CCUS Technology Review

Introduction and Motivation

"Carbon capture, utilization, and storage technologies are key to addressing global emissions issues, particularly important in developing nations, by making carbon-intensive production and generation cleaner than we ever thought possible," said the United States Former Under Secretary of Energy Mark W. Menezes in April 2020 as part of the Department of Energy (DOE) announcement of $131 million of funding available for CCUS Technologies. Carbon dioxide (CO_2) sequestration can be defined as the segregation of CO_2, either chemically, such as in chemical utilization, or physically, such as in geologic storage. Captured carbon can be stored in deep geologic formations or used either to produce oil from depleted wells through the enhanced oil recovery process (which sequesters the CO_2 underground), or in the creation of a variety of products. The integrated concept from capture to sequestration is defined as **carbon capture, utilization, and storage (CCUS).** CO_2 can be captured from various sources and transported by pipeline or marine vessel for use or permanent storage.

As noted by the International Energy Agency (IEA) in their 2020 Energy Technology Perspectives CCUS in clean energy transitions, CCUS will need to play a major role as the only group of technologies that contributes both to reducing emissions in key sectors directly and to removing CO_2 to balance emissions that cannot be avoided or are difficult to abate. This is a critical part of carbon abatement to achieve global net-zero ambitions while ensuring transitory energy needs and sustainable development goals are met. From power generation to industrial sources, carbon capture is the only large-scale option to reduce emissions at a relatively low cost while preserving the value of fossil fuel reserves and existing infrastructure. For CCUS to contribute significantly to the mitigation of CO_2 emissions, global execution of thousands of commercial CCUS projects would have to be implemented over the coming decades.

Technology Principles

Terminology and Definitions

- Carbon capture and storage (CCS) includes applications where the CO_2 is captured and permanently stored.
- Carbon capture and utilization (CCU) is where CO_2 is used in the production of commercial products such as transportation fuels and chemicals for example for use in the food industry as an additive in beverages or a preservative for fruits and vegetables.
- Carbon capture, utilization, and storage (CCUS): includes CCS, CCU, and additionally where CO_2 is both used and stored, for example in Enhanced Oil Recovery (EOR) or in building materials, where partial or full utilization and storage of CO_2 is permanent.

Carbon Capture and Storage

Figure 1 is a schematic representation of a CCS system with power generation or industrial sources of carbon dioxide. CO_2 produced from carbon in the fossil fuels or biomass feedstock is first captured and then compressed to a dense supercritical fluid for transportation and storage. The main storage option is underground injection into a suitable geological formation. The dominant transport mode is by pipeline. Since most anthropogenic (from human activity) CO_2 is a byproduct of the combustion of fossil fuels, CO_2 capture technologies, in the context of CCS, are commonly classified as either pre-combustion or post-combustion systems, depending on whether carbon as carbon dioxide is removed before or after a fuel is burned.

