TECHNOLOGY INSIGHTS

WHAT YOU NEED TO KNOW ABOUT CARBON CAPTURE AND STORAGE

OVERVIEW

Carbon capture and storage (CCS) is a group of technologies designed to reduce the amount of carbon dioxide (CO_2) released into the atmosphere, or to reduce the amount of CO_2 that is already in the atmosphere. CCS can be applied directly to facilities burning carbon-containing fuels such as fossil fuels (coal, oil, and natural gas) and biomass, or in stand-alone facilities that remove CO_2 directly from the atmosphere (called direct air capture, DAC). The captured CO_2 can be compressed, transported to other locations, stored in an underground cavern, and/or used in various ways to prevent its release into the atmosphere (see Figure 1) [1].

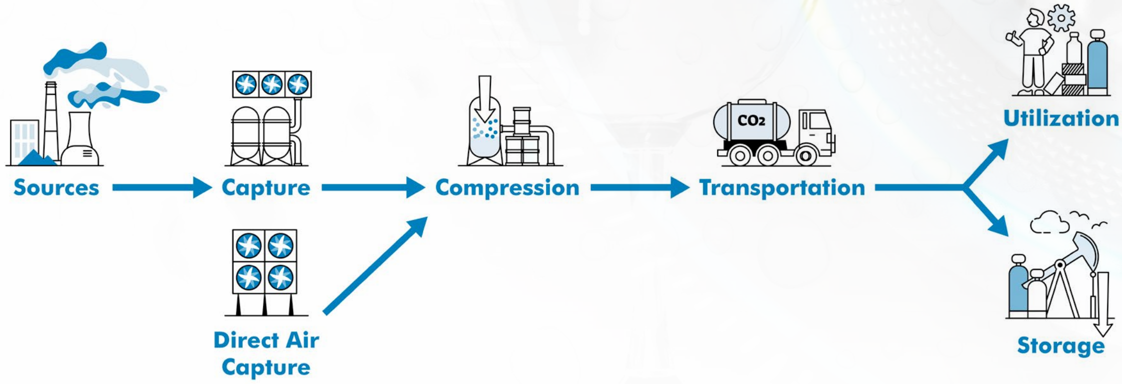

Figure 1. *Carbon can be captured as CO_2 emissions from power plants and industrial facilities, or directly from the air, and can then be compressed, transported, stored, and/or utilized to prevent its release into the atmosphere.*

THE LOW-CARBON RESOURCES INITIATIVE

This report was published under the Low-Carbon Resources Initiative (LCRI), a joint effort of EPRI and GTI Energy addressing the need to accelerate development and deployment of low- and zero-carbon energy technologies. The LCRI is targeting advances in the production, distribution, and application of low-carbon energy carriers and the cross-cutting technologies that enable their integration at scale. These energy carriers, which include hydrogen, ammonia, synthetic fuels, and biofuels, are needed to enable affordable pathways to economy-wide decarbonization by mid-century.

For more information, visit www.LowCarbonLCRI.com.

CARBON CAPTURE

CO_2 can be captured from combustion emissions at power plants and industrial facilities, or directly from the air via DAC. Several carbon capture methods are available today, including chemical absorption, chemical or physical adsorption, membrane separation, and others.

Chemical Absorption (Solvents)

Absorption methods use a chemical solvent, which is a liquid solution that reacts with CO_2 in a gas stream and absorbs it (much like how salt is absorbed and dissolves in water). The solvent enters the top of a column, while flue gas enters the bottom, forcing the two into contact and enabling the reaction. Downstream, the solvent can be heated to release CO_2 in a pure stream, enabling solvent reuse (see Figure 2) [2].

