MEETING THE
DUAL CHALLENGE

A Roadmap to At-Scale Deployment of
CARBON CAPTURE, USE, AND STORAGE

TECHNOLOGY INTRODUCTION

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TECHNOLOGY INTRODUCTION

I. INTRODUCTION

Carbon capture, use, and storage (CCUS), including transport, combines processes and technologies to either reduce the level of carbon dioxide (CO_2) emitted to the atmosphere or remove CO_2 from the air. These technologies work together to capture (separate and purify) CO_2 from stationary sources so it can be compressed and transported to a suitable location where the CO_2 is converted into useable products or injected deep underground for safe, secure, and permanent storage.

CCUS can be delivered via a proven, safe, and well-understood suite of technologies, and Figure TI-1 illustrates a number of these technology combinations. CCUS has been deployed on large stationary source CO_2 emissions in several industries across the United States and globally, including applications in coal-fired power or electricity generation, natural gas processing, hydrogen and fertilizer production, bioethanol fermentation, liquid natural gas (LNG) in Australia, steel in Abu Dhabi, and others.

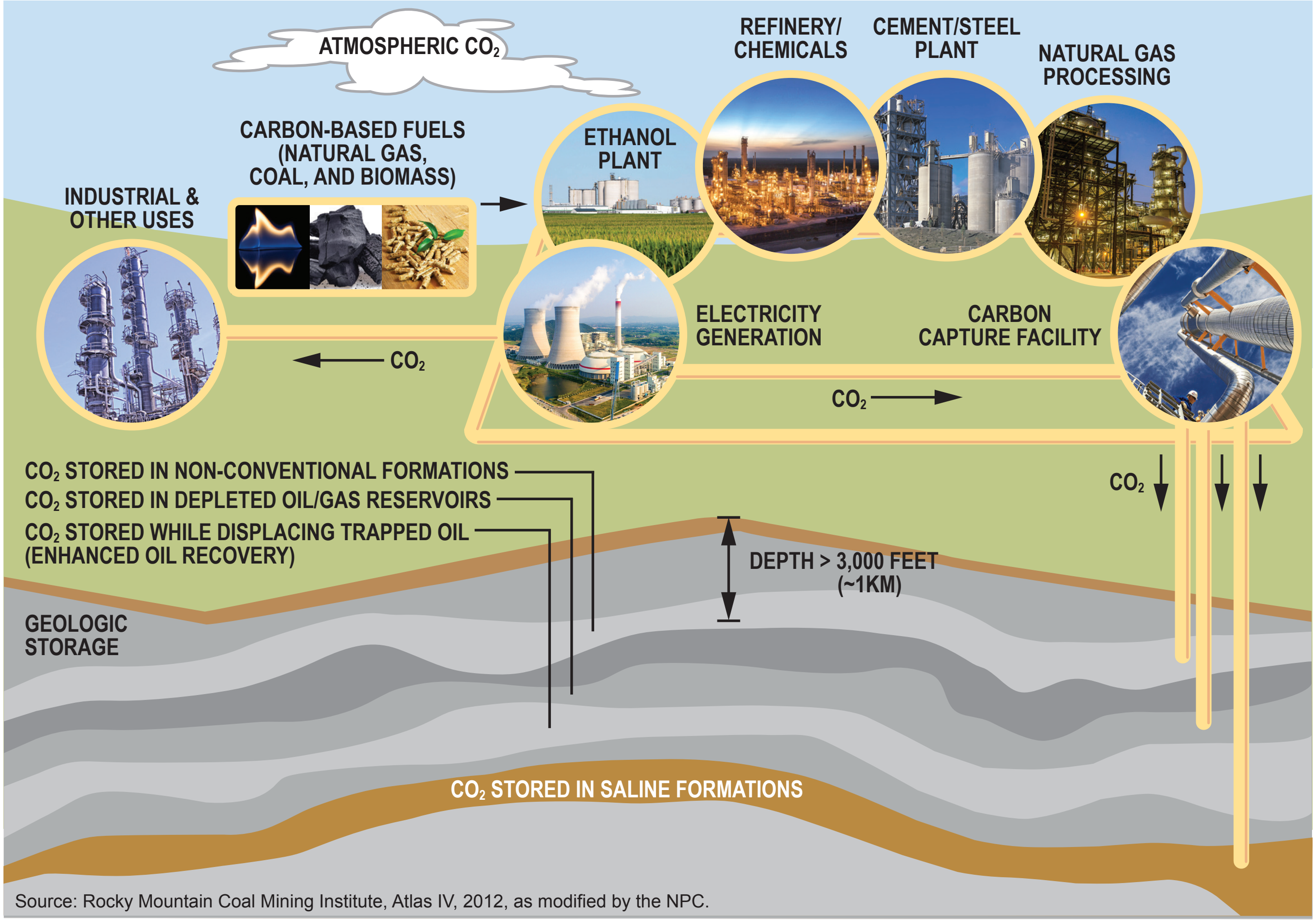
Capturing CO_2 from the exhaust emissions from the source can also help to reduce the release to the atmosphere of other air pollutants, thus providing an environmental co-benefit (see Text Box at the end of this chapter).

