbon capture and storage. Key community concerns in Carson included a potential increase in air pollution from the new capture facility and environmental justice concerns that this facility might disparately affect disadvantaged communities.

Greenville, Ohio

Greenville is a rural town in Darke County and the surrounding area is largely agricultural. The area had no history of oil and gas activities at the time of this project.

In 2007, developers proposed an ethanol carbon capture and storage project in Greenville, Ohio. This project was cancelled in 2009 due to local opposition. The community strongly distrusted the federal government, large corporations, and scientists, according to case studies of the project.[70] Opposition was led by a local grassroots campaign and included a community march and local

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[70] J. Hammond and S. Shackley, "Towards a Public Communication Engagement Strategy for Carbon Dioxide Capture and Storage Projects in Scotland," (working paper, Scottish Centre for Carbon Capture, University of Edinburgh, Scotland, 2010). Lockwood, *Public outreach approaches* (2017).

protest with 700 to 1,000 protestors. Local policymakers supported the opposition campaign.

Wallula, Washington

Wallula is a small town in rural Walla Walla County. The county is a tourist and wine destination and agriculture is essential to the diverse local economy.

In 2007, developers proposed a research project to study carbon capture and storage in basalts on public land, using CO_2 captured from a paper mill in Wallula, Washington. An unassociated but publicly opposed coal-fired power generation facility was proposed at the same site as the research project. Community members voiced opposition at city meetings and submitted multiple local petitions opposing the project, often linking it to the coal-fired power generation facility. The project was moved to private land in 2008, where developers successfully completed it.

Decatur, Illinois

Decatur is the largest city in Macon County. It serves as an important commercial, agricultural, and distribution center for the area.

In 2008, developers proposed an ethanol carbon capture and storage demonstration project in Decatur, Illinois. This project has successfully completed CO_2 injections and is in the monitoring phase. Developers carried out a comprehensive community engagement plan. According to an expert familiar with the project, there was no active opposition.

Table 12: Use of community engagement practices by select carbon capture and storage projects

Community	Jamestown, NY	Carson, CA	Greenville, OH	Wallula, WA	Decatur, IL
Status	Cancelled	Cancelled	Cancelled	Moved	Completed injection
Conducted early engagement	✓	✓	x	x	✓
Communicated through public presentations	✓	✓	✓	✓	✓
Tailored outreach materials to different audiences	–	✓	x	x	✓
Gained local political support	✓	✓	x	x	✓
Effectively characterized local opinions before project development	x	x	x	x	✓
Involved the community in initial project planning	x	x	x	x	✓
Addressed key community concerns	x	x	–	–	✓

Legend: ✓ = yes, **X** = no, — = unknown

Source: GAO analysis of studies, reports, and public meeting minutes. | GAO-22-105274

6.3 Policy options

Community engagement. Policymakers could support and encourage proactive community engagement around carbon capture, utilization, and storage (CCUS) deployment.

This policy option could help address the challenges of effective of community engagement.

Potential implementation approaches:

Support social science research on CCUS to inform decision-making.

Support CCUS education and public awareness campaigns.

Opportunities	Considerations
Better understanding of public opinion in potential CCUS project locations could guide community engagement and decision-making in these areas. Effective community engagement could build local support and reduce project delays caused by local opposition.	Well-designed education and public awareness campaigns could be resource-intensive. May require new funding or reallocation of existing resources to support new efforts.

Source: GAO. | GAO-22-105274

7 Agency and Expert Comments

We provided a draft of this report to the Department of Energy and the Environmental Protection Agency with a request for technical comments. We incorporated agency comments into this report as appropriate.

We also provided a draft of this report to 14 participants from our expert meeting, and incorporated comments as appropriate.

We are sending copies of this report to the appropriate congressional committees and other interested parties. In addition, the report is available at no charge on the GAO website at http://www.gao.gov.

If you or your staff members have any questions about this report, please contact Karen L. Howard, PhD at (202) 512-6888 or howardk@gao.gov. Contact points for our Offices of Congressional Relations and Public Affairs may be found on the last page of this report. GAO staff who made key contributions to this report are listed in appendix VI.

