



## The Future of Carbon Capture, Utilization, and Storage (CCUS): Status, Issues, Needs

An RFF Workshop, hosted May 24, 2017 | Event Summary

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According to the Intergovernmental Panel on Climate Change, the overall costs to keep carbon dioxide (CO<sub>2</sub>) emissions low enough to limit future warming to the international goal of 2°C would be about 140 percent higher if cost-effective carbon capture and storage (CCS) technology is not available.<sup>1</sup>

The world has been storing large quantities of CO<sub>2</sub> underground for over 20 years in the North Sea and for over 40 years via enhanced oil recovery (EOR) in Texas and New Mexico. Twenty-seven large-scale CCS projects are in operation or under construction globally, with the United States having the most projects in number and volume. CCS technology is proven. Experience in operational projects, such as the Weyburn EOR project in Canada (in operation since 2000), have demonstrated the security of CO<sub>2</sub> storage underground. The United States and the world have many decades' worth of geological storage capacity for CO<sub>2</sub> in depleted oil reservoirs and other deep geological formations.

Although the technology is proven, implementing new projects requires detailed geologic storage characterizations. Significant reductions in capture costs are anticipated with the learning that comes from additional projects. Furthermore, government policy can provide direct incentives (e.g., through R&D spending to fuel further innovation and pilot testing of advanced capture technologies) or incentives through policy itself. Bills have been introduced in Congress that will provide effective financial support for more deployment (including tax credits, private activity bonds, and so on). Government support for development of CO<sub>2</sub> pipelines would also help facilitate carbon capture and bring CO<sub>2</sub> to oil fields where it can be used for EOR. Unless significant regulatory incentives to reduce CO<sub>2</sub> emissions are in place, government support will still be needed to help drive down costs, finance investment in CO<sub>2</sub> transportation infrastructure, and prove the capability of particular storage resources.

Converting captured CO<sub>2</sub> into long-lived marketable products is in its early stages, with the Department of Energy (DOE) supporting a number of research projects and new technologies. Successes here will reduce the amount of CO<sub>2</sub> that needs to be sequestered, but because most of the applications being studied will take years

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<sup>1</sup> The term “carbon capture utilization and storage,” or CCUS, is also used in cases where utilization of CO<sub>2</sub>, such as for enhanced oil recovery (EOR), can reduce the overall cost of capture and storage. See: Intergovernmental Panel on Climate Change. 2015. *Climate Change 2014 Synthesis Report Summary for Policy Makers*. [https://www.ipcc.ch/pdf/assessment-report/ar5/syr/AR5\\_SYR\\_FINAL\\_SPM.pdf](https://www.ipcc.ch/pdf/assessment-report/ar5/syr/AR5_SYR_FINAL_SPM.pdf).

to mature and markets are unlikely to be large enough to utilize all of the CO<sub>2</sub> being produced, progress is needed on CCS.

In short, as Dr. Julio Friedmann of Lawrence Livermore National Laboratory said at the workshop: (a) CCS is versatile and can be used for industrial emissions and power generation; (b) experience to date indicates that CCS can be affordable; (c) under the right circumstances, CCS can be profitable; (d) CCS can save communities with fossil fuel-fired power plants; (e) the United States has the potential to be the world's prime export source of CCS experience and technology; and (f) according to the International Energy Agency and others, the world needs CCS to achieve climate change goals in the least-cost fashion.

### **Session 1: Capturing CO<sub>2</sub>**

*Dr. Ed Rubin, Carnegie Mellon University; Lynn Brickett, National Energy Technology Laboratory*