This volume of the NPC CCUS study focuses on the technology components of the CCUS supply chain, which are presented in five chapters:

- CO_2 Capture
- CO_2 Transport
- CO_2 Geologic Storage
- CO_2 Enhanced Oil Recovery
- CO_2 Use.

Capture. CO_2 is produced in combination with other gases during industrial processes, including hydrocarbon-based power generation, steel and cement manufacture, hydrogen production, and refined fuels production. CO_2 results from the combustion of fossil fuels for energy and heat during these operations (combustion emissions), as well as from the processes themselves, such as during the creation of cement (process emissions). CO_2 capture is the separation of CO_2 from these other gases from the exhaust stream of a power plant, industrial flue (vent) gas emissions, or directly from the atmosphere. High-concentration CO_2 sources from ethanol fermentation can be dehydrated (removing entrained water) and compressed directly without requiring separation from an exhaust or flue gas mixture.

Transport. CO_2 transport refers to the transfer of CO_2 from one location to another, or between a CO_2 source and geologic sink or point of use, usually via pipelines. In the United States, over 70 million tonnes per annum (Mtpa) of CO_2 is transported from natural and anthropogenic sources via a pipeline network of more than 5,000 miles. This network represents approximately 85% of the current global CO_2 pipeline infrastructure. Most transported CO_2 is used for enhanced oil recovery (CO_2 EOR) in oil fields in the west, southwest, and Gulf Coast regions of the United States. CO_2 can also be transported safely by other means, including rail, truck, ship, and barge. Transport of CO_2 by ship offers an alternative solution for many regions of the world.



Source: Rocky Mountain Coal Mining Institute, Atlas IV, 2012, as modified by the NPC.

Figure TI-1. *Supply Chain for Carbon Capture, Use, and Storage*

Storage. CO_2 storage, also called CO_2 geologic storage, refers to the injection and permanent trapping of CO_2 in deep underground reservoirs, typically in saline formations. Depleted oil and gas reservoirs, un-mineable coal seams, and basalts also have potential to store CO_2. Large-scale geologic storage in saline formations is understood and has been practiced for over 20 years, starting in Norway in 1996 at the Sleipner Field. The United States has been active in research in this area and has been storing CO_2 in saline formations at various scales of injection since the early 2000s, notably via the U.S. Department of Energy regional carbon sequestration projects. The United States also possesses one of the largest known geologic storage capacities in the world and most states in the continental United States possess some subsurface CO_2 storage potential.

Enhanced Oil Recovery. CO_2 EOR, a form of storage, is the process of injecting compressed CO_2 underground into an oil reservoir to recover more oil and natural gas than originally produced. The injected CO_2 liberates oil that was trapped in the pore spaces of the underground formations and the CO_2 remains trapped in the reservoir in its place. The incidental trapping of CO_2 that is injected for the purposes of EOR is an important co-benefit of the process, and 99% of the CO_2 injected is ultimately trapped in the subsurface formation.[1] The United States is a world leader in the application of CO_2 EOR and has more than 40 years of operational experience with this technology.

Use. CO_2 use represents a new generation of innovative technologies that convert CO_2 into products such as fuels, chemicals, and materials

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[1] International Standards Organization, ISO 27916:2019, Carbon dioxide capture, transportation and geological storage – Carbon dioxide storage using enhanced oil recovery (CO2–EOR), https://www.iso.org/standard/65937.html.

via chemical reactions or biological conversions. CO_2 use is the least mature component in the supply chain of CCUS technologies, but active research continues to pursue multiple technological pathways for converting CO_2 into products. Given the relative immaturity of these technologies, CO_2 use is likely to remain an outlet for only a small fraction of captured CO_2 over the next 10 to 20 years. However, these technologies hold promise for future emissions abatement.