Karen L. Howard

Karen L. Howard, PhD
Director
Science, Technology Assessment, and Analytics

List of Addressees

The Honorable Shelley Moore Capito
Ranking Member
Committee on Environment and Public Works
United States Senate

The Honorable Rob Portman
Ranking Member
Committee on Homeland Security and Governmental Affairs
United States Senate

The Honorable Eddie Bernice Johnson
Chairwoman
The Honorable Frank Lucas
Ranking Member
Committee on Science, Space, and Technology
House of Representatives

The Honorable Carolyn B. Maloney
Chairwoman
Committee on Oversight and Reform
House of Representatives

Appendix I: Objectives, Scope, and Methodology

We describe our scope and methodology for addressing the four objectives outlined below:

1. What carbon capture technologies are available and how mature are they?
2. What opportunities exist for using or storing captured carbon dioxide (CO_2), and what is the status of these technologies?
3. What challenges affect the development, demonstration, and deployment of carbon capture, utilization, and storage (CCUS) technologies?
4. What options could policymakers consider to help address these challenges?

To address all research objectives, we assessed available and developing technologies and opportunities across the CCUS industry and challenges associated with achieving widespread deployment. We also assessed the maturity, strengths, and limitations of technologies for CO_2 capture and utilization. To do so, we conducted four literature searches; reviewed key reports and peer-reviewed articles; conducted an expert meeting in collaboration with the National Academies of Sciences, Engineering, and Medicine (NASEM); interviewed a variety of stakeholders, including agency officials, academic researchers, and representatives of industry organizations, private companies, and nongovernmental organizations; and conducted a site visit to a technology testing facility.

Scope

We assessed carbon capture technologies that result in a concentrated stream of CO_2 (i.e., point-source carbon capture and direct air capture), and opportunities for utilization or storage of CO_2. For CO_2 utilization technologies, we focused our assessment on pathways that convert CO_2 into economically valuable products with the greatest potential CO_2 utilization or climate benefits. We did not assess all possible CCUS technologies. For example, we excluded nonconversion CO_2 utilization technologies, such as enhanced oil recovery, CO_2 pipeline technology, and CO_2 injection technology as these are all mature and deployed.

We selected four examples of CO_2 emitting industrial sectors for vignettes to illustrate variation in sector-specific considerations: power generation, cement manufacturing, iron and steel manufacturing, and bioethanol production. The cost and ease of implementing carbon capture into the facilities of these four industrial sectors vary because of differences in the concentration of CO_2 in the gas stream and number of emission sources. Additionally, we selected four examples of CO_2-based products for vignettes to expand on key metrics for CO_2 conversion technologies: synthetic mineral aggregates, CO_2-cured concrete, commodity chemicals and fuels, and polymers. According to research estimates, these four products have the largest CO_2 utilization potentials or are the closest to full market viability.

Literature search

For all objectives, we reviewed relevant literature identified by agencies, experts, stakeholders, and our literature search. We gathered additional information using a snowball technique.[71] A GAO research librarian conducted four literature searches to find articles regarding CCUS technologies, challenges, and policy options. The librarian searched a variety of databases, including ProQuest, EBSCO, and Scopus using terms such as "carbon capture," "CO_2 utilization," "45Q," "pore space ownership," and "acceptance." We narrowed our search based on our objectives to articles published since 2015.[72] Results of these searches included scholarly or peer reviewed material; government reports; trade or industry papers; legislative materials; and association, nonprofit and think tank publications. We selected the articles most relevant to our objectives for further review.

Expert meeting

We convened a GAO expert meeting with the assistance of NASEM to provide insights to inform our assessment of CCUS technologies.[73] The meeting was held over 3 days with 27 experts. (See app. II for a list of experts and their affiliations).

We worked with NASEM staff to identify experts in subject matter covering significant areas of our assessment from a range of stakeholder groups, including federal agencies, academia, industry, and nonprofits. We evaluated the experts for potential conflicts of interest, which were considered to be any current financial or other interest that might conflict with the service of an individual because it could (1) impair objectivity or (2) create an unfair competitive advantage for any person or organization. We determined the 27 experts to be free of reported conflicts of interest, except those that were outside the scope of the forum or where the overall design of our meeting and methodology was sufficient to address them, and the group as a whole was determined to not have any inappropriate biases.

The comments of these experts generally represented their individual views and not those of the agencies, universities, companies, or nonprofits with which they were affiliated, and are not generalizable to the views of others in the field.

