U.S. DEPARTMENT OF ENERGY | NATIONAL ENERGY TECHNOLOGY LABORATORY

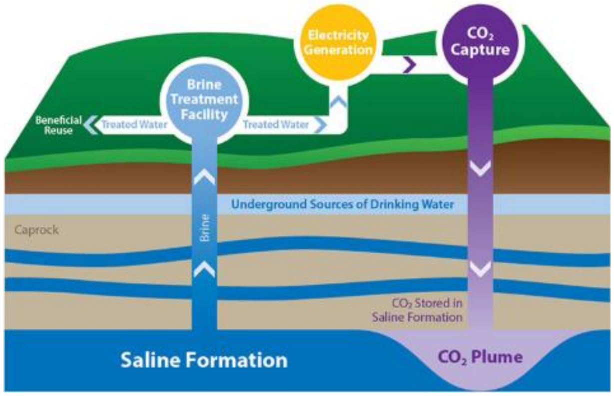
WHAT IS CARBON CAPTURE AND STORAGE?

Carbon capture and storage (CCS) is the separation and capture of carbon dioxide (CO_2) from the emissions of industrial processes prior to release into the atmosphere and storage of the CO_2 in deep underground geologic formations.

CCS enables industry to continue to operate while emitting fewer greenhouse gases (CHGs), making it a powerful tool for addressing mitigation of anthropogenic CO_2 in the atmosphere. However, storage must be safe, environmentally sustainable, and cost-effective. Suitable storage formations can occur in both onshore and offshore settings, and each type of geologic formation presents different opportunities and challenges. Geologic storage is defined as the placement of CO_2 into a subsurface formation so that it will remain safely and permanently stored. The U.S. Department of Energy (DOE) is investigating five types of underground formations for geologic carbon storage:

Saline formations, Oil and natural gas reservoirs, Unmineable coal seams, Organic-rich shales and Basalt formations

DOE's Carbon Storage Program is conducting research and development (R&D) on CCS, developing Best Practice Manuals (BPMs) on topics.
Myth: Carbon capture and storage is not a feasible way to reduce human CO_2 emissions.
Reality: Developing the technologies and know-how to successfully capture and store CO_2 emissions will allow for a viable industry that will reduce the human contribution to atmospheric CO_2 levels.



Carbon storage diagram showing CO2 injection into a saline formation while producing brine for beneficial use

HOW CAN CO_2 BE STORED UNDERGROUND?

Carbon dioxide (CO_2) can be stored underground as a supercritical fluid. Supercritical CO_2 means that the CO_2 is at a temperature in excess of 31.1°C (88ºF) and a pressure in excess of 72.9 atm (about 1,057 psi); this temperature and pressure defines the critical point for CO_2. At such high temperatures and pressures, the CO_2 has some properties like a gas and some properties like a liquid. In particular, it is dense like a liquid but has viscosity like a gas. The main advantage of storing CO_2 in the supercritical condition is that the required storage volume is substantially less than if the CO_2 were at “standard” (room)-pressure conditions.

Temperature naturally increases with depth in the Earth’s crust, as does the pressure of the fluids (brine, oil, or gas) in the formations. At depths below about 800 meters (about 2,600 feet), the natural temperature and fluid pressures are in excess of the critical point of CO_2 for most places on Earth. This means that CO_2 injected at this depth or deeper will remain in the supercritical condition given the temperatures and pressures present.

Myth: The CO_2 gas behaves the same in the atmosphere as it does when injected deep underground.

Reality: The elevated temperatures and pressures that exist at the depths where CO_2 is injected changes its characteristics, allowing for storage of much greater volumes of CO_2 than at the surface.

