GLOBAL TECHNOLOGY ROADMAP FOR CCS IN INDUSTRY

Sectoral Assessment

CO_2 Enhanced Oil Recovery

Prepared by:
Advanced Resources International, Inc.
4501 Fairfax Drive, Suite 910
Arlington, VA 22203 USA

Principal Investigator:
Michael L. Godec

Prepared for:
United Nations Industrial Development Organization

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EXECUTIVE SUMMARY FOR POLICY MAKERS

The overall objective of the Global Technology Roadmap for carbon capture and storage (CCS) in industry is to advance the global development and uptake of low carbon technologies in industry, contributing to the stabilization of greenhouse gas (GHG) concentrations in the atmosphere. This sectoral assessment supports this road mapping activity by providing as input a summary assessment of the potential opportunities and constraints for the application of carbon dioxide enhanced oil recovery (CO_2-EOR), using CO_2 captured from industrial sources.

Enhanced oil recovery (EOR) is a term used for a variety of techniques for increasing the amount of crude oil that can be extracted from an oil field. As part of the CO_2-EOR process, CO_2 is injected into an oil-bearing stratum; though CO_2-EOR operations have traditionally focused on optimizing oil production, not the storage of CO_2. Nonetheless, CO_2-EOR can result in effective storage; in general, most of the initially purchased CO_2 for CO_2-EOR operations (not that which is recycled) can be stored at the end of injection.

CO_2-EOR technologies have been profitable in commercial scale applications for over 30 years, primarily in the United States. Natural CO_2 fields are currently the dominant source of CO_2 for the U.S. CO_2-EOR market, providing CO_2 supplies amounting to 47 million metric tons per year. Anthropogenic sources are accounting for steadily increasing share of this CO_2 supply, currently providing 12 million metric tons per year of CO_2 for EOR. An extensive CO_2 pipeline network has evolved to meet the CO_2 requirements of this market. However, *CO_2 reserves from natural sources have the potential of supporting the production of only a small fraction of the oil resource potential achievable with the application of CO_2-EOR*. Therefore, substantial growth in oil production from the application of CO_2-EOR requires significantly expanded access to industrial sources of CO_2.

The greatest impact associated with CCS in value-added reservoirs such as CO_2-EOR may be derived from their ability to produce incremental oil, with the revenues resulting from this incremental production serving to offset costs associated with deploying CCS. The deployment of CO_2-EOR, especially in areas where it has not been deployed before, also contributes to the body of knowledge needed to implement CCS. Finally, advances in CO_2-EOR technology can both increase oil production from CO_2-EOR and improve the utilization of CO_2 used for EOR. This can result in expanding the volume of the CO_2 storage capacity associated with CO_2-EOR.

The potential global capacity for storage of CO_2 in association with CO_2-EOR can be substantial. In a recent study, a database of the largest 54 oil basins of the world (accounting for approximately 95% of the world's estimated ultimately recoverable oil) was developed. Defined technical criteria were used to identify and characterize world oil basins with potential for CO_2-EOR. From this, a high-level, first-order assessment of the CO_2-EOR oil recovery and CO_2 storage capacity potential in these basins was developed using the U.S. experience as analogue. These basin-level, first-order estimates were compared with detailed reservoir modelling of 47 large oil fields in six of these basins, and the first-order estimates were determined to be acceptable.

Based on this high-level assessment, it is apparent that CO_2-EOR offers a large, near-term option to store CO_2. Fifty of the largest oil basins of the world have reservoirs amenable to the application of miscible CO_2-EOR. Assuming “state-of-the-art” technology, oil fields in these basins have the potential to produce 470 billion barrels of additional oil, and store 140 billion metric tons of CO_2. If CO_2-EOR technology could also be successfully applied to smaller fields, the additional anticipated growth in reserves in discovered fields, and resources that remain in fields that are yet to be discovered, the world-wide application of CO_2-EOR could recover over one trillion additional barrels of oil, with associated CO_2 storage of 320 billion metric tons. Over 230 billion barrels of potential resource potential from CO_2-EOR, or nearly half of the overall global potential, exists in basins in the Middle East and North Africa.

In all regions of the world, the supply of CO_2 from industrial sources is not sufficient to meet the potential requirements for CO_2 for CO_2-EOR. The regions containing the more developed countries, like the U.S., Canada, Australia, and Europe have the largest portions of industrial emissions that could be a CO_2 supply source for CO_2-EOR. Nonetheless, all of the regions have large volumes of CO_2 emitted from industrial sources that are in relatively close proximity (within 50-100 kilometres) to basins that contain fields that are amenable to the application of CO_2 -EOR.

Since significant expansion of oil production utilizing CO_2-EOR will require volumes of CO_2 that cannot be met by natural sources alone; industrial sources of CO_2 will need to play a critical role. Thus, *not only does CCS need CO_2-EOR to help promote economic viability for CCS, but CO_2-EOR needs CCS in order to ensure adequate CO_2 supplies to facilitate growth in the number of and production from new and expanded CO_2-EOR projects.*

However, it is important to note that estimating the actual performance of CO_2-EOR operations in specific applications is a much more complex and data intensive effort than that applied here, and can often take months or years to perform on a single candidate field. Moreover, it requires substantial amounts of detailed field- and project-specific data, most of which is generally only available to the owner and/or operator of a field. While data access and time constraints prevented the application of this level of rigor to estimating the world-wide performance of potential future CO_2-EOR projects for this study, the methodology developed builds upon Advanced Resources’ large volume of data on U.S. crude oil reservoirs and on existing CO_2-EOR operations in the United States. However, it is not a substitute for a more comprehensive assessment when investing in specific CO_2-EOR projects.

In addition to the more than 120 CO_2-EOR projects being pursued around the world, a number of research, development, and demonstration (RD&D) efforts are underway focused on the potential of CO_2-EOR in combination with CO_2 storage. In 2011, the Global CCS Institute reports 77 joint government-industry large-scale integrated projects (LSIPs) at various stages of the asset life cycle. These include eight operating projects and a further four projects in the execution phase of the project life cycle. Of the 77 LSIPs, 34 (44%) are targeted for EOR applications. Five of the eight operating LSIPs and three of the four in execution are injecting CO_2 for EOR. Eight of the nine executing or operating LSIPs target EOR.

Since storing CO_2 in association with EOR can substantially offset the extra costs associated with CCS, it can encourage its application in the absence of other incentives for CCS deployment. However, to encourage the development of the necessary supplies of affordable CO_2 to facilitate large-scale growth in production from CO_2-EOR projects, and facilitate the development of large volumes of industrial-source CO_2 and the infrastructure to gather, transport, and distribute the CO_2 to CO_2-EOR prospects, economic incentives for reducing emissions, such as emissions trading programs, carbon taxes, or other mechanisms, may be necessary. Moreover, within any established framework for regulating and/or incentivizing emissions reductions from wide-scale deployment of CCS (with or without CO_2-EOR), storage must be established as a certifiable means for reducing GHG emissions.

Supporting the factors contributing to successful, economically viable CO_2-EOR and/or CCS projects may be a necessary but not sufficient condition for the ultimate “conversion” of a CO_2-EOR project to a CO_2 storage project. Numerous regulatory and liability issues and uncertainties are currently associated with CCS that are hindering wide-scale deployment. These uncertainties are also hindering the pursuit of CO_2-EOR, particularly because of the lack of regulatory clarity regarding the process and requirements associated with the transition from EOR operations to permanent geologic storage.

INTRODUCTION AND OVERVIEW

The overall objective of the Global Technology Roadmap for carbon capture and storage (CCS) in industry is to advance the global development and uptake of low carbon technologies in industry needed to stabilize greenhouse gas (GHG) concentrations in the atmosphere to prevent dangerous anthropogenic interference with the climate system; specifically:

- To provide relevant stakeholders with a vision of industrial CCS up to 2050
- To strengthen the capacities of various stakeholders with regard to industrial CCS
- To inform policymakers and investors about the potential of CCS technology.[1]

This sectoral assessment supports this road mapping activity by specifically providing as input a summary assessment of the potential opportunities and constraints for the application of carbon dioxide enhanced oil recovery (CO_2-EOR) associated with CCS applied to industrial sources of CO_2 emissions.

This sectoral assessment builds upon on information from three previous reports:

- Advanced Resources International, Inc. and Melzer Consulting, *Optimization of CO_2 Storage in CO_2 Enhanced Oil Recovery Projects*, report prepared for the U.K. Department of Energy & Climate Change (DECC), Office of Carbon Capture & Storage, November 30, 2010 (http://www.decc.gov.uk/en/content/cms/what_we_do/uk_supply/energy_mix/ccs/ccs.aspx)
- IEA Greenhouse Gas R&D Programme, *CO_2 Storage in Depleted Oilfields: Global Application Criteria for Carbon Dioxide Enhanced Oil Recovery*, Report IEA/CON/08/155, Prepared by Advanced Resources International, Inc. and Melzer Consulting, August 31, 2009 (http://www.co2storage.org/Reports/2009-12.pdf)
- U.S. Department of Energy/National Energy Technology Laboratory, *Storing CO_2 and Producing Domestic Crude Oil with Next Generation CO_2-EOR Technology: An Update*, report DOE/NETL-2010/1417 prepared by Advanced Resources International, April 2010 (http://www.netl.doe.gov/energy-analyses/refshelf/PubDetails.aspx?Action=View&PubId=309)

This report begins with a brief overview of CO_2-EOR, how it works, under what conditions is it deployed, how it compares to other approaches for oil development and production, how it has evolved over time, and how CO_2 is utilized over time in an CO_2-EOR development and production operation. This is followed by an overview of the CO_2-EOR industry, describing where and how much oil is currently produced from the application of CO_2-EOR, and how the CO_2-EOR industry -- and its key participants -- is structured. This is followed by a detailed discussion of the economics of CO_2-EOR, including an overview of the baseline costs associated with CO_2-EOR, as well as the relative cost impact of CO_2-EOR on CCS. The next section provides a summary of a recent assessment of the global potential for CO_2-EOR, and the relative location of industrial CO_2 sources to basins amenable to CO_2-EOR. This is followed

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[1] United Nation Industrial Development Organization, *Carbon Capture and Storage in Industrial Applications: Technology Synthesis Report Working Paper*, November 2010 (http://www.unido.org/fileadmin/user_media/Services/Energy_and_Climate_Change/Energy_Efficiency/CCS/synthesis_final.pdf)

by a description of current activities and plans related to the joint deployment of CO_2-EOR and CCS, including government sponsored research, development, and demonstration projects, along with planned commercial projects. Finally, the current barriers to greater CO_2-EOR implementation are discussed; including the current lack of CO_2 supplies for substantial growth in oil production from CO_2-EOR, existing barriers specific to CO_2-EOR project implementation and specific to CO_2-EOR with CCS, including potential barriers that may be associated with the quality specifications for industrial CO2 use for CO_2-EOR.

What is EOR and CO_2-EOR?

Oil fields can be developed in up to three distinct phases. Primary recovery generally uses just the reservoir pressure to facilitate production. Normally only 30% of the oil in a reservoir can be extracted from conventional pressure depletion methods. Secondary recovery generally involves the injection of water, or sometimes gas, to maintain pressure in the reservoir. In water flooding, water is injected back into the reservoir, usually to: (1) to support pressure of the reservoir (also known as voidage replacement), and (2) to sweep or displace oil from the reservoir, and push it towards a well. Water injection increases that percentage recovered (known as the recovery factor) and maintains the production rate of a reservoir over a longer period of time. Tertiary or enhanced oil recovery (EOR) is a term used for a wide variety of techniques for increasing the amount of crude oil that can be extracted from an oil field. It is often compared to, and pursued after, a field is developed using water injection, or water flooding.

Three major categories of EOR have been found to be commercially successful to varying degrees:

- Thermal recovery, which involves the introduction of heat, usually as steam, to lower the viscosity, or thin, the heavy viscous oil, and improve its ability to flow through the reservoir.

