

# The Elephant in the Room: Dealing with Carbon Emissions From Synthetic Transportation Fuels Production

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## ABSTRACT

There has been considerable interest in producing synthetic transportation fuels via coal-to-liquids (CTL) hydrocarbon conversion, particularly in countries where there is an abundant domestic coal resource. In the United States, there is currently a public policy debate over the use of coal to produce liquid transportation fuels to increase energy security and decrease dependence on imported petroleum and refined products. There are a number of challenges to be faced by a possible CTL industry, and one of the largest relates to the magnitude of carbon dioxide (CO<sub>2</sub>) generated, from synthetic fuel production as well as from the combustion of the synthetic transportation fuel itself.

CO<sub>2</sub>, produced by conversion of hydrocarbons to energy, primarily via fossil fuel combustion, is one of the most ubiquitous and significant greenhouse gases (GHGs). Concerns over climate change precipitated by rising atmospheric GHG concentrations have prompted many industrialized nations to begin adopting limits on emissions to inhibit increases in atmospheric CO<sub>2</sub> levels. The United Nations Framework Convention on Climate Change states as a key goal the stabilization of atmospheric GHGs at a level that prevents “dangerous anthropogenic interference” with the world’s climate systems. This will require sharply reducing CO<sub>2</sub> emissions across the globe, and ultimately a fundamental shift in the way in which energy is produced and consumed.

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This article provides an overview of the challenge posed by the magnitude of CO<sub>2</sub> that would be produced from a developing CTL industry. The status and costs associated with carbon dioxide capture and geologic storage (CCS) technologies are discussed as a means of helping to mitigate the CO<sub>2</sub> issue, along with remaining challenges that must be overcome for an emerging CTL industry to move toward maturity. However, even if CCS can be safely and successfully applied to CTL plants, CO<sub>2</sub> emissions will still likely be greater than conventional liquid transportation fuel production from conventional petroleum.

## INTRODUCTION

Currently, over 50 percent of electricity in the United States is generated from coal combustion, and the U.S. government has predicted that coal will meet a growing percentage of our future electricity needs ([www.eia.doe.gov/oiaf/ieo/coal.html](http://www.eia.doe.gov/oiaf/ieo/coal.html)). Concerns about energy security and current and future oil and natural gas prices have catalyzed interest in a wide range of alternative technologies for meeting growing demand for electricity and transportation fuels. Contributing factors include increasing demand for petroleum by growing economies like India and China, the possibility that world petroleum consumption has exceeded discovery of new conventional sources, [1] and increased imports of natural gas. Because coal is the most abundant fossil fuel in the United States, providing approximately 95 percent of total U.S. domestic fossil energy reserves\*, much of the attention in this country is focused on alternative technologies that employ coal as a feedstock.

There are a number of environmental concerns regarding coal use, including those associated with the impact of mining operations, process water requirements, and air emissions from both the combustion and chemical conversion of coal. One of the most pressing environmental issues centers on the production of CO<sub>2</sub> via coal combustion or conversion, and its contribution to climate change.

Atmospheric concentrations of CO<sub>2</sub> have risen sharply since the start of the industrial revolution. Today, the United States produces about 5.8 billion metric tons of CO<sub>2</sub>/year, or about 24 percent of global

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\*By heat content, <http://www.eia.doe.gov/oiaf/ieo/coal.html>

carbon dioxide emissions.\* China, a country heavily reliant on coal for energy production, may soon surpass the United States as the leader in worldwide CO<sub>2</sub> emissions, given the anticipated growth in coal-fired power generation required to meet the growing energy demand of China's booming economy.

The 1992 United Nations Framework Convention on Climate Change, ratified thus far by 191 nations including the United States,† states as its overarching goal the "stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system." While there is general agreement that stabilization of greenhouse gas concentrations is the best way to frame decisions about addressing climate change, there is no scientific consensus yet regarding what an appropriate target concentration should be or the potential impacts associated with higher concentrations.

The Intergovernmental Panel on Climate Change's (IPCC's) fourth report (published in 2007) on the state of the science on climate (<http://ipcc-wg1.ucar.edu/wg1/wg1-report.html>) concludes that North America, along with the rest of the world, is already seeing the effects of climate change today. The summary highlights 75 long-term studies documenting significant biological and physical changes in nature. Among these changes are melting glaciers, permafrost warming, birds nesting earlier in the year, fish migration changes, earlier melting of snow packs, modified river flows, and many more changes in natural events.[2]

For these reasons, and to augment other advanced energy technology research, the United States and other countries have launched research, development, demonstration, and deployment of technologies to capture CO<sub>2</sub> from use of coal and store (or sequester) that CO<sub>2</sub> to prevent it from being released into the atmosphere.

