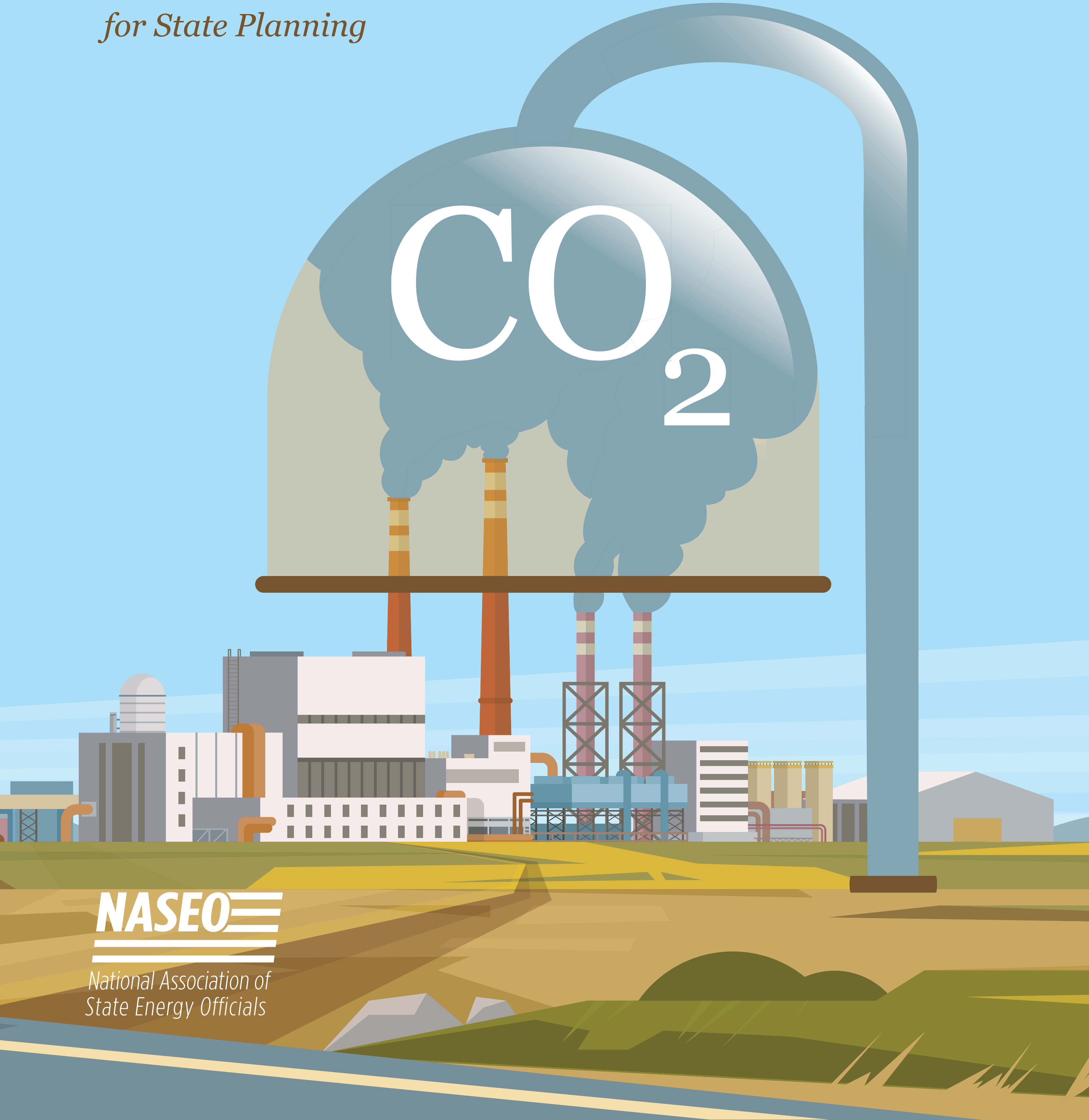
Carbon Capture, Utilization, and Storage:

Overview and Considerations for State Planning



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Abstract

Increasingly urgent concerns about climate impacts from carbon dioxide (CO_2) and other greenhouse gases (GHG) are prompting the federal government along with a growing numbers of states, localities, and private companies to enact policies and establish targets to reduce emissions. Carbon capture, utilization, and storage (CCUS) offers an important approach to reduce emissions from energy and industrial facilities and can, at times, provide additional economic value when recovered CO_2 is used in production processes or incorporated into useful materials and products. Innovative approaches toward biomass utilization, hydrogen production, and new CO_2-derived products can facilitate new industrial development. Investment in carbon capture, processing, use, and related infrastructure can yield economic benefits and create employment opportunities. State Energy Offices and other pertinent bodies should consider CCUS options and opportunities, including supportive policy and regulatory measures, in developing energy, environmental, and economic development plans.

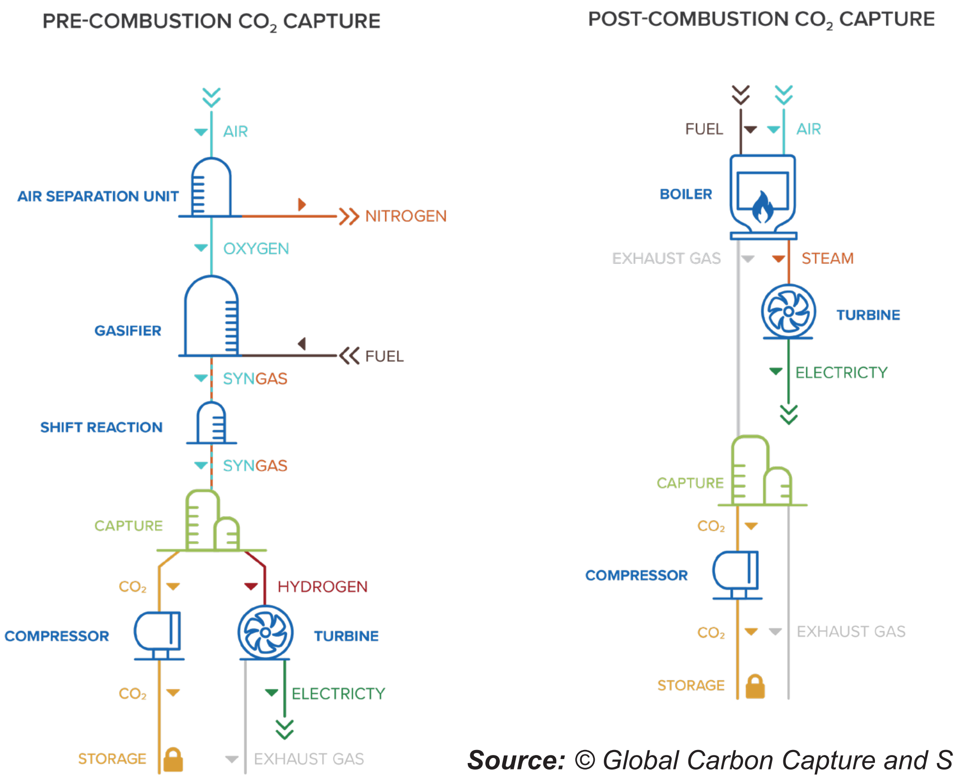
Overview

Even as renewable energy and complementary energy storage and management technologies become more cost-competitive and gain market share, large amounts of fossil fueled power generation are likely to remain in service for some time. Also, hard to decarbonize industrial processes such as for iron and steel, cement, ethanol, ammonia, and petrochemical manufacture will remain vital to the economy. In addition, CCUS[1] can provide a foundation for net-zero and even net-negative emissions biofuel production and biomass-based power generation. In complement to renewable and nuclear energy, CCUS can help enable hydrogen as a clean energy storage and transport medium.

The Carbon Capture Coalition reports that there are 21 large carbon capture and storage (CCS) or CCUS facilities capturing about 42 million metric tons of CO_2 annually around the world.[2] Thirteen such facilities operate in the United States, capturing about 25 million metric tons of CO_2 annually. The Clean Air Task Force (CATF) lists a total of 32 U.S. projects at some stage of development.[3]

Carbon capture can be performed before or after CO_2 is generated in an energy or industrial operation. Pre-combustion processes remove carbon from fossil or biomass fuels to create a hydrogen-rich synthesis gas that can be used for energy or chemical process input. Various current carbon capture facilities employ post-combustion processes that capture CO_2 after it is created through combustion or other chemical process. Depending on CO_2 concentration, technologies used for pre- or post-combustion removal can also be used to separate naturally occurring CO_2 in natural gas and from petroleum extraction and processing. While this document focuses on carbon capture from industrial and power generation emissions, direct air capture (DAC) of CO_2 from the air also garners growing attention as part of the climate solution.[4] Figure 1 provides a schematic of pre- and post-combustion CO_2 capture.