There are many ways to separate and capture CO<sub>2</sub> from gases released during power plant or industrial processes such as ethanol production or steel manufacturing. They include absorption, adsorption, cryogenics, membranes, and microbial/algal systems. The three most common current approaches for power plants are post-combustion CO<sub>2</sub> capture, currently used at Sask Power's Boundary Dam power plant in Canada and NRG Energy's Petra Nova power plant in Texas; oxy-combustion CO<sub>2</sub> capture, demonstrated at large pilot plants such as Vattenfall's Schwarze Pumpe Station in Germany; and pre-combustion CO<sub>2</sub> capture, widely deployed commercially for capture in industry today and to be used at the Kemper Power Plant in Mississippi. While significant commercial experience with carbon capture exists in certain industrial sectors, too few facilities have been built and tested in the power sector to have resulted in enough learning-by-doing to bring costs down significantly. Thus, new plants using current CCS technology are estimated to incur increases in electricity generation costs varying from about \$20–\$50 per MWh (2013\$) for a natural gas combined cycle plant to \$30–\$70 per MWh for a supercritical pulverized coal plant, with the added cost for an integrated gasification combined cycle plant being midway between those values. In all cases, the cost of capture (including compression) accounts for the major portion (approximately 80 percent) of this cost, with the remainder due to transport and storage costs based on deep geological storage. The corresponding costs per metric ton of CO<sub>2</sub> emissions avoided for the three different technologies are estimated to range from approximately \$60–\$140 for natural gas combined cycle plants, \$50–\$100 for supercritical pulverized coal plants, and \$40–\$80 for integrated gasification combined cycle plants, relative to the same plant type without CCS. In all cases, the overall cost of CCS can be reduced significantly if the captured CO<sub>2</sub> is sold for use in EOR (with the magnitude of savings dependent on the prevailing oil price).

The participants at the RFF workshop expect that second-generation technologies will improve CCS economics, and could have 25–30 percent lower capital costs and 20–30 percent lower operating costs if current R&D goals are met. But these would not be ready for use at scale until 2025. Since capture accounts for most of total CCS cost, this is where substantial efforts are needed and are underway at DOE and elsewhere. Fortunately, there are many ideas in various stages of development that may reduce capture costs, such as using membranes, fuel cells, solid sorbents, biomass co-firing, ionic liquids, and advanced, more-efficient power plant designs. Hybrid approaches whereby two different capture technologies are used in sequence need to be evaluated, as they may be a cheaper approach to CO<sub>2</sub> capture. These expectations and developmental ideas indicate that strong policy drivers that create markets for CCS would help to spur innovations that significantly reduce the cost of capture.

### **Session 2: Transporting and Storing CO<sub>2</sub>; Enhanced Oil Recovery**

*Dr. Julio Friedmann, Lawrence Livermore National Laboratory; Daniel Kim, Occidental Petroleum*

The domestic geological potential for storing CO<sub>2</sub> both onshore and offshore is enormous, equaling 100 years of current emissions or more. The CO<sub>2</sub> can be stored in hydrocarbon or saline formations indefinitely—these

formations lie much deeper than the roughly 1,000-foot depth of potable water resources (commonly a mile deep or more). Saline formations have the ability to store carbon, as well as formations from which hydrocarbons have been or are currently being produced. The largest and longest offshore storage of CO<sub>2</sub> has been in saline storage in the Sleipner field off Norway for 20 years. The longest onshore EOR project has been the Scurry Area Canyon Reef Operators (SACROC) project in West Texas for over 40 years, and the largest onshore EOR project, with 7 million tons of CO<sub>2</sub> per year used in EOR or stored, is the Shute Creek operation in Wyoming.

We have a good understanding of mechanisms of pore-scale CO<sub>2</sub> displacements and other aspects of long-term storage, such as secondary trapping mechanisms, saline formations, site characterization, and geomechanical effects. These provide high confidence to assure safe storage indefinitely. Because each site is somewhat different, detailed evaluation of the relevant formations will be required in order to identify potential risks that will need to be managed, such as potentially transmissive faults or induced seismicity. Monitoring technologies are well understood from decades of use, and can help confirm the absence of leaks and assist in risk management.

Transportation of CO<sub>2</sub> via pipelines in the United States is not significantly different than transporting oil, gas, or natural gas liquids, all of which are currently regulated by the US Department of Transportation. Over 5,000 miles of CO<sub>2</sub> pipelines operate today in the United States that, over their 40-year history, have had an outstanding safety record with zero associated fatalities from CO<sub>2</sub> release. Pipeline pressures can be higher because the CO<sub>2</sub> is transported in a dense phase liquid state to sites where it is stored. Most CO<sub>2</sub> pipelines operate under a standard that requires low water content and low concentrations of hydrogen sulfide.