## CARBON DIOXIDE FROM CTL PLANTS

In a typical CTL plant, coal is fed into a gasifier where it is broken down into its chemical constituents as a gas stream. This gas stream is further processed to produce synthesis gas ("syngas"), which is fed

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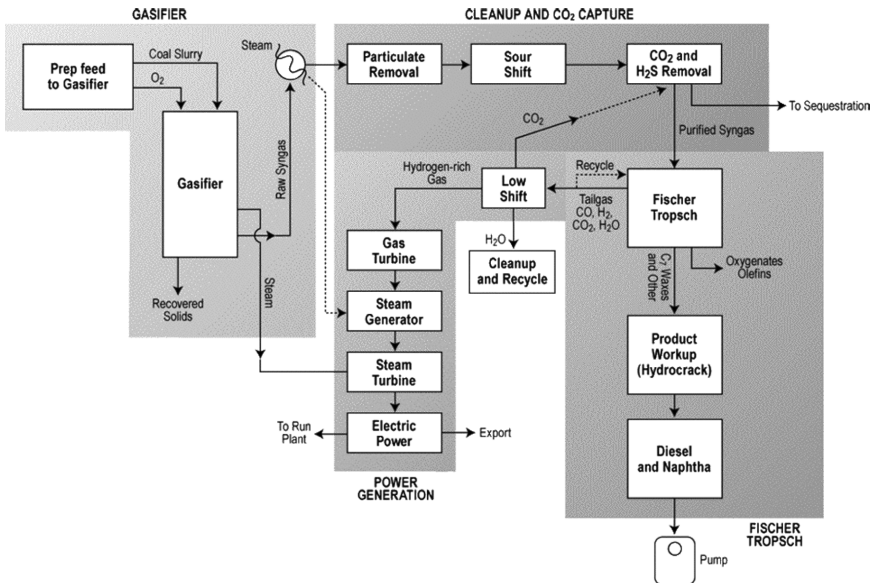
\*<http://www.eia.doe.gov/oiaf/aeo/emission.html>

†United Nations Framework Convention on Climate Change. List of Signatories & Ratification of the Convention Parties <http://unfccc.int/resource/conv/ratlist.pdf>

into a Fischer-Tropsch (FT) catalytic reactor to produce liquid fuels (see Figure 1).

The raw syngas stream from the gasifier must be treated to separate CO<sub>2</sub> from the syngas to prevent CO<sub>2</sub> and other constituents in the syngas stream from contaminating the catalyst used in the FT reactor downstream. The raw syngas stream in a CTL plant is made up of water, light hydrocarbons (primarily methane), hydrogen, carbon monoxide (CO), CO<sub>2</sub>, sulfur (as sulfur dioxide and hydrogen sulfide), nitrogen, volatile organic compounds, and heavy metals (primarily mercury). The syngas can be treated using commercial technology\* to capture 95 to 98 percent of the CO<sub>2</sub> contained in the syngas stream. The CO<sub>2</sub>, along with the sulfur, organic compounds, and heavy metals, is thus separated prior to the production of liquid fuels in the FT reactor.

A typical representation of the pathway and fate of the carbon contained in the coal feedstock of a plant producing synfuels using FT technology is shown in Figure 2. In this scenario, approximately 54 percent of the carbon in the coal feed is separated as CO<sub>2</sub> from the



**Figure 1. Functional block diagram of a typical CTL plant.**

\*These processes include Selexol® ([www.uop.com](http://www.uop.com)) and Rectisol® ([www.linde-anlagenbau.de](http://www.linde-anlagenbau.de))

syngas stream and is in a form that would be amenable for sequestration. The CO<sub>2</sub> in the syngas stream is relatively highly concentrated, and the separated CO<sub>2</sub> is very high-purity, and should CO<sub>2</sub> sequestration be desired, it would require very little post-separation processing other than compression to 2,000 to 2,500 psi for pipeline transport.\*

Another 34 percent of the feedstock carbon exits the FT process contained in the liquid transportation fuel products and will be released as CO<sub>2</sub> when the fuels are combusted by the end user. The balance of the input carbon (12 percent) is released to the atmosphere as the FT tail gas product is combusted in power generating turbines and process heaters. These emissions streams contain very dilute concentrations of CO<sub>2</sub>—and at a much lower pressure than the CO<sub>2</sub> in the syngas stream. Capture of CO<sub>2</sub> from these dilute streams is very costly and complex, and thus is generally not included into the design of a CTL plant.

The challenge associated with coal-derived liquid transportation fuel from a climate perspective is that coal is carbon-rich and hydrogen-poor and thus a significant quantity of CO<sub>2</sub> is produced when coal is combusted or gasified in an oxygen-rich environment.† Since CO<sub>2</sub> is the principal heat-trapping gas responsible for climate change, the increased use of coal-derived liquid fuels for transportation seems inconsistent with the need to employ technologies that lessen our carbon consumption and related emissions.‡

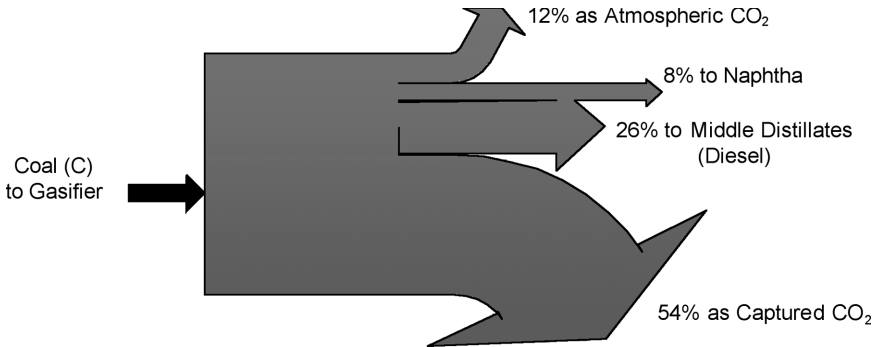
To assess the climate change implications of coal-derived liquid fuels, the total life-cycle (or “mine-to-wheels”) emissions of these new fuels should be examined and compared to conventional transportation fuels, primarily petroleum. There have been several carbon mine-to-wheels analyses undertaken for coal-derived liquid fuels. These studies

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\*This is a key difference between the CTL process and coal-fed power plants using integrated gasification combined cycle (IGCC) for coal conversion. Current IGCC power plant designs do not require the separation of CO<sub>2</sub> from the syngas prior to the combustion turbine, given that CO<sub>2</sub> is not detrimental to downstream process (unlike the FT process for a CTL plant) and CO<sub>2</sub> is currently not a regulated pollutant. Thus, the separation of this primary CO<sub>2</sub> stream is already included in a typical base CTL plant, resulting in a much lower marginal cost of capture and compression compared to an IGCC plant.