Figure 1. Schematics of Pre- and Post-Combustion CO_2 Capture



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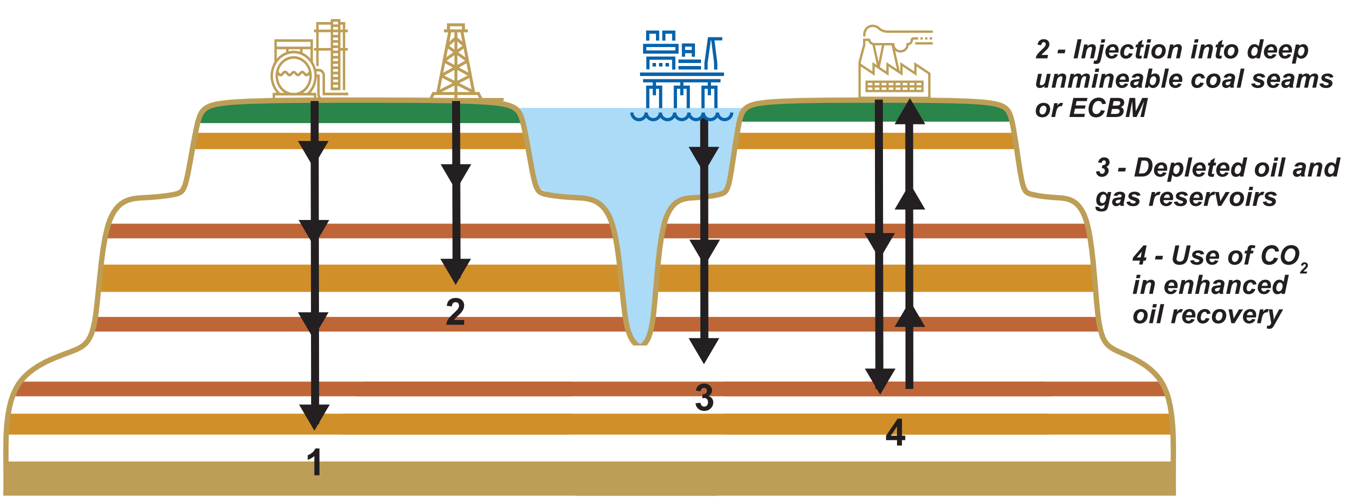
CO_2 can be geologically sequestered in saline formations, old oil and gas fields, and deep unmineable coal seams, but utilization of captured CO_2 can provide value to mitigate costs. Since the 1930s, CO_2 has been recovered from industrial processes, such as petroleum refining, ammonia manufacture, and ethanol production, for use in food, beverage, and other industries and to make dry ice and liquid CO_2 for other applications. Since 1972, enhanced oil recovery (EOR) using CO_2 has increased oil field production. Figure 2 illustrates storage, including EOR.

Figure 2. CO_2 Storage Overview - Site Options



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Utilization as feedstock to produce fuels, chemicals, and new materials, and to enhance agriculture, offer growing opportunity. Lux Research projects that the global market for CO_2 utilization will grow to $70 billion in 2030 and $550 billion in 2050, led by building material applications (86 percent in 2040) with other uses for fuels, chemicals, carbon additives, polymers, and proteins (for feed).[5] However, volumes of emissions are far greater than potential utilization markets. Also, while some utilization (e.g., EOR and some material production) may sequester CO_2 long-term or permanently, other uses (e.g., food and beverage, dry ice applications) only delay emissions. If utilization or suitable geology for sequestration is not close to the site of capture, then piping/transport can present financial, planning, and implementation challenges. However, CO_2 piping infrastructure development also offers investment and employment opportunities.

As with renewable energy and energy storage, costs of CCUS have been declining as technologies advance, are demonstrated, and grow in scale. Application, context, and scale affect costs. It is easier to remove CO_2 from highly concentrated streams, such as from some industrial and natural gas processing operations, than less concentrated streams from power plants flue gas. Cost of capture, compression, deep injection, and monitoring can range from about $25 per ton for an ethanol or hydrogen plant to roughly $100 and $120 per ton for coal- and natural gas-fueled power plants, respectively.[6] DAC may be in the $600 to $1,000 a ton range. EOR or other utilization can defray costs. As noted previously, pipeline or other transport imposes cost too.

State Energy Offices should be cognizant that policies and regulations are critical to the current viability of CCUS. Government provided or incentivized research, development, and demonstration (RD&D) can advance CCUS technical and economic performance. Pricing CO_2 emissions explicitly or implicitly through emission limits can incite demand for CCUS. For example, the California Low Carbon Fuel Standard (LCFS), which regulates the carbon-intensity of transportation fuels used in California, provides credits that certain in- and out-of-state CCUS projects, including DAC facilities, can earn. Federal and state fiscal incentives can also propel CCUS development. The federal 45Q tax credit for eligible CCUS projects commencing construction by 2024 provides a valuable incentive.[7] U.S. Environmental Protection Agency (EPA) and state regulation and permitting of CO_2 underground injection must be complied with to assure long term sequestration and environmental protection. States also play critical roles in underground ownership rights, liability, and pipeline siting and permitting important for CCUS implementation. State Energy Offices and other agencies can consider policy, program, and regulatory options that can encourage CCUS development and implementation that supports state economic and environmental objectives.

This paper lays out policy and planning factors for State Energy Office consideration and provides an overview of CO_2 sources and CCUS technologies and activities.

State Energy Planning and Policy Considerations

State Energy Offices should consider whether and how CCUS can fit into the state's energy, environmental, and economic development plans and strategies. Consistent with questions below, planners should consider current and projected CO_2 emitting sources, geology, regional options for achieving economies-of-scale, and opportunities to pair CCUS technology with new biomass energy, biofuels, hydrogen, and other industrial applications to support innovation and competitive advantage.

State Energy Offices should take stock of existing federal, state, and local policies in considering opportunities for and impediments to CCUS in their states. They should also consider prospective policies and regulations and, if in their remit, identify policy options and recommendations. The purpose of CCUS is to reduce CO_2 emissions and lower—or at least slow the rate of growth of— atmospheric CO_2 concentration. It is, at base, a climate protection measure though it has wider energy and economic development aspects, as discussed in the report and elsewhere.

Even with EOR and other utilization markets, CCUS will not, with current technologies, financially pay for itself absent supportive policies. To make CCUS valuable and financially worthwhile, a policy tool kit can include the following options:

- options for placing a direct or indirect “price on carbon”;
- crediting CCUS in clean energy programs and standards;
- providing fiscal incentives through tax and other mechanisms;
- creating conducive planning and financing approaches;
- addressing siting and permitting matters, including associated issues of liabilities and subsurface ownership rights; and
- supporting RD&D, among others.

The following are some of the issues for state energy planning and policy consideration:

Planning Issues and Considerations

Sources and Volumes of CO_2 Emissions Suitable for CCUS	Planners should identify current and prospective power generation and industrial emitters that may be amenable to CCUS. Planned retirements of plants as well as potential new industrial sources should be considered. CO_2 volumes and concentrations in emission streams differ based on power generation and industrial processes used, affecting the choice and economics of carbon capture technologies. Data sources may include state environmental agencies; electric and gas utilities; oil and gas industries; petroleum refiners; iron and steel producers; and other industries (such as ammonia, ethanol, petrochemical, and food and beverage).
Suitable Geology for Sequestration	Even with growing interest in using captured CO_2 in products, volumes of emissions are far greater than potential markets for recovered CO_2. Thus, geological (and biological, via forests, grasslands, soils, and marine and aquatic vegetation) sequestration will be needed if CCUS is to make a big difference in net emissions. Deep saline aquifers, depleted oil and gas formations, and deep unmineable coal seams offer suitable geology. EOR as well as enhanced gas recovery and recovery of coal bed methane can yield valuable product to defray CCUS cost where geology permits. However, the economic feasibility of EOR depends on oil prices. State geologist offices, U.S Geological Survey, and oil and gas industries may offer pertinent data to assist states in determining whether the geology is suitable for CO_2 sequestration.

Potential for Economic Development Synergies	Spreading the cost of pipelines, compressors, site development, and other components over large volumes of CO_2 drawn from multiple source facilities reduces sequestration cost per ton significantly. Regional concentrations of sources, such as ethanol plants, fossil fueled power plants, and petrochemical industry, linked with suitable sequestration geology can support economies of scale. They can become CCUS “hubs” or “clusters” that also achieve economies of agglomeration where the concentration of experience, expertise, and physical capital can encourage additional innovation and investment, including in new CCUS technologies, such as new utilization processes and creative bioenergy and hydrogen opportunities. In considering economic development opportunities, state energy planners should also take stock of pertinent research and expertise in their colleges and universities, national laboratories, private firms, and non-governmental organizations that can be tapped to evaluate and develop opportunities and build skilled workforces.
Status of Policy and Regulatory Environment	Federal, state, and local policies and rules greatly affect the economic and technical viability of CCUS, providing both impetus and impediment to development of technologies, investment in facilities and infrastructure, and commercial implementation. The federal 45Q tax credit can defray costs in applicable CCUS projects. States could consider their own tax and fiscal incentives as well as funding mechanisms. The California LCFS can generate marketable credits for certain eligible CCUS (including DAC) projects outside of California. States could consider placing a “price on carbon” through a fee on emissions or a tradable emission allowance system that includes credits for CCUS. They can include CCUS in utility clean energy portfolio standards. States can also support and encourage RD&D and commercialization of relevant technologies. Federal, state, and local siting and land use laws, regulations, and processes will be critical to pipeline and sequestration site development. U.S. EPA Underground Injection Control regulations under the Safe Drinking Water Act are applicable, with states (North Dakota and Wyoming so far) being able to obtain “primacy” from EPA for administering such rules for CO_2 injection.

Policy Issues and Considerations

Emission Limitations and Price on Carbon

Although there is growing interest, there are no current federal laws or regulations that directly limit or charge a fee for CO_2 emissions. Federal vehicle fuel economy standards, appliance energy efficiency standards, and consideration of GHGs in Best Available Control Technology determinations in air quality permitting, have either indirect or tenuous effects on the "price of carbon." Placing a price on carbon either by charging a fee per ton of CO_2 emitted (or CO_2-equivalent if extended to other GHGs) or by imposing a regulated limit which can be traded (tradable allowance or permit) can encourage CCUS by placing a monetary value for sequestering or utilizing CO_2—if CCUS is an allowable carbon reduction category in the policy.