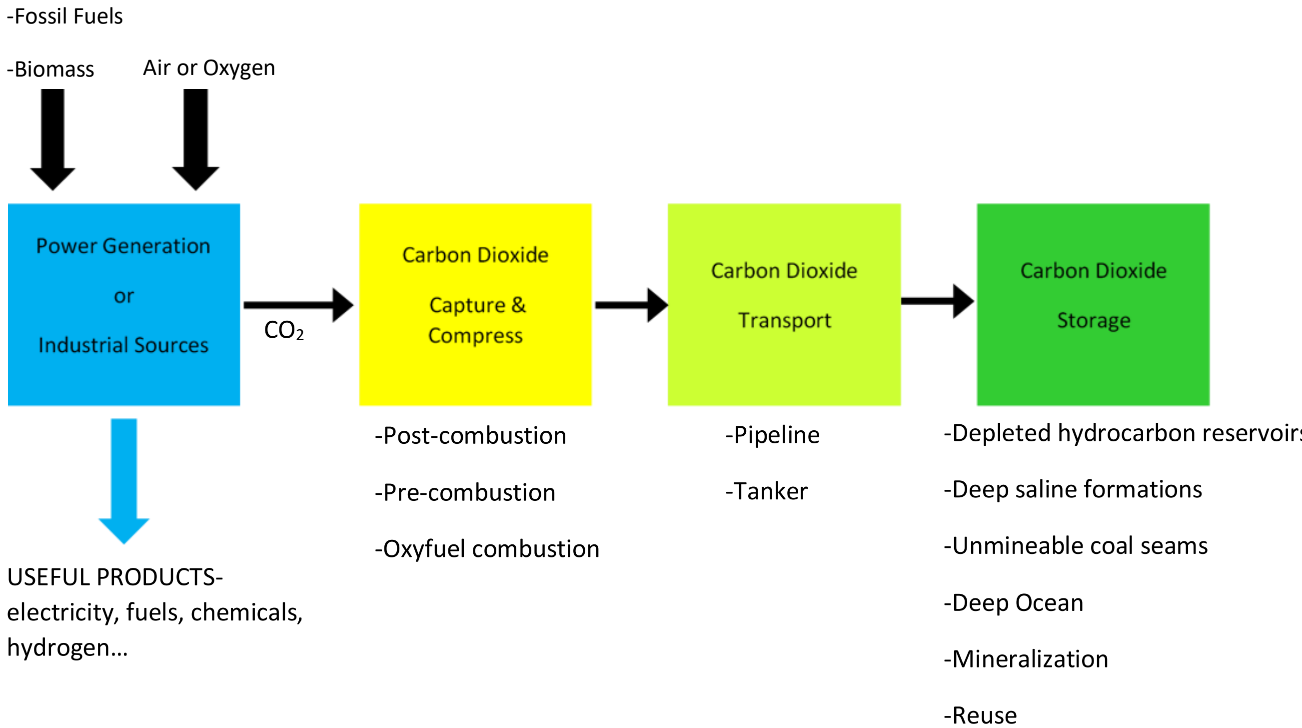

Figure 1: Schematic of a CCS system- CO_2 capture, transport, and storage (modified after Rubin et. al., 2012)

An overview of CO_2 *capture technologies*

Carbon capture and storage (CCS) is widely seen as a critical technology for reducing atmospheric emissions of carbon dioxide (CO_2) from point sources such as fossil-fuel based power plants and other large industrial facilities, which are major sources of greenhouse gas (GHG) emissions linked to global climate change. Vallejo et. al., (2021) have noted that CO_2 emitted from fossil fuel combustion and cement production represents about 70% of total GHG emissions annually. The National Energy Technology Laboratory (NETL) is progressing toward promoting safe, reliable, and affordable energy nationwide while protecting the environment for future generations. NETL's Carbon Capture Technology program is working to advance technologies to develop the next generation of CO_2 capture concepts which have the potential to provide step-change reductions in both cost and energy requirements compared to currently available first-generation technologies. The major approaches to CO_2 capture from power and industrial point sources are post-combustion, pre-combustion and oxy-fuel combustion capture and are improved, lower-cost, lower energy penalty CCS technology options compared to a decade ago.

Post-combustion capture- these systems separate CO_2 from the flue gas stream produced by conventional fossil fuel-fired power plans after fuel combustion in air.

Pre-combustion capture- these systems are designed to separate CO_2 and Hydrogen (H_2) from the synthesis gas stream.

A variety of technologies for separating CO_2 from a mixture of gases (gas stream) are commercially available and widely used today, using a variety of physical, chemical, and biological technologies. These methods are typically applied as a purification step in industrial processes which include coal-fired power plants, hydrocarbon refining and fertilizer industries. The technology application isolates the CO_2 from the various sources and produces a form that is suitable for transport and storage. Figure 2 illustrates the variety of technology approaches available depending on the desired outcome and particular application. As many of the first-generation capture technologies have been fully commercialized, their maturity can be represented by **Department of Energy Technology Readiness Levels 8-9** (DOE TRL 8-9).
See Appendix 1 for a detailed description of Technology Readiness Levels.