†Coal contains a higher ratio of carbon to hydrogen than other hydrocarbons. For example, coal contains double the amount of carbon per unit of energy compared to natural gas, and about 20 percent more than petroleum. The precise ratio of carbon to hydrogen in coal depends on the type of coal, but the differences are small compared to those exhibited between coal and other fuels.

‡The transportation sector is responsible for approximately one-third of our nation’s global warming pollution ([www.eia.doe.gov/oiaf/1605/ggrrpt/carbon.html](http://www.eia.doe.gov/oiaf/1605/ggrrpt/carbon.html)).



**Figure 2. Fate of carbon contained in coal fed to a CTL plant.**

have produced slightly different numbers, but can be generalized as follows:\*

- Absent carbon capture and sequestration from a CTL plant (as is the case for the Sasol plants), use of liquid transportation fuel derived from coal will roughly double GHG emissions compared to conventional petroleum on a life-cycle basis. For example, without carbon capture at the plant, FT liquid fuels would produce approximately 50 pounds of CO<sub>2</sub> per gallon of gasoline equivalent, whereas conventional gasoline production from petroleum results in approximately 25 pounds of CO<sub>2</sub> per gallon of gasoline equivalent. [4]
- With capture and storage of most (85 to 90 percent) of the CO<sub>2</sub> produced at the CTL plant, GHG emissions will be closer to those produced from conventional petroleum-based transportation fuel, but still measurably higher.

\*A preliminary EPA analysis ([www.epa.gov/otaq/renewablefuels/420f07035.htm](http://www.epa.gov/otaq/renewablefuels/420f07035.htm)) concluded that the mine-to-wheels GHG emissions of liquid coal, if there were no carbon controls at the plant, is 119 percent more than the equivalent well-to-wheels emissions of conventional petroleum, dropping to 4 percent more if there are carbon controls at the plant. An Argonne National Laboratory study performed a life-cycle analysis for both diesel fuel and gasoline, finding that for diesel, greenhouse gas emissions for liquid coal were 125 percent and 20 percent more than conventional diesel fuel, depending on the existence of plant carbon controls, and for gasoline, greenhouse gas emissions were 66 percent more and 11 percent less than conventional gasoline, again depending on control of carbon at the plant. [3]

From these comparisons, two basic conclusions emerge. First, producing a liquid transportation fuel from coal without CCS would contribute significantly more CO<sub>2</sub> to the atmosphere than transportation fuel from petroleum. Second, even with CCS, using coal to produce liquid transportation fuel would not be compatible with the need to develop a low CO<sub>2</sub>-emitting transportation sector fuel unless technologies are developed to significantly reduce emissions from the overall process (mine-to-wheels). Since coal-based liquid transportation fuels contain the same amount of carbon as an equivalent volume of gasoline or diesel made from crude, the potential for achieving large CO<sub>2</sub> emission reductions compared to conventional petroleum is limited and makes the goal of achieving overall GHG emissions reduction from transportation fuels a significant challenge.

There are strategies being investigated to mitigate the mine-to-wheels CO<sub>2</sub> that include co-gasification of biomass material with coal to take advantage of the relatively lower carbon-containing biomass and its photosynthetic (as a crop) capture of CO<sub>2</sub>. Though in theory this strategy holds promise, there are a number of engineering and policy issues that remain to be resolved for it to be proven viable at sufficient scale. A more detailed discussion of this concept can be found in references [4] and [5].

## MANAGING THE CARBON: CARBON DIOXIDE CAPTURE AND STORAGE

The large quantity of CO<sub>2</sub> resulting from synfuels production poses a significant challenge to the potential development of a coal-based liquid transport fuel industry. Because the atmospheric concentration of CO<sub>2</sub> depends on cumulative (not annual) global emissions, [6] stabilization will require global CO<sub>2</sub> emissions to be drastically reduced. This will require developing and implementing fundamentally new and cleaner ways of generating and using the energy that drives the economies of the United States and every other nation of the world. Eventually, net additions of greenhouse gases to the atmosphere would not be consistent with the long-term goal of stabilization. Therefore, for a synfuel industry to develop and grow in a way that is consistent with climate change mitigation goals, it will need to appropriately manage its large potential CO<sub>2</sub> emissions, or find other means of offsetting them.

Total production-related emissions from a CTL industry of a relatively modest two-million barrels per day would exceed 650 million tons of CO<sub>2</sub> per year.\* This represents 25 percent of total current emissions from the entire U.S. electric power sector before including the tailpipe emissions.† Left unmanaged, a U.S. CTL industry could quickly grow into a major source of CO<sub>2</sub> with a contribution that would make it even more challenging for the nation to meet climate change mitigation goals.