California's Low Carbon Fuel Standard "is designed to reduce greenhouse gas emissions associated with the life cycle of transportation fuels used in California and diversify the state's fuel mix." CCUS projects associated with transportation fuel production (petroleum, alternative fuels, and even electricity for EV charging) outside California can earn credits but only for fuels consumed in California. An exception exists for DAC projects that sequester CO_2 underground which can be located anywhere and do not need a fuel-related component. The 11 states participating in the Regional Greenhouse Gas Initiative (RGGI) is another example of a CO_2 limitation program with a tradeable allowance component. RGGI states auction limited numbers of allowances to utility-scale electricity generators to cap total power sector emissions in the member states. The allowances can be bought and sold. RGGI has provisions for creation of offset allowances for certain GHG reduction projects that could be sold to power plants wanting to buy allowances for compliance. However, currently CCUS is not an allowable category.

A state could consider imposing fees, charges, or taxes on CO_2 emissions from one or multiple emitting sectors including, if desired, transportation based on fuel consumption emissions. Such a policy would encourage emissions reductions directly from emitting facilities, including via CCUS, and could include an offset provision crediting companies for CCUS performed by others. Similarly, a state could impose emissions limitations via a tradeable allowance system (as done by RGGI but allowing credit for CCUS) and/or through an emissions footprint standard such as the California LCFS. A state could decide to limit CCUS eligibility to in-state projects, come to agreement with other states (which could be beneficial for developing regional "clusters" or "hubs" that offer economies of scale and enhance regional economic development), or, like California, allow broader geographic applicability.

Clean Energy/ Renewable/ Alternative Energy Standard Eligibility and Low Carbon Credits	Thirty states, the District of Columbia, and three territories have Renewable, Clean Energy, and/or Alternative Energy Portfolio Standards that require electric utilities to deliver a portion of their electricity from eligible sources. Most of the states with such standards have targets of 10 to 45 percent generation from renewable or other eligible clean or alternative sources while 14 states, the District of Columbia, Puerto Rico, and U.S. Virgin Islands have targets of over 50 percent and, in some cases, 100 percent non-carbon generation goals. Also, seven states and Guam have voluntary utility goals. States with or contemplating such standards could include electric utility plant CCUS as eligible generation resources. At least two states, Illinois and New York, have incentivized continued power purchases from certain nuclear power generators to keep those zero-carbon emitting plants operating. An analogous mechanism could be used to incentivize CCUS in power generation.
Tax and Fiscal Incentives	Federal and state tax incentives are tools to support RD&D and deployment of CCUS.The federal Internal Revenue Code Section 45Q provides an income tax credit for CCUS of $20 per metric ton CO_2 geologically stored and $10 per metric ton used for EOR or enhanced gas recovery. The Bipartisan Budget Act of 2018 revised the credit so that it will rise over time to a 2026 rate of $35 per metric ton of CO_2 utilized (for EOR or other utilization) and $50 per metric ton geologically sequestered. Qualified facilities must begin construction by January 1, 2024 and must meet size and other criteria. The credit usually goes to the owner of the carbon capture equipment but can be transferred to the entity that sequesters or uses the CO_2. The credit has some similarities to the wind power production tax credit. States can consider offering tax credits, deductions, exemptions, and other incentives for CCUS investments and reduction or waivers of severance taxes on EOR-produced oil. For example, the Petra Nova CCUS plant was supported by Texas fiscal incentives, including franchise tax credits, some sales tax exemptions, and reductions in severance tax. Also, the capture system was deemed to be a pollution control device which allowed it to be exempt from property tax under Texas law.
Infrastructure Planning and Support	States, individually and regionally, and in cooperation with the federal government could consider opportunities for infrastructure planning. CCUS economics is sensitive to economies of scale. A piping infrastructure that could gather CO_2 from multiple, varied sources and deliver the gas to use and sequestration sites would bring economies of scale that would significantly reduce the cost of CCUS and enhance state and regional CCUS-related economic development opportunities. An analogy is made with how Texas unleashed a large, vibrant wind power industry by creating competitive renewable energy zones (CREZ) that facilitated the construction of high voltage transmission lines to bring abundant wind power from west Texas to meet the needs of populous central and southeastern Texas. Texas law in 2005 directed the Public Utility Commission to oversee siting and select transmission developers. The transmission line developed is open access. For CCUS, the notion would be for federal and state authorities to pursue an analogous approach for national and/or regional pipeline development.

Financing	Private activity bonds (PAB) can be made available by states, with federal permission, to secure low-cost, long-term fixed rate debt for qualifying projects. For example, the Wyoming Infrastructure Authority was created by the Wyoming legislature in 2004 to advance infrastructure development and was authorized to issue up to $1 billion to finance energy infrastructure, which could include CO_2 pipelines. States could make PAB bonding available for CCUS projects. Several states, including California, Connecticut, Hawaii, New York, and Rhode Island, have green banks to offer loans, loan guarantees, and other credit enhancements and services to advance clean energy development and deployment. State-affiliated green banks and infrastructure banks can be authorized and encouraged to support CCUS projects. State could also choose to directly fund or finance pertinent projects.
Siting and Permitting	CCUS pipeline and sequestration facilities may be subject to federal, state, and local siting procedures, land-use regulation, and environmentally-related permitting requirements. States can pay attention to such processes and requirements and, where warranted, try to streamline reviews and approvals. Under the federal Safe Drinking Water Act, the U.S. EPA enacted Underground Injection Control regulations. Class VI wells are those used for geologic sequestration of CO_2. Regulations and guidance address siting, construction, operation, testing, monitoring, and closure. Except for North Dakota and Wyoming, which obtained state-level primacy for the Class VI well program, EPA retains primary enforcement authority and directly implements the Class VI program. Other states, territories, and tribes can apply to EPA for primacy if they wish.
Subsurface Ownership and Long-Term Liability	Subsurface ownership rights and potential liabilities can be issues that impede sequestration site development and CCS deployment. Montana, North Dakota, and Wyoming passed laws that define ownership of injected CO_2 and of the pore space into which it is injected. The three states also set requirements for landowner consent needed for projects to proceed. CO_2 storage long-term liabilities may be of concern as well. EPA's rules and guidance govern Class VI wells, including monitoring and closure. Louisiana and North Dakota passed laws that transfer CO_2 storage site liability to the state after 10 years while Montana transfers liability after 30 years. Illinois had passed a law on liability that applied only to the now inactive FutureGen project and Texas law applies only to offshore wells. Several states—Kansas, Louisiana, Montana, Texas, and Wyoming--have also established funds to assure long-term monitoring and management of carbon sequestration sites. Per-ton fees for CO_2 injection, operator permitting and application fees, annual fees, and penalties for released CO_2 are among funding sources potentially available.

These high-level considerations will likely generate more detailed questions for deliberation by State Energy Offices and other pertinent planners and policymakers.

CO$_2$ Source Sectors and CCUS Activities

Large, relatively concentrated streams of CO$_2$ from fossil fuel power plants and industrial process exhaust are most conducive to CCUS. Smaller industrial, commercial, and transportation sources are generally less or not feasible targets for carbon capture at the source.[8]

Industrial CO$_2$ results from fuel combustion as well as from chemical and biological production processes, such as iron ore reduction, cement production, hydrogen production from natural gas and coal,[9] and fermentation of sugars to make ethanol. Petroleum and natural gas extraction and processing also release CO$_2$ that is separated from the hydrocarbon products.

Table 1 shows U.S. CO$_2$ emission trends from the electric power sector and major industrial source categories.[10] In 2018, electric power plants accounted for about 32 percent of total and about 35 percent of fossil fuel combustion CO$_2$ emissions, mostly from coal, which has been decreasing over time, and natural gas, which has been increasing. Industrial fossil fuel combustion emits less than half as much CO$_2$ as does the power sector. Industrial process- and product-related emissions are smaller still. The EPA inventory of greenhouse gas emissions does not include biomass/biogenic energy and industrial emissions that may be attractive CCUS targets, such as from ethanol and related biorefining, estimated at an annual 45 million metric tons CO$_2$.[11]

Table 1. Trends in U.S. CO$_2$ Emissions, Selected Sources (million metric tons)

Source	1990	2005	2015	2018
Total CO$_2$	***5,128.3***	***6,131.9***	***5,412.4***	***5,424.9***
Fossil Fuel Combustion	***4,740.0***	***5,740.7***	***5,031.8***	***5,031.8***
Electric Power	1,820.0	2,400.0	1,900.6	1,752.8
Coal	1,546.5	1,982.8	1,351.4	1,152.9
Natural Gas	175.4	318.9	525.2	577.4
Industrial	857.0	850.1	801.3	833.2

Major Industrial Processes and Product Use	***1990***	***2005***	***2015***	***2018***
Iron and Steel & Metallurgical Coke Production	104.7	70.1	47.9	42.9
Cement Production	33.5	46.2	39.9	40.3
Petroleum Systems	9.6	12.2	32.6	36.8
Natural Gas Systems	32.2	25.3	29.3	35.0
Petrochemical Production	21.6	27.4	28.1	29.4
Ammonia Production	13.0	9.2	10.6	13.5
Lime Production	11.7	14.6	13.3	13.2
Waste Incineration	8.0	12.5	10.8	11.1
Other Process Uses of Carbonates	6.3	7.6	10.5	10.0