Expanding the deployment of CCUS to the scale described in this study will require more efficient integration of the existing suite of technologies, the development of new and emerging technologies to deliver new CCUS pathways, and a reduction in the cost of delivering CCUS solutions. Continuing and expanded technology investment is warranted to deliver CO_2 mitigation methods at scale.

Investment in research, development, and demonstration (RD&D) in CCUS technologies, plus deployment of CCUS in early projects that integrate a suite of CCUS technologies at scale, offers numerous benefits. Continued CCUS RD&D offers the means to lower project integration costs through "learning by doing," scale-up of less mature technologies for potential application in commercial projects, and progress new and emerging technology solutions to create new and less costly CCUS pathways.

Less mature technology options exist for each component of the CCUS supply chain. Further development of these options offers opportunities for modularization, cost reductions, region-specific solutions, and cross-sector applications. The framing of CCUS component technologies in the form of technology readiness levels (TRLs) is presented below, providing a useful way of describing options and identifying opportunities that may become important in the future.

Reducing the cost of CCUS is essential to achieving at-scale deployment. CO_2 capture can represent up to 75% of the cost of CCUS when applied to large-scale stationary emissions sources. Development of transport infrastructure to connect CO_2 sources and sinks, and identification and characterization of large-scale geologic storage formations, offer other means of reducing the cost of at-scale CCUS deployment. With lower overall costs, the levels of incentives and financial support requested in Chapter 3, "Policy, Regulatory, and Legal Enablers," should also decrease with time. (See Volume II of this report.)

Finally, the long-term growth of CCUS at scale will depend on the development of people and institutional capabilities across a broad spectrum of organizations, including academic, scientific, industry, trade organizations, professional societies, financial, government, think-tanks, and non-governmental organizations (NGOs). Investment in RD&D not only provides the funds to progress important research, but also supports development of the next generation of scientists, engineers, and entrepreneurs in advancing CCUS technologies, testing business models, and improving operational processes.

This introduction offers context on the following topics:

- Technology readiness and maturity
- Research, development, and demonstration opportunities
- Capability development.

These topics lead to a more detailed discussion of the CCUS component technologies presented in Chapters 5 through 9, and support the recommendations on RD&D noted in Chapter 3 in Volume II.

II. TECHNOLOGY READINESS AND MATURITY

The United States has made significant strides in the development of CCUS technologies during the last two decades, which has been aided by public-private partnerships that have driven cost reductions and performance improvements. Some technologies are in use and available for commercial deployment today while others require demonstration to prove their viability in a commercial setting. Other technologies remain in earlier stages of development.

Figure TI-2 describes the range of technology readiness levels (TRL) for many of the component technologies described in this study, using the U.S. Department of Energy's TRL definitions.[2] Each technology is assigned a technology readiness level range that represents its stage of technical development and maturity (vertical axis). The TRL scale ranges from 1 (basic principle observed) through 9 (operational at scale). The higher the TRL level (i.e., ≥ 8), the closer a technology is to commercial readiness and deployment.

Figure TI-2 illustrates the TRL ranges of CCUS component technologies as assessed by members of the NPC CCUS Study Technology Task Group. Full CCUS supply chains can be executed today, but as Figure TI-2 shows, there is a limited suite of high TRL (greater than TRL 7) technology options available to deliver at-scale CCUS projects. Typical projects consist of CO_2 capture via amine absorption, transport from source to sink by pipeline, and the CO_2 injected deep underground for storage in saline formations or used for conventional CO_2 EOR.

In general, it is expected that there will be limited options for cost and efficiency improvements associated with high TRL technologies where transformational improvements are not anticipated. For these mature technologies, only incremental cost and performance gains are expected as a result of operational efficiency gains that come from "learning by doing" through the delivery of many examples of the same kinds of projects.