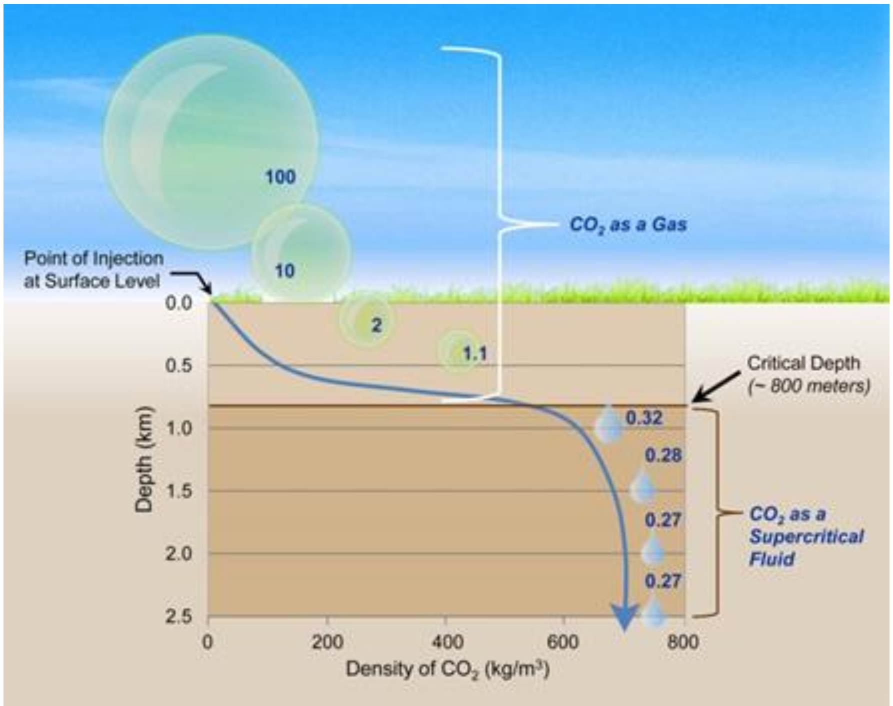
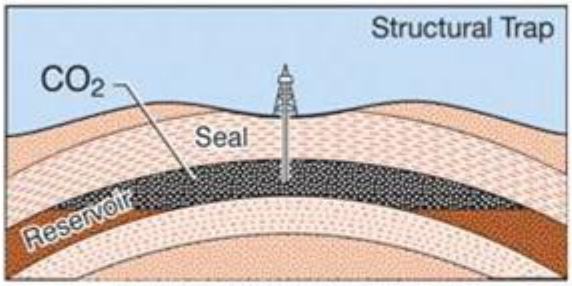


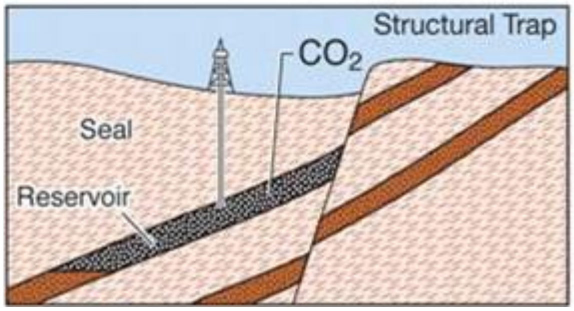
Illustration of Pressure Effects on CO2 (based upon image from CO2CRC). The blue numbers show the volume of CO2 at each depth compared to a volume of 100 at the surface.

HOW IS CO_2 TRAPPED IN THE SUBSURFACE?

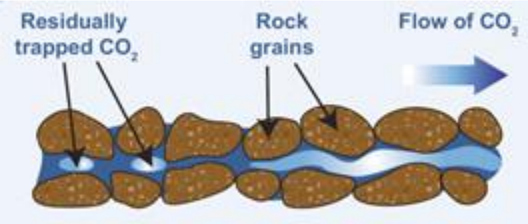
Trapping refers to the way in which the carbon dioxide (CO_2) remains underground in the location where it is injected. There are four main mechanisms that trap the injected CO_2 in the subsurface. Each of these mechanisms plays a role in how the CO_2 remains trapped in the subsurface. The following provides a description of each type of trapping mechanism.