The processes that govern the global carbon cycle are complex, involving interactions between the atmosphere, oceans, soils, and biota. Terrestrial and marine environments are home to significant natural sinks, and research is ongoing to find ways of enhancing CO<sub>2</sub> uptake in these systems. For example, it may be possible to improve uptake of CO<sub>2</sub> by biomass and soils via terrestrial sequestration methods, including modified agricultural practices and reforestation/afforestation. While these strategies will be important to the overall goal of stabilizing CO<sub>2</sub> concentrations (particularly from more diffuse sources), to reduce the large quantities of CO<sub>2</sub> from industrial point sources like synfuels plants, CO<sub>2</sub> capture and geologic storage may offer a more suitable strategy.

Carbon dioxide capture and storage involves a variety of integrated processes that focus on the separation of CO<sub>2</sub> at power stations, CTL plants, or other large industrial emissions sources, and injection into geologic formations that are suitable for long-term storage of the captured CO<sub>2</sub>. In most cases, CO<sub>2</sub> would be injected as a supercritical fluid into the permeable and porous layers of formations at depths greater than 800 meters (0.5 miles) below the surface.‡ This depth and the properties of selected storage formations would help ensure that the CO<sub>2</sub> remains safely isolated away from the atmosphere as well as from groundwater aquifers that supply drinking and irrigation water. An effective system of structural or stratigraphic traps above the storage zone is also critical to prevent upward migration of the injected

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\*The United States consumes about 40 million barrels of transportation fuels per day, and thus two million barrels/day CTL fuel would represent approximately 5 percent of the current domestic transportation fuel consumption.

†[[www.eia.doe.gov/oiaf/aec/emission.html](http://www.eia.doe.gov/oiaf/aec/emission.html) and [www.eia.doe.gov/oiaf/1605/ggrpt/carbon.html](http://www.eia.doe.gov/oiaf/1605/ggrpt/carbon.html)].

‡Because the trapping mechanisms are different in coal-based CO<sub>2</sub> storage projects, CO<sub>2</sub> is not necessarily injected as a supercritical fluid, which means that the depth criteria do not necessarily apply for coal-based CCS projects.



CO<sub>2</sub> and provides the principal means of trapping the CO<sub>2</sub> in the deep subsurface over the long term.

The primary geologic targets being evaluated for long-term storage of CO<sub>2</sub>, as shown in Figure 3, include deep saline water-filled sedimentary formations, depleted oil and gas reservoirs, and unmineable coal seams. Other candidate formations being investigated include salt caverns, basalt formations, and organic shales. While these main types of deep geologic formations vary in terms of costs, available capacity, and potential risks, they are all potentially feasible options for storing CO<sub>2</sub> in the coming decades.\*

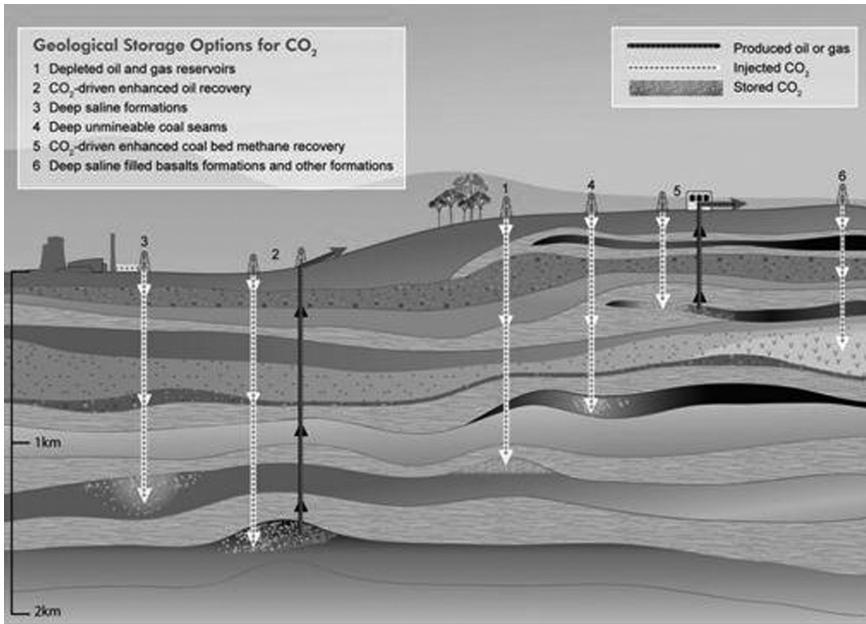
The potential cumulative onshore CO<sub>2</sub> storage capacity in the United States has been estimated at over 3,000 gigatons of CO<sub>2</sub>. [7] If a significant portion of this can be accessed for storage, it would offer enough capacity to store emissions from the nation's large industrial sources for hundreds of years. As seen in Figure 4, this storage potential is distributed throughout most of the country and across a variety of formation types. Deep saline formations are both the most widespread and the most capacious, representing well over 90 percent of the total potential capacity. Other types of reservoirs, such as depleted oil and gas fields and unmineable coals, represent a much smaller, though still sizeable and valuable, portion of the total.

Although offering a smaller overall capacity, depleted oil and natural gas reservoirs can offer an attractive storage option in those regions in which they are located. One main reason is that they have proven to be effective traps for oil and natural gas over the very long time frames that are desirable for CO<sub>2</sub> storage. A key potential benefit of storing CO<sub>2</sub> within oil fields is that it may not only reduce emissions, but that it may help recover a valuable product in the process. The injection of CO<sub>2</sub> into depleting oil fields has been practiced within the United States for over 35 years. CO<sub>2</sub>-flood enhanced oil recovery (EOR) utilizes the ability of the CO<sub>2</sub> to not only repressurize the field, but also to reduce the viscosity of the oil so that it flows more readily to the producing well.