Alternatively, less mature and emerging technologies (TRL 6 and below) offer the greatest potential for step changes in performance

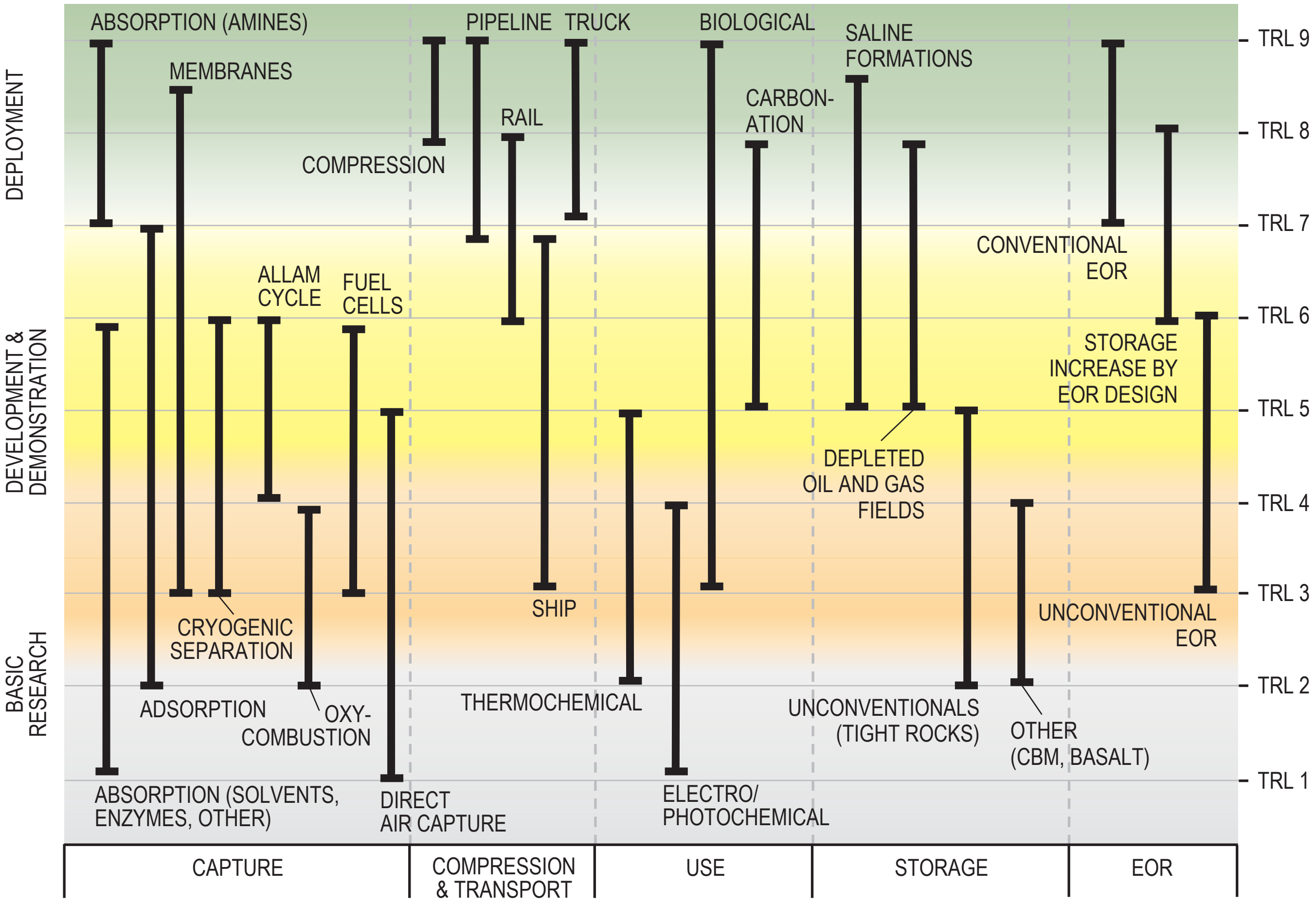

Figure TI-2. Technology Readiness Level (TRL) Ranges for CCUS Technologies

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[2] U.S. Department of Energy, DOE G 413.3-4A Chg 1 (Admin Chg), Technology Readiness Assessment Guide, last update October 22, 2015, https://www.directives.doe.gov/directives-documents/400-series/0413.3-EGuide-04-admchg1.

and cost reductions. Figure TI-2 highlights a number of these less mature technologies that should benefit from continued progress in RD&D activity.

The technology chapters that follow include an assessment of the maturity of each technology component as well as a view on what is needed to achieve technical potential and scalability in the future. Please see Chapters 5 through 9 for additional details.

III. RESEARCH, DEVELOPMENT, AND DEMONSTRATION OPPORTUNITIES

To achieve more substantive cost reductions, improve performance, create competition, and accelerate innovation in support of at-scale CCUS deployment, continuing investment in the RD&D of emerging technologies is necessary and funding levels should increase.