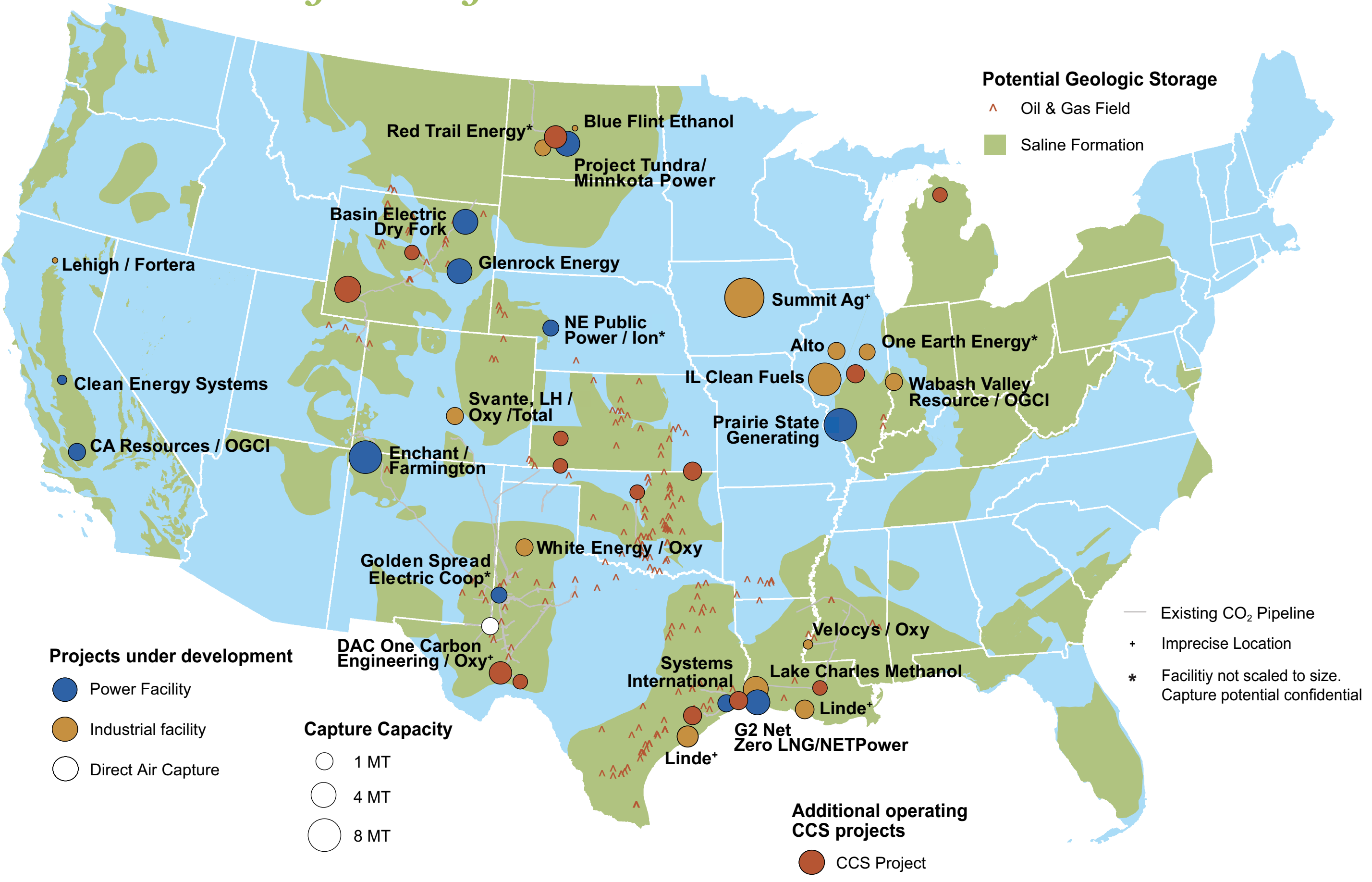
Note: *Industrial categories emitting less than 10 million metric tons are omitted. Biogenic emissions, such as from ethanol production, are not included. Commercial, residential, and transportation emissions are omitted.*

*[**Source:** U.S. Environmental Protection Agency (2020), 'Inventory of U.S. Greenhouse Gas Emissions and Sinks', 1990-2018.]*

The table is meant to convey the scale of emissions and, thus, of the challenge to abate or reverse emissions to meet GHG and climate objectives. As previously noted, current large-scale CCS/CCUS projects capture about 25 million metric tons of CO_2 annually in the United States and about 42 million metric tons per year globally. For scale comparisons, the Carbon Capture Coalition cites International Energy Agency and Intergovernmental Panel on Climate Change estimates that 2,000 facilities capturing 2.8 billion metric tons per year would be needed to limit global warming to 2°C. and 10 billion metric tons of annual capture would be needed to meet a 1.5°C target.[12]

However, industrial sectors and facilities that are small from national and global emissions perspectives may be large state or regional level sources that can support successful CCUS development. Figure 3 shows some projects under development in the United States; 27 projects spanning power, ethanol and biofuels, chemicals, gas processing, hydrogen, cement, waste-to-energy, and DAC are listed in the CATF CCUS Project Tracker.[13]

Figure 3. U.S. CCS/CCUS Projects Under Development and Potential Geologic Storage



Source: *Great Plains Institute, June 2021. Based on data from Clean Air Task Force and the Global CCS Institute. Modified with permission.*

The following are selected sectors to which CCUS may be applicable:

Power Generation

Electric generating plants burning coal and natural gas are still mainstays of the power sector, providing reliable and low cost power. CCUS creates the chance for continued use of fossil fuels in new power plants and in retrofitted existing plants while achieving large GHG emission reductions. CCUS can also be applied to biomass-burning power plants. Also, new concepts, such as the Allam Cycle (discussed later), under development, could enable more efficient combustion-based power production with net-zero emissions.[14]

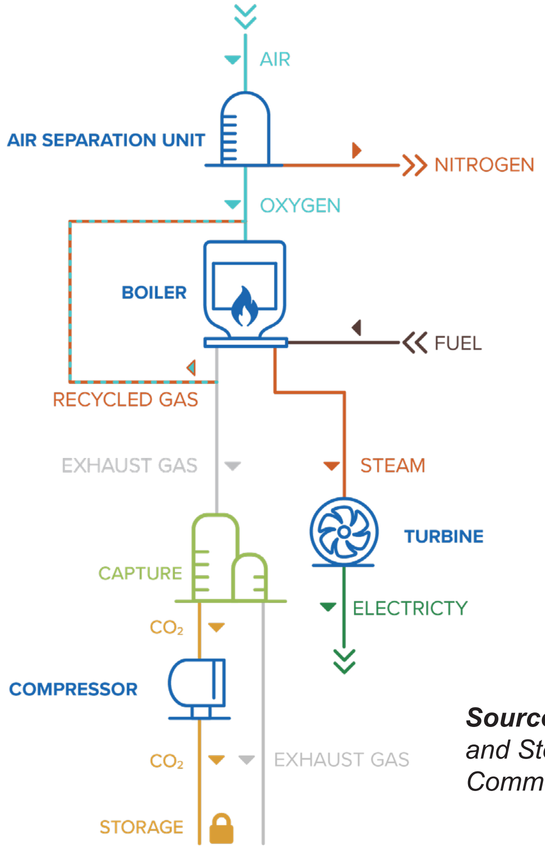
Building on earlier smaller scale pilot demonstrations in power and other sectors in North America and abroad, there are now two major power sector CCUS examples in North America. SaskPower's Boundary Dam Unit 3 Carbon Capture Project near Estevan, Saskatchewan, Canada became the world's first utility scale, post-combustion carbon capture facility at a coal-burning power plant when it opened in 2014.[15] Using an amine-based capture technology, the plant is designed to capture 90 percent of the unit's CO_2 with 90 percent of that piped 66 km (about 40 miles) for EOR and the remainder injected into a saline formation.[16] The gross 160 megawatt (MW) plant is 110 MW net considering carbon capture energy use. The billion dollar

Petra Nova project at the NRG Energy W.A. Parish coal-fired plant near Houston, Texas was delivered in 2016 and is the largest current power sector CCUS project. While the power plant has a 3.4 gigawatt (GW) capacity, the Petra Nova facility can treat a portion of the 650 MW Unit 8's emissions, equivalent to the emissions of a 240 MW coal-fired plant using an amine-based system developed by Mitsubishi Heavy Industries.[17] Designed to capture 1.6 million metric tons per year, the CO_2 is piped to an oilfield 80 miles away where oil output was expected to grow from 300 barrels per day to 15,000 barrels. The NRG - JX Nippon Oil and Gas Exploration Corporation joint venture business model includes equity investment in the oilfield operator and depends on oil-related revenues which were expected to yield project break even at $50 per barrel oil prices.[18] However, low oil prices led operators to put the carbon capture facility into a "reserve shutdown status" in May 2020, allowing the facility to be reactivated when economics become more favorable.[19] The project also benefited from $190 million of U.S. Department of Energy cost-share, a Japan Bank for International Cooperation loan of $250 million, and various Texas tax concessions.

The sector also includes an unfortunate example, Southern Company's Mississippi Power attempted to develop a lignite-fired integrated gasification combined cycle (IGCC) power plant with carbon capture at Kemper, Mississippi. Schedule slippage and large cost overruns led to a decision to suspend the coal-related and carbon capture processes and continue to operate as a natural gas-fueled plant.[20]

Oxy-combustion, in which nitrogen is removed from air so fuel is burned in an oxygen atmosphere, is a means to avoid nitrogen oxides pollutant emissions while also making CCUS easier. As compared to conventional air-fired combustion, oxy-combustion yields much smaller volumes of flue gas that is primarily CO_2. Figure 4 is a schematic of the oxy-combustion process.