- Chemical injection, which can involve the use of long-chained molecules called polymers to increase the effectiveness of water floods, or the use of detergent-like surfactants to help lower the surface tension that often prevents oil droplets from moving through a reservoir.

- Gas injection, which uses gases such as natural gas, nitrogen, or CO_2 that expand in a reservoir to push additional oil to a production wellbore, or other gases that dissolve in the oil to lower its viscosity and improves its flow rate.

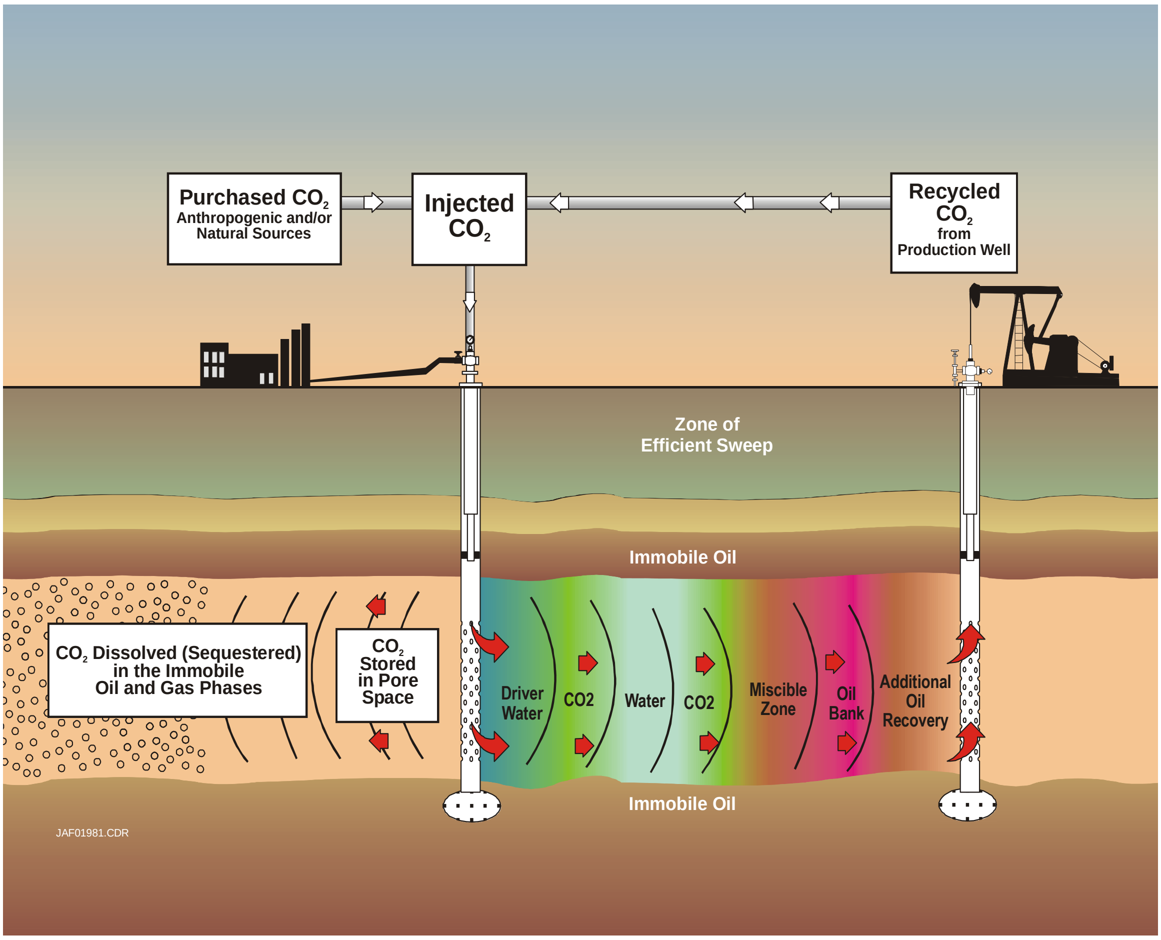
Another EOR technique currently in the experimental stage is microbial injection. To date, this technique has been rarely used, both because of its higher cost and because the developments in this field are more recent than other techniques.

As part of the CO_2-EOR process, CO_2 is injected into an oil-bearing stratum under high pressure. Oil displacement by CO_2 injection relies on the phase behavior of the mixtures of gas and the oil, which are strongly dependent on reservoir temperature, pressure and oil composition. There are two main types of CO_2-EOR processes:

- Miscible CO_2-EOR is a multiple contact process involving interactions between the injected CO_2 and the reservoir's oil. During this multiple contact process, CO_2 vaporizes the lighter oil fractions into the injected CO_2 phase and CO_2 condenses into the reservoir's oil phase. This leads to two reservoir fluids that become miscible (mixing in all parts), with favorable properties of low viscosity, enhanced mobility, and low interfacial tension. The primary objective of miscible CO_2-EOR is to remobilize and reduce the residual oil saturation in the reservoir's pore space after water flooding. Figure 1 provides a one-dimensional schematic showing the dynamics of the miscible CO_2-EOR process. Miscible CO_2-EOR is by far the most dominant form of CO_2-EOR deployed.

- Immiscible CO_2-EOR occurs when insufficient reservoir pressure is available or the reservoir's oil composition is less favorable (heavier). The main mechanisms involved in immiscible CO_2 flooding are: (1) oil phase swelling, as the oil becomes saturated with CO_2; (2) viscosity reduction of the swollen oil and CO_2 mixture; (3) extraction of lighter hydrocarbons into the CO_2 phase; and, (4) fluid drive plus pressure. This combination of mechanisms enables a portion of the reservoir's remaining oil to still be mobilized and produced, and is commercial in many instances.

Figure 1. One-Dimensional Schematic Showing the Miscible CO_2-EOR Process



CO_2-EOR operations have traditionally focused on optimizing oil production, not the storage of CO_2. However, CO_2-EOR can nonetheless result in very effective storage. In general, nearly 100% of the initially acquired/purchased CO_2 for CO_2-EOR operations (not that which is recycled) will be stored at the end of active injection.

The Evolution of CO_2-EOR Technology

Considerable evolution has occurred in the design and implementation of CO_2-EOR technology since it was first introduced in the 1970s. Traditionally, the combination of high CO_2 costs and low oil prices led operators to inject relatively small volumes of CO_2 to maximize profitability. This low volume CO_2 injection strategy was pursued because operators had ved capability to observe and control the sub-surface movement of the injected CO_2 in the reservoir.

With higher oil prices and adequate supplies of affordable CO_2, CO_2-EOR economics today favor using larger volumes of CO_2. However, these increased CO_2 volumes need to be "managed and controlled" to assure that they contact, displace, and recover additional residual oil, rather than merely circulate through a high permeability zone of the reservoir.

As a result, "state-of-the-art" CO_2-EOR technology has evolved considerably compared to "traditional" practices. Notable changes include the use of much larger volumes of injected CO_2; the incorporation of tapered water alternating with gas (WAG) and other methods for mobility control; and the application of advanced well drilling and completion strategies to better contact previously bypassed oil. As a result, the oil recovery efficiencies of today's "state-of-the-art" CO_2-EOR projects have steadily improved.

Key characteristics that underlie performance of "state-of-the-art" CO_2-EOR technology include:

- Rigorous CO_2-EOR monitoring, management and, where required, remediation activities that help assure that the larger volumes of injected CO_2 contact more of the reservoir's pore volume and residual oil, rather than merely channel through high permeability streaks in the reservoir.
- The injection of much larger volumes of CO_2 (1.0 hydrocarbon pore volume (HCPV)),[2] rather than the smaller (on the order of 0.4 HCPV) volumes used in the past.[3]
- Appropriate well spacing (including the drilling of new infill wells)
- Use of a tapered WAG process
- The maintenance of minimum miscibility pressure (MMP)[4] throughout the reservoir.

The application of "state-of-the-art" technology for CO_2-EOR can then be contrasted with "next generation" technologies. Four "next generation" CO_2-EOR technology advances address some of the constraints faced by "state-of-the-art" CO_2-EOR practices and result in more oil production and additional CO_2 utilization and storage:

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[2] Hydrocarbon Pore Volume (HCPV) is a measure of the volume of reservoir pore space available for fluid injection.

[3] Merchant, David H., "Life Beyond 80 – A Look at Conventional WAG Recovery Beyond 80% HCPV Injection in CO_2 Tertiary Floods," SPE Paper No. 139516-PP presented at the SPE International Conference on CO_2 Capture, Storage, and Utilization, New Orleans, LA, November 10-12, 2010

[4] Minimum miscibility pressure (MMP) is defined as the minimum pressure at which reservoir crude oil is miscible with the injected fluids. In general, the operating pressure should be maintained at or higher than the MMP to ensure miscibility is reached in a miscible flooding process.

- *Increasing the volume of CO_2 injected into the oil reservoir*. This involves increasing CO_2 injection volumes from 1.0 HCPV, currently used in "state-of-the-art", to 1.5 HCPV.
- *Optimizing well design and placement*, including adding infill wells, to achieve increased contact between the injected CO_2 and the oil reservoir. The well design and placement objective is to ensure that both the previously highly waterflood-swept portions of the oil reservoir and the poorly waterflood-swept portions of the oil reservoir are optimally contacted by the injected CO_2.
- *Improving the mobility ratio between the injected CO_2/water and the residual oil*. This assumes a relative increase in the viscosity of the injected water (as part of the CO_2-WAG process).
- *Extending the miscibility range*. This helps achieve higher oil recovery efficiency.

It is important to note that all of these "next generation" technologies are currently being deployed, at least at pilot scale, in CO_2-EOR projects today. However, these technologies still focus primarily on recovering more oil, even though they will generally involve injecting, and ultimately storing, more CO_2.

Because the deployment of "next generation" technologies is more costly than that for "state-of-the-art," it may not be the economically preferred option in some settings.

On yet another front with regard to expanding the potential applicability of CO_2-EOR, recent developments in the Permian Basin of the U.S. indicate that vast, previously unrecognized opportunities for additional oil production from CO_2-EOR exist that can provide substantial additional capacity for permanently storing CO_2. This potential is associated with residual oil zones (ROZs) below the oil/water contact in oil reservoirs that are widespread and rich in unrecovered oil.[5] Field pilots are showing that applying CO_2-EOR in ROZs can be commercially viable. Pursuing this resource potential could result in a two-to-three fold increase in the potential CO_2 storage capacity associated with the application of CO_2 -EOR. Preliminary work is indicating that the Permian Basin is not alone in possessing extensive ROZs. ROZs exist where formation water has encroached into oil entrapments due to tectonic readjustment in a post-entrapment phase. Many places in the world exist where such a subsidence and entrapment phase has been followed by a subsequent tectonic episode.

And finally, other "second generation" approaches to increase the volume of CO_2 storage in conjunction with CO_2-EOR may further increase total storage capacities. Such approaches include targeting both the main pay zone and an underlying ROZ, with continued CO_2 injection into and storage in an underlying saline aquifer, including injecting continuous CO_2 (no water) after completion of oil recovery operations. In fact, some approaches for CO_2-EOR that focus on increasing CO_2 storage may be able to store more CO_2 than is associated with the CO_2 emissions over the life cycle of the incremental oil produced from CO_2-EOR, including emissions from consumption.[6]

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[5] Melzer, L. Stephen, *Stranded Oil in the Residual Oil Zone*, report prepared for Advanced Resources International and the U.S Department of Energy/Office of Fossil Energy - Office of Oil and Natural Gas, February 2006 (http://www.netl.doe.gov/KMD/cds/disk44/D-CO2%20Injection/Advanced%20Resources%20International/ROZ%20Melzer%20Document.pdf)

[6] More detailed descriptions of the potential is associated with residual oil zones (ROZs) and that for "second generation" approaches to increase the volume of CO_2 storage in conjunction with CO_2-EOR … can be found in Advanced Resources

CO_2 Demand in an Individual Field or Reservoir over Time

At the individual project level, a "typical" project life cycle for a CO_2-EOR project is difficult to describe because few have run through the entire cycle. CO_2-EOR projects started in 1983 are still purchasing CO_2. Original projections for many of the larger fields would have these fields on total recycle by now; most are still purchasing CO_2. Higher oil prices have justified project expansions into more marginal areas of fields currently under CO_2-EOR; improved technologies are being deployed to "squeeze out" more oil from these fields; and projects are being initiated by smaller and intermediate size independent oil companies.