We divided the 3-day meeting into seven moderated discussion sessions: (1) carbon capture technologies, (2) CO_2 utilization technologies, (3) transportation and storage of CO_2, (4) challenges to widespread deployment of CCUS, (5) financial and economic challenges to CCUS and strategies to address them, (6) forward-looking approaches to carbon management, and (7) policy options. The experts were divided into panels for sessions 1-6 such that each panel included between three and nine experts.

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[71] The snowball technique involves identifying new articles or reports in those a researcher has already found on the topic.

[72] Some articles identified using the snowball technique were published before this date.

[73] This meeting of experts was planned and convened with the assistance of NASEM to better ensure that a breadth of expertise was brought to bear in its preparation, however all final decisions regarding meeting substance and expert participation are the responsibility of GAO.

After the panelists responded to all the questions we developed, the floor was opened for discussion among all of the experts for the time remaining in the session. Session 7 was a moderated, open discussion among all of the experts. The meeting was transcribed to ensure that we accurately captured the experts' statements. After the meeting, we reviewed the transcripts to characterize their responses and inform our understanding of all four researchable objectives. Consistent with our quality assurance framework, we provided the experts with a draft of our report and solicited their feedback, which we incorporated as appropriate.

Interviews

We interviewed key stakeholders with experience and perspectives on the above objectives. Stakeholders included

- Two relevant federal agencies: the Department of Energy, including the Office of Fossil Energy and Carbon Management and the National Energy Technology Laboratory, and the Environmental Protection Agency's Underground Injection Control Program;
- Seven academic researchers;
- Fourteen industry organizations or private companies;
- Two non-governmental organizations;
- Two public-private partnership test centers, one of which was conducted during a site visit; and
- Two federal advisory committees.

Because this is a small sample of the stakeholders involved in researching and using CCUS, the results of our interviews are illustrative and represent important perspectives, but are not generalizable.

Policy options

We intend policy options to provide policymakers with a broader base of information for decision-making.[74] The options are neither recommendations to federal agencies nor matters for congressional consideration. They are also not listed in any specific rank or order. We are not suggesting that they be done individually or combined in any particular fashion.

Additionally, we did not conduct work to assess how effective the options may be, and express no view regarding the extent to which legal changes would be needed to implement them. We developed seven policy options to enhance the benefits of or address the challenges to development, demonstration, and deployment of CCUS technologies based on our literature review, expert meeting, and interviews with stakeholders. We then analyzed each policy option by identifying the potential opportunities and considerations of implementing them. The policy options and

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[74] Policymakers is a broad term including, for example, Congress, federal agencies, state and local governments, academic and research institutions, and industry.

analyses were supported by documentary and testimonial evidence.

We conducted our work from May 2021 to September 2022 in accordance with all sections of GAO's Quality Assurance Framework that are relevant to technology assessments. The framework requires that we plan and perform the engagement to obtain sufficient and appropriate evidence to meet our stated objectives and to discuss any limitations to our work. We believe that the information and data obtained, and the analysis conducted, provide a reasonable basis for any findings and conclusions in this product.

Appendix II: Expert Participation

With the assistance of the National Academies of Sciences, Engineering, and Medicine, we convened a 3-day meeting of experts to inform our work on CCUS technologies; the meeting was held virtually on February 4, 8, and 11, 2022. The experts who participated in this meeting are listed below. Many of these experts gave us additional assistance throughout our work, including 14 who agreed to review our draft report for accuracy, several of whom provided technical comments.

William Bates
National Program Manager, Underground Injection Control Program
Environmental Protection Agency

Jeffrey M. Bielicki
Associate Professor
The Ohio State University

Lynn Brickett
Carbon Capture Program Manager, Office of Fossil Energy and Carbon Management
Department of Energy

Matt Bright
Carbon Capture Policy Manager
Clean Air Task Force

Etosha Cave
Co-Founder and Chief Science Officer
Twelve

Andres Clarens
Professor and Associate Director of the Pan-University Environmental Resilience Institute
University of Virginia

Kipp Coddington
Senior Advisor
University of Wyoming School of Energy Resources

Jonathan Goldberg
Founder and CEO
Carbon Direct

Sallie E. Greenberg
Principal Scientist of Energy & Minerals
Illinois State Geological Survey - University of Illinois