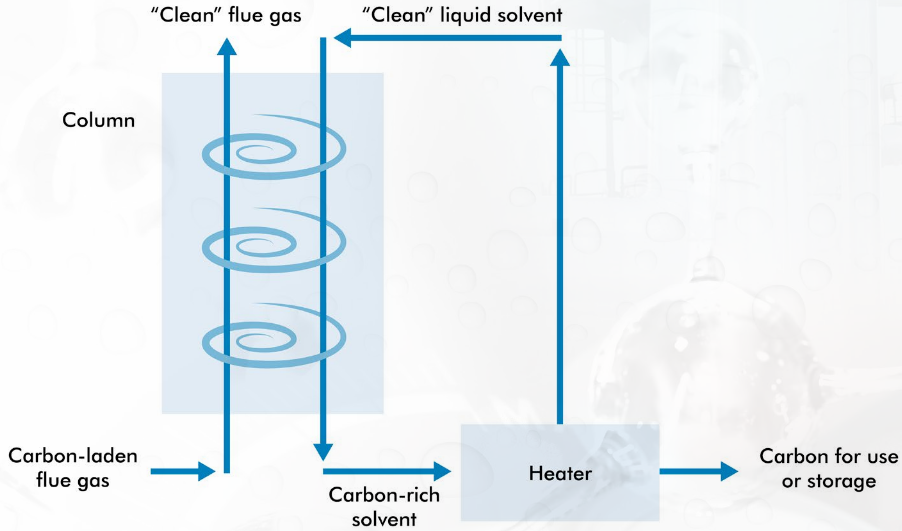

Figure 2. *In chemical absorption, a solvent absorbs carbon from the flue gas in a column. A heater releases the carbon from the solvent, so the solvent can be reused in the cycle, and the carbon can be utilized or stored.*

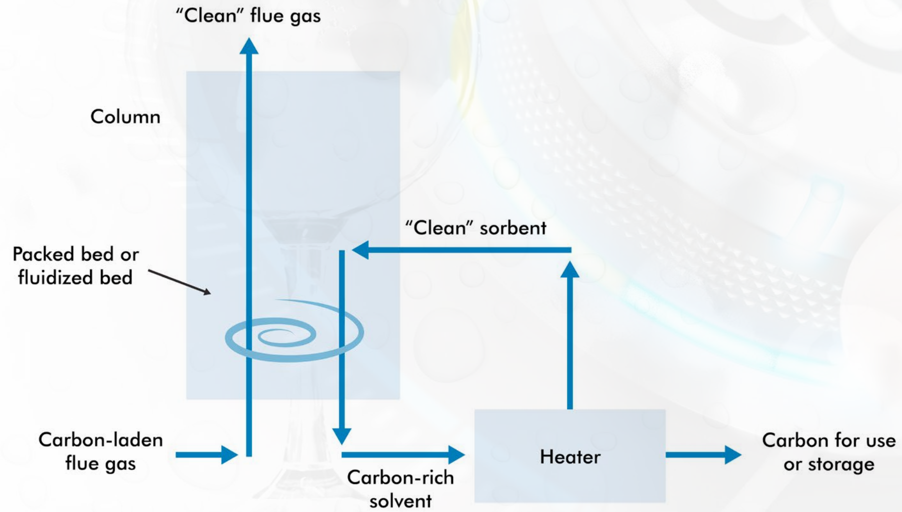

Figure 3. *In chemical or physical adsorption, a sorbent adsorbs carbon from the flue gas stream in a packed or fluidized bed. A heater releases the carbon from the sorbent, so the sorbent can be reused in the cycle, and the carbon can be utilized or stored.*

Chemical or Physical Adsorption (Sorbents)

Adsorption is the chemical bonding or physical bonding of a molecule like CO_2 to the surface of other substances (like water condensing on a glass windowpane). In a column, sorbent materials are either placed in a packed bed or more loosely as particles in a fluidized bed over which the flue gas flows to capture CO_2 in the gas stream. Sorbent materials can be heated to release CO_2 in a pure stream, enabling sorbent reuse (see Figure 3) [2].

Membrane Separation and Other Methods

Specialized membranes can filter CO_2 from a gas stream by only allowing CO_2 to pass through the membrane, either using small holes in the membrane sized to only allow CO_2 to pass, or by dissolving CO_2 in the membrane which allows it to diffuse across to the other side (see Figure 4).