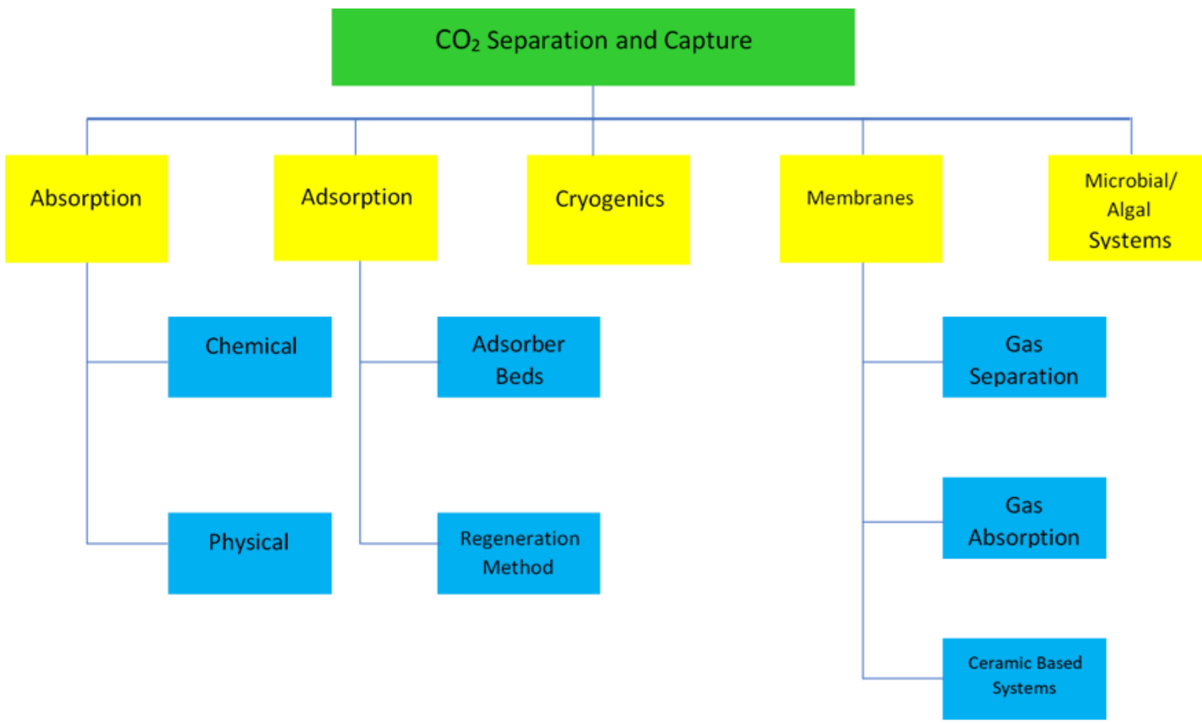

Figure 2: Technical options for CO_2 capture (after Rubin et.al., 2012)

Physical absorption- CO_2 removal through physical absorption is based on CO_2 solubility in solvents used as absorbents. A higher CO_2 partial pressure and lower feed gas temperature increases the solubility of CO_2 in the solvent absorbents, which are then regenerated by pressure reduction or heating resulting in physical separation. This method is suitable for removing CO_2 from natural gas and for removing CO_2 from synthesis gas which is used in the production of hydrogen, ammonia, and methanol. Physical absorption is not a cost-effective approach because of the energy requirements of flue gas pressurization for gas streams with a CO_2 partial pressure lower than 15% by volume.

Chemical absorption- chemical absorption can capture CO_2 at low partial pressures of CO_2, making this the preferred method in the post-combustion capture of CO_2 in power plants. Chemical absorption produces a relatively pure CO_2 stream making this approach suitable for CO_2 capture at an industrial scale. The ideal chemical solvent has a high CO_2 reactivity, high absorption capacity low regeneration cost requirements, high thermal stability, reduced solvent degradation, low environment impact and low solvent costs. The amine-based scrubbing solvents monoethanol amine and ammonia solutions are two of the most important, yielding higher capture capability and lower energy requirements. However, these types of solvents have high corrosivity and toxicity, while requiring large amounts of heat for solvent regeneration resulting in increased operating costs. Research to find new solvents continues, including research into low volatility, highly thermally and chemically stable ionic liquids.

Adsorption- this is one of the most promising technologies for CO_2 capture and is applicable in the post-combustion process at an industrial scale because of the lower energy requirements relative to absorption technologies. Additionally, CO_2 capture using adsorbents in the pre-combustion process increases yields of H2, which is becoming increasingly important as part of the transitory and future energy mix. Further research and testing is ongoing with the objective of improving the quality of CO_2 removal and to further decrease the energy consumption requirements of capture plants.

Microbial/Algal systems- CO_2 capture and fixation through algal biomass production strains of green algae. CO_2, Suphur Oxides and Nitrous Oxides are the common gas contaminants derived from fossil fuel combustion. The green algal species grows more rapidly in high concentrations of these contaminant oxides. Green algae can also produce form H_2. This is an ongoing area of research and development.