The timing of development of CO_2-EOR projects has been highly dependent on the availability of CO_2. This applies both to new CO_2-EOR projects within a basin, as well as to development within an individual project. Project development is also often highly dependent on the availability of investment capital, field services like drilling and work-over rigs, and materials and construction workers for development of CO_2 processing, recycling, compression, and distribution facilities.

Nonetheless, experience indicates that the volume of CO_2 needed for a CO_2-EOR project changes over a field's life. The general model for the use of CO_2 in a reservoir may be described in sequence as follows:

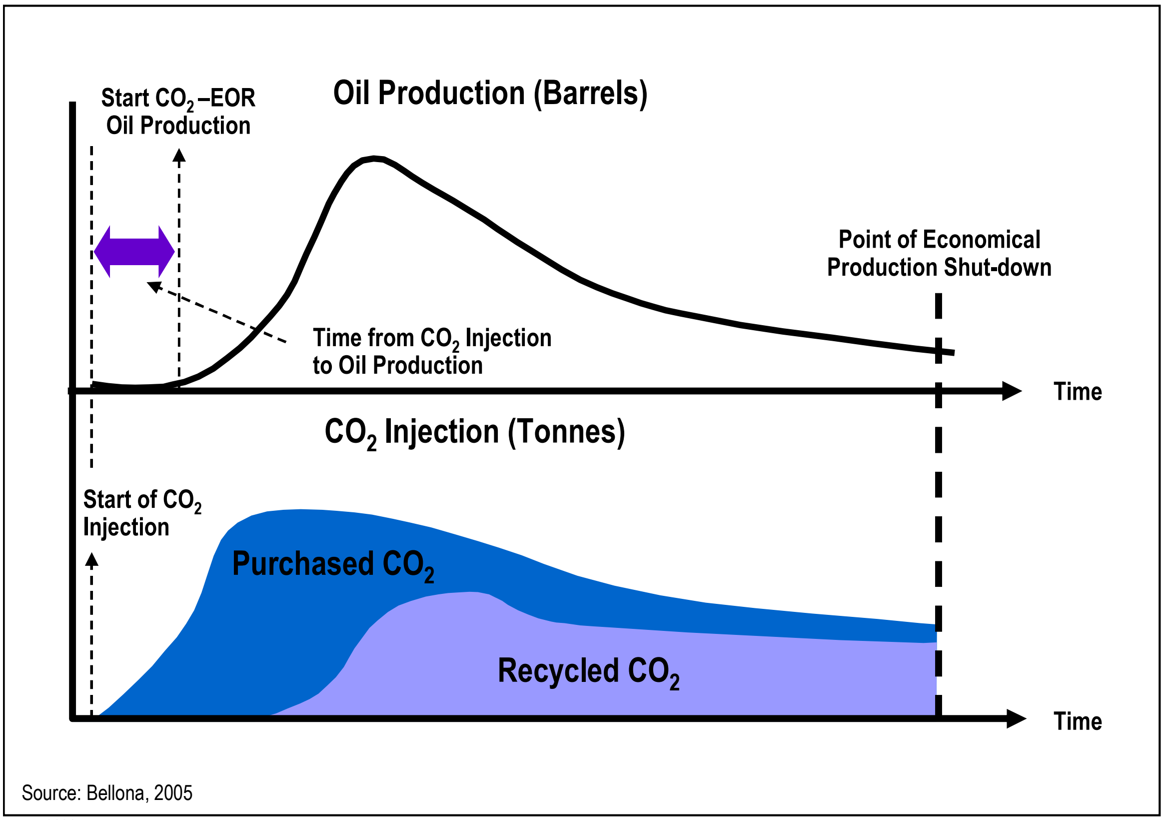
1. Initially the reservoir is flushed with significant amounts of CO_2, though it may take time before the effect of the injected CO_2 on oil production is seen. A rule-of-thumb is that it may take between 18 to 24 months from initial injection of CO_2 until production starts.
2. The more CO_2 added to the reservoir, the more oil may be expected to be produced. The objective is to have as large an amount of CO_2 injected as economically possible to achieve optimum production.
3. After a period of CO_2 injection, the produced oil will contain CO_2. The CO_2 in this oil is separated and thereafter re-injected back into the oil field. The result is that the field's need to purchase fresh CO_2 is gradually reduced as more and more of the CO_2 injected is actually produced with the oil itself, and then the CO_2 is recycled and re-injected.

This is illustrated schematically for a "typical" project in Figure 2.[7]

International, Inc. and Melzer Consulting, *Optimization of CO_2 Storage in CO_2 Enhanced Oil Recovery Projects*, report prepared for the U.K. Department of Energy & Climate Change (DECC), Office of Carbon Capture & Storage, November 30, 2010

[7] Jakobsen Viktor E, Frederic Hauge, Marius Holm, and & Beate Kristiansen, *Environment and value creation - CO_2 for EOR on the Norwegian shelf, – a case study*, Bellona report, August 2005

Figure 2. Profiles for CO_2 Injection and Oil Production in CO_2-EOR



Source: Bellona, 2005

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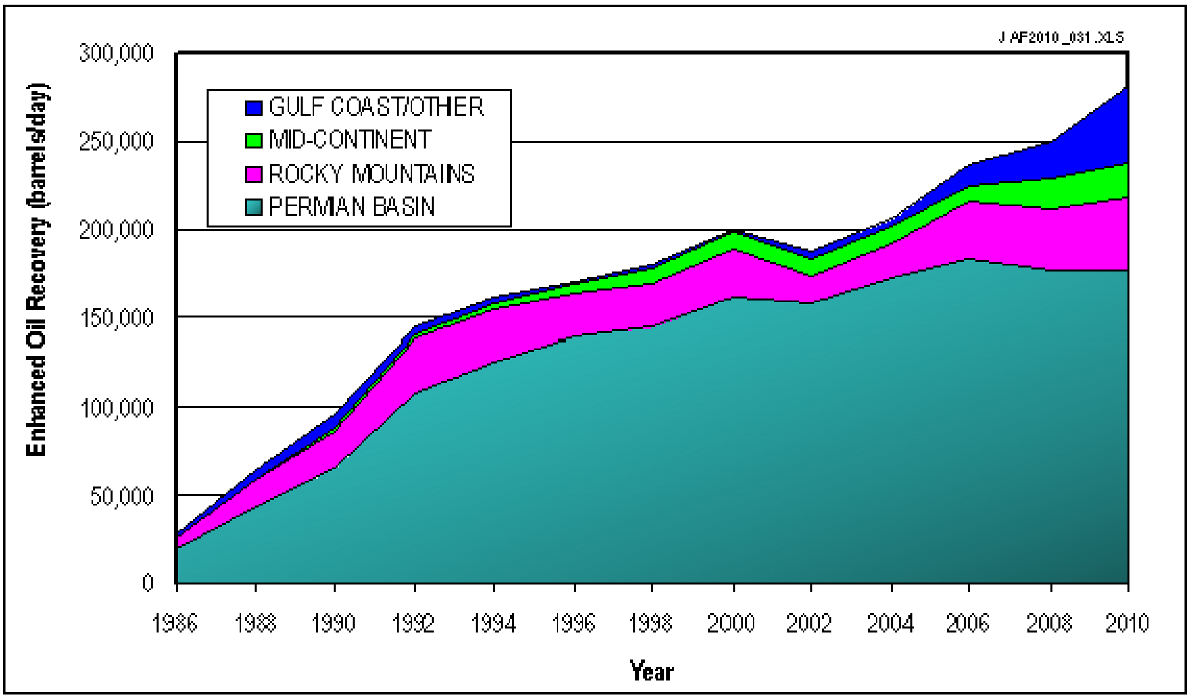
This often creates a dilemma for an individual CO_2-EOR project matching up with an individual source of CO_2 emissions. The source of emissions tends to generate CO_2 over the life of the facility at a relatively constant rate, while an individual CO_2-EOR project would want to take decreasing amounts of CO_2 over time. To overcome this dilemma, applying CCS to a cluster of CO_2 sources matched to a cluster of CO_2-EOR prospects may provide the necessary economies of scale for successful deployment. There are a number of propositions currently under consideration for industrial collaborations on CCS in the U.S., Canada, Europe and Australia which seek to exploit such opportunities.

OVERVIEW OF THE CO_2-EOR INDUSTRY

Current Production from the Application of CO_2-EOR in the U.S.

CO_2-EOR technologies have been demonstrated to be profitable in commercial scale applications for 30 years. The most comprehensive review of the status of CO_2-EOR around the world is the biennial EOR survey published by the *Oil and Gas Journal*; the most recent issue was published in April 2010.[8] The latest survey reports that the number of CO_2-EOR projects and the level of production are increasing in all regions of the United States, Figure 3.

Figure 3. U.S. CO_2-EOR Production (1986-2010)



Natural CO_2 fields are the dominant source of CO_2 for the U.S. CO_2-EOR market, providing CO_2 supplies amounting to an estimated 47 million metric tons per year in 2010 (Table 1). Where this occurs, like in the Permian Basin, an extensive CO_2 pipeline network has evolved to meet these CO_2 requirements. Moreover, in these networks, managing the supply and demand of CO_2 between the sources (the natural CO_2 fields) and sinks (the CO_2-EOR projects) is done in much the same way as that for natural gas – the large number of projects taking CO_2 ensure that all CO_2 transported in the pipeline has a field that is utilizing it – if some areas of a project or field are down for maintenance, for example, another project area or field will likely be able to take the excess CO_2. Moreover, the process of managing the water-alternating-gas (WAG) operations takes into consideration the needs to balance supply and demand at an individual field level as well. Finally, if the supply of CO_2 exceeds demand for an extended period, production from some of the wells producing CO_2 at the source field can be cut off, and least temporarily.

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[8] Koottungal, Leena, “SPECIAL REPORT: EOR/Heavy Oil Survey: 2010 worldwide EOR survey,” *Oil and Gas Journal*, April 19, 2010

Table 1. Significant Volumes of Anthropogenic CO_2 Are Being Injected for EOR

State/Province (Storage Location)	Source Type (Location)	CO_2 Supply (MM tonnes/year)		
		Natural	Anthropogenic	Total
Texas-Utah-New Mexico-Oklahoma	Geologic (Colorado-New Mexico) Gas Processing	30	2	32
Colorado-Wyoming	Gas Processing (Wyoming)		6	
Mississippi-Louisiana	Geologic (Mississippi)	17		17
Michigan	Ammonia Plant (Michigan)		0	0
Oklahoma	Fertilizer Plants (Oklahoma)		1	1
Saskatchewan	Coal Gasification (North Dakota)		3	3
Total		**47**	**12**	**59**

Source: Advanced Resources International, 2010; numbers do not add exactly due to rounding.

Anthropogenic sources are accounting for steadily increasing share this CO_2 supply, currently providing 12 million metric tons per year of CO_2 for EOR. The largest source of industrial CO_2 used for CO_2-EOR in the U.S. is the six million metric tons per year of CO_2 captured from ExxonMobil's Shute Creek gas processing plant at the La Barge field in western Wyoming.[9] This is followed by the capture of about three million metric tons per year from the Northern Great Plains Gasification plant in Beulah, North Dakota and its transport, via a 320 kilometre cross-border CO_2 pipeline, to two EOR projects (Weyburn and Midale) in Saskatchewan, Canada.