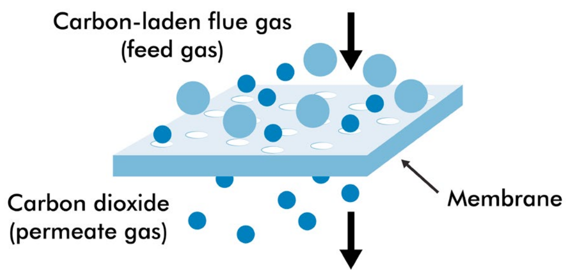

Figure 4 . *In membrane separation, only carbon dioxide passes through the membrane, effectively filtering the carbon out of the flue gas stream.*

Other methods being developed include cryogenic separation and carbonate fuel cells. Cryogenic separation liquifies CO_2 at extremely low temperatures in a gas stream for removal. Carbonate fuel cells use membranes to separate CO_2 from a gas stream and chemically react it with oxygen and additional hydrocarbon inputs. This produces pure streams of CO_2 and water vapor, as well as produces clean electricity without pollutant emissions [2].

CO_2 Compression

Captured CO_2 is compressed to either a liquid or supercritical state. Supercritical CO_2 is an ideal working fluid; it is non-explosive, non-flammable, non-toxic, and readily available at relatively low cost. When CO_2 is held at temperatures and pressures higher than its critical point (1073 psi/7.4 MPa and 88°F/31°C) [2], it exists in a "supercritical" state, in which the densities of the liquid and gas phases are so close that liquid and gaseous CO_2 are indistinguishable and behave in much the same manner.

CO_2 Transport

Compressed CO_2 is transported primarily through pipelines to a suitable storage or utilization location. About 5000 mi (8000 km) of CO_2 pipelines currently operate in North America [3]. Other methods include rail, tanker truck by land, ship, underwater pipeline by sea, and land pipelines. The latter is the most economical method today.

CARBON STORAGE

Underground Reservoirs

The most economical method of carbon storage is through injection of large volumes of CO_2 in supercritical phase into porous underground geologic reservoirs. Advantageous geologic formations have inherent rock properties (such as porosity, permeability) that create suitable conditions for large capacities. Additionally, prospective storage reservoirs need to have an overlying caprock, or impermeable formation, to prevent upward migration of the buoyant CO_2. Geologic formations with depths greater than 2600 ft (800 m) are preferred for CO_2 storage in most circumstances. These depth conditions offer ideal pressures and temperatures to ensure that CO_2 remains in a supercritical state [3].

There are three primary types of storage reservoirs (see Figure 5):

- Depleted oil and gas fields are geologic reservoirs that previously contained hydrocarbons, have been extracted, and now host partially vacated pore space and reduced pressure to accommodate compressed CO_2. Depleted oil and gas fields feature three-dimensional structural or stratigraphic traps that create a barrier for fluid or gas migration. Storage volumes are typically lower than those found in saline aquifers. Using CO_2 in depleted fields for enhanced oil recovery (EOR) is commonplace in the oil and gas industry and could help lower the cost of storage in these formations.