Carbon Dioxide Transport

Technologies associated with gas to liquid compression and transport of carbon dioxide will not be discussed in detail in this technical report. These technologies have been demonstrated for several decades and are largely commercially available. The captured CO_2 is first compressed to a supercritical state where it behaves as a liquid that can be readily transported via pipeline or marine vessel for utilization purposes or to be stored in geological formations, as discussed later in this report. Pipeline transportation of CO_2 is fully mature technology at **DOE TRL 9** and is the most technically mature step in CCS. Transportation via tanker is in the small-scale pilot demonstration phase of technology development **(DOE TRL 4-7)** and continued innovation will improve cost competitiveness and unlock new global opportunities.

Carbon Dioxide Storage

CCS is a vital option for significantly reducing CO_2 emissions from large-scale emission sources thereby allowing economies and corporations to meet their net-zero carbon ambitions. When its only purpose is for CO_2 sequestration, the storage sites may include deep saline formations, deep unmineable coal seams, depleted oil or gas reservoirs, and rock salt caverns. This technology is mature (**DOE TRL 8-9**) but still very expensive for widespread commercial application. The cost of CCS today is relatively high, due mainly to the high cost of CO_2 capture (which includes the cost of CO_2 compression needed for transport and storage). Many governmental and private research efforts are focused on developing, assessing, and verifying safe and cost-effective commercial-scale geologic storage sites for anthropogenic CO_2 emissions. Additionally, there are ongoing efforts to assess the technical and economic viability of carbon capture or purification technologies for sources that will supply CO_2 to the storage sites, to support a commercial return and/or meet a regulatory requirement.

A growing area of application is mineralization for permanent disposal of anthropogenic CO_2 emissions. Matter et.al., (2016) described the first successful application of permanent disposal of CO_2 as environmentally benign carbonate minerals in basaltic rock at the CarbFix site in Iceland.

Carbon Utilization

Figure 3 shows the CO_2 Utilization Pathways as documented by the National Energy Technology Laboratory.

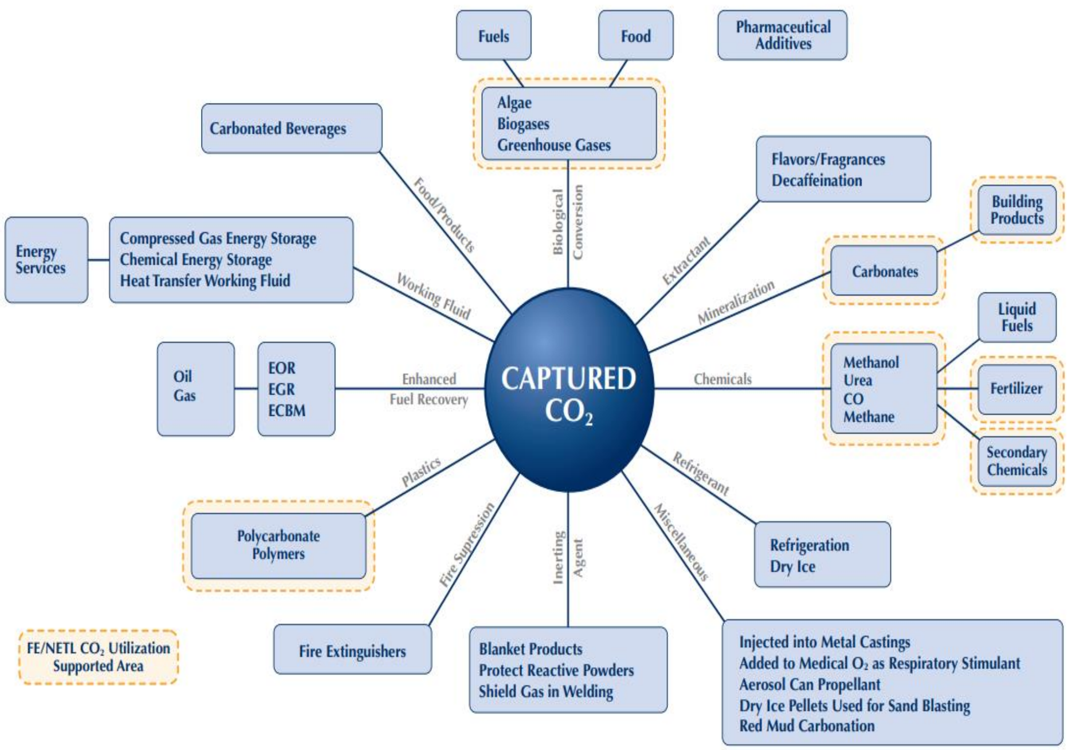

Figure 3: CO_2 Utilization Pathways (Source: National Energy Technology Laboratory www.netl.doe.gov)