In coal seams, injected CO<sub>2</sub> is preferentially adsorbed onto the surface of the coal matrix, releasing methane in the process. As a result, CO<sub>2</sub> storage in coals has been shown to result in enhanced coal bed

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\*See, for example, Chapter 5 of the recently released IPCC Special Report on Carbon Dioxide Capture and Storage [http://arch.rivm.nl/env/int/ipcc/pages\\_media/SRCCS-final/IPCCSpecialReportonCarbondioxideCaptureandStorage.htm](http://arch.rivm.nl/env/int/ipcc/pages_media/SRCCS-final/IPCCSpecialReportonCarbondioxideCaptureandStorage.htm).



**Figure 3. Overview of a major candidate CO<sub>2</sub> storage formation (courtesy Australian CO<sub>2</sub>CRC)**

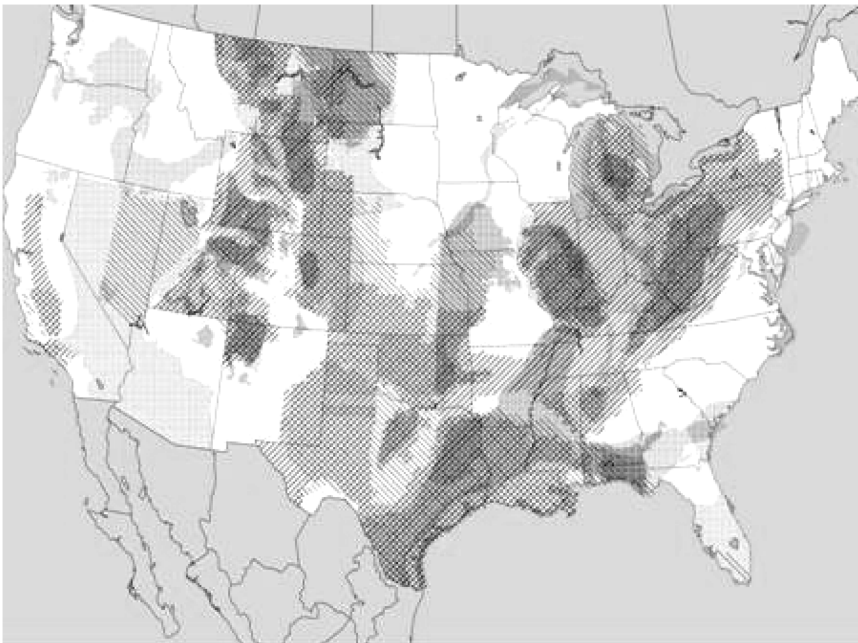
methane recovery (ECBM). Like EOR, ECBM offers some potential for reducing the cost of CCS by recovering additional hydrocarbons in the process. However, a number of challenges remain and ECBM is not yet a commercially viable technology.

## CURRENT STATUS OF CCS STRATEGIES

Because CO<sub>2</sub> injection is already a commercial practice used to help increase oil production (i.e., EOR), there is a significant knowledge base regarding how to handle CO<sub>2</sub> and inject it into deep geologic structures. In fact, many component technologies for CCS systems already exist, including CO<sub>2</sub> capture, transportation via pipeline, and deep underground injection. First-generation CO<sub>2</sub> capture systems are available, and a few are currently in operation at coal- and natural gas-fired power plants to supply niche commercial CO<sub>2</sub> markets. There are also a number of natural gas processing and other industrial facilities that routinely separate and sell CO<sub>2</sub> for various industrial uses, including

EOR. A wide variety of emerging concepts have also been proposed for separating CO<sub>2</sub> from various dilute process streams, to facilitate widespread deployment of CCS systems.

The transport of large volumes of CO<sub>2</sub> via pipeline is already a well-established practice within segments of the oil and gas industry. At present, there are over 3,000 miles of dedicated CO<sub>2</sub> pipelines in North America, delivering CO<sub>2</sub> to commercial EOR projects in areas such as the Permian Basin of West Texas and southeastern New Mexico; the Rocky Mountain region of Utah, Wyoming, and Colorado; and the Weyburn Field in Saskatchewan that receives CO<sub>2</sub> from the Dakota Gasification Company Great Plains Synfuels Plant in Beulah, North Dakota (see Figure 5). The 30-inch-diameter Cortez pipeline originating near the Four Corners region of the country is the longest of these pipelines, transporting CO<sub>2</sub> 500 miles from the naturally occurring CO<sub>2</sub> deposits of McElmo Dome to the Denver City Hub in the Permian Basin.\*



**Figure 4. Map of candidate CO<sub>2</sub> storage formations in the United States [7]**

\*The Cortez pipeline has a carrying capacity between 1 and 4 billion cubic feet/day of CO<sub>2</sub>. ([http://www.enhancedoilrecovery.info/CO2\\_Pipelines\\_of\\_the\\_PB.html](http://www.enhancedoilrecovery.info/CO2_Pipelines_of_the_PB.html)).