Figure 4. Oxy-Combustion Process with CO_2 Capture



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Oxy-combustion and CCS are key to NET Energy's development of a pilot power plant in LaPorte, Texas to demonstrate the Allam Cycle as a new power generation approach. In the Allam Cycle, fuel (natural gas at LaPorte) is burned in oxygen with hot recuperated CO_2 that would have been exhausted in a conventional plant. Supercritical CO_2 from combustion serves as the working fluid to turn the turbine, in contrast to steam in a conventional plant. Most CO_2 generated from combustion is recuperated after moisture removal while excess is sent for sequestration.[21]

Another advanced concept, called chemical looping combustion (CLC), takes oxygen from air in a reactor using a metal oxide or limestone and transfers it to a separate "fuel reactor" to burn fuel in an oxygen atmosphere, thus generating a CO_2-rich exhaust conducive to CCUS.[22] The National Energy Technology Laboratory has a 50 kW test facility in Morgantown, West Virginia.

Future power sector plans include possible CCUS projects in North Dakota (Minnkota Power Cooperative) and Wyoming (Basin Electric Power Cooperative), and potential multisector "hubs" that would take CO_2 from power plants, ethanol plants, and perhaps other industries (in Illinois, Nebraska-Kansas).[23] The CATF lists 11 coal and natural gas power station projects under development in eight states.[24]

In considering power sector CCUS potential, State Energy Office planners should be cognizant of the remaining useful life and retirement plans for existing power plants, price and performance trends of competing generation technologies (particularly renewables), and distributed and demand-side resources including energy efficiency, electrification of heating and transportation, energy storage, and flexible demand management, which are affecting demand for power.

Natural Gas Processing

Natural gas as extracted from the ground is often 90 percent or more methane with other hydrocarbons such as ethane and propane. There are variable amounts of CO_2 and hydrogen sulfide that can be corrosive, as well as water, nitrogen, oxygen, and other components, that, if at high enough concentration, need to be removed before the natural gas can be injected into pipelines for distribution and use by customers.[25] The first major carbon capture commercial deployment occurred in 1972 in west Texas at a natural gas processor, with the captured CO_2 used for EOR.[26] The natural gas processing industry is the largest practitioner of CCUS in the United States and globally.

A prominent U.S. natural gas processing CCUS facility is the ExxonMobil Shute Creek Treating Facility in LaBarge, Wyoming which opened in 1986. The facility added CCUS capability in 2008 that was subsequently expanded. It treats gas that is 65 percent CO_2 and 21 percent methane with smaller amounts of nitrogen, hydrogen sulfide, and helium. The facility utilizes a cryogenic process to freeze out CO_2 and liquefy some other components. Methane at pipeline quality and helium are sold as is a portion of CO_2 for EOR.[27] ExxonMobil intends to expand carbon capture at the facility.[28]

Ethanol

The high concentration of relatively pure CO_2 from fermentation makes CCUS from ethanol biorefineries relatively inexpensive as compared to other sectors. More than 200 biorefineries in the United States emit 45 million metric tons of CO_2 from fermentation processes. Lawrence Livermore National Laboratory reported that about 27 million metric tons could be captured for under $25 per metric ton, though pipelines and sequestration entail additional costs.[29]

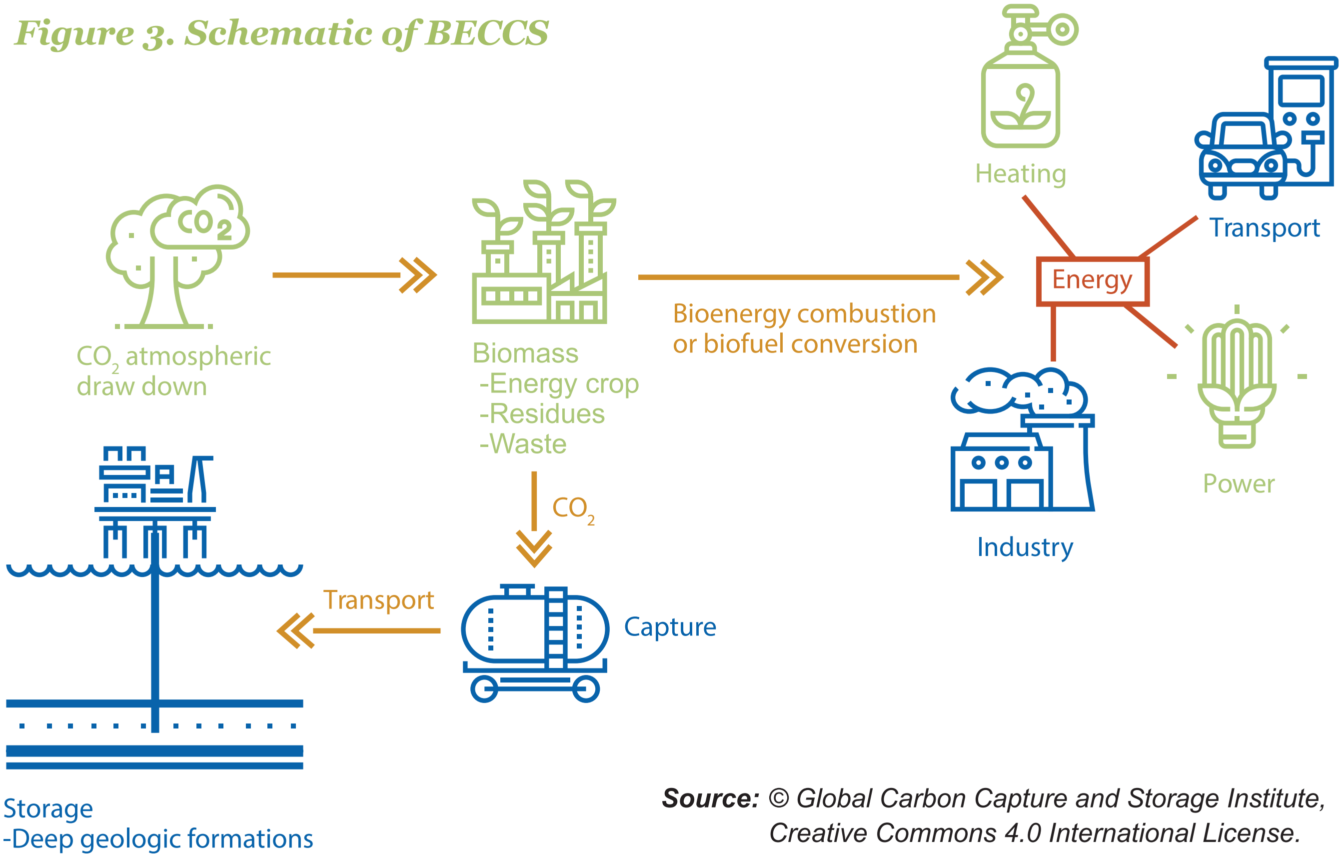
The Archer Daniels Midland Industrial Carbon Capture and Storage (ICCS) Project in Decatur, Illinois reportedly captures and stores about 1 million metric tons per year of CO_2.[30] Several smaller ethanol plants in the United States and Canada also conduct CCS.[31] The CATF CCUS Project Tracker list six ethanol and three “biofuels” projects under development.[32]

CCUS opportunities from ethanol production will depend on the health of the ethanol industry. The federal Renewable Fuel Standard has incited much of the 14.4 billion gallons of fuel ethanol consumption that occurred in the United States in 2018.[33] The California LCFS can be a source of marketable credits for ethanol as well as biodiesel and petroleum facilities that perform CCUS in producing fuels entering the California market. Growth in electric vehicle markets and, potentially, hydrogen may, over time, have material impact on ethanol as well as petroleum-based fuel demand.

Bioenergy with Carbon Capture and Sequestration (BECCS)

Related to ethanol and power sector CCS is the BECCS concept which can offer net-zero or even net-negative carbon energy outcomes. BECCS relies on growing biomass, which takes in atmospheric CO_2, then applying CCS/CCUS to bioenergy combustion power plants or biofuel conversion facilities that produce power or fuel for users. Figure 3 offers a schematic.

Figure 3. Schematic of BECCS



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BECCS systems can use dedicated energy crops (woody and herbaceous), agricultural and forestry residue, and, potentially, algae and municipal organic solid wastes as inputs. The choice of carbon capture technology will depend on the biomass energy process employed. Post-combustion CO_2 recovery from a biomass-burning power plant will likely resemble that used in fossil fuel-fired power plants. Conversion of biomass to liquid and gaseous fuels through fermentation, pyrolysis, or other means produces more concentrated CO_2 streams as found in ethanol plants and is less expensive per ton of CO_2 removed. The only existing large BECCS facility is the aforementioned Archer Daniels Midland ICCS project which injects CO_2 into a saline aquifer. Several smaller ethanol plants in Kansas and Saskatchewan pipe captured CO_2 to oil fields for EOR.[34]

State Energy Offices and other planners can consider BECCS in conjunction with agricultural, forestry, and rural economic development policies as well as environmental and energy policy.