This review will focus on CO2 utilization with application to the fossil fuel industry. In comparison with pure CCS technology, CCUS technology is more focused on utilization of the captured CO_2 while sequestration plays a secondary role. CCUS can reduce the cost of sequestration while bringing benefits by enhancing the production of fossil fuels. There are a number of related methods with differing levels of technology maturity- Enhanced Oil Recovery (EOR), Enhanced Coalbed Methane Recovery (ECBM), Enhanced Gas Recovery (EGR), Enhanced Shale Gas Recovery (ESG), and Enhanced Geothermal System (EGS), as shown schematically in Figure 4.

As with CCS technology, CCUS technology application is complex with its success dependent on the integration of subsurface engineering and science disciplines including geology, geophysics, and environmental engineering for site selection with safety, environmental and economic considerations, and drivers. Other considerations include project purpose and objectives, storage duration, injection depth and rate, fluid, and reservoir types, drilling and completions schemes and post-injection monitoring.

The conventional method to produce coalbed methane is to decrease the pressure in the coalbed reservoir, allowing the methane to desorb from the matrix. This method however has less than 50% recovery efficiency. An improvement to the method is to desorb more methane from the coalbed matrix by injecting CO_2 into the coalbed layer. The coalbed has a much strong adsorption capacity for CO_2, the adsorbed methane is desorbed, therefore enhancing methane recovery. This technology can bring both economic benefits and guarantee safe storage of CO_2, however the maturity of its commercial application is still very low (**pilot scale, DOE TRL 4-7**). Pilot scale CO_2-ECBM projects include those in Alberta Canada and in the San Juan Basin, USA.

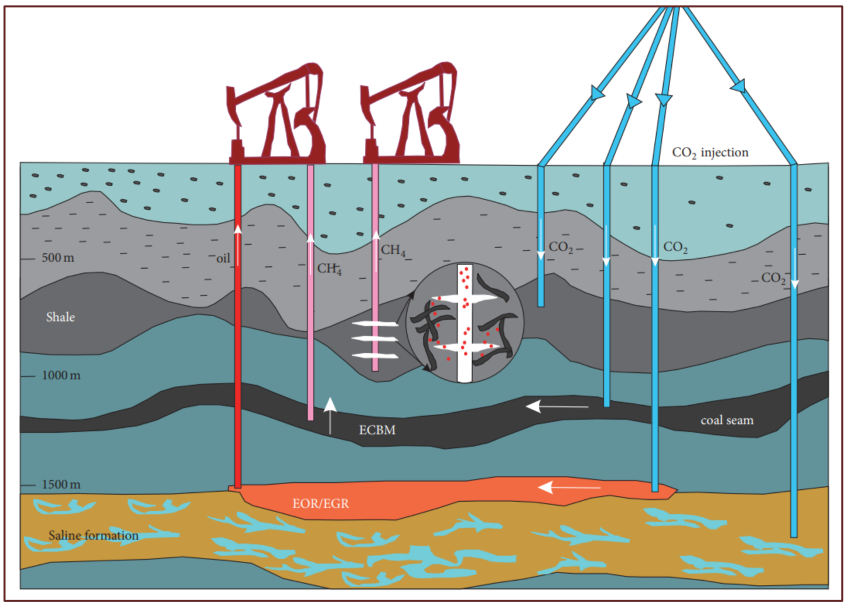

Figure 4: Schematic representation of CCUS technology in different geological reservoirs for sequestration of CO_2 (Source: Liu et. al., 2017)

Studies on injecting CO2 into depleted gas reservoirs to enhance gas recovery started in the 1990s and is still in the pilot-scale stage (**DOE TRL 4-7**). The efficiency of CO_2-EGR is very dependent on reservoir type and heterogeneity, subsurface temperature and pressure conditions, and production strategy. The rapid breakthrough of CO_2 in a production well is a potential outcome, resulting in a high concentration of CO_2 in the produced resource. On the positive side the gas recovery factor can be increased but in other instances, the recovery factor has decreased or seen no change. Pilot projects include the Rio Vista project in the USA and projects in the Netherlands, Germany, Australia, and Norway.