While it is true that many component technologies for CCS exist and are commercially available, and that there are decades of experience in injecting CO<sub>2</sub> for EOR, the world's experience with full end-to-end CCS systems is very limited compared to the scale that may be necessary for significant and sustained CO<sub>2</sub> emissions reductions. In fact, many consider there to be only a very limited number of complete, commercial end-to-end CCS systems operating in the world today. These are the Sleipner project in the Norwegian North Sea, the Weyburn Enhanced Oil Recovery Project in Saskatchewan (see Figure 5), and the In Salah Project in Algeria.

Each of these projects injects approximately one million tons of CO<sub>2</sub> per year and is expected to inject roughly 20 million tons over its lifetime. All three also use CO<sub>2</sub> taken from high-purity sources (i.e., those with low capture cost) such as natural gas processing or coal gasification facilities, and while useful as early CCS projects, are not fully representative of the nature and scale of deployment that may be on the horizon should binding climate policies and regulations be enacted.

A number of research-scale projects are also underway or being planned around the world in an effort to learn more about the potential large-scale application of CCS in many different geologic settings. For example, the U.S. Department of Energy's Regional Carbon Sequestration Partnership Program is studying CO<sub>2</sub> storage potential across seven different regions of the United States and Canada, and is in the process of initiating a number of small-scale injection projects.\* In addition, the FutureGen Alliance is planning to demonstrate the storage of CO<sub>2</sub> captured from a near-zero emissions power plant.† None of these projects, however, will operate at a scale that would be needed by a very large coal-fired power plant or CTL facility.

Aside from the previously noted Weyburn EOR project in Saskatchewan, the roughly 80 other ongoing EOR projects that are injecting CO<sub>2</sub> to stimulate tertiary oil recovery are not generally considered CCS projects for a number of reasons. First, the majority of these ongoing projects are injecting CO<sub>2</sub> produced from natural underground accumulations rather than CO<sub>2</sub> from anthropogenic sources that would otherwise be released into the atmosphere. Some projects, however, do purchase and inject anthropogenic CO<sub>2</sub> from natural gas plants, which

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\*[www.fe.doe.gov/programs/sequestration/partnerships/](http://www.fe.doe.gov/programs/sequestration/partnerships/)

†[www.futuregenalliance.org](http://www.futuregenalliance.org)

must strip out the  $\text{CO}_2$  to make it saleable, as well as from fertilizer plants that produce a concentrated stream of  $\text{CO}_2$ . Even so, operations within the industry to date as a whole are not managed for the purpose of keeping the injected  $\text{CO}_2$  within the field, but rather for the purpose of maximizing oil recovery. In fact, due to the value associated with the purchased  $\text{CO}_2$ , it is common practice to “blow down” the reservoir at project completion to recover the injected  $\text{CO}_2$  for use elsewhere.

Ensuring the long-term retention of  $\text{CO}_2$  within the reservoir, a process necessary for proving that a given project’s  $\text{CO}_2$  injection meets climate change mitigation purposes, does not necessarily conflict with achieving efficient oil recovery, but changes in the EOR management approach would be needed, along with installation of measurement, monitoring, and verification (MMV) systems and protocols to assess the long-term reliability of storage and potential loss of  $\text{CO}_2$  during its handling, injection, and recycling. The fate of the  $\text{CO}_2$  is being closely monitored at Weyburn by a broad international scientific consortium, resulting in its more common acceptance as a CCS project. Thus, although we have considerable experience in CCS, the scale is relatively small compared to the scale required for CCS for the U.S. electric power industry or a mature CTL industry. Therefore, there remains considerable research and development required to prepare for future large-scale CCS.



**Figure 5. Carbon dioxide sources and pipelines serving enhanced oil recovery projects in the United States.**

## CCS COSTS

The primary cost components for a CCS system include CO<sub>2</sub> capture from the source stream, compression of the concentrated CO<sub>2</sub> to pipeline pressures, transport by pipeline, and the injection and monitoring of the stored CO<sub>2</sub> via an injection field. Estimates within the literature for the cost of capture from a dilute CO<sub>2</sub> stream, such as from a conventional fossil-fired power plant, run as high as \$60 per ton of CO<sub>2</sub>. Higher pressure process gas streams and those with a higher CO<sub>2</sub> concentration will be less expensive to separate.

The levelized cost of dehydrating and compressing the CO<sub>2</sub> depends on the characteristics and pressure of the CO<sub>2</sub> as well as the flow rate. However, this generally ranges between about \$6/ton CO<sub>2</sub> for larger CO<sub>2</sub> streams and \$10/ton for smaller streams. Pipeline costs depend predominantly on the mass flow rate of CO<sub>2</sub> and the distance and terrain between the source and storage reservoir. Storage costs include all of the costs associated with the injection field, such as injection and monitoring wells, field distribution pipeline, and MMV systems. Actual costs will vary significantly depending on a number of factors such as formation type, depth, and number of injection wells needed for the CO<sub>2</sub> stream, which is driven largely by formation porosity, thickness, and injectivity. [8]