Currently, one type of CO<sub>2</sub> storage common in North America is CO<sub>2</sub>-EOR, a process that has been used for over 40 years, particularly in West Texas and New Mexico. The CO<sub>2</sub> is pumped down into existing mature oil fields to the oil bearing formation and then, often in conjunction with injected water, it mobilizes additional oil that would otherwise remain in the reservoir without EOR. Much of the injected CO<sub>2</sub> remains in the reservoir. The CO<sub>2</sub> that returns to the surface with the produced oil is recovered and reinjected, creating a closed-loop system that results in the safe and permanent geologic storage of the CO<sub>2</sub>. Currently about 65 million tons of CO<sub>2</sub> (mostly from natural sources, with the rest from industrial and power plants) are used annually for EOR in over 5,000 wells. Larger companies such as Occidental Petroleum and smaller ones such as Denbury Resources are active EOR operators. Companies can receive a tax credit for carbon captured and subsequently stored via CO<sub>2</sub>-EOR by opting into Subpart RR of the Environmental Protection Agency's (EPA's) Greenhouse Gas Reporting Program and implementing an EPA-approved monitoring, reporting, and verification (MRV) plan. Subpart RR requires the reporting of data on CO<sub>2</sub> injected, produced, emitted, and ultimately stored in the oil field via a mass balance approach to calculating CO<sub>2</sub> storage. The RFF workshop participants indicated that leakage of injected CO<sub>2</sub> (outside the reservoir) has not been observed in over 40 years of practice.

### **Session 3: Lessons Learned from Completed Projects**

*David Greeson, NRG Energy; John Gale, IEA Greenhouse Gas R&D Programme*

CCS technology is proven and in use around the world. Globally, 27 large-scale CCS projects are in operation or under construction (see Table 1 at the end of this document), 13 of which are in the United States. If this continues, the United States can be the world's resource for CCS technology and relevant suppliers of goods and services. The current global CO<sub>2</sub> capture capacity is about 40 million tons per year, which is a tiny fraction of the 36 billion tons per year of CO<sub>2</sub> emitted around the globe from fossil and industrial sources.

NRG Energy's Petra Nova project near Houston, Texas, was completed on time and on budget, capturing 90 percent of the CO<sub>2</sub> from a 240 MWe slipstream of flue gas from a 640 MW coal-fired power unit. The CO<sub>2</sub> is used

in an EOR project specifically designed for the amount of CO<sub>2</sub> being captured at the power plant (see Figure 1 at the end of this document). One challenge for retrofitting existing plants with CCS is the additional steam and electricity required for use by the CCS facilities. In the Petra Nova project, steam and electricity are provided by a highly efficient and built-for-purpose natural gas-powered cogeneration plant—effectively reducing the parasitic energy needed by over 30 percent versus extracting that energy from the host coal unit.

Significant progress has been made on CCS demonstration project deployment. Most of the projects required government financial support, although some involving industrial emissions did not. The early projects have identified cost reductions for next build plants. In this area, as with most new technologies, costs are reduced through R&D and learning from experience with multiple projects. To date, multiple business models have been utilized with no single one being applicable to all situations. Unless a significant regulatory limit on CO<sub>2</sub> emissions is enacted, government support will still be needed to help drive down costs, finance investment in CO<sub>2</sub> transportation infrastructure, and prove the capability of particular storage resources.

#### **Session 4: Other CO<sub>2</sub> Utilization Possibilities**

*Dr. Daniel Matuszak, US Department of Energy*

Captured CO<sub>2</sub> can be converted to other marketable products, which have varying sequestration possibilities. Some such products, like long-lived building products, can essentially sequester the CO<sub>2</sub> permanently, whereas others, like dry ice or carbonated beverages, do not. DOE has supported a range of technologies that convert CO<sub>2</sub> to chemicals and solid products, and some such technologies transitioned to commercial operation. (For example, Novomer's polyols business was spun out and acquired by Saudi Aramco Energy Ventures, which continues technology development and is planning construction of a plant to make CO<sub>2</sub>-based polyols. And Skyonic's Capital SkyMine is a first-of-a-kind, commercial-scale plant using flue gas from an adjacent coal-fired cement plant to make sodium bicarbonate [baking soda] and other products.) Recently, DOE is supporting early stage research to develop technologies that use biological or mineralization-based concepts or novel physical and chemical processes, which aim to generate economic value while having a lower carbon footprint relative to existing approaches. Recent projects selected by DOE include direct electron beam synthesis to create chemical products, using microalgae to convert CO<sub>2</sub> to bioplastics, and CO<sub>2</sub>-negative construction materials via industrial waste reprocessing and power plant heat integration. Unfortunately, although successes here will reduce the amount of CO<sub>2</sub> that needs to be sequestered, most processes will take years to mature and markets are unlikely to be large enough to utilize all the CO<sub>2</sub> being produced. Hence, sequestration in storage projects will also be necessary to meet climate goals.