Christina Harvick
Director of CO_2 Facilities, Pipelines, and Supply
CapturePoint LLC

Nigel John Jenvey
Executive
Baker Hughes

Christopher Jones
Professor
Georgia Institute of Technology

Amishi Kumar
Carbon Utilization Research and Development Program Manager, Office of Fossil Energy and Carbon Management
Department of Energy

John Litynski
Director of Carbon Transport and Storage, Office of Fossil Energy and Carbon Management
Department of Energy

Sasha Mackler
Energy Project Director
Bipartisan Policy Center

Molly McEvoy
General Engineer, Underground Injection Control Program
Environmental Protection Agency

Richard Middleton
Co-founder and CEO
Carbon Solutions LLC

Gregory Nemet
Professor, La Follette School of Public Affairs
University of Wisconsin at Madison

John Northington
Director
National Carbon Capture Center

Sheila Olmstead
Professor, Lyndon B. Johnson School of Public Affairs
University of Texas at Austin

Ah-Hyung (Alissa) Park
Professor of Climate Change and Director of the Lenfest Center for Sustainable Energy
Columbia University

Tara Righetti
Professor of Law
University of Wyoming College of Law and School of Energy Resources

Santhosh Shankar
Strategy advisor
Shell Environmental Products

Sean Simpson
Founder and Chief Science Officer
LanzaTech

Brittany Tarufelli
Energy Research Economist
Pacific Northwest National Laboratory

Chiara Trabucchi
Principal and Director
Industrial Economics, Incorporated

Cathy L. Tway
Technology and Applications Director for Catalyst Technologies
Johnson Matthey

Appendix III: Technical Descriptions of Carbon Capture

Carbon Capture Systems

There are different types of carbon capture systems, some for capturing carbon dioxide (CO_2) from combustion of fossil fuels and biomass and others for capturing CO_2 from industrial processes or from ambient air. Different systems can be applied to capture CO_2 depending on circumstances.

Pre-combustion capture applies to gasification power generation facilities that first convert fuel to a fuel gas called synthesis gas (syngas). The system captures CO_2 from the syngas before it is combusted. Pre-combustion capture is applied to integrated gasification combined cycle power generation facilities, in which carbon-based fuels react with steam and oxygen under pressure to form syngas. The syngas then fuels a gas turbine generator to produce electricity.

Post-combustion capture refers to the capture of CO_2 from flue gases produced as a result of fuel combustion. As the name implies, CO_2 is separated from the flue gases after complete combustion of fuels.

Oxyfuel combustion uses oxygen instead of air for combustion of the primary fuel, resulting in a flue gas that is mainly water vapor and CO_2.

Other industrial process capture systems involve processes (e.g., natural gas processing, direct reduction of iron in steel manufacturing, and calcination of limestone in cement manufacturing) that emit gas streams containing CO_2. These systems present opportunities to capture CO_2 in large quantities.

Direct air capture systems capture CO_2 from ambient air and concentrate it so that it can be transported for use or injection into a storage site. Air is brought into contact with a CO_2-absorbing agent. A regenerator then separates the CO_2 from the agent. The CO_2-absorbing agent is then recycled to capture additional CO_2.

Gas Separation Technologies

In most cases, carbon capture involves separating the CO_2 from a mixture of gases. Different technologies can be used for this separation, depending on the circumstances.

Solvent-based gas separation involves chemical or physical absorption of CO_2 from a gas mixture (e.g., flue gas or air) into a liquid carrier (the solvent) that bonds with CO_2. The solvent is regenerated by increasing its temperature or reducing its pressure to break the solvent-CO_2 bond and release the CO_2. High levels of CO_2 capture are possible with commercially available solvent-based systems.

Sorbent-based gas separation involves the chemical or physical adsorption of CO_2 onto the surface of a solid sorbent. Like solvents, solid sorbents are usually regenerated by increasing temperature or reducing pressure to release the captured CO_2; however, solid sorbents may require less energy to regenerate compared to solvents due to lower heat capacities.

Membrane-based gas separation uses permeable or semi-permeable materials that act like a filter to separate CO_2 from a gas mixture. Gas separation is achieved by a chemical or physical interaction between the membrane and CO_2.