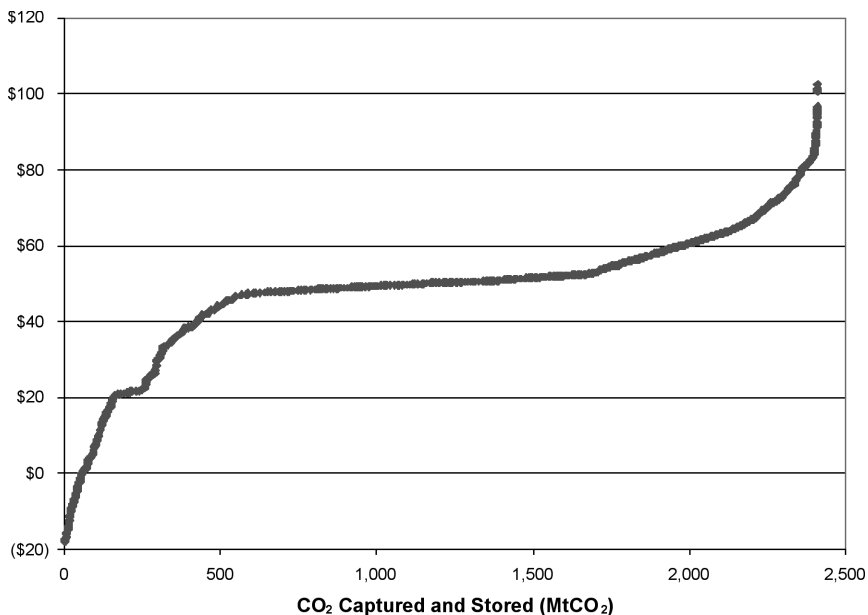
Figure 6 shows a CCS cost curve for the United States, showing the volume of stored CO<sub>2</sub> compared to the cost for the annual emissions of existing sources. [7] This highlights the range in system costs that may be expected for the existing large CO<sub>2</sub> point sources and their nearby candidate storage reservoirs. From previous analyses, the range in potential transport and storage costs can be large and the vast majority of geologic CO<sub>2</sub> storage capacity in the United States should be available at or below \$12 to \$15/ton of CO<sub>2</sub>. [9] CO<sub>2</sub> capture costs have been added in to the following curve and also account for the costs of long-term measurement, monitoring, and verification, which are expected to be well below \$1 per ton of injected CO<sub>2</sub>.

As noted, for a CTL plant producing liquid transportation fuels, there will be two primary streams of CO<sub>2</sub>: a large, high-purity CO<sub>2</sub> stream resulting from syngas cleanup, and a smaller dilute CO<sub>2</sub> stream from the power generation block's exhaust and process heaters. The marginal cost of capturing the large, high-purity stream will be very low, as this is a necessary step in the process. This is one potential

advantage for a CTL plant—its emissions may be very large, but at least the bulk of them are in a concentrated form that can be handled rather inexpensively. The dilute CO<sub>2</sub> streams, however, would be very expensive to capture and likely would not be treated for CO<sub>2</sub> capture in the absence of a strong incentive to prevent atmospheric release. In this case, options other than CCS for offsetting the CO<sub>2</sub> emissions, such as purchasing offsets from another entity or investing in terrestrial sequestration projects, would likely be most cost-effective.

Beyond capture, an additional capital and operating cost is necessary for the CO<sub>2</sub> to be prepared for pipeline transport (at 2,000 to 2,500 psia) to a suitable injection site. For a 20,000-bbl/day plant using bituminous coal, the capital cost for a compressor to bring the CO<sub>2</sub> to pipeline quality is roughly \$100,000, representing only a small fraction of the syngas cleanup equipment cost. The power required to compress CO<sub>2</sub> to pipeline specifications is 50 to 70 MW, equating to an annual compressor operating cost of about \$26 to \$31 million per year [10], or approximately \$6 to \$7 per ton of CO<sub>2</sub> captured.

While the majority of CO<sub>2</sub> storage capacity is likely to be accessible



**Figure 6. CCS cost curve for the United States, current sources and technology.**

for costs in the range of about \$5 to \$15 per ton, there is a significant quantity that can likely be accessed for less than \$0 per ton (negative cost). In such instances, costs can be offset by revenue from the resulting oil or gas sales from EOR or ECBM operations. Field operators may pay to obtain the high-purity CO<sub>2</sub>, as is common practice today for the operating CO<sub>2</sub>-EOR projects. One report concluded that, aside from a myriad of institutional constraints that will need to be overcome by public policies, one of the major impediments to full exploitation of the large CO<sub>2</sub>-driven EOR potential has been the inadequate supplies of low-cost CO<sub>2</sub>. [11] This is a constraint that could be surmounted by exploiting the low CO<sub>2</sub> capture cost at CTL plants. In Texas alone, the potential for additional EOR using CO<sub>2</sub> is estimated at 5.7 billion barrels of oil, requiring roughly 650-million tons of additional CO<sub>2</sub>. [12] This represents approximately 1.5 years of CO<sub>2</sub> captured from CTL plants producing 2 million barrels of synthetic transportation fuels per day.

However, given that a typical CO<sub>2</sub>-EOR project will inject CO<sub>2</sub> at a rate engineered to maximize oil recovery, which often involves alternating injection cycles over its 15- to 30-year life, it is unlikely that there will be sufficient EOR demand for more than a fraction of the industry's CO<sub>2</sub> at any given time. Though significant quantities of low and even potentially negative cost opportunities may exist in select regions across the country, not all plants will be able to count on taking advantage of them and most should not plan on doing so over the long term. Further, unlike some other candidate CO<sub>2</sub> storage options, the timing of CO<sub>2</sub> storage resource availability within oil and gas fields is an important factor to be considered. Analyses have shown that while storage in depleting oil and gas pools offers a generally attractive option, should significant emissions reductions be required, all types of storage formations available within a region, and particularly deep saline formations, will be important. [13] This is particularly true as more and more large industrial CO<sub>2</sub> sources start looking to CCS to manage their emissions.