The Shute Creek plant also supplies anthropogenic CO_2 to Chevron's CO_2-EOR project in the Rangely Field (Weber Sand Unit) in Western Colorado. The gas is transported 77 kilometres by a ExxonMobil pipeline to Rock Springs, where it is transferred to a Chevron pipeline which transports it 208 kilometres to the Rangely field. The Rangely Oil Field is one of the oldest and largest oil fields in the Rocky Mountain region of the U.S., having produced nearly 800 million barrels of oil. The field has been injecting CO_2 for EOR since 1986. To date, an estimated 26 million metric tons of CO_2 have been sequestered in the field.[10]

New CO_2 pipelines and refurbished gas treatment facilities, such as ExxonMobil's expansion of the Shute Creek gas processing plant, Denbury's 512 kilometre Green Pipeline in the U.S. Gulf Coast, the proposed 360 kilometre Encore Pipeline and refurbished Lost Cabin gas plant in the Rockies, and the new Century gas processing plant in West Texas (Figure 4) will help connect existing, new, and expanded facilities providing CO_2 from both natural and anthropogenic sources, and facilitate expanded availability and use of CO_2 in U.S. oil fields, leading to increased oil production from CO_2-EOR. In addition, the greater number of and

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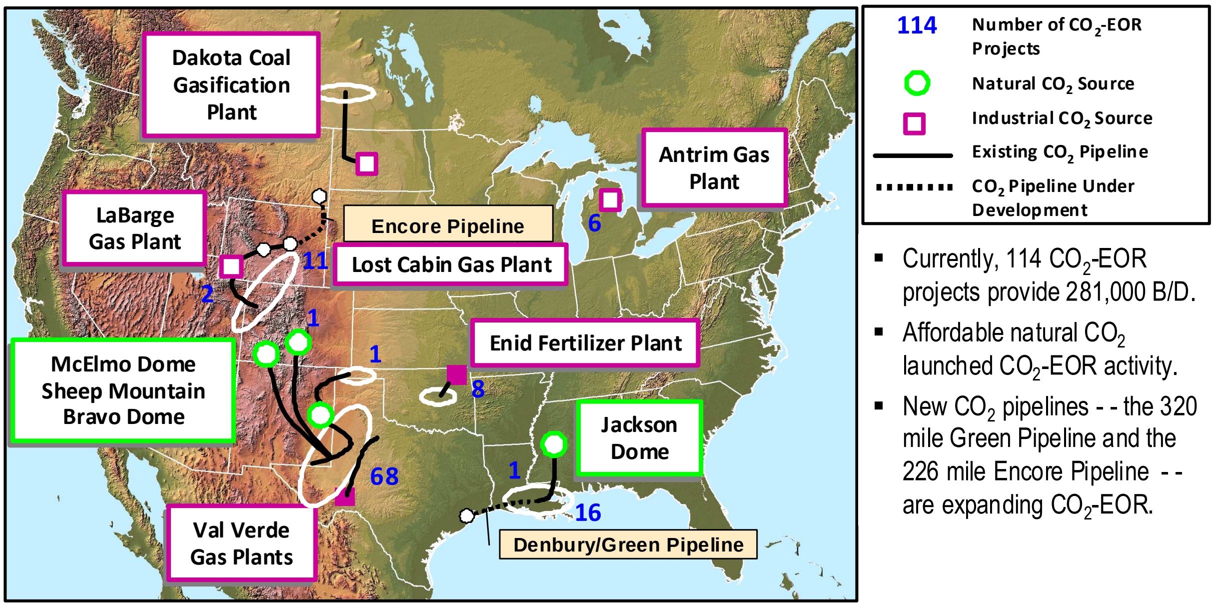
[9] Skip Thomas, "LaBarge Field and Shute Creek Facility," presentation to the Wyoming Enhanced Oil Recovery Institute, 3rd Annual Wyoming CO_2 Conference, June 24, 2009

[10] http://www.iea.org/work/2009/ccs_bridging/lee.pdf

volume from CO_2 sources, matched up with a growing number of CO_2-EOR projects, will allow for greater flexibility to manage CO_2 supply and demand for CO_2-EOR

Figure 4. Current U.S. CO_2-EOR Activity



- Currently, 114 CO_2-EOR projects provide 281,000 B/D.
- Affordable natural CO_2 launched CO_2-EOR activity.
- New CO_2 pipelines - - the 320 mile Green Pipeline and the 226 mile Encore Pipeline - - are expanding CO_2-EOR.

Source: Advanced Resources International, Inc., based on Oil and Gas Journal, 2010 and other sources.

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Current Production from the Application of CO_2-EOR outside the U.S.

Outside the U.S, the Weyburn field in Canada is the “poster child” of a combined CO_2-EOR and geologic storage project. This Cenovus Energy (formerly EnCana) CO_2 flood has been expanded to over 60% of the unit, and production from the field has continued to increase. The implementation of the CO_2-EOR project, along with the continued infill well development program, has resulted in a 65% increase in oil production.[11] The Weyburn project plans to inject 23 million metric tons in association with CO_2-EOR (17 million metric tons have been injected to date).[12] The ultimate plan is to inject a total of 55 million metric tons by continuing injection by controlling the gas-oil ratio (GOR) in the project, so that 32 million metric tons would be injected solely for purposes of CO_2 storage.[13] Simulation studies have indicated that greater volumes of storage could be realized with more aggressive efforts to optimize the volume stored.

Another CO_2-EOR project has been in operation by Apache Canada since 2005 in the nearby Midale field, using the same CO_2 source as Weyburn, within which 2.1 million metric tons have been stored to date. A small CO_2-EOR project has been in operation at the Joffre field in Alberta since 1984, operated by Penn West, using CO_2 from a nearby petrochemical plant.

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[11] Moritis, Guntis, “SPECIAL REPORT: More US EOR projects start but EOR production continues decline,” *Oil and Gas Journal*, April 21, 2008

[12] Whittaker, Steve, “An Update on the Saskatchewan CO_2 Floods (Weyburn + Midale) and Storage Monitoring Activities,” presented at the 16th Annual CO_2 Flooding Conference, Midland Texas, December 9-10, 2010

[13] See Law, David, et al., “Theme 3: CO_2 Storage Capacity and Distribution Predictions and the Application of Economic Limits,” in Wilson, M. and M. Monea, eds., *IEA GHG Weyburn CO_2 Monitoring and Storage Project Summary Report 2000-2004*, Petroleum Technology Research Centre, Regina, Saskatchewan, Canada, 2004

Outside of North America, only a few (mostly immiscible) CO_2-EOR projects are underway (in Brazil, Turkey, and Trinidad), according to the *Oil and Gas Journal* survey.[14] In Brazil, CO_2 injection for CO_2-EOR has been carried out by Petrobras since 1987 in the Recôncavo Basin (Bahia) oil fields. In Trinidad, four immiscible CO_2-EOR pilot floods were implemented by Petrotrin at its Forest Reserve and Oropouche fields over the period 1973 to 1990. In Turkey, an immiscible CO_2-EOR project was initiated in the Bati Raman field.

Previous CO_2-EOR pilots have reportedly been implemented in China, though, at least in some cases, the injection stream is flue gas or other waste stream, often with a relatively low concentration of CO_2.[15,16]

- Liaohe Complex.[17,18] Perhaps the most documented application of CO_2/flue gas injection for EOR in China was a pilot project begun in 1998 in the Liaohe oilfield complex. The initial objective of the project was to inject steam and flue gas containing 12-13% CO_2, simultaneously into a test well, without pre-mixing. Following injection of approximately 2,500 tonnes of the CO_2 and flue gas mixture, the well was closed for several days to allow the gases to fully diffuse and penetrate the reservoir. Preliminary results indicated that the EOR effect created by steam-flue gas pumping was considerable. With steam injection alone, oil production increases of 20-30% were reported. Reportedly, using a combination of steam and flue gas injection, oil production increased by 50 to 60%. The technique was applied equally well to two wells and multiple units covering a large area.

- Shengli Complex. The Shengli oilfield complex has been under production since the 1960s. Output from primary production began to decline in the early 1990s, and has since been supported by water flooding, infill drilling, and other advanced recovery technologies.[19] A CO_2-EOR pilot project was begun in 2007 in the Shengli oilfield complex that injected flue gas from a coal fired power plant in the area. The flue gas contained 13.5% CO_2, and was injected into 4 injection wells to mobilize stranded oil toward 12 production wells.[20]

- Dagang Complex. In 2007, a CO_2-EOR pilot test injected CO_2 into the Kongdian reservoir of the Dagang oilfield complex. The operation, which injected natural gas with 20% CO_2 from a nearby natural gas field into a single injection well, lasted about 1.5 years. It is reported that oil production from the well was increased from 13.6 to 68 barrels per day.[21]

- Zhongyuan Oilfield. In 2002, CNPC began injecting CO_2 it captured from a nearby oil refinery into its Zhongyuan oil field. Detailed results are not available, though the

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[14] Koottungal, Leena, “SPECIAL REPORT: EOR/Heavy Oil Survey: 2010 worldwide EOR survey,” *Oil and Gas Journal*, April 19, 2010

[15] Dahowski, RT, X Li, CL Davidson, N Wei, JJ Dooley, and RH Gentile, “A Preliminary Cost Curve Assessment of Carbon Dioxide Capture and Storage Potential in China, “ *Energy Procedia*, 1 (2009) 2849-2856

[16] Meng, KC, R.H. Williams, and M.A. Celia, “Opportunities for low-cost CO_2 storage demonstration projects in China,” *Energy Policy*, 35, 2368-2378, (2007)

[17] What is often referred to as the Liaohe oil field is actually a complex of many oil fields within close proximity. This observation applies to all of the major “oil fields” discussed as CO2-EOR candidates in this report.

[18] http://www.cnpc.com.cn/en/aboutcnpc/ourbusinesses/explorationproduction/operatediol/Dagang_Oil_Province.htm

[19] http://english.peopledaily.com.cn/90001/90776/90884/6566709.html

[20] Li, Mingyuan. CO2-EOR and Storage in China. China University of Petroleum. Beijing, China. March 27, 2009.

[21] Luo, Zhongyang. Status of CCS in China. 2nd US-China Symposium on CO2 Emission Control Science and Technology. Hangzhou, China May 28-30, 2008.

company reports capturing and injecting 20,000 tonnes per year from this refining unit. At the time, this appeared to be the largest volume of CO_2 being injected for EOR in China. Another CO_2 capture facility was placed online in 2003, though data is not available about the volumes of CO_2 it captured.[22]

- Daqing Complex. In December 2006, a CO_2 injection pilot was begun by the Gas Production Branch of Daqing oil field. CO_2 was injected into two wells (No. 9711 and 9117) with the intent of increasing incremental oil recovery. Detailed results of this pilot have not been published.

- Jilin Complex. Commercial development began in the Jilin oilfield complex in the early 1960s; today producing 40 million barrels per year.[23] Allegedly, the first combined CO_2-EOR and CO_2 storage project in China was initiated by PetroChina in the Xinli Unit of the Jilin Oil Field in 2006. This project consisted of 10 CO_2 injectors and 28 production wells. The CO_2 source was a natural gas field containing 10% to 14% CO_2. Several tests were conducted which demonstrated that the oil recovery rate increased by 10% to 20% in formations where miscibility was achieved, and increased by 5% to 10% in formations where miscibility was not achieved.[24,25] In 2010, 18 wells are injection 1.6 million metric tons per year.

In the North Sea, five hydrocarbon gas injection projects have been initiated with some success, but none utilized CO_2.[26]

In the Recôncavo Basin in Brazil, Petrobras have been injecting CO_2 for the purposes of EOR into a number of oil fields for 24 years. At present the EOR activities are relatively small scale at approximately 120 metric tons of CO_2 per day, collected from an ammonia plant and an ethylene oxide production facility.