Cryogenic separation involves low-temperature distillation. The process depends on the different condensation points of various gases in the mixture. The mixture of gases is cooled to temperatures at which one or more components liquefies or solidifies and separates from the main gas stream.

Other hybrid and emerging technologies under investigation include hybrid systems that combine attributes from multiple technologies (e.g., solvents and membranes), novel process conditions (e.g., heat integration), and novel catalyst materials for reaction rate enhancement.

Table 13: Examples of gas separation technologies and their technology readiness level (TRL)

Type	Gas separation technology	TRL	References
Solvent-Based	Benfield process and variants	9	Global CCS Institute, 2021
	Physical solvent (Selexol, Rectisol)	9	Global CCS Institute, 2021
	Traditional amine solvents	9	Global CCS Institute, 2021
	Sterically hindered amine	6-9	Global CCS Institute, 2021
	Chilled ammonia process	6-7	Global CCS Institute, 2021
	Water-lean solvent	4-7	Global CCS Institute, 2021
	Phase change solvents	5-6	Global CCS Institute, 2021
	Amino- acid based solvents	4-5	Global CCS Institute, 2021
	Encapsulated solvents	2-3	Global CCS Institute, 2021
	Ionic liquids	2-3	Global CCS Institute, 2021
Sorbent-Based	Pressure swing adsorption/vacuum swing adsorption	9	Global CCS Institute, 2021
	Temperature swing adsorption	5-7	Global CCS Institute, 2021
	Enzyme catalyzed adsorption	6	Global CCS Institute, 2021
	Enhanced water gas shift	5	Global CCS Institute, 2021
	Electrochemically mediated adsorption	1	Global CCS Institute, 2021
Membranes	Gas separation membranes for natural gas processing	9	Global CCS Institute, 2021
	Electrochemical membrane integrated with molten carbonate fuel cells	7	Global CCS Institute, 2021
	Polymeric membranes	7	Global CCS Institute, 2021
	Room temperature ionic liquid membranes	2	Global CCS Institute, 2021

Cryogenics	Conventional liquid-vapor separation Unconventional solid-vapor separation	3-6	National Petroleum Council, 2021 Font-Palma, 2021
Other	Solid looping	5-7	Global CCS Institute, 2021
	Allam cycle	4-7	Global CCS Institute, 2021 National Petroleum Council, 2021
	Hybrid: polymeric membranes and cryogenic separation	6	Global CCS Institute, 2021
	Calix advanced calciner	5-6	Global CCS Institute, 2021
	Fuel cells	3-6	National Petroleum Council, 2021
	Hybrid: polymeric membranes and solvents	4	Global CCS Institute, 2021

Source: GAO summary of peer-reviewed article and literature. | GAO-22-105274

Note: C. Font-Palma, D. Cann, and C. Udemu, “Review of Cryogenic Carbon Capture Innovations and Their Potential Applications,” *Journal of Carbon Research*, vol. 7, article 58 (2021); Global CCS Institute, *Global Status of CCS 2021: CCS Accelerating to Net Zero*, (Melbourne, Australia: 2021); and National Petroleum Council, *Meeting the Dual Challenge: A Roadmap to At-Scale Deployment of Carbon Capture, Use, and Storage* (Washington, D.C.: National Petroleum Council, 2019).

Appendix IV: Department of Energy Definitions and Descriptions of Technology Readiness Levels

Table 14: Department of Energy technology readiness levels (TRL) (2011)