## CHALLENGES AHEAD FOR CCS DEPLOYMENT

As discussed, the majority of CO<sub>2</sub> produced by the CTL process is in a form that will be relatively inexpensive and easy to capture. However, that alone does not mean that applying CCS within the industry



will not face significant challenges. Carbon dioxide capture and storage from electric power generation and chemical process plants is a developing technology, and as such, there are a number of challenges to be addressed on the path towards readying CCS technologies for successful large-scale deployment. While many of the components needed for CCS exist, there remains a significant void in the technical, operational, and regulatory experience base for integrated CCS systems at the scale needed for a mature CTL industry.

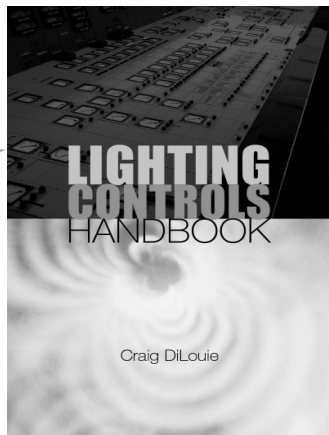
Formation characterization and injection system construction standards are likely to be needed, but currently there is no widely recognized set of such standards for CCS. At a properly designed and well-managed CCS facility, the chance of appreciable CO<sub>2</sub> leakage from the deep geologic storage formation will be very small. The principal MMV requirement for the injected CO<sub>2</sub> centers on the demonstration of long-term retention of the CO<sub>2</sub> to both regulators and the public. New and improved MMV techniques and standards need to be developed to provide proof of public and environmental safety and to ensure that each CCS project is effective as a means of mitigating climate change.

Consideration of long-term environmental, health, and safety liability is a key element in assessing the viability of CCS. The way in which liability is addressed may have a direct impact on costs and an indirect impact on public perceptions of geologic storage. This may involve a permitting process for storage that ensures proper characterization of storage integrity and capacity, and protection of groundwater and other resources. A framework must be developed for CCS systems before they begin to deploy widely. Potential issues related to mineral and property rights will also need to be vetted as part of the regulatory process. As an example, the state of Texas has proposed such a framework that could serve as a model for other states or regions. [14]

Another obstacle for the CTL industry's deployment of CCS may be the vital need for geologic storage capacity by the electric power sector in a GHG-constrained world. The potential CO<sub>2</sub> output from a CTL industry of this size could offer significant competition for the available storage resource, particularly within certain regions. [15] Plant siting and evaluation of geologic storage options will therefore be especially critical to the development of carbon management plans for a developing CTL industry.

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## SUMMARY AND CONCLUSIONS

Two conclusions emerge for the large-scale production of synthetic transportation fuels from coal. First, producing a liquid fuel from coal without 85 to 90 percent capture of CO<sub>2</sub> from the plant and subsequent storage would contribute significantly more CO<sub>2</sub> to the atmosphere than fuel produced from conventional petroleum. Second, even with CCS, using coal to produce liquid transportation fuel would not be compatible with the need to develop a low CO<sub>2</sub>-emitting transportation-sector fuel unless technologies are developed and deployed to significantly reduce emissions from the overall mine-to-wheels life cycle.

There appears to be a potential pathway to capture, transport, and sequester CO<sub>2</sub>. The process for capturing the bulk of CO<sub>2</sub> from a high-purity syngas stream is straightforward, but needs to be demonstrated at full scale in the United States. And cost-effective technology for capture of CO<sub>2</sub> from dilute gas streams needs to be developed. Nevertheless, there are a number of challenges to be addressed before demonstrating CCS as a fully compatible technology for a growing synfuels industry.

Research to date indicates that there is likely adequate overall CO<sub>2</sub> storage capacity within the United States to accommodate the potential demand for CO<sub>2</sub> storage from a mature CTL industry. However, the number of CTL plants and the resulting potential quantities of pipeline-quality CO<sub>2</sub> needing to be injected into deep geologic formations could stress the supply of geologic CO<sub>2</sub> storage within certain regions. This could potentially result in heightened competition for the available CO<sub>2</sub> storage space in these regions between these yet-to-be constructed CTL plants and the owners and operators of existing or planned electricity power production facilities who would plan to use some of these same deep geologic formations for their own future CCS projects.

Under certain circumstances, use of CO<sub>2</sub> for EOR may offer a cost savings or even a profit to the operator of select CTL plants. However, there remain a number of challenges and such opportunities are unlikely to be widespread or long-lived given the potential mismatch between industry CO<sub>2</sub> production and the nature of the demand for CO<sub>2</sub>. Therefore, it will be important to examine all available storage options.

While progress with CCS technologies is being made, there is a lack of a comprehensive technical knowledge and operational experience surrounding the application of CCS systems at the scale likely to be

required for a potential CTL industry. The next decade constitutes a critical window in which to amass needed operational experience with CCS technologies in real-world conditions. Field demonstrations, additional early commercial CCS projects, continued research, demonstration, and a sound public policy framework for establishing CO<sub>2</sub> regulations are all needed to augment existing industry experience. This approach is critical to ensure that CCS technologies can deploy safely and effectively with emerging CTL plants, as well as existing power plants and other industrial facilities, to meet the challenge of stabilizing concentrations of CO<sub>2</sub> in the atmosphere.

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