Structure of the CO_2-EOR Industry

Prior to the early 1990s, almost all CO_2-EOR projects in the U.S. were being pursued by a small group of major oil companies -- Amerada Hess, Amoco, ARCO, Chevron, Exxon, Mobil, Shell, and Texaco. The combination of higher oil prices, a proactive technology transfer program by the U.S. Department of Energy in the 1990s, the development of large sources of high-grade, low-cost CO_2, and an overall shift in major oil company investment from the U.S. to elsewhere in the world led to the current situation where large independent producers now dominate the roster of CO_{2}-EOR operators (Table 2).

Table 2. CO_2-EOR Producing Companies in the U.S. in 2009

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[22] "Zhongyuan Oilfield completes carbon dioxide unit. (Project News).(Brief Article)." China Chemical Reporter. China National Chemical Information Center. 2003. *HighBeam Research.* 1 Jul. 2009 <http://www.highbeam.com>

[23] http://www.epmag.com/article/print/3662

[24] Guo, X., Z. Du, L. Sun, Y. Fu, W. Huang, and C. Zhang, "Optimization of Tertiary Water-Alternate-CO2 Flood in Jilin Oil Field of China: Laboratory and Simulation Results," SPE Paper No. 99616 presented at the 2006 SPE/DOE Symposium on Improved Oil Recovery, Tulsa, Oklahoma, USA April 22-26, 2006

[25] Pingping Shen and Huaiyou Jiang, "China Utilization of Greenhouse Gas as Resource in EOR and Storing It Underground," Research Institute of Petroleum Exploration and Development, PetroChina (http://www.netl.doe.gov/publications/proceedings/08/CO2E/PDF/session%205/China%20Utilization%20of%20Greenhouse%20Gas.pdf)

[26] Awan, A. R., R. Teigland, and J. Kleppe, "A Survey of North Sea Enhanced Oil Recovery Projects Initiated During the Years 1975 to 2005," *SPE Reservoir Evaluation and Engineering Magazine*, June 2008, pp. 497-512

Company	**No. of Projects**	**CO_2-EOR Production (barrels per day)**	**Locations**
Occidental	32	108,207	Texas, New Mexico
Denbury Resources	18	43,050	Mississippi, Louisiana
KinderMorgan	1	26,530	Permian Basin (TX&NM)
Chevron	7	24,221	Texas, Colorado, New Mexico
Hess	4	20,400	Texas
Whiting Petroleum	4	20,000	Texas, Oklahoma
Merit Energy	7	13,640	Wyoming, Oklahoma
Anadarko	5	12,600	Wyoming
ExxonMobil	2	11,700	Texas, Utah
ConocoPhillips	2	5,450	Texas, New Mexico
Apache	4	4,580	Texas
Chaparral Energy	7	2,820	Texas, Oklahoma
XTO Energy Inc.	4	2,575	Texas
Devon	1	2,425	Wyoming
Energen Resources	1	827	Texas
Fasken	5	535	Texas
Resolute Natural Resources	1	400	Utah
Core Energy	6	365	Michigan
Great Western Drilling	1	170	Texas
Orla Petco	1	128	Texas
Stanberry Oil	1	102	Texas

Source: Koottungal, Leena, “SPECIAL REPORT: EOR/Heavy Oil Survey: 2010 worldwide EOR survey,” Oil and Gas Journal, April 19, 2010

CO_2-EOR requires large up front investments and is relatively slow in providing financial returns on those investments. As a result, internal rates of returns for CO_2-EOR projects may not be as robust as other oil and gas exploration and development investments. Therefore, companies needing relatively quick payback and high rates of return may not find CO_2-EOR investments attractive without incentives. On the other hand, the advantage of CO_2-EOR is that it generally has lower risks than exploration projects, large reserves associated with its application can be booked initially, increasing company value, and production from CO_2-EOR can provide sustained company cash flow for extended periods of time.

In addition, some company cultures are not well-suited for dealing with the vagaries and uncertainties associated with engineering, developing, and operating CO_2-EOR projects. Historically, CO_2-EOR projects tended to be performed by large, somewhat entrepreneurial integrated oil companies and large independents, though as shown in Table 2, some smaller independents are now having some success pursuing CO_2-EOR. For example, the SACROC Unit, where commercial CO_2-EOR began, is now in the hands of an independent -- Kinder Morgan CO_2 Company -- which is the second largest producer of oil in Texas and one of the nation’s largest owners and transporters of CO_2. Kinder Morgan has more than tripled SACROC production since acquiring a majority interest in the unit in 2000.

Perhaps the best way to explain the typical “business model” for a CO_2-EOR company is to look at the two largest in the U.S., both in terms of the number of projects and in the volume of CO_2-EOR production – Occidental Petroleum (Oxy) and Denbury Resources.

The most active CO_2-EOR operator in the U.S. is Oxy, which operates more than half of the current CO_2 floods in the Permian Basin, and is the one of the largest oil producers in Texas. Oxy currently operates 32 CO_2-EOR projects in the U.S., and injected 28 million metric tons of CO_2 for EOR in 2009. Of this amount, over half is recycled from producing wells. Oxy is actively pursuing projects with other parties, such as the Century hydrocarbon gas processing plant in West Texas where CO_2 that otherwise would have been emitted will instead be captured for injection in Oxy's CO_2-EOR operations. Oxy states that it believes that underground injection of CO_2, especially as practiced during CO_2-EOR, is a ready method for the large-scale geologic sequestration of CO_2 that otherwise would be emitted to the atmosphere. Oxy believes that CO_2-EOR validates the commercial and technical availability of geologic storage.[27]

Denbury Resources has taken significant steps over the past decade to strategically position itself through a focused acquisition, divestiture and organic growth strategy to emerge as the largest independent, purely CO_2-EOR-focused company in the U.S. For example, Denbury divested of its lucrative Barnett Shale assets to purchase the Conroe Oil Field in Southeast Texas, and more recently acquired Encore Acquisition Company -- nearly doubling the size of the company – to expand its interest in CO_2-EOR from just the Gulf Coast to the Rocky Mountain region. In addition, it is effectively advocating to environmental and governmental policy makers that depleted and depleting oil fields are a source of significant domestic recoverable oil reserves and a proven “CO_2 solution” for industrial CCS.[28]

Denbury Resources is going beyond just incremental increases in capacity by taking a more strategic, long-term approach to pursuing CO_2-EOR projects, and to secure the CO_2 to supply these projects. Today, Denbury relies on natural CO_2 from its massive Jackson Dome CO_2-filled reservoir in Mississippi. However, as Denbury’s inventory of candidate oil fields for CO_2-EOR grows, it recognizes that it needs to develop additional sources of natural CO_2 at Jackson Dome and to acquire access to additional supplies from anthropogenic sources of CO_2. Denbury Resources has entered into contingent purchase contracts for 14 million metric tons per year of anthropogenic CO_2 in the Gulf Coast, and has identified 17 million metric tons per year of anthropogenic CO_2 potentially available for EOR in the Rockies.[29]

Moreover, Denbury plans to expand its existing infrastructure to bring additional captured CO_2 to the CO_2-EOR market that already exists. The company’s signed CO_2 purchase contracts, along with other anthropogenic sources of CO_2 supplies it is actively pursuing to supplement its natural reserves (Figure 5); supplies which are projected to decline beginning around 2015 (Figure 6) . Denbury is also increasing its CO_2 pipeline capacity into East Texas. The 510 kilometre “Green Pipeline” is designed to transport up to 13 million metric tons per year of both natural and anthropogenic CO_2.[30]

Figure 5. U.S Gulf Coast CO_2 Sources for Denbury Resources

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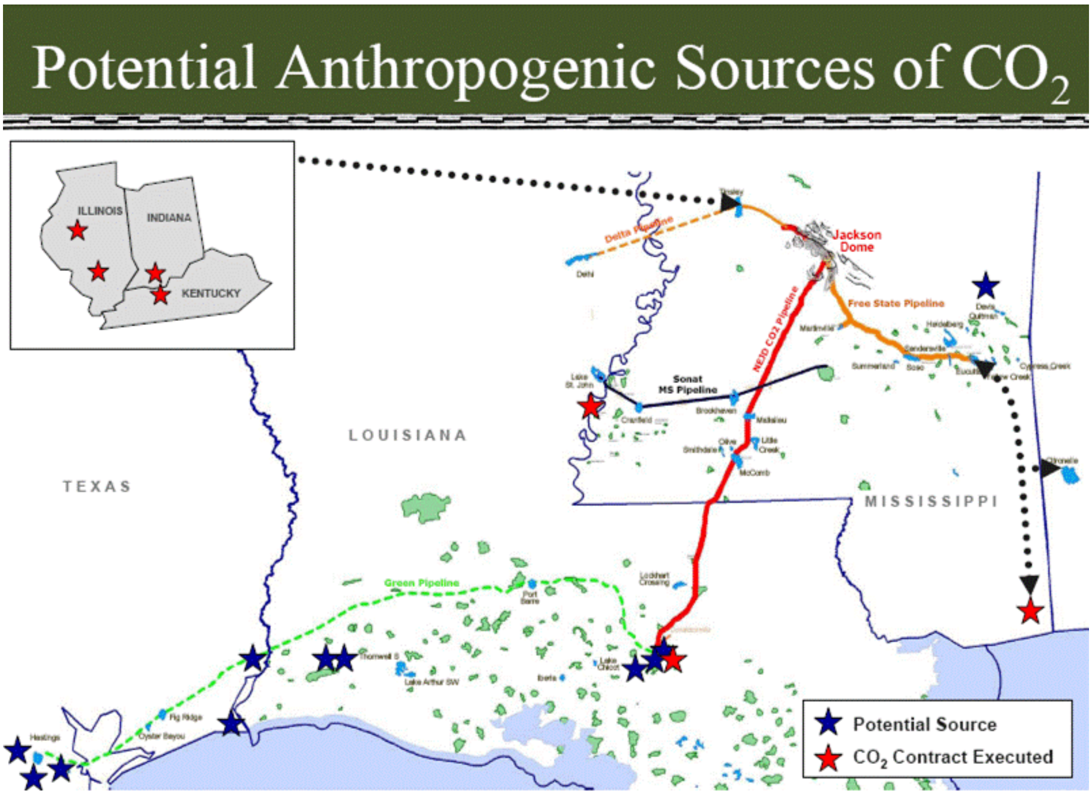
[27] http://www.oxy.com/sr/4-6_climate_change.asp

[28] Schnacke, Greg, “Denbury’s Business Model Demonstrates Feasibility Of CO_2-EOR In Mature Fields, *American Oil and Gas Reporter*, February 2010 (http://www.aogr.com/index.php/magazine/cover_story_archives/february_2010_cover_story)