A. The Case for RD&D

Commitment to RD&D and expansion of academic, government, and industry research across multiple technology pathways are required to reduce CCUS costs, create competition, and help accelerate innovation. Support for RD&D at all phases of technology development will drive improvements and offer more options to reduce CO_2. RD&D funding and activity should ramp up with time as the United States builds capability and the technology portfolio evolves and broadens.

Innovations in proven technologies are common once the technology is deployed many times. In addition to cost reductions and efficiencies gained through delivering multiple CCUS projects, technology enhancements that help increase efficiencies and drive down costs will occur because of:

- Delivery of many examples of the same kinds of projects and industry standardization leading to project execution and operational efficiencies, and
- Innovation and improvements in components, materials, and mechanisms improving the technologies themselves.

B. Potential for Step Change and Technology Maturity

One of the biggest challenges in technology development is the need to pilot and demonstrate emerging technologies, moving them from basic research to demonstrating proof of concept and actual deployment. The demonstration and deployment phases require significant increases in funding, project development skills, and planning and permitting capabilities. Planning and permitting is often a major hurdle to progressing a proven technology to commercialization. Funding and government and industry collaborations are often required to move a proven technology forward.

The portfolio of basic research technologies for CCUS has the potential to deliver step changes in performance and cost by broadening the range of potential CCUS technology solutions and applications. Although there is great uncertainty in which technologies will fully mature, numerous concepts and technologies already exist, each of which requires research investment to mature. Many of these less-mature technologies hold promise for significant breakthroughs, but most remain unproven and success is uncertain.

With continued research and development, the portfolio of CCUS technologies will increase, potentially yielding a wider range of applications and low-carbon products (Figure TI-3). Some of these new technologies could offer a 10% to 30% improvement in the cost of large-scale CCUS applications over the next 20 to 30 years, as described in Chapter 2, “CCUS Supply Chains and Economics.” Investment in RD&D and infrastructure development could therefore yield a tenfold return in the longer term.

Chapter 3, “Policy, Regulatory, and Legal Enablers,” describes this study’s RD&D funding recommendations in detail, expanding from the current level of funding to accelerating the funding needed for deployment at scale.

IV. CAPABILITY DEVELOPMENT

The long-term growth of CCUS at scale also depends on the development of people and