#### **Session 5: Major US Policy Issues and Needs**

*Michael Moore, North American Carbon Capture Association; Brad Crabtree, Great Plains Institute*

Fossil fuels will be needed for the foreseeable future in transportation, power, building heating, and industry, both in the United States and abroad. However, as a result of the Paris Agreement and the pledge to decarbonize all fossil fuels by 2050, activities by many investment funds, as well as demonstrations and opposition from the "Keep it in the Ground" movement and others, there is increasing public pressure on users of fossil energy to reduce their use. Thus, CCUS/CCS matters significantly for the United States and other countries with significant fossil fuel resources by providing a way to decarbonize consumed fossil fuels while taking advantage of low-cost and abundant fossil fuels. A desirable path forward for the United States is to provide policy parity for low-carbon fuels, which include fossil energy complemented by CCS.

Environmental and energy policy NGOs, unions, project developers, industrial suppliers of CO<sub>2</sub>, technology vendors, ethanol producers, electric utilities, oil and gas producers, coal companies, and others are jointly urging and supporting federal financial support for CCS. They support legislation that increases the financial certainty for carbon capture project investors, increases the credit value for EOR and other geologic storage, expands

industrial participation in CCS, and enhances flexibility in utilization of the tax credit to allow multiple business models. Bills introduced in the 2015–2016 Congress, S 3179 and HR 4622, satisfied these principles, and both were sponsored by a significant bipartisan number of members. Each will be re-proposed in this Congress. In addition, bills to make CCS projects eligible for private activity bonds have been proposed on a bipartisan basis in both houses. Bipartisan-sponsored legislation was introduced in the past two Congresses to allow CCS facilities to qualify for the Master Limited Partnership structure, which is a limited partnership that is publicly traded. Some groups have also requested that the president include several identified carbon capture projects as part of any major infrastructure effort.

There is growing state support for CCS and CO<sub>2</sub>-EOR. There is also a CO<sub>2</sub>-EOR bipartisan work group, made up of 16 states, which is helping state policymakers better understand states' potential for CCS and recommending policies for states and the federal government. The group urged the Trump administration and Congress in February to make pipelines a priority component of a broader national infrastructure agenda.

*See following pages for table and figure mentioned above.*

**Table 1. Large Scale CCS Projects Around the World as Reported by the Global CCS Institute**

Project Name	Location	Operation Date	Industry	Capture Type	Capture Capacity (Mtpa)	Transport Type	Primary Storage Type	Stage
Terrell Natural Gas Processing Plant (formerly Val Verde Natural Gas Plants)	United States	1972	Natural gas processing	Pre-combustion capture (natural gas processing)	0.4–0.5	Pipeline	EOR	Operate
Enid Fertilizer CO <sub>2</sub> -EOR Project	United States	1982	Fertilizer production	Industrial separation	0.7	Pipeline	EOR	Operate
Shute Creek Gas Processing Facility	United States	1986	Natural gas processing	Pre-combustion capture (natural gas processing)	7	Pipeline	EOR	Operate
Sleipner CO <sub>2</sub> Storage Project	Norway	1996	Natural gas processing	Pre-combustion capture (natural gas processing)	1	No transport required (direct injection)	Dedicated geological storage	Operate
Great Plains Synfuels Plant and Weyburn-Midale Project	Canada	2000	Synthetic natural gas	Pre-combustion capture (gasification)	3	Pipeline	EOR	Operate
Core Energy/South Chester Gas Processing Plant	United States	2003	Natural gas processing	Pre-combustion capture (natural gas processing)	0.4	Pipeline	EOR	Operate
Snøhvit CO <sub>2</sub> Storage Project	Norway	2008	Natural gas processing	Pre-combustion capture (natural gas processing)	0.7	Pipeline	Dedicated geological storage	Operate
Chaparral/Conestoga Energy Partners' Arkalon Bioethanol Plant	United States	2009	Ethanol production	Dehydration and compression from fermentation	0.17	Pipeline	EOR	Operate
Century Plant	United States	2010	Natural gas processing	Pre-combustion capture (natural gas processing)	8.4	Pipeline	EOR	Operate
Conestoga Energy Partners/PetroSantander Bonanza Bioethanol Plant in Kansas	United States	2012	Ethanol production	Dehydration and compression from fermentation	0.1	Pipeline	EOR	Operate
Air Products Steam Methane Reformer EOR Project	United States	2013	Hydrogen production	Industrial separation	1	Pipeline	EOR	Operate