Hydrogen and Synthetic Fuels

Most industrial hydrogen is produced from methane in natural gas through steam methane reforming (SMR) or a partial oxidation process. These and other chemical processes can also be used to turn heavier hydrocarbons, including coal and petroleum coke ("petcoke") into hydrogen-rich synthesis gases ("syngases"). Hydrogen can be separated from syngas for use or turned into methane in the case of a coal gasification plant. Hydrogen or methane so created can be used for energy or as input for chemical production. These processes create concentrated CO_2 waste streams that are amenable to CCUS. An alternative to SMR being developed to extract hydrogen from natural gas (and potentially other hydrocarbons) employs pyrolysis. Natural gas is heated in the absence of oxygen to drive off hydrogen for use as fuel or chemical input, leaving behind solid carbon for sequestration or alternative use.[35] Since 2013, Air Products has coupled SMR with CCS at its Port Arthur, Texas plant to mitigate 5 million metric tons of CO_2. Similarly, Shell Canada reported 4 million metric tons of CO_2 sequestered from hydrogen operations at the Quest CCS plant near Edmonton, Alberta, Canada.[36] Both facilities supply CO_2 to EOR operations.

The world's largest CCS project and only commercial-scale coal gasification plant in the United States is the Great Plains Synfuels Plant near Beulah, North Dakota, owned and operated by the Dakota Gasification Company, a for-profit subsidiary of the Basin Electric Power Cooperative.[37] The $2.1 billion plant began operations in 1984, gasifying lignite into liquid and gaseous products. After several years of U.S. DOE ownership, it was acquired by Dakota Gasification in 1988. The plant pipes an average of 153 million cubic feet of synthetic natural gas per day to Iowa for distribution further east. Between 2.5 and 3 million metric tons of CO_2 is exported to Saskatchewan, Canada for EOR.

Beyond current industrial uses, hydrogen is of particular interest for energy policy, planning, and programs as a clean energy storage and transport medium. Some clean energy scenarios center on zero-carbon renewable and nuclear power electrolyzing water during periods of low power demand to make hydrogen that can then be used to produce electricity via fuel cells or combustion in lieu of CO_2-emitting generation during periods of high electricity demand. Hydrogen would, thus, serve a similar function as batteries, compressed air, pumped hydro, and other storage. "Green" hydrogen can also cleanly power fuel cell vehicles. Zero-carbon-generated hydrogen can also be blended with natural gas to lower the carbon footprint of natural gas-using equipment and power plant operations.

By enabling zero-emission use of natural gas and, potentially, net-negative carbon use of biological feedstocks (see BECCS discussion above), CCUS may be able to support an expanded role for hydrogen in transitioning the energy system to a more sustainable, climate-friendly footing.

Ammonia

Ammonia is a critical input to chemical processes, including for production of nitrogen fertilizers. The ammonia production process is energy intensive, reacting hydrogen and nitrogen at high temperature and high pressure. Energy is needed to make the hydrogen, usually from methane using SMR which results in CO_2 (as discussed above) or from electrolysis of water, and to sustain necessary temperature and pressure. If methane from natural gas is the source of hydrogen, then the CCS/CCUS factors noted in the hydrogen section are applicable. In addition, if the ammonia plant uses fossil fuels onsite for process energy, CCUS may also be applicable.

In 2019, OGCI Climate Investments announced investment in a project to capture 1.5 to 1.75 million tons of CO_2 annually from Wabash Valley Resources' (WVR) ammonia plant in Indiana to make it the world's first near zero carbon ammonia plant. Captured CO_2 will be injected into a saline sandstone aquifer. The $600 million project is expected to start construction in 2020 and be completed in 2022.[38] The project builds on an earlier phase started in 2016 to convert what was originally a coal gasification facility into WVR's ammonia plant.

Interestingly, ammonia plants using CCUS would produce lower carbon-footprint fertilizer that, if used on corn, would yield lower carbon footprint ethanol fuel, especially if the ethanol production plant also employs CCUS.

Chemicals Production

Other chemical and petrochemical processing and production activities that generate CO_2 streams can be amenable to CCUS. Hydrogen (discussed above) produced by SMR is usually used as a chemical input not only for ammonia production (discussed above) but also for other chemical and petrochemical processing. For example, the previously noted Air Products, Port Arthur, Texas plant serves the Valero Port Arthur Refinery.

The chemical industry can also be the "U" in CCUS as in the production of urea from the reaction of CO_2 with ammonia, for production of methanol, and for making larger carbon-based molecules, including polymers such as plastics.

Iron and Steel

Iron and steel production is highly energy- and carbon-intensive. The blast furnace-basic oxygen furnace (BF-BOF) process, usually using coal-based reductant (coke), is used to produce 70 percent of virgin steel globally.[39] CO_2 is released from the reaction of carbon with oxygen in iron ore to produce reduced (i.e., the metal) iron. It is also emitted from making coke from coal and from onsite combustion to produce heat and power. About 2.3 metric tons of CO_2 are produced per metric ton of crude steel when accounting for direct and indirect emissions.[40]

About 60 percent of CO_2 from BF-BOF plants comes from the blast furnace where it is co-emitted with hydrogen and carbon monoxide. The high CO_2 concentration would be suitable for using carbon capture approaches employed in hydrogen plants. However, many steel plants collect together blast furnace, basic oxygen furnace, and coke oven gases to fuel a combined heat and power (CHP) plant to produce both electricity and process heat. CCS from a CHP facility would be like post-combustion removal from power plant flue gas, with solvent-based (such as amine-based) processes best demonstrated. Direct reduction ironmaking (DRI) avoids using coal-based coke, instead relying on natural gas (which is reformed into hydrogen and carbon monoxide) for reducing iron ore.[41] The only existing iron and steel CCS project is the Abu Dhabi CCS project which captures about 800,000 metric tons per year of CO_2 from a DRI plant for EOR.[42] Also pertinent is an innovative steelmaking process called HIsarna being developed by Tata Steel and piloted in the Netherlands which produces a flue gas that is over 90 percent CO_2 and, thus, more easily captured.

Cement

Cement production entails CO_2 release from both its chemical process and the energy needed by the plant. Around 60 percent of the CO_2 emitted is from calcination of limestone while about 40 percent comes from burning fuels to produce the approximately 1450°C required of the process.[43] About 1 metric ton of CO_2 is emitted per metric ton of clinker.

In Norway, Norcem, a subsidiary of the HeidelbergCement Group, is planning a CCS facility at its Brevik cement plant.[44] The plant would use residual heat for regenerating the amine-based absorbent. CO_2 will be transported by ship to a facility on Norway's West Coast then piped to a subsea sequestration site in the North Sea in a partnership with Equinor, Shell, and Total.

In China, a 50,000 metric ton per year CCS project was announced as having been commissioned at an Anhui Conch Cement Company plant in Wuhu, Anhui Province, also using amine-based carbon capture technology.[45]

Waste-to-Energy

As with fossil fuel and biomass fueled power plants, waste-to-energy facilities burn materials that produce CO_2 that can be addressed by CCUS.

Direct Air Capture

DAC is not an emitting industrial or production sector category as most of the entries above are. However, it is receiving growing attention as analysts point to a need to actively take CO_2 out of the ambient air to meet the objective of limiting warming to 2°C. this century. Even with aggressive decarbonization of amenable sectors and implementation of CCUS at large industrial sources, many smaller dispersed sources of CO_2 (such as aviation) and other GHGs (such as some agricultural emissions) will not be offset.[46] Also, there is need to counter weakening natural carbon sinks and warming-reinforcing positive feedbacks in Earth's systems (e.g., increased burning of forests, peatlands, grasslands, and tundra; emissions from warming tundra; reduced snow and ice cover increases surface heat absorption). These suggest need for an all-of-the-above response to mitigate climate change, including DAC along with biological and natural capture (e.g., forest enhancement), industrial CCUS, and decarbonization of energy and other processes.

DAC projects can be eligible for credits under the California Low Carbon Fuel Standard irrespective of location and without need of nexus to California transportation fuel production, unlike other eligible CCUS options.

Climeworks, Global Thermostat, and Prometheus, among other firms, are pioneering DAC applications, including CO_2 utilization in fuels and materials.[47] In 2019, Carbon Ventures, LLC, a subsidiary of Occidental Petroleum, announced a joint venture with Carbon Engineering, Ltd. to design and engineer a DAC facility that would capture 500,000 metric tons per year for EOR use.[48]

CO_2 Capture Technologies

The choice of technologies to capture CO_2 depends on the physical and chemical environment of the gaseous stream. Some processes are most applicable to streams that have a high concentration of CO_2. This can include pre-combustion separation of CO_2 from hydrogen-rich syngas from gasifying coal or biomass. Similar processes would be used in hydrogen and ammonia industries where CO_2-rich streams exist. In contrast, post-combustion CO_2 is relatively dilute in the flue gas of conventional power plants. Even more dilute is the ambient air, from which DAC is performed. As a rule, it is easier and cheaper to capture, transport, and sequester a ton of CO_2 from a concentrated stream than a dilute stream. In addition to CO_2 concentration, other factors affect the choice--and effectiveness, limitations, and cost--of carbon capture technologies. Temperatures, pressures, and concentration of other chemicals and contaminants are among the important factors.

RD&D continues for improving existing CCUS technologies and developing new ones across the spectrum of capture, processing, transport, uses, and sequestration, including geological research and monitoring and verification of long term sequestration.

This section briefly outlines several major categories of capture technologies but does not address the rich technical array of chemical, material, and engineering issues, challenges, and opportunities in play. A later section of this report highlights some major uses and touches on some innovative applications but does not cover all utilization options and challenges. This report does not cover geological and related engineering research concerning sequestration siting, site development, and long term monitoring and verification.