Structural Trapping – Structural trapping is the physical trapping of CO_2 in the rock and is the mechanism that traps the greatest amount of CO_2. The rock layers and faults within and above the storage formation where the CO_2 is injected act as seals, preventing CO_2 from moving out of the storage formation. Once injected, the supercritical CO_2 can be more buoyant than other liquids present in the surrounding pore space. Therefore, the CO_2 will migrate upwards through the porous rocks until it reaches (and is trapped by) an impermeable layer of seal rock. Diagram depicting two examples of structural trapping. The top image shows the CO_2 being trapped beneath a dome, preventing it from migrating laterally or vertically. The bottom image shows that CO_2 is prevented from migrating vertically by the overlying seal rock and a fault to the right of the CO_2.

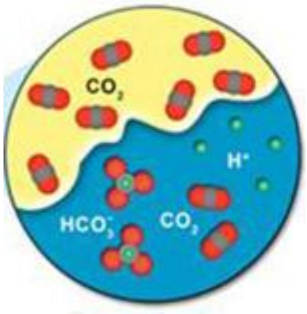




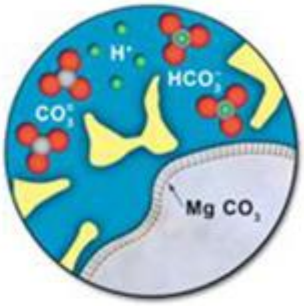
Residual Trapping – Residual trapping refers to the CO_2 that remains trapped in the pore space between the rock grains as the CO_2 plume migrates through the rock. The existing porous rock acts like a rigid sponge. When supercritical CO_2 is injected into the formation, it displaces the existing fluid as it moves through the porous rock. As the CO_2 continues to move, small portions of the CO_2 can be left behind as disconnected, or residual, droplets in the pore spaces which are essentially immobile, just like water in a sponge. Diagram depicting the pockets of residually trapped CO_2 in the pore space between the rock grains as the CO_2 migrates to the right through the openings in the rock.



Solubility Trapping – In solubility trapping, a portion of the injected CO_2 will dissolve into the brine water that is present in the pore spaces within the rock. Diagram depicting the CO_2 interacting with the brine water, leading to solubility trapping. At the CO_2/brine water interface, some of the CO_2 molecules dissolve into the brine water within the rock's pore space. Some of that dissolved CO_2 then combines with available hydrogen atoms to form HCO_{3-}.



Mineral Trapping – Mineral trapping refers to a reaction that can occur when the CO_2 dissolved in the rock's brine water reacts with the minerals in the rock. When CO_2 dissolves in water it forms a weak carbonic acid (H_2CO_3) and eventually bicarbonate (HCO_3-). Over extended periods, this weak acid can react with the minerals in the surrounding rock to form solid carbonate minerals, permanently trapping and storing that portion of the injected CO_2. Diagram depicting the formation of minerals on the surface of a rock grain (bottom right of image) as it reacts with the dissolved CO_2 in the brine water. The magnesium in the rock grain combines with the CO_3 in the water to produce the mineral $MgCO_3$ on the grain's surface.