Coffeyville Gasification Plant	United States	2013	Fertilizer production	Industrial separation	1	Pipeline	EOR	Operate
Lost Cabin Gas Plant	United States	2013	Natural gas processing	Pre-combustion capture (natural gas processing)	0.9	Pipeline	EOR	Operate
Petrobras Santos Basin Pre-Salt Oil Field CCS Project	Brazil	2013	Natural gas processing	Pre-combustion capture (natural gas processing)	1	No transport required (direct injection)	EOR	Operate
Boundary Dam Carbon Capture and Storage Project	Canada	2014	Power generation	Post-combustion capture	1	Pipeline	EOR	Operate
Quest	Canada	2015	Hydrogen production	Industrial separation	1	Pipeline	Dedicated geological storage	Operate
Uthmaniyah CO <sub>2</sub> -EOR Demonstration Project	Saudi Arabia	2015	Natural gas processing	Pre-combustion capture (natural gas processing)	0.8	Pipeline	EOR	Operate
Abu Dhabi CCS Project (Phase 1 being Emirates Steel Industries [ESI] CCS Project)	United Arab Emirates	2016	Iron and steel production	Industrial separation	0.8	Pipeline	EOR	Operate
Illinois Industrial Carbon Capture and Storage Project	United States	2017	Chemical production	Industrial separation	1	Pipeline	Dedicated geological storage	Operate
Petra Nova Carbon Capture Project	United States	2017	Power generation	Post-combustion capture	1.4	Pipeline	EOR	Operate
Gorgon Carbon Dioxide Injection Project	Australia	2017	Natural gas processing	Pre-combustion capture (natural gas processing)	3.4–4.0	Pipeline	Dedicated geological storage	Execute
Kemper County Energy Facility	United States	2017	Power generation	Pre-combustion capture (gasification)	3	Pipeline	EOR	Execute
Alberta Carbon Trunk Line ("ACTL") with Agrum CO <sub>2</sub> Stream	Canada	2018	Fertilizer production	Industrial separation	0.3–0.6	Pipeline	EOR	Execute
Alberta Carbon Trunk Line ("ACTL") with North West Sturgeon Refinery CO <sub>2</sub> Stream	Canada	2018	Oil refining	Industrial separation	1.2–1.4	Pipeline	EOR	Execute



Yanchang Integrated Carbon Capture and Storage Demonstration Project	China	2018	Chemical production	Pre-combustion capture (gasification)	0.4	Combination	EOR	Execute
Tomakomai Carbon Capture and Storage Demonstration Project	Japan	2017	Hydrogen production (oil refining)	Industrial separation	0.1	No transport required direct injection	Dedicated geological storage	Operate
Osaki CoolGen Project	Japan	2019	Power generation	Pre-combustion capture (gasification)	1	No transport involved	Storage not involved	Execute

*Note:* Three US projects, Core Energy/South Chester, Chaparral/Conestoga Energy Partners, and Conestoga EnergyPartners/Petro Santander, were identified by Great Plains Institute and added at their suggestion.

**Figure 1. Carbon Capture System Site Layout**



*Note:* The Petra Nova Carbon Capture Site is a 50/50 joint venture of NRG Energy, Inc., and JX Nippon Oil & Gas Exploration.