TRL	Definition	Description
1	Basic principles observed and reported	This is the lowest level of technology readiness. Scientific research begins to be translated into applied research and development. Examples might include paper studies of a technology's basic properties or experimental work that consists mainly of observations of the physical world. Supporting Information includes published research or other references that identify the principles that underlie the technology.
2	Technology concept and/or applications formulated	Once basic principles are observed, practical applications can be invented. Applications are speculative, and there may be no proof or detailed analysis to support the assumptions. Examples are still limited to analytic studies. Supporting information includes publications or other references that outline the application being considered and that provide analysis to support the concept. The step up from TRL 1 to TRL 2 moves the ideas from pure to applied research. Most of the work is analytical or paper studies with the emphasis on understanding the science better. Experimental work is designed to corroborate the basic scientific observations made during TRL 1 work.
3	Analytical and experimental critical function and/or characteristic proof of concept	Active research and development is initiated. This includes analytical studies and laboratory-scale studies to physically validate the analytical predictions of separate elements of the technology. Examples include components that are not yet integrated or representative tested with simulants. Supporting information includes results of laboratory tests performed to measure parameters of interest and comparison to analytical predictions for critical subsystems. At TRL 3 the work has moved beyond the paper phase to experimental work that verifies that the concept works as expected on simulants. Components of the technology are validated, but there is no attempt to integrate the components into a complete system. Modeling and simulation may be used to complement physical experiments.
4	Component and/or system validation in laboratory environment	The basic technological components are integrated to establish that the pieces will work together. This is relatively "low fidelity" compared with the eventual system. Examples include integration of ad hoc hardware in a laboratory and testing with a range of simulants and small scale tests on actual waste. Supporting information includes the results of the integrated experiments and estimates of how the experimental components and experimental test results differ from the expected system performance goals. TRL 4-6 represent the bridge from scientific research to engineering. TRL 4 is the first step in determining whether the individual components will work together as a system. The laboratory system will probably be a mix of on hand equipment and a few special purpose components that may require special handling, calibration, or alignment to get them to function.

5	Laboratory scale, similar system validation in relevant environment	The basic technological components are integrated so that the system configuration is similar to (matches) the final application in almost all respects. Examples include testing a high-fidelity, laboratory scale system in a simulated environment with a range of simulants and actual waste. Supporting information includes results from the laboratory scale testing, analysis of the differences between the laboratory and eventual operating system/environment, and analysis of what the experimental results mean for the eventual operating system/environment. The major difference between TRL 4 and 5 is the increase in the fidelity of the system and environment to the actual application. The system tested is almost prototypical.
6	Engineering/pilot-scale, similar (prototypical) system validation in relevant environment	Engineering-scale models or prototypes are tested in a relevant environment. This represents a major step up in a technology's demonstrated readiness. Examples include testing an engineering scale prototypical system with a range of simulants. Supporting information includes results from the engineering scale testing and analysis of the differences between the engineering scale, prototypical system/environment, and analysis of what the experimental results mean for the eventual operating system/environment. TRL 6 begins true engineering development of the technology as an operational system. The major difference between TRL 5 and 6 is the step up from laboratory scale to engineering scale and the determination of scaling factors that will enable design of the operating system. The prototype should be capable of performing all the functions that will be required of the operational system. The operating environment for the testing should closely represent the actual operating environment.
7	Full-scale, similar (prototypical) system demonstrated in relevant environment	This represents a major step up from TRL 6, requiring demonstration of an actual system prototype in a relevant environment. Examples include testing full-scale prototype in the field with a range of simulants in cold commissioning. Supporting information includes results from the full-scale testing and analysis of the differences between the test environment, and analysis of what the experimental results mean for the eventual operating system/environment. Final design is virtually complete.
8	Actual system completed and qualified through test and demonstration	The technology has been proven to work in its final form and under expected conditions. In almost all cases, this TRL represents the end of true system development. Examples include developmental testing and evaluation of the system with actual waste in hot commissioning. Supporting information includes operational procedures that are virtually complete. An Operational Readiness Review (ORR) has been successfully completed prior to the start of hot testing.
9	Actual system operated over the full range of expected mission conditions	The technology is in its final form and operated under the full range of operating mission conditions. Examples include using the actual system with the full range of wastes in hot operations.

Source: Department of Energy. | GAO-22-105274

Appendix V: Technical Descriptions of Carbon Dioxide (CO_2) Conversion Pathways

Mineral carbonation

Mineral carbonation is a reaction between CO_2 and alkaline solids, such as calcium- (Ca) or magnesium- (Mg) rich materials, to produce mineral carbonates (e.g., $CaCO_3$, $MgCO_3$). This reaction occurs in nature as well. For example, calcium-rich rocks react with atmospheric CO_2 over geologic timescales to form limestone ($CaCO_3$) deposits.