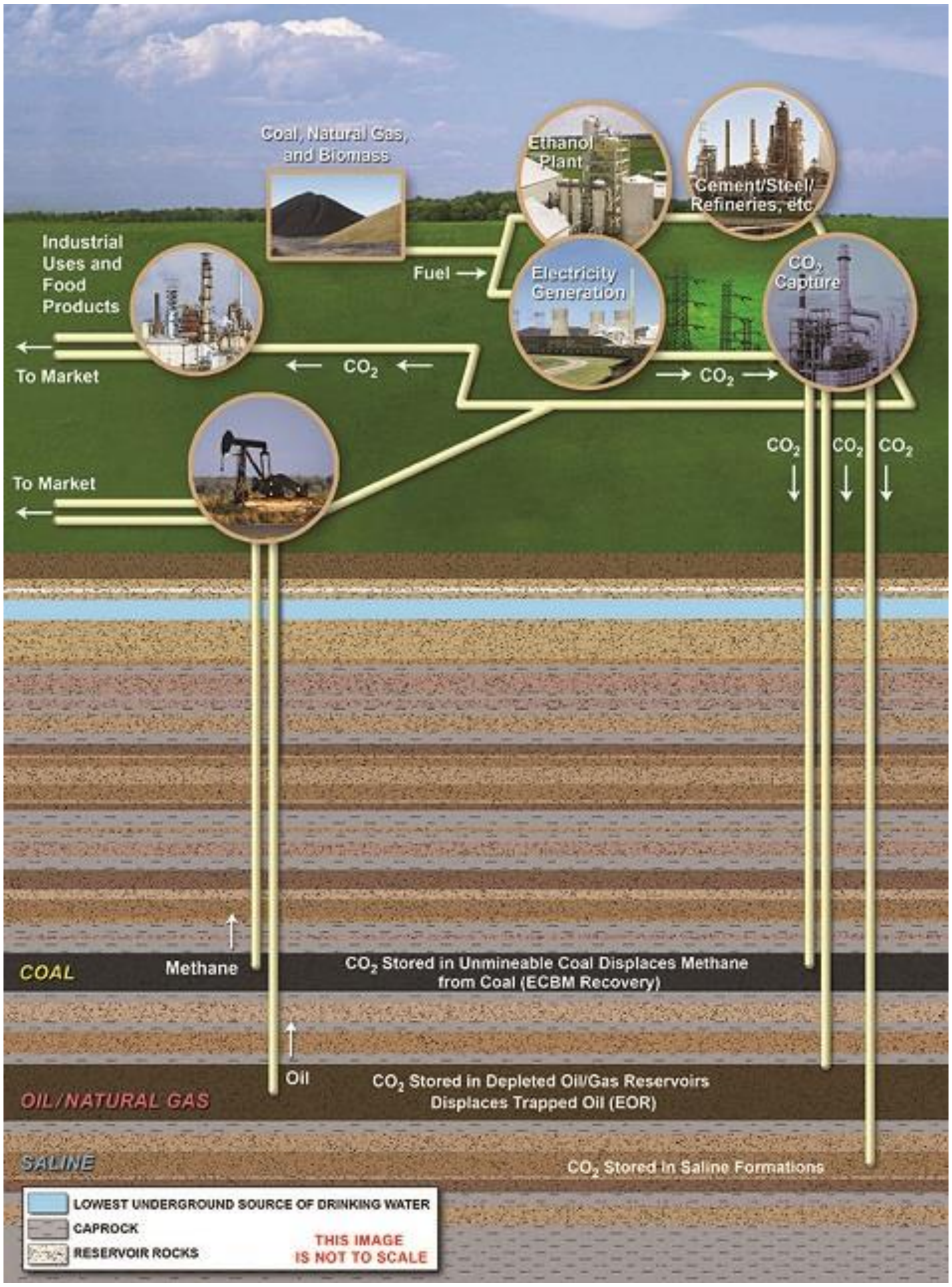
Myth: There is nothing preventing injected CO_2 from migrating to the Earth's surface through the overlying rock, making CO_2 leakage inevitable.
Reality: There are four main mechanisms that help trap CO_2 in the subsurface and prevent it from migrating to the surface.

WHAT ARE THE CHARACTERISTICS OF A SUBSURFACE CARBON STORAGE COMPLEX?

When assessing a storage site, some of the reservoir characteristics that are studied for long-term carbon dioxide (CO_2) storage include storage resource, injectivity, integrity, and depth. The term "subsurface storage complex" refers to the geologic storage site that is targeted to safely and permanently store injected CO_2 underground. It includes a storage formation with at least one, or usually multiple, regionally continuous sealing formations called caprocks or seals.

- **Storage Resource** – A storage site needs to have sufficient storage resource (space) to contain large amounts (millions of metric tons) of compressed CO_2. The storage resource is a fraction of the pore volume of porous and permeable sedimentary formations available for storage.
- **Injectivity** – This refers to the rate at which CO_2 can be injected into the subsurface. Injectivity of the CO_2 is directly related to the permeability of the formation. The permeability of a formation is a measure of the resistance to fluid flow through it. If fluid can easily pass through the formation, it has “high permeability.”
- **Integrity** – This refers to the ability to confine CO_2 safely within a predetermined volume without a breach from the storage complex. A storage complex must have one or more confining zones that seal above the injected formation that are intact and do not have leakage pathways.
- **Depth** – The CO_2 storage zone needs to be located at a sufficient depth and pressure so that CO_2 can be injected as a supercritical fluid. Supercritical CO_2 is dense and behaves more like a liquid than a gas, allowing for storage of higher concentrations of CO_2 by volume.