The National Energy Technology Laboratory (NETL) identifies four major categories of CO_2 capture technologies: solvent-based capture, adsorbents/sorbents-based capture, membranes, and hybrid or novel concepts.[49, 50] Drawing largely on NETL, a report of the National Association of Regulatory Utility Commissioners, and earlier text in this report, these are discussed below.[51] Also included are brief discussions of cryogenics, which is used for some industrial gas separations and has niche CCUS application, and microalgae-based carbon capture. Other sources provide more detailed tables with full references comparing CO_2 capture methods.[52]

Solvent-based CO2 Capture

Solvent-based capture systems rely on the chemical or physical absorption of CO_2 from a CO_2-rich gas into a liquid carrier. Once absorbed, the liquid carrier is transported to a separate step where heat or pressure drop is used to release the CO_2 and regenerate the carrier for another round of CO_2 absorption. Amine-based absorbents are most frequently used and are relatively mature and commercially available compared to some other approaches.

Solvent-based absorbents can be used in both pre- and post-combustion settings and for non-combustion situations. A pre-combustion or non-combustion example would be absorption of CO_2 from syngases in hydrogen production or in a coal or biomass gasification plant. The Boundary Dam and Petra Nova power plant projects are post-combustion examples where flue gas is run through amine-based absorbent solvent to remove CO_2.

Significant energy is needed to run solvent-based processes. Another challenge is the life and durability of the solvents, which degrade after multiple absorption-desorption cycles, are lost to evaporation, and can be adversely affected by contaminants, leading to diminished performance and need for removal and replacement. Solvent-based systems that reduce energy requirements, offer improved durability, and enhance capacity and selectivity of absorption are R&D foci.

Adsorbent/sorbent-based CO2 Capture

Solid sorbents, such as carbon, zeolites, and metal organic frameworks, can take up CO_2. As with liquid solvent sorbent-based systems, heat and/or pressure reduction can release the CO_2 to regenerate the sorbent. In some systems an inert gas can displace the CO_2 and refresh the sorbent for another cycle. Sorbents offer potential energy savings, waste reduction, and process simplification, but they are less mature than solvent-based absorption. Sorbent durability, capacity, specificity for CO_2, and cost reduction are challenges subject to R&D.

Membranes

Permeable or semi-permeable materials—metal-, polymer-, or ceramic-based--can be used to selectively separate CO_2 from other gases or hydrogen from syngas. Improved selectivity, permeability, mechanical and chemical durability and stability, low pressure drop, and tolerance to high temperatures and contamination are R&D targets.

Cryogenics

Some gases are commercially purified using cryogenic processes where the gas is cooled until different constituents liquefy or freeze. Large amounts of energy and, thus, cost are needed to bring large volumes of gases to such low temperatures. For CCUS, the technique can be feasible for very high CO_2 concentration streams, such as its use at the ExxonMobil Shute Creek Treating Facility where CO_2 makes up 65 percent of CO_2 in the gas stream and where methane and helium are also separated for sale.

Microalgae-based CO_2 Capture

Spanning capture and utilization, CO_2-enriched waste streams from flue gas can be used to enhance plant growth in greenhouses and for algae cultivation. Microalgae cultures—in closed reactors or open ponds--turn CO_2 into biomass for production of food, animal feed, nutritional supplements, fuels, and chemical products. Numerous laboratory and pilot studies have been undertaken during the last decade.[53] One example is the University of Kentucky, Center for Applied Energy Research partnership with Duke Energy to pilot an algae system at the utility's East Bend Station in Kentucky.[54] Another is Cranston, Rhode Island-based Agcore Technologies, which produces spirulina-based food, feed, and nutritional supplements, that is developing waste CO_2 capture and utilization approaches using algae.[55]

The kinetics of algal growth are a limitation. Algae (and plants) will not remove large amounts of CO_2 from waste gas streams quickly or in as compact a space as do other physical-chemical approaches. Algae are sensitive to temperature, pH, salinity, and other conditions as well as to chemical and biological contamination. Culture systems and processing can be cumbersome, but the value of resulting products can be high.

Hybrid and novel concepts

These include approaches that combine characteristics of multiple technologies, exploring new process conditions, and the use of new materials, including nanomaterials.

Utilization of CO_2

The "U" in CCUS can provide value to defray costs of capture and enhance economic development options. This already occurs in chemical and petrochemical industries where in-plant CO_2 streams can be used as inputs to chemical processes or are sold to others for well-stablished applications. EOR is also a well-demonstrated use for captured CO_2.

As discussed below, there are other existing and emerging applications for recovered CO_2 that can offer economic value. However, state energy planners should keep in mind that feasible markets are very small compared to amounts emitted as they think about the role of utilization for mitigating GHG emissions and climate change. Also, many CO_2 uses, such as for beverage carbonation or dry ice refrigeration merely delay release rather than effecting long term removal from the atmosphere.

Potential economic opportunities for CO_2 utilization should be considered in light of commodity prices and the costs of competing materials and processes. For example, the value of EOR depends on oil prices. Another example: captured CO_2 may or may not be cost-competitive with conventional inputs for making plastics.

The viability of utilization and CCUS broadly will likely depend on policies that directly or indirectly increase the cost of CO_2 emissions and/or reward CO_2 capture and use or sequestration.

Enhanced Oil and Natural Gas Recovery

With initial application dating back to 1972, EOR is a well-established use of captured CO_2, providing value by increasing the recovery of oil while effecting permanent sequestration of CO_2. As described above, CO_2 from various sectors has been used for EOR. However, increasing the production of oil, which is overwhelmingly burned as fuel, counters climate benefits of CO_2 sequestration. From a climate standpoint EOR reduces the carbon footprint of oil somewhat but does not negate its impacts. The value and economic benefit of EOR depends on oil prices; EOR is less valuable when oil is cheap, and more valuable when it is dear. The principles of EOR also apply to methane from natural gas fields and deep unmineable coal seams, where CO_2 injected displaces methane for recovery. Economics of enhanced natural gas recovery appear unattractive given current prices.

Chemicals and Plastics

As noted, CO_2 can be and is used as feedstock to make methanol, urea, and other chemicals which are either used directly in end uses or are inputs for conversion into other chemical products. Urea and its derivatives, for example, are used in fertilizer, road deicers, explosives, animal feed, food processing applications, air pollution control devices, personal care products, pharmaceuticals, flame-proofing materials, and thermosetting resins. Chemical products derived from recovered CO_2 can be made into polycarbonate and other polymers. Several contenders for the NRG COSIA Carbon X-Prize competition are developing innovative CO_2 utilization processes aimed at producing methanol, ethanol, ethylene, and other chemical precursors and intermediaries as well as bioplastics and carbon nanotubules as material additives.[56]

Bioconversion and Bioproducts

CO_2-enriched air enhances greenhouse production of plants. Microalgae grown in closed reactors or open ponds with CO_2-enriched air, such as from power plant, engine, or boiler exhaust, can be used to produce food and nutritional supplements, animal feed, biodiesel fuel, and chemical and pharmaceutical precursors and products. CO_2 utilization for bio-based chemicals and products can be integrated into a broader BECCS framework, though, system-wide, most recovered CO_2 would need to be sequestered rather than utilized.

Food and Beverage Processing

Soft drink and beer producers use CO_2 for carbonation. CO_2 is also used in controlled atmosphere storage and modified atmospheric packaging to retard spoilage, kill insect pests, and extend packaged food shelf life for grains, fruits, vegetables, meats, and processed foods.[57] Liquid and supercritical CO_2 is used to extract flavors, oils, and other chemical components (e.g., decaffeination of coffee and tea). There are other food processing applications in baking, dairy, and other sectors. Dry ice and liquid CO_2 are used for freezing and refrigeration processes.

Extraction and Cleaning Solvent

Liquid and supercritical CO_2 has physical-chemical properties well suited for various extraction applications. As noted above, CO_2 can be used for extraction of flavors, oils, and other components in the food industry. Outside of foods, liquid and supercritical CO_2's solvent characteristics are employed for fragrance and other extraction processes. Liquid CO_2 also provides a green alternative to conventional organic solvent-based dry cleaning.[58, 59]

Refrigerant

While dry ice and liquid CO_2 are used directly in refrigeration and freezing applications, CO_2 itself can serve as the working fluid in refrigerant systems. Designated as R744, CO_2 refrigerants are non-ozone depleting, non-toxic, and are very low global warming potential (GWP=1, by definition) relative to hydrofluorocarbons (HFC). They can be used in air conditioners, heat pumps, and commercial and industrial refrigeration systems.

Mineralization and Concrete

Recovered CO_2 has potential applications for making carbonate alternatives to Portland cement (itself CO_2-intensive in manufacture) and for new concrete formulations.[60] Two carbon X Prize contenders provide examples of new CCUS application for concrete, such as CarbonCure's nano-sized mineral additive and CO2Concrete's mineralization approach.[61, 62]

Inerting Agents and Fire Suppression

The relatively inert nature of CO_2 is useful as a shielding gas for welding and as a blanketing product, similar to controlled atmosphere storage and modified atmospheric packaging in the food industry. CO_2 is also used in fire extinguishers.

Miscellaneous

Dry ice pellets are used as abrasives for cleaning, analogous to sand blasting. CO_2 is added to medical oxygen. It is also used as aerosol propellant.