The USA has been carrying out shale gas desorption since 1821, however, limited development of the technology made this process difficult to apply before the 21st century. In 2000, shale gas contributed only 1% of the whole natural gas supply, while, by the end of 2011, this percentage had increased to 30% due to a breakthrough in drilling and completions technology. There has also been progress in replacing water by supercritical CO_2 as the injection fluid in fracturing technology. This process is however still in the very early exploration stages (**DOE TRL 1-3**).

The first study of EGS technology started in Fenton Hill, USA, in 1970. Conventional EGS technology uses water as the injection fluid and circulation media. Based on current research, injected hot wastewater CO_2 is the more favorable circulation fluid compared with water because of its large compressibility and expansibility, and its ability to enhance the porosity and permeability of the system. Injection of CO_2 into a hydrothermal or hot dry rock reservoir can maintain the reservoir pressure, promoting the flow rate of the in-situ water towards the production well, enhancing heat recovery and additionally recovery of methane dissolved in the aquifer water. This technology is in the early development stage and is not available at commercial scale (maturity **DOE TRL 1-3)**.

History of development

The timeline shown in Figure 5 below shows key CCUS technology milestones for each of the decades from the 1970s onwards. There are many more demonstrations and global applications than what reasonably could be depicted on the timeline, but this clearly illustrates progress through the decades and the increasing pace of technology development and commercialization.

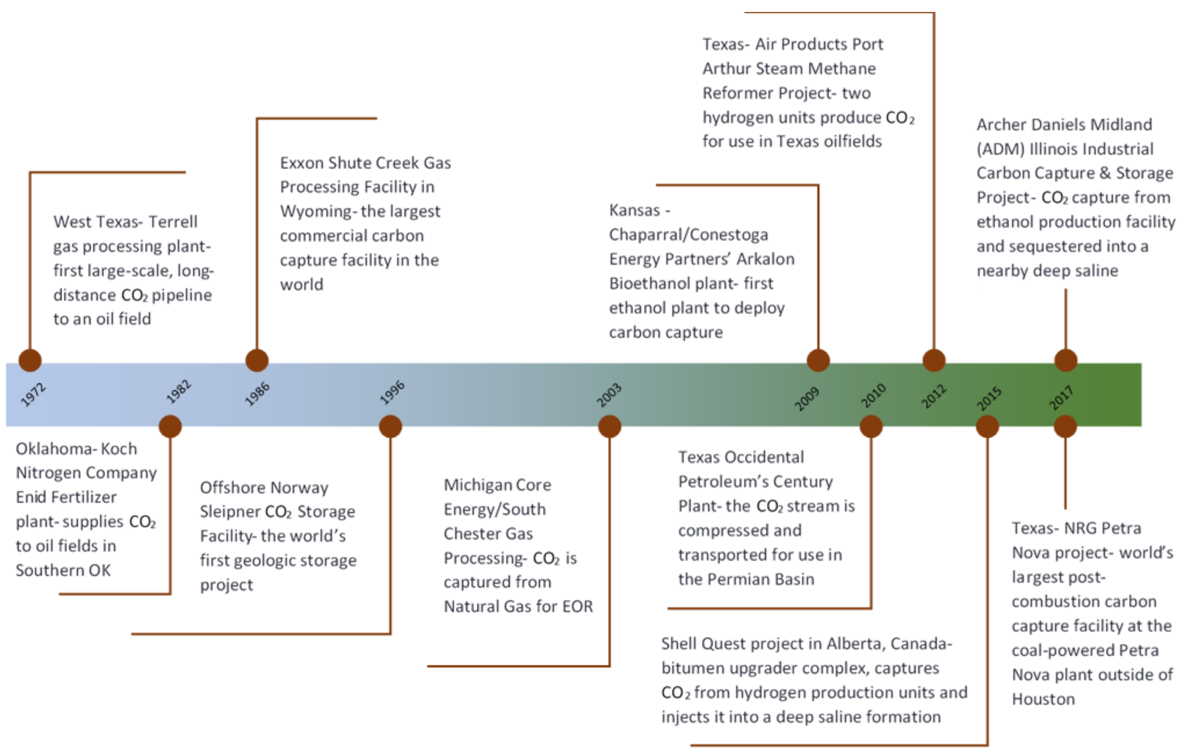

Figure 5: Timeline showing several key CCUS technology development and commercialization milestones