All of these characteristics are examined in order to determine if a potential storage complex has adequate conditions for CO_2 storage.
Image depicting the features of different types of carbon storage complexes including saline formations, oil and natural gas reservoirs, unmineable coal areas, organic-rich shales, and basalt formations. All of the complexes include: (1) a confining zone that includes a thick (or several) sealing layer(s) above the storage zone, separating the stored CO_2 from drinking water sources and the surface; (2) adequate integrity within the storage formation and sealing layers; (3) sufficient porosity and permeability to store large amounts of CO_2; and (4) are at supercritical depth to allow for concentrated storage.



Myth: Any location that has an injection well can be used to inject and store carbon.

Reality: A specific set of characteristics are needed to make a setting appropriate to act as a storage complex. These characteristics are determined through a rigorous characterization process that includes assessing potential storage risks and meeting the regulations under the U.S. Environmental Protection Agency's (EPA) permitting process that grants permission to inject CO_2 for carbon storage purposes.

WHAT ARE THE DIFFERENT STORAGE TYPES FOR GEOLOGIC CO_2 STORAGE?

Suitable storage formations can occur in both onshore and offshore settings, and each type of geologic formation presents different opportunities and challenges. The U.S. Department of Energy (DOE) is investigating five types of underground formations for geologic carbon storage:

- Saline formations
- Oil and natural gas reservoirs
- Unmineable coal seams
- Basalt formations
- Organic-rich shales

A complete description of these storage types can be found in DOE's Carbon Storage Atlas, Fifth Edition (Atlas V).

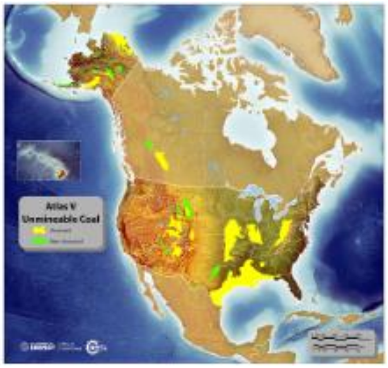
SALINE FORMATIONS

Saline formations are porous formations filled with brine, or salty water, and span large volumes deep underground. Carbon capture and storage (CCS) focuses on formations that contain brine with total dissolved solids (TDS) levels greater than 10,000 ppm TDS. Studies show that saline formations have the largest potential volume for storing carbon dioxide (CO_2) around the world. Image depicting the saline storage resources in the United States and portions of Canada. Extensive saline formations exist in the large sedimentary basins located across the country.

OIL AND NATURAL GAS RESERVOIRS

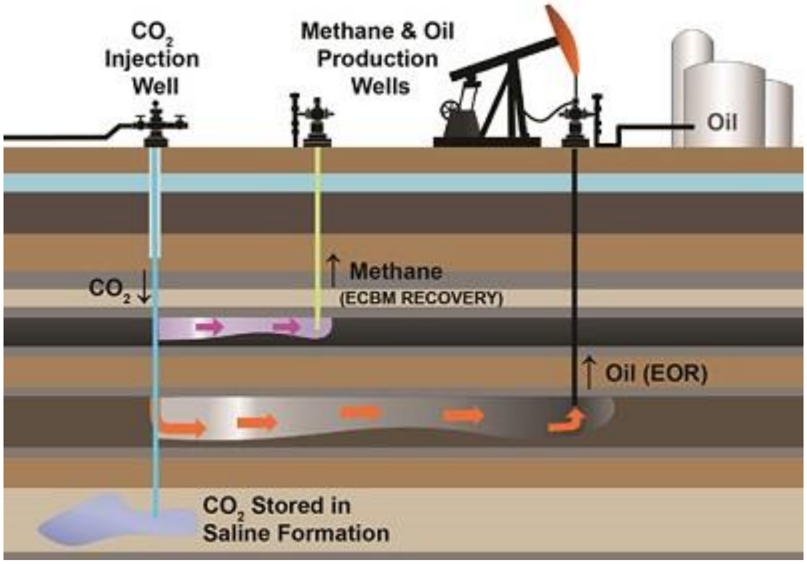
Oil and natural gas reservoirs can be found in many places in the United States and around the world. Once the oil and natural gas is extracted from an underground formation, it leaves a permeable and porous volume that can be readily filled with CO_2.