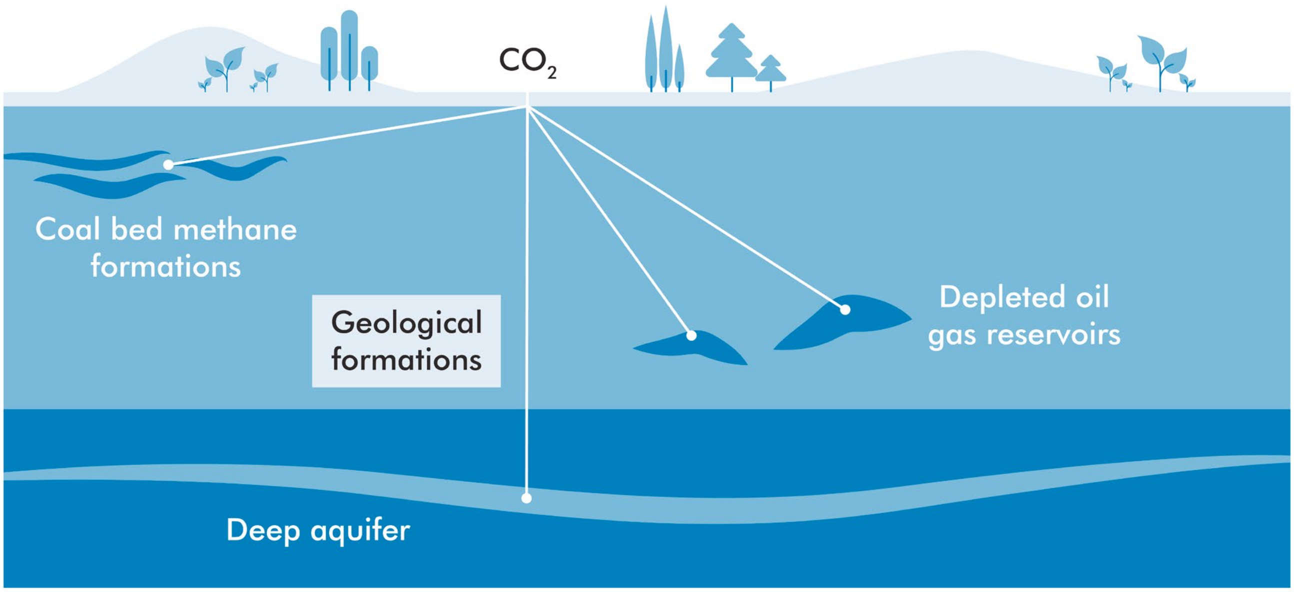

Figure 5. *The three primary types of geologic storage reservoirs are depleted oil and gas fields, saline aquifers, and deep coal seams. (Note: This figure is not to scale.)*

- Saline aquifers are deep, porous geologic formations that host saline water, also referred to as formation fluid or brine, in their pore space. They are found in most geologic basins, are commonly thick packages of rock, and span large distances. Therefore, they have the largest capacities and can accommodate the largest volumes of CO_2 of any prospective geologic storage type. Upon injection, CO_2 diffuses through the formation and interacts with the brine in the pore space.
- Deep coal seams, including coal bed methane seams, are less commonly utilized for geologic CO_2 storage. Coal is a low density, often highly fractured rock and can contain high porosity and permeability, but may be uneconomical to mine in some locations due to depth or thickness. In this scenario, CO_2 can be injected into deep coal seams where it is trapped between overlying and underlying impermeable rock or adsorbed into the matrix of the coal through chemical interactions.

Carbon Trapping

Once CO_2 is injected into the wells, several trapping mechanisms keep it in the formations including the following [4]:

- Structural and Stratigraphic Trapping: Physical barriers such as impermeable rock, three-dimensional structures, or faults prevent CO_2 from migrating.
- Capillary (Residual) Trapping: Injected CO_2 becomes disconnected from other CO_2 molecules, is surrounded by brine, rendered immobile in pore space, and further diffusion is prevented.
- Solubility Trapping: Dissolution of CO_2 in brine present in storage formations. This reduces the buoyancy of injected CO_2.
- Mineral Trapping: CO_2 reacts with mineral and organic matter in the storage formation to form stable, solid carbonate minerals. In the highest-capacity geologic formations, this process takes hundreds to thousands of years.

Figure 6 shows how the percent of CO_2 trapped via these methods changes over time.

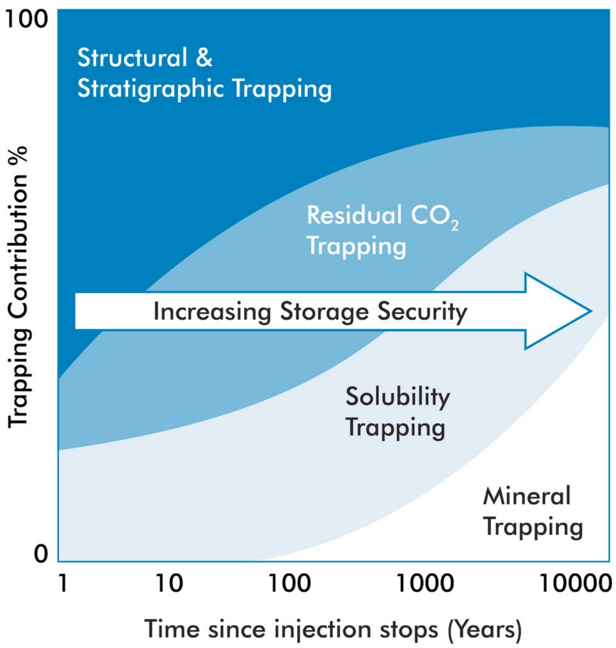

Figure 6. *CO_2 trapping contributions through time following CO_2 injection.*

POTENTIAL CHALLENGES

Once a potential storage site is identified during project development, operators develop a monitoring, verification, and accounting (MVA) plan to address potential challenges and risk [5]. The MVA plan covers the pre- and post-injection period and is tailored to site-specific geologic and operational conditions. The MVA plan is designed with a broad scope and covers containment of CO_2, internal quality control, risk management, and verification for regulators and accounting for monetization benefits of geologic storage. While geologic CO_2 storage projects are increasing, research efforts continue to investigate risk and address challenges.