Noteworthy is that the first commercial application in 1972, with the Texas Terrell gas pas processing plant supplying CO_2 in the first largescale, long-distance pipeline to an oilfield in West Texas. One main observation from the timeline is the relative steady state of technology development, demonstration, and commercialization for the first thirty years shown, followed by rapid acceleration and increase in project implementation through to current day.

Current state and prospects for the future (2020/2021 view)

As noted in the Global CCS Institute, Global Status of CCS 2020 report, there are now 65 commercial CCS facilities globally:

- 26 are operational
- 2 have suspended operations
- 3 are under construction
- 13 are in advanced development reaching front end engineering design (FEED)
- 21 are in early development.

CCS facilities currently in operation can capture and permanently store around 40 Mt of CO_2 every year. There are another 34 pilot and demonstration-scale CCS facilities in operation or development and 8 CCS technology test centres.

A couple of detailed examples of commercial facilities are shown below in Figure 6.

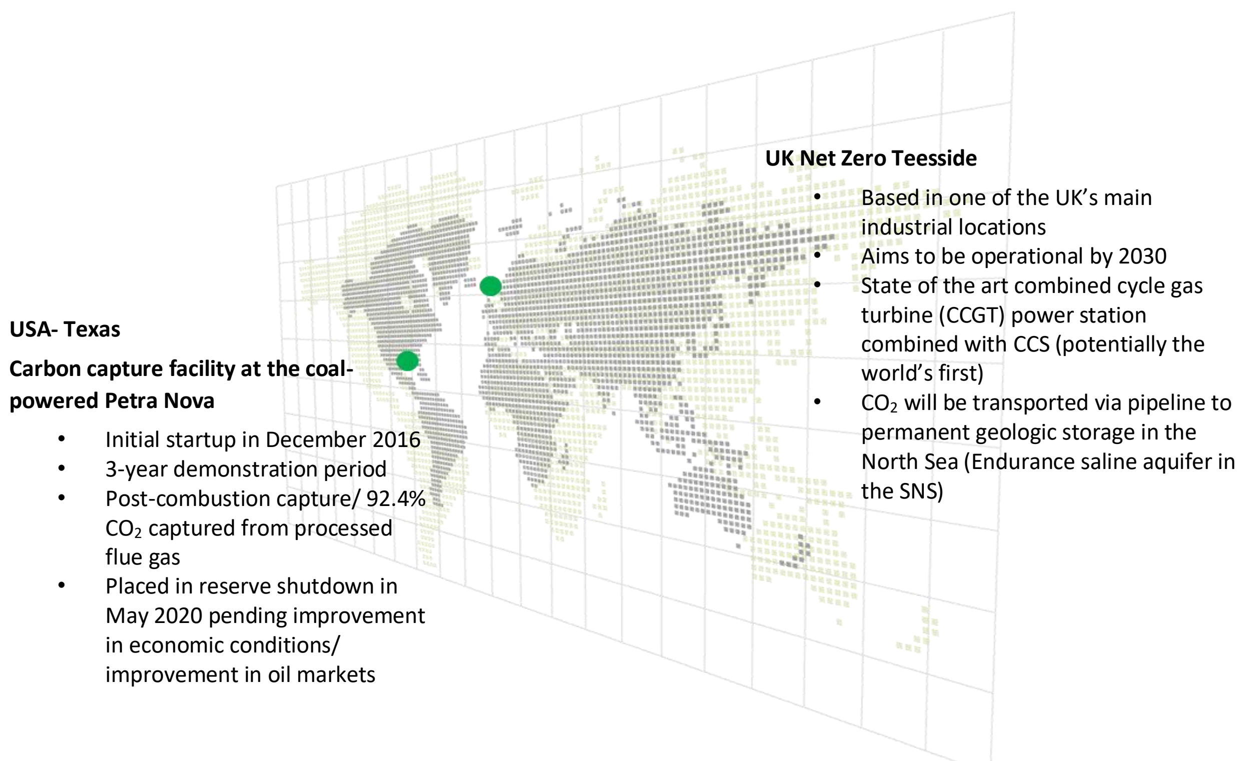

Figure 6: Map of world showing current status of a subset of the world's commercial CCS facilities