Oil and natural gas reservoirs are ideal geologic storage sites because they have held hydrocarbons for thousands to millions of years and have conditions suitable for CO_2 storage. Injecting CO_2 can also enhance oil production by pushing fluids towards producing wells through a process called enhanced oil recovery (EOR). Images depicting the oil reservoirs, natural gas reservoirs, and unmineable coal storage resources in the United States and portions of Canada.



UNMINEABLE COAL SEAMS

Coal that is considered unmineable because of geologic, technological, and economic factors (typically too deep, too thin, or lacking the internal continuity to be economically mined) may still serve as locations to store CO_2. To be considered for CO_2 storage, the ideal coal seam must have sufficient permeability and be considered unmineable. Coal seams may also contain methane (CH_4), which can be produced in conjunction with CO_2 injection in a process called enhanced coal bed methane (ECBM) recovery (see depiction below). In coal seams, the injected CO_2 can be chemically trapped by being adsorbed (or adhered) to the surface of the coal while CH_4 is released and produced. This trapping mechanism allows for permanent storage of CO_2. Diagram depicting ECBM and EOR recovery process by which CO_2 is injected and used to drive the natural gas or oil towards a recovery well.



BASALT FORMATIONS

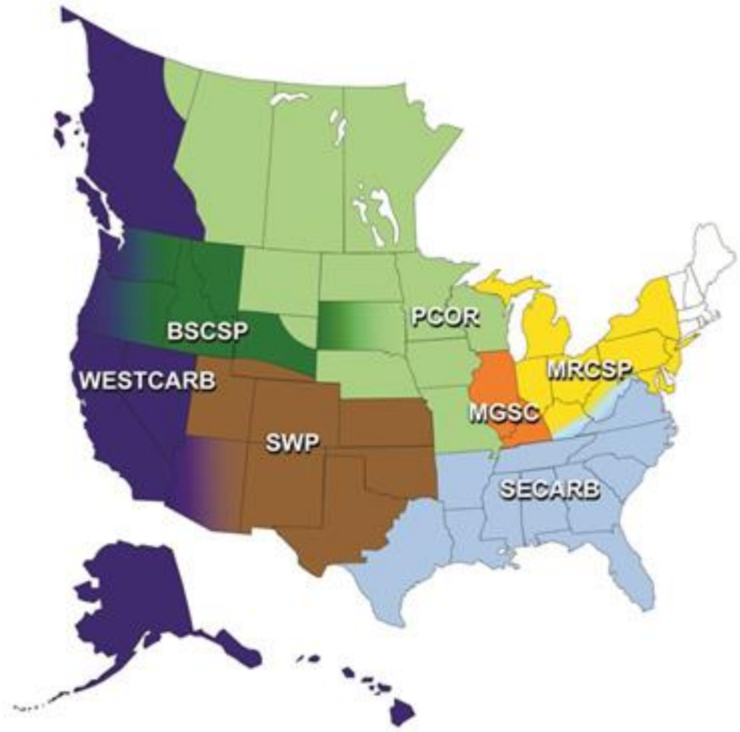
Basalt is a type of formation that was deposited when large flows of lava spread from volcanoes, cooled, and then solidified. Over time, thick layers of basalt were built up (with other formation types often layered in between) and have been identified in buried deposits across the United States. The chemical and physical properties of these basalts, as well as the other formation types in between basalt layers, make them good candidates for CO_2 storage systems. The chemistry of basalts potentially allows injected CO_2 to react with magnesium and calcium in the basalt to form the stable carbonate mineral forms of calcite and dolomite. This mineralization process shows promise to be a valuable tool for CCS because the mineralization process permanently locks carbon in the solid mineral structure, thereby permanently trapping the CO_2. Image depicting Basalt Formations in the United States. Basalts may offer a highly secure method of CO_2 storage because of their potential to allow the CO_2 to react with the minerals in basalt to form carbonates, thereby permanently trapping the CO_2.