Conclusion

CCUS can be an important component in the portfolio of measures needed to reduce CO_2 and GHG emissions and mitigate climate change. CCUS can provide a way to address emissions from hard-to-decarbonize industrial sectors and to allow long-term roles for fossil fuel resources. Utilization of captured CO_2 in processes, materials, and products can mitigate costs and capture additional value. Innovative approaches for pairing CCUS with biomass utilization, hydrogen production, and new CO_2-derived products can enable new industrial development and employment. And investment in carbon capture, processing, use, and related infrastructure can yield economic benefits. State Energy Offices should consider CCUS options and opportunities, including policy and regulatory measures, in their energy, environmental, and economic development planning.

For more information on CCUS and additional resources, please visit the NASEO website at www.naseo.org.

Resources

Research Organizations and Reports on Carbon Capture and Utilization

Carbon Capture Coalition	https://carboncapturecoalition.org/
Carbon Utilization Research Council	http://www.curc.net/
Center for Climate and Energy Solutions (C2ES) - *Carbon Capture*	https://www.c2es.org/content/carbon-capture/
Circular Carbon Economy	https://circularcarboneconomy.co/
Clean Air Task Force - *The Status of Carbon Capture Projects in the U.S. (And Why They Need to Break Ground)*	https://www.catf.us/2020/04/the-status-of-carbon-capture-projects-in-the-u-s-and-what-they-need-to-break-ground/
Columbia University, Center on Global Energy Policy - *Carbon Management Research Initiative*	https://energypolicy.columbia.edu/our-work/topics/carbon-management-research-initiative
Kearns, D., H. Liu, and C. Consoli, "Technology Readiness and Costs of CCS"	https://columbiauniversity.globalccsinstitute.com/wp-content/uploads/sites/6/2021/04/Technology-Readiness-and-Costs-for-CCS-2021-1.pdf
Great Plains Institute *- Carbon Management*	https://www.betterenergy.org/our-work/carbon-management/
Lux Research - *CO2 Capture & Utilization: The Emergence of a Carbon Economy (Executive Summary), 2021*	https://www.luxresearchinc.com/hubfs/2021%20Executive%20Summaries/CO2%20Capture%20%26%20Utliziation%20-%20The%20Emergence%20of%20a%20Carbon%20Economy%20Executive%20Summary.pdf
National Academy of Sciences, Engineering, and Medicine - *Negative Emissions Technologies and Reliable Sequestration*	https://www.nap.edu/catalog/25259/negative-emissions-technologies-and-reliable-sequestration-a-research-agenda
National Association of Regulatory Utility Commissioners (NARUC) - *Zitelman, K. et. al., "Carbon Capture, Utilization, and Storage: Technology and Policy Status and Opportunities", November 2018*	https://pubs.naruc.org/pub/03689F64-B1EB-A550-497A-E0FC4794DB4C
National Carbon Capture Center	https://www.nationalcarboncapturecenter.center.com/
National Energy Technology Laboratory *- CCUS Analysis Tools and Resources*	https://netl.doe.gov/node/9384

National Petroleum Council *- Meeting the Dual Challenge: A Road-Map to At-Scale Deployment of Carbon Capture, Use, and Storage*	https://dualchallenge.npc.org/
State CO2-EOR Deployment Work Group *- "Electricity Market Design and Carbon Capture Technology: The Opportunities and the Challenges," June 2017*	https://www.betterenergy.org/wp-content/uploads/2018/01/Electric_Markets_and_CCS_White_Paper.pdf
U.S. Congress, Congressional Research *- Service The Tax Credit for Carbon Sequestration (Section 45Q), June 2021*	*https://fas.org/sgp/crs/misc/IF11455.pdf*
U.S. Environmental Protection Agency *- Capture, Supply, and Underground Injection of Carbon Dioxide*	*https://www.epa.gov/ghgreporting/capture-supply-and-underground-injection-carbon-carbon-dioxide*
U.S. Environmental Protection Agency *- Class VI – Wells Used for Geologic Sequestration of* CO_2	*https://www.epa.gov/uic/class-vi-wells-used-geologic-sequestration-co2*

Endnotes

[1] CCS for carbon capture, and sequestration if utilization is not included.

[2] Carbon Capture Coalition, 2020, “Carbon Capture Jobs and Project Development Status,” https://carboncapturecoalition.org/wp-content/uploads/2020/06/Carbon-Capture-Jobs-and-Projects.pdf

[3] Clean Air Task Force, CCUS Project Tracker, https://docs.google.com/spreadsheets/d/115hsADg3ymy3lKBy4PBQRXz_MBknptqlRtlfuv79XV8/edit#gid=1540463113, accessed February 22, 2021.

[4] Biological carbon sequestration of atmospheric CO2 through forests, prairies, aquatic and marine environments, and soil management are not in this document’s scope but are important carbon solutions that can support state economic, energy, and environmental goals for agriculture, forestry, recreation, fish and wildlife, and other resources. Industrial and power sector emissions captured to produce algae for fuel or chemical production is in scope as is CO2 captured from biomass energy facilities.

[5] Lux Research, 2021, “CO2 Capture & Utilization: The Emergence of a Carbon Economy (Executive Summary),” https://www.luxresearchinc.com/hubfs/2021%20Executive%20Summaries/CO2%20Capture%20%26%20Utliziation%20-%20The%20Emergence%20of%20a%20Carbon%20Economy%20Executive%20Summary.pdf

[6] Interview of Julio Friedman by Daniel Raimini, May 5, 2020, Resources for the Future, Resources Radio “Going Deep on Carbon Capture, Utilization, and Storage (CCUS), with Julio Friedman” https://www.resourcesmag.org/resources-radio/going-deep-carbon-capture-utilization-and-storage-ccus-julio-friedmann/

[7] The credit is variable, rising over time to a 2026 rate of $35 in per metric ton of CO2 utilized (for EOR or other application and for DAC) and $50 per metric ton geologically sequestered. U.S. Department of Energy (2019), “Internal Revenue Code Tax Fact Sheet” https://www.energy.gov/sites/prod/files/2019/10/f67/Internal%20Revenue%20Code%20Tax%20Fact%20Sheet.pdf

[8] DAC is considered separately and augmenting biological carbon sinks is not a focus of this report.

[9] Most U.S. hydrogen production is from natural gas and is used in petroleum refining and ammonia production. A significant initiative is underway to expand hydrogen as a chemical input and an energy carrier. Fossil fuel-based hydrogen production would need CCUS for achieving carbon neutrality but carbon-free hydrogen can also be produced from renewable and nuclear power generation.

[10] U.S. Environmental Protection Agency, 2020, Inventory of U.S. Greenhouse Gas Emissions and Sinks, 1990-2018. https://www.epa.gov/ghgemissions/inventory-us-greenhouse-gas-emissions-and-sinks

[11] Lawrence Livermore National Laboratory, 2018, “LLNL Maps Out Deployment of CCS for Ethanol Production,” Ethanol Producer Magazine. http://ethanolproducer.com/articles/15236/llnl-maps-out-deployment-of-ccs-for-ethanol-production

[12] Carbon Capture Coalition, 2020, “Carbon Capture Jobs and Project Development Status,” https://carboncapturecoalition.org/wp-content/uploads/2020/06/Carbon-Capture-Jobs-and-Projects.pdf

[13] Clean Air Task Force, op cit., accessed June 11, 2020.

[14] Patel, S., 2019, “Inside NET Power: Gas Power Goes Supercritical,” Power (April 1, 2019) https://www.powermag.com/inside-net-power-gas-power-goes-supercritical/

[15] Preston, C., C. Bruce, and M. Monea, 2018, “An Update on the Integrated CCS Project at SaskPower’s Boundary Dam Power Station,” 14th Greenhouse Gas Control Technologies Conference https://papers.ssrn.com/sol3/papers.cfm?abstract_id=3365632

[16] Massachusetts Institute of Technology, 2016, “Boundary Dam Fact Sheet: Carbon Dioxide Capture and Storage Project,” https://sequestration.mit.edu/tools/projects/boundary_dam.html

[17] Zitelman et al., op cit.

[18] Patel, S., 2017, op cit.

[19] NRG, Petra Nova: Carbon Capture and the Future of Coal Power, https://www.nrg.com/case-studies/petra-nova.html

[20] Katie Fehrenbacher, 2017, “Carbon Capture Suffers a Huge Setback as Kemper Plant Suspends Work,” GreenTechMedia https://www.greentechmedia.com/articles/read/carbon-capture-suffers-a-huge-setback-as-kemper-plant-suspends-work

[21] Patel, S., 2019, “Inside NET Power: Gas Power Goes Supercritical,” Power (April 1, 2019) https://www.powermag.com/inside-net-power-gas-power-goes-supercritical/

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[23] Global Carbon Capture and Storage Institute, 2019, “Global Status of CCS 2019” https://www.globalccsinstitute.com/resources/global-status-report/

[24] Clean Air Task Force, ibid., accessed June 11, 2020.

[25] British Geological Survey, “Removal of CO2 from Natural Gas Processing” https://www.bgs.ac.uk/discoveringGeology/climateChange/CCS/RemovalCO2NaturalGas.html

[26] Carbon Capture Coalition, “About Carbon Capture” https://carboncapturecoalition.org/about-carbon-capture/

[27] Massachusetts Institute of Technology, 2016, “LaBarge Fact Sheet: Carbon Dioxide Capture and Storage Project” https://sequestration.mit.edu/tools/projects/la_barge.html

[28] Baker, A., 2020, “ExxonMobil Seeking to Build $263M carbon Capture Project at Wyoming Natural Gas Field,” NGI’s Shale Daily (January 28, 2020) https://www.naturalgasintel.com/articles/120880-exxonmobil-seeking-to-build-263m-carbon-capture-project-at-wyoming-natural-gas-field

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