Leakage and Seismic Activity

CO_2 leakage during the injection and post-injection periods pose risks to safe and permanent CO_2 storage. CO_2 stored underground has potential to migrate upward through poorly plugged or cemented well infrastructure. When designing and constructing injection wells, specific infrastructure is installed to ensure containment. However, legacy wells that penetrate the storage reservoir pose a risk to CO_2 leakage. If leakage occurs, CO_2 may impact underground sources of drinking water (USDW). CO_2 leaks can be detrimental to human health and equipment operating in the area if not addressed promptly. Federal and state regulators, including the U.S. Environmental Protection Agency and the U.S. Department of Transportation's Pipeline and Hazardous Materials Safety Administration, are monitoring the risks of these leakages [6,7,8].

Injection of large volumes of CO_2 into deep geologic formations may affect subsurface stress and increase pressures within the formation. This has the potential to induce seismic activity, although the risk of causing significant earthquakes is generally considered to be low [9].

Cost, Energy Requirements, and Other Challenges

CCS systems add costs for existing and new power generation and industrial assets. CCS requires energy to capture, compress, transport, and store CO_2. Energy requirements for capture is affected by the concentration of CO_2 and the capture methods used. For instance, solvent capture methods require greater energy inputs for recycling the capture medium than sorbent methods due to water's higher heating requirements.

Carbon capture requires energy to capture, compress, store, and transport CO_2. Thermal energy is consumed to release CO_2 from solvents or sorbents used to clean the flue gas. Electricity may be used in membrane and cryogenic capture methods. Compressing CO_2 for transport and storage requires additional energy inputs. Power plants utilizing CCS to decarbonize will see penalties to their process efficiencies that will vary by plant and by desired capture rate, with higher capture rates requiring greater energy inputs [10].

Other challenges include long-term liability and public acceptance. Ensuring the long-term liability of storage sites, particularly if a company responsible for the site ceases operations, is an important consideration. Public perception and acceptance of CCS projects are also important factors for successful implementation [11].

These risks can be addressed through comprehensive assessments, continuous monitoring, and regulatory frameworks to ensure the safe and effective CCS deployment. CCS can be a valuable potential tool for mitigating climate change. It compliments other essential strategies, such as renewable energy adoption, nuclear technologies, low-carbon fuels, and energy efficiency improvements. A comprehensive approach is needed to address the challenges of climate change effectively.

ADDITIONAL INFORMATION ON CCS

Following are organizations that offer more information on CCS:

- **EPRI.** Founded in 1972, EPRI is the world's preeminent independent, non-profit energy research and development organization, with offices around the world. More information on CCS can be found here: https://www.epri.com/research/programs/113063; and https://www.lowcarbonlcri.com/.
- **Global CCS Institute.** This independent organization focuses on accelerating the deployment of CCS worldwide. Its website offers resources and information on CCS projects and developments: https://www.globalccsinstitute.com/.
- **International Energy Agency (IEA).** The IEA's Technology Collaboration Programme on Carbon Capture and Storage offers insights into the global status of CCS and ongoing projects. Learn more here: https://www.iea.org/energy-system/carbon-capture-utilisation-and-storage/co2-capture-and-utilisation.
- **Intergovernmental Panel on Climate Change (IPCC).** See the "Special Report on Carbon Dioxide Capture and Storage." https://www.ipcc.ch/report/carbon-dioxide-capture-and-storage/.
- **United States Department of Energy (DOE).** See the Office of Fossil Energy. https://www.energy.gov/fecm/carbon-storage-research.
- **United States Department of Energy (DOE).** The National Energy Technology Laboratory website provides information on CCS projects, research, and technologies. Learn more here: https://netl.doe.gov/carbon-management/carbon-capture.

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