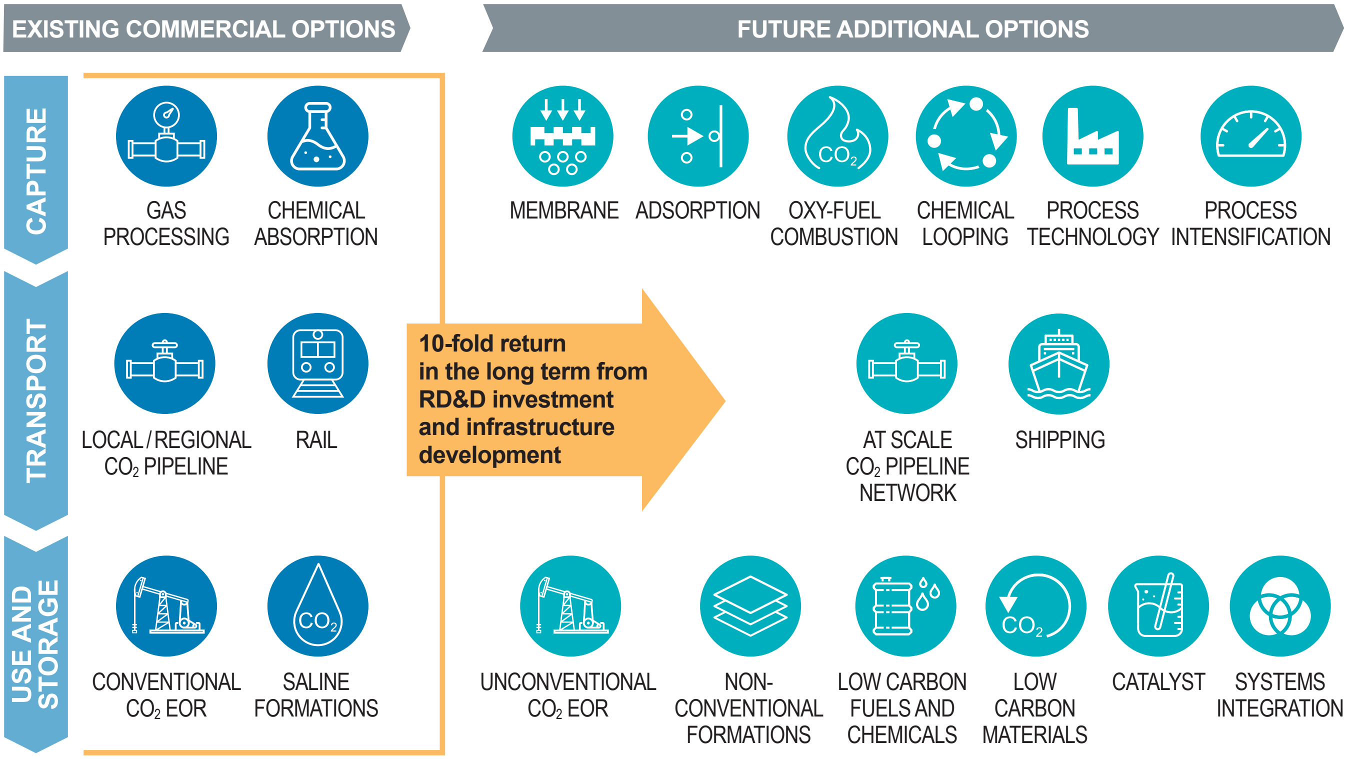


Figure TI-3. Current and Future Portfolio of CCUS Technologies

institutional capabilities across a broad spectrum of organizations, including academic, scientific, industry, trade organizations, professional societies, financial, government, think-tanks, and NGOs. Investment in RD&D not only provides the funds to progress important research, but also supports training and development of the next generations of scientists, engineers, and entrepreneurs in advancing CCUS technologies, testing business models, training people for capabilities in government permitting, and improving safe and environmentally sound operational processes.

Although the examples below do not represent an exhaustive list, they do provide insight into how capability development is necessary to support CCUS at scale.

A. Industries

Energy companies and other carbon-intensive industries will expand technical capabilities to plan, build, and deploy CCUS projects. The skills required to support this expansion will include operational safety, subsurface, environmental assessment, and project planning and execution. The oil and gas industry is uniquely positioned to lead CCUS deployment due to its relevant experience, capability, and technical and financial resources.

B. Academic and Scientific Incentivization

The creation of CCUS-specific academic disciplines, recognized by both industry and government, is necessary to support scale-up in deployment of CCUS. These disciplines could evolve in much the same way that computer science has evolved over the last few decades. Following this model, industry and government grants would provide the funding for the creation of “CCUS sciences” or “carbon engineering” departments at universities and laboratories. These departments might include the curricula for the science and engineering needed for CCUS technology development and also curricula for business schools and MBA programs, much like the “business of energy” programs developed at universities. Universities specializing in applicable basic

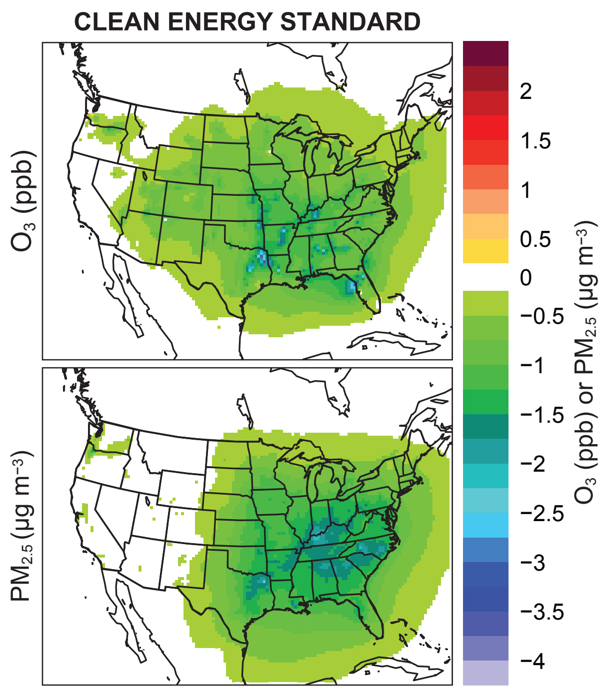
ADDITIONAL ENVIRONMENTAL BENEFITS OF CCUS

There are human health co-benefits from reducing greenhouse gases (GHGs) via CCUS, such as reductions in various conventional air pollutants. Actions designed to capture GHGs can benefit air quality. Capturing emissions from a variety of industrial sources (hydrocarbon-based power generation, steel and cement manufacture, hydrogen production, refined fuels production, etc.) will also separate out other air pollutants because the types of equipment used can also remove other impurities before or during the capture process.