Emerging Technologies

Numerous research initiatives and considerable research and development (R&D) efforts are being made to develop and deliver new systems and processes for **converting CO_2 into useful products**. These emerging applications are mostly in early concept to laboratory or pilot scale. However, market intelligence shows that Chinese companies have already started to commercialize CO_2-based polymers. Research continues in these areas.

R&D is underway to develop technologies based on advanced solvents, sorbents, membranes, hybrid systems and other novel concepts in **post-and pre-combustion carbon capture**. CCS continues to be expensive for widespread commercial application due to the high cost of capture, transport and storage. There is opportunity to achieve cost-effective commercial-scale application through continued research efforts.

CO_2 capture from industrial facilities, such petroleum refineries, iron and steel processing plants, and ethanol plants where CO_2 emissions may be present at a higher concentration than coal-fired power plants, is a vital element in reducing CO_2 emissions. R&D is underway to **develop carbon capture technologies specific to industrial (or point) CO_2 sources**.

Negative emissions technologies aim to remove CO_2 from the atmosphere, with the resultant carbon stored or utilized. An increasingly important and active area of research is **Direct Air Capture and Storage (DACCS)** with the potential to significantly reduce carbon mitigation costs. R&D is underway to develop chemical processes and materials for application of **Direct Air Capture (DAC)**, which allows for CO_2 capture from all emissions sources to address both current and legacy emissions. This research area also includes investigating biomass co-firing to reduce emissions from coal-fueled power plants.

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Appendix 1

Source: U.S. Department of Energy, Energy Efficiency & Renewable Energy

EERE 200.5 Technology Readiness Levels (TRLs)

1. **TRL-1**. Basic principles observed and reported: Scientific problem or phenomenon identified. Essential characteristics and behaviors of systems and architectures are identified using mathematical formulations or algorithms. The observation of basic scientific principles or phenomena has been validated through peer-reviewed research. Technology is ready to transition from scientific research to applied research.

2. **TRL-2**. Technology concept and/or application formulated: Applied research activity. Theory and scientific principles are focused on specific application areas to define the concept. Characteristics of the application are described. Analytical tools are developed for simulation or analysis of the application.

3. **TRL-3**. Analytical and experimental critical function and/or characteristic proof of concept: Proof of concept validation has been achieved at this level. Experimental research and development is initiated with analytical and laboratory studies. System/integrated process requirements for the overall system application are well known. Demonstration of technical feasibility using immature prototype implementations are exercised with representative interface inputs to include electrical, mechanical, or controlling elements to validate predictions.

4. **TRL-4**. Component and/or process validation in laboratory environment- Alpha prototype (component): Standalone prototyping implementation and testing in laboratory environment demonstrates the concept. Integration and testing of component technology elements are sufficient to validate feasibility.

5. **TRL-5**. Component and/or process validation in relevant environment- Beta prototype (component): Thorough prototype testing of the component/process in relevant environment to the end user is performed. Basic technology elements are integrated with reasonably realistic supporting elements based on available technologies. Prototyping implementations conform to the target environment and interfaces.

6. **TRL-6**. System/process model or prototype demonstration in a relevant environment- Beta prototype (system): Prototyping implementations are partially integrated with existing systems. Engineering feasibility fully demonstrated in actual or high fidelity system applications in an environment relevant to the end user.

7. **TRL-7**. System/process prototype demonstration in an operational environment- Integrated pilot (system): System prototyping demonstration in operational environment. System is at or near full

scale (pilot or engineering scale) of the operational system, with most functions available for demonstration and test. The system, component, or process is integrated with collateral and ancillary systems in a near production quality prototype.

8. **TRL-8**. Actual system/process completed and qualified through test and demonstration- Pre-commercial demonstration: End of system development. Full-scale system is fully integrated into operational environment with fully operational hardware and software systems. All functionality is tested in simulated and operational scenarios with demonstrated achievement of end-user specifications. Technology is ready to move from development to commercialization.