[29] http://www.denbury.com/CO2Assets.htm

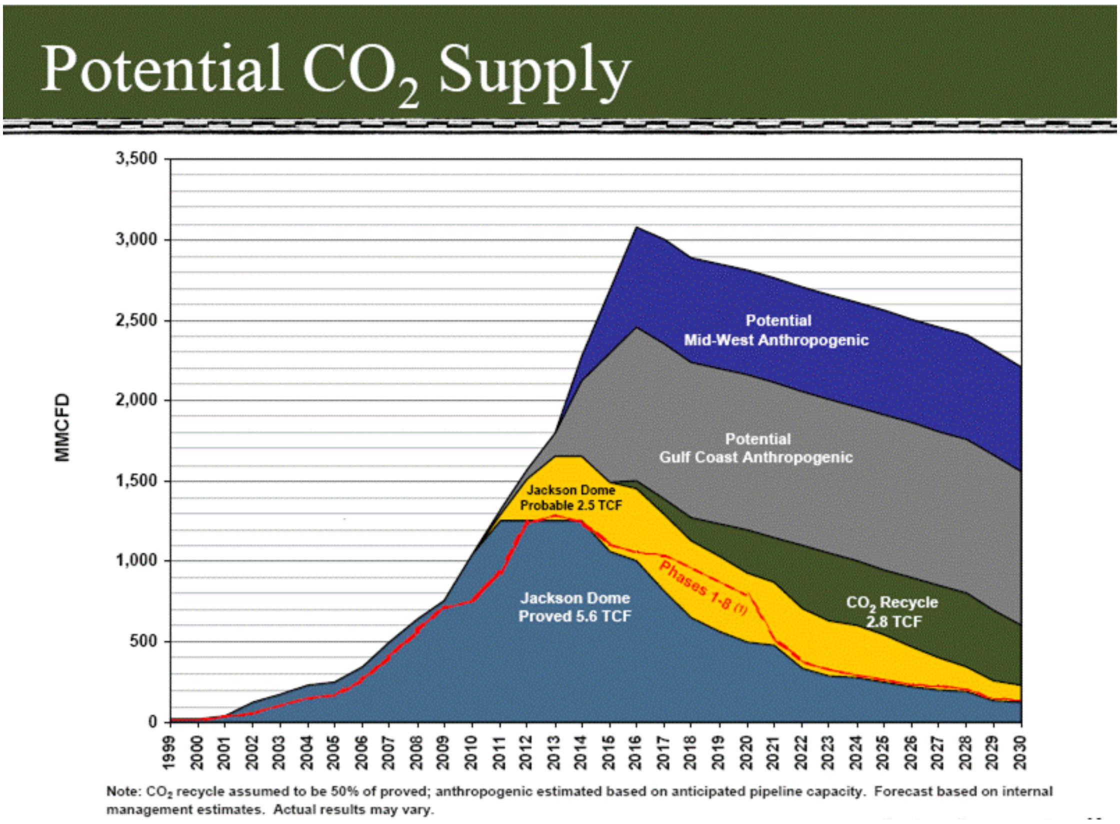
[30] http://www.denbury.com/index.php?id=51



Potential Anthropogenic Sources of CO_2

Source: Denbury Resources Inc., June 2009 Corporate Presentation

Figure 6. Denbury Resources' Strategic Vision for Supplying U.S. Gulf Coast CO_2-EOR Market



Note: CO_2 recycle assumed to be 50% of proved; anthropogenic estimated based on anticipated pipeline capacity. Forecast based on internal management estimates. Actual results may vary.

Source: Denbury Resources Inc., June 2009 Corporate Presentation

Finally, Denbury is also looking at even bigger plans for moving CO_2 from areas where there are high concentrations of emissions, to areas where there is large potential for CO_2-EOR. In July 2009, Denbury initiated a feasibility study of a possible CO_2 pipeline project connecting proposed gasification plants in the Midwest to its existing CO_2 pipeline infrastructure in Mississippi and Louisiana (Figure 7). The study is expected to determine the most likely pipeline route, the estimated costs of constructing such a pipeline, and review regulatory, legal and permitting requirements.[31] Denbury has already entered into contingent purchase contracts for 18 million metric tons per year of anthropogenic CO_2 in the Midwest to supply this pipeline, should it be built.

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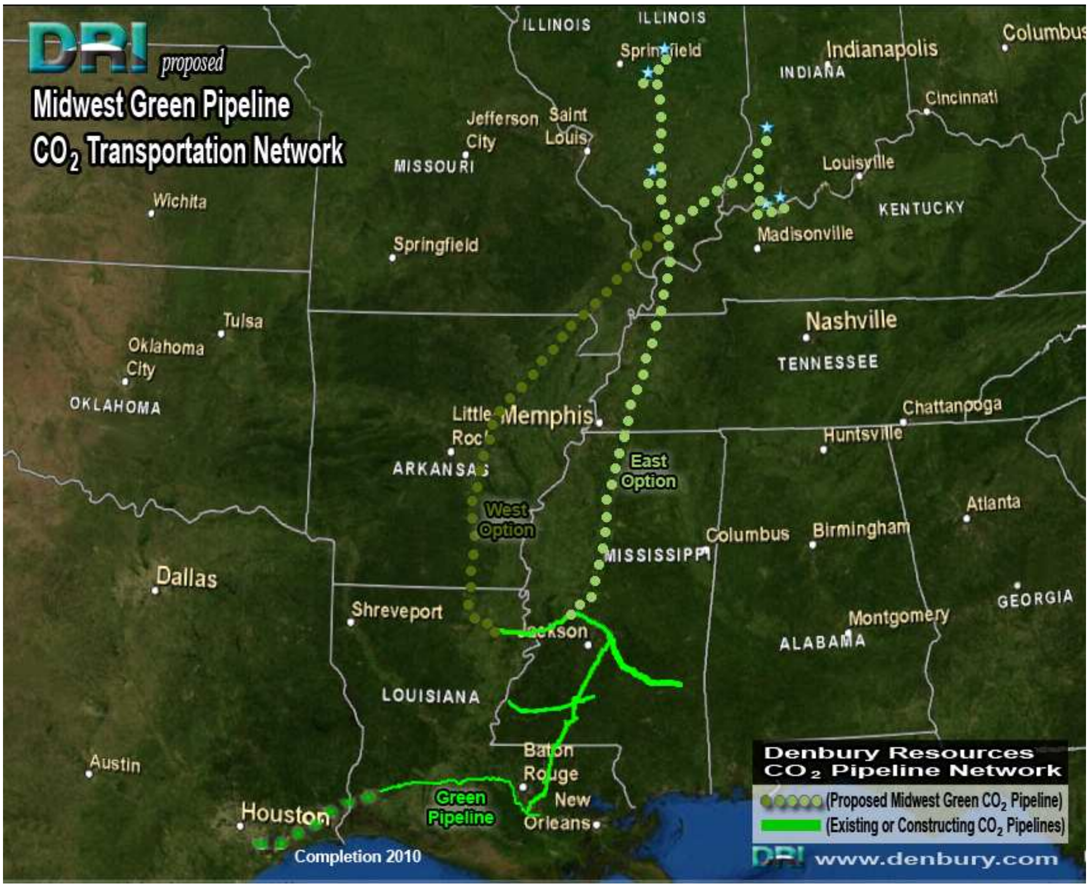
[31] Denbury Undertakes Midwest CO_2 Pipeline Feasibility Study, Denbury Press Release, July 13, 2009 (http://phx.corporate-ir.net/phoenix.zhtml?c=72374&p=irol-newsArticle&ID=1307101&highlight=) and http://www.denbury.com/index.php?id=53

Figure 7. Denbury Resources' Strategic Vision for Moving Midwest CO_2 Supplies to the U.S. Gulf Coast CO_2-EOR Market



Source: Denbury Resources Inc.

ECONOMICS OF CO_2-EOR

Summary of Costs for CO_2-EOR

CO_2-EOR projects have been successfully pursued when oil prices were as low as $15 per barrel. Nonetheless, as oil prices increase, the economic viability of CO_2-EOR improves. The relationship between the price of oil, the cost of CO_2, and the volume of economically recoverable volumes of oil through the application of CO_2-EOR are discussed later in this report.

The costs associated with a CO_2-EOR project are site and situation-specific. Detailed reservoir studies, project plans, and economic assessments are required to determine the economic viability of a specific CO_2-EOR project. Costs for CO_2-EOR operations can vary widely based on location, the geologic characteristics of the CO_2-EOR target, the state of development/depletion of the target field, and the amount of CO_2 required.

Implementing a CO_2-EOR project is a capital-intensive undertaking, even though generally the single largest project expense is the purchase of CO_2. Total CO_2 costs (both purchase price and recycle costs) can amount to 25% to 50% of the cost per barrel of oil produced. As such, operators have historically strived to optimize and reduce the cost of its purchase and injection wherever possible.

However, CO_2 costs are not the only costs affecting the economics of CO_2-EOR projects. Up front expenditures also include mechanical integrity reviews of well bores and surface production facilities; pressure testing casing and replacing old tubing; installing new wellheads, flow lines, as well as addressing any potential local environmental concerns. In addition, large CO_2 separation facilities must be built to separate, recycle, and compress CO_2 recovered from produced oil for subsequent reinjection. New injection and production wells (to reduce pattern spacing) may need to also be drilled, and CO_2 (and possibly water) distribution lines will need to be installed. Once injection begins, it can be a number of months before sufficient oil field pressure is reached and oil production can be realized.

However, these costs are comparable to conducting secondary oil recovery operations. In geologically and geographically favorable settings, and the cost increase specific to CO_2-EOR operations would be relatively modest, especially relative to the total costs of the full CCS stream from capture to storage. Importantly, when the CO_2 flood is started while secondary oil recovery operations are still underway, there could be the opportunity of sharing some field operating costs and utilizing water injection wells for CO_2 injection, reducing capital costs. Moreover, incremental development costs associated with CO_2-EOR in an existing field would be substantially less than in a new development.

Given this variability, caution should be exercised in quoting general cost numbers for CO_2-EOR projects. Nonetheless, the key factors influencing the various categories of costs for a CO_2-EOR project are summarized below.

1. Well Drilling and Completion. New wells may need to be drilled to configure a CO_2-EOR project into an injection/production pattern amenable for CO_2-EOR production. Well drilling and completion costs are generally a function of location and the depth of the producing formations.

2. Lease Equipment for New Producing Wells. The costs for equipping new production wells consists of a fixed costs for common items, such as free water knock-out, water

disposal and electrification, and a variable cost component to capture depth-related costs such as pumping equipment.

3. Lease Equipment for New Injection Wells. The costs associated with equipping new CO_2 injection wells include gathering lines, a header, electrical service, and a water pumping system. These costs also include a fixed cost component and a depth-related cost component, which varies based on surface pressure requirements.

4. Converting Existing Production Wells into Injection Wells. To implement a CO_2-EOR project, it is generally necessary to convert some existing oil production wells into CO_2 and water injection wells, which requires replacing the tubing string and adding distribution lines and headers. For existing fields, it can be assumed that all surface equipment necessary for water injection are already in place on the lease. Again, existing well conversion costs include a fixed cost component and a depth-related cost component, which varies based on the required surface pressure and tubing length.

5. Reworking an Existing Waterflood Production or Injection Well for CO_2-EOR (First Rework). For some existing wells, it may be necessary to rework them for CO_2-EOR application. This requires pulling and replacing the tubing string and pumping equipment. These well reworking costs are depth-dependent.

6. Annual O&M, Including Periodic Well Workovers. The annual operations and maintenance (O&M) costs associated with CO_2-EOR projects include both normal oil field O&M costs along with additional costs specific to the application of CO_2-EOR. To account for the O&M cost differences between traditional water flooding and CO_2-EOR, two adjustments are usually considered. First, workover costs are, on average, about double for CO_2-EOR because of the need for more frequent remedial well work. Second, traditional lifting costs should be subtracted from annual waterflood O&M costs to allow for the more rigorous accounting of liquid lifting volumes and costs for CO_2-EOR.

7. CO_2 Recycle Plant Investment. Operation of CO_2-EOR requires a recycling plant to capture, separate, and reinject the produced CO_2. The size of the recycle plant is based on peak CO_2 production and recycling requirements. The O&M costs of CO_2 recycling are a function of energy costs.

8. Fluid Lifting for CO_2-EOR. Liquid (oil and water) lifting costs are calculated based on total liquid production. This cost includes liquid lifting, transportation and re-injection.

9. CO_2 Distribution. The CO_2 distribution system is similar to the gathering systems used for natural gas. A distribution “hub” is constructed with smaller pipelines delivering purchased CO_2 to the project site. The distribution pipeline cost is dependent on the injection requirements for the project, and the distance of the CO_2-EOR project from the CO_2 source.

Detailed documentation of the specific unit costs associated with of CO_2-EOR can be found in a series of studies of the CO_2-EOR potential of various U.S. basins sponsored by the U.S. DOE,[32] and will not be reproduced here.