ORGANIC SHALE FORMATIONS

Shale formations are found across the United States and are typically low-porosity and low permeability formations best suited as confining zones. However, some shales have similar properties to coal, having the ability to trap CO_2 through adsorption (adherence to the surface), subsequently releasing methane and making them potentially attractive for storage. Image depicting basins containing organic-rich shales in the United States and portions of Canada.

Myth: There are limited options to store CO_2 underground, and little is known about these options.
Reality: There are many storage types that can store CO_2 and geologic storage of oil, natural gas, and CO_2 in the subsurface has been occurring naturally for millions of years.

WHAT IS THE UNITED STATES DEPARTMENT OF ENERGY DOING TO DEMONSTRATE THE COMMERCIAL VIABILITY OF CCS?



Regional Footprints for the RCSP Initiative

The Regional Carbon Sequestration Partnership (RCSP) Initiative is an initiative implemented through the U.S. Department of Energy (DOE), Office of Fossil Energy (FE), and National Energy Technology Laboratory (NETL). The initiative supports research into the best regional approaches for permanently storing carbon dioxide (CO_2) in geologic formations through characterization and field projects. The partnerships include more than 400 distinct organizations, spanning 43 states and 4 Canadian provinces; have conducted 19 small-scale field projects building on research and are developing the framework needed to validate geologic carbon storage technologies. There are several large-scale CO_2 tests (tests injecting at least 1 million metric tons [MMT] of CO_2) currently being conducted or recently finished in the United States:

- Cranfield Project (SECARB) (Mississippi)
- Citronelle Project (SECARB) (Alabama)
- Illinois Basin Decatur CO_2 Project (MGSC)(Illinois)
- Bell Creek Field Project (PCOR Partnership)(Montana)
- Farnsworth Unit, Ochiltree Project (SWP)(Texas)
- Michigan Basin Project (MRCSP) (Michigan)
- Kevin Dome Project (BSCSP) (Montana)

In addition to the RCSP's efforts to implement small- and large-scale field projects, the RCSPs are also working to develop human capital, encourage stakeholder networking, develop carbon mitigation plans, and enhance public outreach and education on carbon capture and storage (CCS).

Myth: In the United States, there have only been laboratory studies related to the viability of CCS.
Reality: The United States has supported a concerted effort that includes many large-scale CO_2 storage projects that are designed to verify the viability of long-term carbon storage.

WHERE AROUND THE WORLD IS CO_2 STORAGE HAPPENING TODAY?

Sleipner Project (Norway)

Carbon dioxide (CO_2) storage is currently happening across the United States and around the world. Large, commercial-scale projects, such as the Sleipner CO_2 Storage Site in Norway and the Weyburn-Midale CO_2 Project Project in Canada, have been injecting CO_2 for many years. Each of these projects stores more than 1 million metric tons (MMT) of CO_2 per year. Large-scale efforts are also currently underway in China, Australia, and Europe. These commercial-scale projects are demonstrating that large volumes of CO_2 can be safely and permanently stored.

Additionally, a multitude of other carbon capture and storage (CCS) efforts are underway in different parts of the world to demonstrate the capability of geologic storage and technologies for future long-term CO_2 storage. To date, more than 200 CO_2 capture and/or storage operations (including in-development and completed) have been carried out worldwide.

Myth: There is little to no international work being done to actively validate the concept of long-term carbon storage.

Reality: There are many projects within the United States and around the world where geologic storage of CO_2 is being successfully performed.