Mineral carbonation reactions are slow, with the rate of the reaction depending on the concentration of CO_2 and the mineral undergoing carbonation. For example, portlandite undergoes carbonation more rapidly than Ordinary Portland Cement.[75] Elevated pH levels facilitate the formation of carbonates; however, dissolving CO_2 in water to induce the carbonation reaction lowers the pH.[76] Optimal pH levels for mineral carbonation can be maintained through the use of a high pH buffer system.[77] The reaction can also be water sensitive. While water accelerates the carbonation reaction on mineral surfaces and is a co-product of the reaction, it can keep CO_2 from reaching the interior surfaces of a porous mineral for continued reaction.

Chemical conversion

Hydrogenation refers to any reaction between molecular hydrogen (H_2) and another chemical. There are two types of hydrogenation reactions with CO_2, *direct* and *indirect*. *Direct hydrogenation* uses heat and a metal catalyst to facilitate a reaction between CO_2 and H_2.[78] *Indirect hydrogenation* is a multistep process for converting CO_2 to products. First, CO_2 is converted to carbon monoxide (CO) which can be done through either the reverse water-gas shift reaction or through electrochemistry.[79] CO can then be mixed with H_2 to create a gas mixture known as syngas. CO is more reactive than CO_2 and can be an end product or a feedstock for a wide range of chemicals. Syngas conversion to other valuable products can occur through hydrogenation or through the Fischer-Tropsch process to make liquid fuels such as aviation fuel and gasoline.[80]

Electrochemistry is a process to convert CO_2 to products using electricity instead of heat. Direct electrochemical reduction of CO_2 produces CO and molecular oxygen (O_2).

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[75] Portlandite is hydrated limestone, $Ca(OH)_2$, and is sometimes also called slaked lime. Ordinary Portland Cement—the most commonly used binder in concrete—is a low-rank silicate, containing primarily two or more parts lime (CaO) to every one part silicate (SiO_2).

[76] The pH is a measure of how acidic or alkaline a solution is. A pH below 7 is acidic and a pH above 7 is alkaline.

[77] Buffer systems prevent acidic or basic reactants from causing large changes in pH over a specific range.

[78] A catalyst is a substance that increases the rate of a reaction without being consumed by the reaction.

[79] The reverse water-gas shift reaction is a reaction between CO_2 and H_2 to produce CO and water (H_2O).

[80] The Fischer-Tropsch process is a widely commercialized chemical reaction that converts CO and H_2 into water and a mixture of liquid hydrocarbons that can be used as fuels.

Other electrochemical processes can reduce CO_2 to formic acid or to methanol.

Co-polymerization is the process of making polymers using two or more different starting molecules—called monomers. Certain polymers can have a percentage of the fossil fuel-based monomers, such as ethylene and propylene oxides, replaced with CO_2. Polymers do not require as much energy input for conversion compared to other commodity chemicals because reaction energy is provided by the fossil fuel feedstock that is not replaced by CO_2.

Microbial conversion

Algae, a type of photosynthetic microbe, converts sunlight and CO_2 into energy for growth, and its biomass can be used to produce usable products. Algae cultivation can be land and water intensive and cultivation optimization is an ongoing area of research. Some ways to minimize land and water intensity include algae cultivation on non-farmable land or the use of wastewater, brackish, or seawater instead of freshwater. There are generally two cultivation methods for algae: open raceway ponds and closed photobioreactors. Open raceway ponds are of interest for biofuels to minimize production costs. Closed photobioreactors have higher capital and operating expenses, but can have tighter control over cultivation conditions and enhanced product purity compared to open raceway ponds. Thus, closed photobioreactors are preferred for the production of high value materials such as nutraceuticals and animal feed.

Nonphotosynthetic microbes, such as acetogens or methanogens, convert CO_2 or CO to usable products without the need for sunlight in a process known as gas fermentation. Acetogens can convert CO and water to ethanol via gas fermentation, but the carbon efficiency is only 33.3 percent.[81] Using H_2 instead of water increases the carbon efficiency up to 100 percent. Acetogens can also convert CO_2 to ethanol via gas fermentation, but, in contrast to using CO as a feedstock, the process does require H_2 to be an energy source to activate the reaction as well as provide the hydrogen atoms necessary for ethanol formation.[82]

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[81] Carbon efficiency is defined as the percent of carbon atoms going into the reaction to produce the desired product.

[82] CO can serve as both a carbon and energy source in the gas fermentation process.

Appendix VI: GAO Contact and Staff Acknowledgments

GAO contact

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Staff acknowledgments

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