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[32] http://fossil.energy.gov/programs/oilgas/eor/Ten_Basin-Oriented_CO2-EOR_Assessments.html

Despite the wide range in potential costs, Table 3 provides some illustrative costs associated with three representative CO_2-EOR projects in the U.S., assuming that it costs $45 per metric ton for purchased CO_2, and that "next generation" technology is deployed for EOR.

In general, oil prices have by far the largest impact on the economic viability of a CO_2-EOR project. The second largest impact on economic viability tends to be associated with the cost of CO_2 to the CO_2-EOR operator.

In today's CO_2-EOR market place, the exact contract terms between buyers and sellers of CO_2 are not generally disclosed. Historical CO_2 pricing within the Permian Basin can be viewed as establishing the current standard for pricing for CO_2 -EOR. When source fields and associated pipelines were completed in the early 1980s, CO_2 delivered to the oil lease was priced at around $19 to $24 per metric ton. At the time, oil price expectations were optimistic. The oil price crash in 1986 changed this. New contracts had delivered CO_2 prices of $9 to $11 per metric ton, and oil price escalators were incorporated into contract terms.

With the advent of the CO_2 market supply deficiencies in the Permian Basin, index (base) prices have climbed, escalators start at higher levels, and CO_2 prices are not capped like in the past. Some suppliers are keeping the CO_2 for themselves whereas, in the past, some supplier competition was always present. Moreover, many current contracts were originally written without assuming today's relatively higher anticipated oil prices. Should oil prices remain at sustainably higher levels, new contract terms may evolve. In today's market, with oil prices in excess of $100 per barrel, delivered CO_2 costs where some CO_2 -EOR projects remain economically viable could be as high as $40 to $45 per metric ton.

On the other hand, under a market where CO_2 emission reductions have value, "gas-on-gas" competition for new CO_2 sources entering the market may put downward pressure on CO_2 prices. If increasingly strict requirements are implemented for limiting CO_2 emissions, particularly for new energy sources, producers/emitters of CO_2 may become increasingly willing to provide CO_2 supplies to CO_2-EOR projects at competitive or even lower delivered CO_2 costs. Assuming that such policies serve to reduce prices for delivered CO_2 to merely the cost of compression and transportation, costs of CO_2 on the order of $15 per metric ton are conceivable.

Table 3. Illustrative Costs for Representative CO_2-EOR Projects in the U.S.

Example EOR Field	**East Texas Reservoir**	**California Reservoir**	**Oklahoma Reservoir**
Field Info			
Depth	5,750	5,319	6,700
Total Oil Production (Million Barrels)	112.0	140.0	81.3
Discount Rate	10%	10%	10%
Injected CO_2 (Tonnes/Bbl)	0.24	0.28	0.23
Produced Oil (Bbls/ton of Captured CO_2)	**4.12**	**3.63**	**4.33**
Project Info			
No of Patterns	24	40	257
Existing Injectors Used	24	7	0
Convertible Producers Used	0	0	0
New Injectors Drilled	0	0	257
Existing Producers Used	0	54	290
New Producers Drilled	0	54	290
API Gravity (° API)	43	24	37
Project Length (years)	34	29	23
Technology Case	Next Gen	Next Gen	Next Gen
Capital Costs ($Million, discounted)			
Wells			
New Well - D&C	$ 32.10	$ -	$ -
New Well - Next Generation D&C	$ 32.10	$ 80.31	$ 654.96
Reworks - Producers to Producers	$ -	$ 4.62	$ 27.80
Reworks - Producers to Injectors	$ -	$ 7.61	$ 63.99
Reworks - Injectors to Injectors	$ 2.11	$ 1.32	$ -
Surface Equipment (new wells only)	$ 14.15	$ 10.51	$ 79.55
Plugging Costs	$ 1.35	$ 19.23	$ 17.25
Sub Total	**$ 81.81**	**$ 123.59**	**$ 843.54**
$/Bbl	**$ 2.12**	**$ 2.33**	**$ 23.76**
Other			
CO_2 Recycling Plant	$ 45.90	$ 66.94	$ 43.35
Trunkline Construction	$ 3.15	$ 3.15	$ 3.15
Next Generation Capex	$ 13.09	$ 19.37	$ 89.00
Cap Ex G&A	$ 28.79	$ 42.61	$ 195.81
Pipeline to Field	$ 54.30	$ 54.30	$ 54.30
Sub Total	**$ 145.22**	**$ 186.37**	**$ 385.61**
$/Bbl	**$ 3.76**	**$ 3.52**	**$ 10.86**
Total Capex	**$ 227.03**	**$ 309.96**	**$ 1,229.15**
$/Bbl	**$ 5.88**	**$ 5.85**	**$ 34.61**
O&M Costs ($/Bbl, discounted)			
Operating & Maintenance	$ 0.73	$ 0.85	$ 6.33
Operating & Maintenance Next Gen	$ 0.07	$ 0.08	$ 0.63
Lifting Costs	$ 1.51	$ 3.19	$ 2.04
G&A	$ 0.45	$ 0.81	$ 1.67
Pipeline	$ 0.05	$ 0.05	$ 0.05
Total O&M Costs	**$ 2.80**	**$ 4.98**	**$ 10.72**

Relative Cost Impact of CO_2–EOR on CCS

The greatest impact associated with CCS in value-added reservoirs such as CO_2-EOR may be derived from their ability to produce incremental oil, offsetting other costs associated with deploying CCS. CO_2-EOR also offers benefits to the body of knowledge needed to implement CCS, including useful experience in handling and injecting CO_2. Finally, and perhaps most importantly from the perspective of CO_2-EOR, advances in CO_2-EOR technology will perhaps have greater impact on expanding the volume of the CO_2 storage capacity and injectivity associated with CO_2-EOR.

Therefore, many have concluded that CO_2-EOR can represent a critical step towards the development of long-term, commercial scale CCS. This results from the fact that the application of CCS with CO_2-EOR can provide multiple benefits, such as:[33,34,35]

- Lowering the cost of deploying CCS for large stationary point sources of CO_2
- Accelerating the deployment of the “essential” backbone for a CO_2 pipeline network that would be used by later CCS adopters[36]
- Enhancing a country’s energy security
- Stimulating economic development and employment growth

The application of CO_2-EOR is a relatively mature technology, and will not likely have the same types of learning curve cost efficiency improvements believed possible for CO_2 capture. While some cost reductions could be realized, especially in areas where CO_2-EOR has been deployed only minimally or not all, large scale costs reductions specific to EOR are unlikely.

However, as producing oil fields around the world begin to reach a level of maturing that is comparable to that in the U.S. today, more of these depleting oil fields become potential prospects for CO_2-EOR. When they begin to reach this point, greater pressure may be placed on finding more sources of low-cost, reliable supplies of CO_2 to facilitate the deployment of CO_2-EOR.

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[33] Advanced Resources International, *U.S. Oil Production Potential from Accelerated Deployment of Carbon Capture and Storage*, prepared for the Natural Resources Defense Council, 2010 (http://www.adv-res.com/pdf/v4ARI%20CCS-CO2-EOR%20whitepaper%20FINAL%204-2-10.pdf)

[34] Southern States Energy Board, *America's Energy Security: Building a Bridge to Energy Independence and to a Sustainable Energy Future*, 2006

[35] Fernando, H., Venezia, J., Rigdon, C., Verma, P., *Capturing King Coal: Deploying Carbon Capture and Storage Systems in the U.S. at Scale*, World Resources Institute and Goldman Sachs Center for Environmental Markets, 2008

[36] ICF, *Developing a Pipeline Infrastructure for CO_2 Capture and Storage: Issues and Challenges*, report prepared for the Interstate Natural Gas Association of America Foundation, 2009

GLOBAL POTENTIAL FOR CO_2-EOR

Potential Technically Recoverable Reserves from CO_2 –EOR

In a recent study performed by Advanced Resources and published IEA GHG,[37] a data base of the largest 54 oil basins of the world (that account for approximately 95% of the world's estimated ultimately recoverable (EUR) oil potential) was developed. Defined technical criteria were used to identify and characterize world oil basins with potential for CO_2-EOR. From this, a high-level, first-order assessment of the CO_2-EOR oil recovery and CO_2 storage capacity potential in these basins was developed using the U.S. experience as analogue.[38] This methodology is outlined in brief in Table 4.

Table 4. Overview of Methodology for Screening-Level Assessment of CO_2-EOR Potential and CO_2 Storage in World Oil Basins

Step	Basin-Level Average Data Used	Basis	Result
1. Select World Oil Basins favorable for CO_2-EOR operations	Volume of oil cumulatively produced and booked as reserves	Basins with significant existing development, and corresponding oil and gas production expertise, will likely have the most success with CO_2-EOR.	List of 54 (14 U.S., 40 in other regions) oil basins favorable for CO_2-EOR
2. Estimate the volume of original oil in place (OOIP) in world oil basins	API gravity; ultimately recoverable resource	Correlation between API gravity and oil recovery efficiency from large U.S oil reservoirs.	Volume of total OOIP in world oil basins
3. Characterize oil basins, and the potential fields within these basins, amenable to CO_2-EOR	Reservoir depth in basin, API gravity	Characterization based on results of assessment of U.S. reservoirs amenable to miscible CO_2-EOR	OOIP in basins and fields amendable to the application of miscible CO_2-EOR
4. Estimate CO_2-EOR flood performance/recovery efficiency	API gravity; reservoir depth	Regression analysis performed on large dataset of U.S. miscible CO_2-EOR reservoir candidates	CO_2-EOR recovery efficiency (% of OOIP)
5. Estimate the volume of oil technically recoverable with CO_2-EOR	OOIP; CO_2-EOR recovery efficiency	Regression analysis performed on large dataset of U.S. miscible CO_2-EOR reservoir candidates	Volume of Oil recoverable with CO_2-EOR
6. Estimate volume of CO_2 stored by CO_2-EOR operations	Technically recoverable oil from CO_2-EOR	Ratio between CO_2 stored and oil produced in ARI's database of U.S. reservoirs that are candidates for miscible CO_2-EOR	Volume of CO_2 used and ultimately stored during CO_2-EOR operations

Source: IEA Greenhouse Gas R&D Programme, *CO_2 Storage in Depleted Oilfields: Global Application Criteria for Carbon Dioxide Enhanced Oil Recovery,* Report IEA/CON/08/155, Prepared by Advanced Resources International, Inc. and Melzer Consulting, August 31, 2009

These basin-level, first-order estimates were compared with detailed reservoir modelling of 47 large oil fields in six of these basins, and the first-order estimates were determined to be acceptable.

Accurately estimating the actual performance of CO_2-EOR operations is a much more complex and data intensive effort than that conducted here. This process can often take months or years to perform on a single candidate field. Moreover, it requires substantial amounts of

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[37] IEA Greenhouse Gas R&D Programme, CO_2 Storage in Depleted Oilfields: Global Application Criteria for Carbon Dioxide Enhanced Oil Recovery, Report IEA/CON/08/155, Prepared by Advanced Resources International, Inc. and Melzer Consulting, August 31, 2009

[38] U.S. Department of Energy/National Energy Technology Laboratory, *Storing CO_2 and Producing Domestic Crude Oil with Next Generation CO_2-EOR Technology: An Update*, report DOE/NETL-2010/1417 prepared by Advanced Resources International, April 2010

detailed field- and projectspecific data, most of which is generally only available to the owner and/or operator of a field.

While data access and time constraints prevented the application of this level of rigor to estimating the worldwide performance of potential future CO_2-EOR projects, this methodology was developed which builds upon Advanced Resources' large volume of data on U.S. crude oil reservoirs and on existing CO_2-EOR operations in the United States. However, it is not a substitute for a more comprehensive assessment when investing in such projects.