One of these impurities—fine particulate matter of less than 2.5 microns in size ($PM_{2.5}$)—is entrained in gases from power plants and other industries and is recognized as an air pollutant.* Ozone (O_3), which is formed by chemical reactions between nitrogen oxides and volatile organic compounds, will also be captured. The concentrations of ground-level ozone and $PM_{2.5}$ can serve as air quality indicators.

One team of researchers modeled levels of ozone and $PM_{2.5}$ across the continental United States for certain future scenarios, including natural gas power generation coupled with CCUS.† The results are shown in the figure below in the form of spatial maps that show the difference in pollution concentration between a clean energy standard (CES) option, which includes natural gas with CCUS, and a reference case with no GHG emissions reductions. The figure presents two maps showing predicted changes by 2030 in ozone levels in the upper panel (O_3 season average daily maximum 8-h O_3, parts per billion [ppb]) and in $PM_{2.5}$ levels in the lower panel (annual average, microgram per cubic meter).

In summary, this research team's work predicts air quality improvements by 2030 associated with deployment of CCUS and other greenhouse gas reduction measures. Other researchers found similar results on a global scale. For example, one team showed that the global concentrations of $PM_{2.5}$ and ozone will both decline through the year 2100 as a result of assumed CCUS deployment.‡



Source: Adapted from Thompson et al., 2014.

Ozone and $PM_{2.5}$ Pollutant Levels in 2030

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* PM stands for particulate matter (also called particle pollution): the term for a mixture of solid particles and liquid droplets found in the air. $PM_{2.5}$ refers to fine inhalable particles, with diameters that are generally 2.5 micrometers and smaller; 2019 U.S. EPA.gov reference: https://www.epa.gov/pm-pollution/particulate-matter-pm-basics.

† Thompson, T. M., Rausch, S., Saari, R. K., and Selin, N. E., "A systems approach to evaluating the air quality co-benefits of US carbon policies," *Nature Climate Change*, August 24, 2014, vol. 4, p. 917, Nature Publishing Group, https://www.nature.com/articles/nclimate2342#supplementary-information.

‡ West, J. J., Smith, S. J., Silva, R. A., Naik, V., Zhang, Y., Adelman, Z., Fry, M. M., Anenberg, S., Horowitz, L. W., and Lamarque, J.-F., "Co-benefits of mitigating global greenhouse gas emissions for future air quality and human health," *Nature Climate Change*, September 22, 2013, Vol. 3, Nature Publishing Group, https://doi.org/10.1038/nclimate2009.

research could receive industry and government grants to encourage advances in CCUS-related research.

C. Industry Trade Organizations and Professional Societies

Industry trade organizations and professional societies could play a pivotal role in "socializing" CCUS to graduates from universities and technical training schools to help develop a CCUS workforce, encouraging them to pursue a career in industries dedicated to reducing and managing carbon emissions. These organizations could assist in facilitating general public understanding of how CCUS enables a broad range of industries, including low-carbon energy production, reduced carbon manufacturing, and reduced carbon building materials. Professional societies can also play a role in defining CCUS standards and accrediting third-party assessors.

D. Financial Institutions

Banks, institutional investors, government or sovereign investment funds, and private equity funds could all contribute to meeting the financial and investment needs of developing CCUS at scale. Sovereign and institutional investors could create investment vehicles that encourage the application and growth of CCUS technologies across many industries, which would help to foster a positive perception that investments in CCUS can profitably contribute to a lower carbon world. Financial vehicles could be created that encourage funding and loans for establishing entrepreneurial enterprises, such as small businesses, to provide products and services to every element of the CCUS value chain.

E. Think-Tanks and NGOs

The full impact of CCUS on industry, the global economy, environment, and society could be observed, measured, and reported on by think tanks, NGOs, and other independent coalitions. Organizations such as these could work closely with industry, policymakers, labor organizations, and each other to educate and inform the public about the benefits and challenges of CCUS and support policies that would enable at-scale deployment to meet societal and industrial demands, as described in Chapter 4, "Building Stakeholder Confidence," in Volume II of this report.

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