The results of the application of this methodology in the above-referenced IEA GHG study are shown in Table 5. The study concluded that CO_2-EOR offers a large, near-term option to store CO_2. Fifty of the largest oil basins of the world have reservoirs amenable to the application of miscible CO_2-EOR, and have the potential to produce 470 billion barrels of additional oil, and store 140 billion metric tons of CO_2 with the application of “state-of-the-art” CO_2-EOR technology.

Of the original 54 basins, three of the top world oil basins (San Jorge Basin, Northwest Java Basin, and the Central Sumatra Basin) were determined to not be amenable to CO_2-EOR because they were, on average, too shallow, and therefore, the CO_2 injected would not achieve miscibility. One basin (Bombay Basin) was screened out because the oil in the basin, on average, was too light (API gravity greater than 50 degrees API) for miscible CO_2-EOR.

If CO_2-EOR technology could also be successfully applied to smaller fields, the additional anticipated growth in reserves in discovered fields, and resources that remain in fields that are yet to be discovered, the world-wide application of “state-of-the-art” CO_2-EOR technology could recover over 1 trillion additional barrels of oil, with associated CO_2 storage of 320 billion metric tons.

As shown in Table 5, over 230 billion barrels of potential resource potential from CO_2-EOR, or nearly half of the overall global potential, exists in basins in the Middle East and North Africa. Only about 18 billion barrels, or about 4% of the overall global potential, is estimated to exist in Southeast Asia.

Table 5. Estimated CO_2 Storage Potential from the Application of "State-of-the-Art" CO_2-EOR in World Oil Basins

Region Name	CO_2 EOR Oil Recovery (MMBO)	Miscible Basin Count	CO_2 Oil Ratio (tonnes/Bbl)	CO_2 Stored (Gigatonnes)
Asia Pacific	18,376	6	0.27	5.0
Central and South America	31,697	6	0.32	10.1
Europe	16,312	2	0.29	4.7
Former Soviet Union	78,715	6	0.27	21.6
Middle East and North Africa	230,640	11	0.30	70.1
North America/Non-U.S.	18,080	3	0.33	5.9
United States	60,204	14	0.29	17.2
South Asia	-	0	N/A	-
Sub-Saharan Africa and Antarctica	14,505	2	0.30	4.4
Total	**468,530**	**50**	**0.30**	**139.0**

Source: IEA Greenhouse Gas R&D Programme, *CO_2 Storage in Depleted Oilfields: Global Application Criteria for Carbon Dioxide Enhanced Oil Recovery,* Report IEA/CON/08/155, Prepared by Advanced Resources International, Inc. and Melzer Consulting, August 31, 2009

A detailed compilation of the estimates of original oil in place, ultimate primary and secondary oil recovery, incremental technically recoverable oil from CO_2-EOR, and the volume of CO_2 stored in association with CO_2-EOR is provided in Table 6 for the 50 world oil basins with favorable conditions for miscible CO_2-EOR considered in this assessment.

Based on previous Advanced Resources' work on U.S. basins, a set of curves were developed that represent incremental oil production potential from the application of CO_2-EOR and associated CO_2 requirements as a function of crude oil price and the cost of delivered CO_2, at sufficient pressure to achieve miscibility, paid by the oil producer.[39] Specifically, these curves represent incremental oil recovery potential from "state-of-the-art" CO_2-EOR technology as a percentage of original oil in place (OOIP) in U.S. oil fields amenable to miscible CO_2-EOR, as shown in Table 7.

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[39] IEA Greenhouse Gas R&D Programme, *CO_2 Storage in Depleted Oilfields: Global Application Criteria for Carbon Dioxide Enhanced Oil Recovery*, Report IEA/CON/08/155, Prepared by Advanced Resources International, Inc. and Melzer Consulting, August 31, 2009

Table 6. Summary of Results for the Basins Considered in the IEA GHG Assessment

Basin Name	Main Country	Location	Known Oil (MMBO)	Recovery Efficency	Discovered Fields OOIP (MMBO)	OOIP in Large Fields for CO2-EOR (MMBO)	Large Field OOIP Favorable for Miscible CO2-EOR (MMBO)	EOR Recovery Efficency	Large Field EOR Oil Technically Recoverable (MMBO)	CO2/Oil Ratio (tonnes /Bbl)	CO2 Stored in Large Fields (Gigatons)
Mesopotamian Foredeep Basin	Saudi Arabia	Onshore	292,442	32%	908,501	663,206	449,559	20%	89,069	0.31	27.2
West Siberian Basin	Russia	Onshore	139,913	34%	412,441	301,082	204,091	21%	43,683	0.27	11.7
Greater Ghawar Uplift	Saudi Arabia	Onshore	141,700	36%	394,328	287,859	195,128	22%	43,348	0.30	13.2
Zagros Fold Belt	Iraq	Onshore	121,601	33%	369,291	269,582	182,739	21%	39,274	0.30	11.8
Rub Al Khali Basin	Emirates	Offshore	89,827	37%	245,615	179,299	121,539	23%	27,977	0.31	8.8
Volga-Ural Region	Russia	Onshore	63,937	33%	193,683	141,388	95,841	20%	19,130	0.27	5.2
North Sea Graben	United Kingdom	Offshore	43,894	34%	127,914	93,377	63,297	23%	14,373	0.28	4.0
Maracaibo Basin	Venezuela	Offshore	49,072	31%	157,328	114,849	77,851	18%	14,307	0.32	4.5
Permian Basin	United States	Onshore	31,131	33%	95,400	72,380	61,426	22%	13,428	0.31	4.1
Villahermosa Uplift	Mexico	Onshore	35,022	34%	104,134	76,018	51,529	24%	12,333	0.34	4.1
Sirte Basin	Libya	Onshore	37,073	34%	110,538	80,693	54,698	22%	11,765	0.29	3.4
North Slope	United States	Onshore	20,848	33%	64,074	62,295	61,434	19%	11,373	0.27	3.1
Niger Delta	Nigeria	Offshore	34,523	32%	106,913	78,047	52,905	20%	10,448	0.30	3.1
East/Central Texas Basins	United States	Onshore	37,287	34%	109,000	67,372	44,024	21%	9,392	0.26	2.4
East Venezuela Basin	Venezuela	Onshore	30,203	31%	96,942	70,767	47,970	18%	8,707	0.31	2.7
Bohaiwan Basin	China	Onshore	24,554	33%	73,998	54,018	36,617	20%	7,443	0.27	2.0
Widyan Basin-Interior Platform	Saudi Arabia	Onshore	17,435	27%	65,553	47,854	32,438	22%	7,068	0.32	2.3
Mid-Continent Basins	United States	Onshore	24,461	27%	89,600	53,133	28,005	23%	6,359	0.25	1.6
South Caspian Basin	Turkmenistan	Offshore	17,439	34%	51,984	37,948	25,723	22%	5,697	0.30	1.7
Trias/Ghadames Basin	Algeria	Onshore	15,203	35%	43,514	31,766	21,533	24%	5,185	0.29	1.5
Alberta Basin	Canada	Onshore	15,279	36%	42,573	31,078	21,067	22%	4,724	0.31	1.4
LA Offshore	United States	Offshore	9,571	34%	28,100	22,251	22,055	21%	4,594	0.35	1.6

Table 6. Summary of Results for the Basins Considered in the IEA GHG Assessment (continued)

Basin Name	Main Country	Location	Known Oil (MMBO)	Recovery Efficency	Discovered Fields OOIP (MMBO)	OOIP in Large Fields for CO2-EOR (MMBO)	Large Field OOIP Favorable for Miscible CO2-EOR (MMBO)	EOR Recovery Efficency	Large Field EOR Oil Technically Recoverable (MMBO)	CO2/Oil Ratio (tonnes /Bbl)	CO2 Stored in Large Fields (Gigatons)
Songliao Basin	China	Onshore	15,575	33%	47,592	34,742	23,550	19%	4,495	0.26	1.2
Gulf Coast Basins	United States	Onshore	16,950	38%	44,400	26,413	19,978	21%	4,131	0.32	1.3
West-Central Coastal	Gabon	Offshore	13,717	32%	43,459	31,725	21,505	19%	4,057	0.31	1.3
Timan-Pechora Basin	Russia	Onshore	13,120	33%	39,404	28,765	19,498	20%	3,943	0.27	1.1
North Caspian Basin	Kazakhstan	Onshore	10,809	43%	25,140	18,352	12,440	26%	3,226	0.34	1.1
Red Sea Basin	Egypt	Offshore	9,860	32%	30,632	22,362	15,158	20%	3,072	0.32	1.0
Campos Basin	Brazil	Offshore	10,056	31%	32,947	24,051	16,303	19%	3,072	0.36	1.1
Middle Caspian Basin	Turkmenistan	Offshore	9,552	34%	28,507	20,810	14,106	22%	3,036	0.29	0.9
Rockies Basins	United States	Onshore	10,437	31%	33,600	23,662	13,779	19%	2,625	0.28	0.7
San Joaquin Basin	United States	Onshore	15,691	36%	43,861	39,595	8,792	25%	2,164	0.25	0.5
Junggar Basin	China	Onshore	6,810	33%	20,809	15,191	10,297	20%	2,084	0.29	0.6
Putumayo-Oriente-Maranon Basin	Colombia	Onshore	6,601	31%	21,050	15,367	10,416	19%	1,945	0.32	0.6
Carpathian-Balkanian Basin	Romania	Onshore	5,908	33%	17,928	13,087	8,871	22%	1,939	0.32	0.6
Baram Delta/Brunei-Sabah Basin	Brunei	Offshore	6,898	31%	22,213	16,215	10,992	17%	1,895	0.29	0.6
Llanos Basin	Colombia	Onshore	5,403	33%	16,380	11,958	8,106	23%	1,867	0.35	0.6
Williston Basin, US	United States	Onshore	3,739	28%	13,200	9,299	7,153	26%	1,827	0.27	0.5
Tampico-Misantla Basin	Mexico	Onshore	6,895	30%	22,689	16,563	11,227	16%	1,799	0.30	0.5
Interior Homocline-Central Arch	Saudi Arabia	Onshore	4,700	32%	14,616	10,670	7,233	20%	1,421	0.30	0.4
Fahud Salt Basin	Oman	Onshore	4,473	35%	12,645	9,231	6,257	22%	1,346	0.29	0.4
Gippsland Basin	Australia	Offshore	3,861	36%	10,832	7,907	5,360	24%	1,286	0.25	0.3
Coastal California Basin	United States	Onshore	3,535	25%	14,008	12,646	4,786	25%	1,179	0.29	0.3
Malay Basin	Malaysia	Offshore	3,608	36%	10,109	7,380	5,002	23%	1,173	0.24	0.3
Illizi Basin	Algeria	Onshore	3,670	35%	10,608	7,744	5,249	21%	1,114	0.23	0.3
Los Angeles Basin	United States	Onshore	7,019	28%	25,431	22,958	7,563	14%	1,096	0.27	0.3
Williston Basin, Canada	Canada	Onshore	3,505	39%	9,011	6,578	4,459	23%	1,024	0.31	0.3
Appalachia	United States	Onshore	1,144	8%	14,000	11,657	3,905	22%	856	0.34	0.3
Cook Inlet	United States	Onshore	1,388	43%	3,226	3,137	3,026	22%	670	0.32	0.2
Illinois Basin	United States	Onshore	6,170	35%	17,800	11,985	4,422	12%	512	0.27	0.1
Total			**1,503,509**	**33%**	**4,537,521**	**3,316,311**	**2,240,904**	**21%**	**468,530**	**0.30**	**139**

Source: IEA Greenhouse Gas R&D Programme, *CO_2 Storage in Depleted Oilfields: Global Application Criteria for Carbon Dioxide Enhanced Oil Recovery,* Report IEA/CON/08/155, Prepared by Advanced Resources International, Inc. and Melzer Consulting, August 31, 2009

Table 7. Economic Incremental Oil Recovery Potential from Miscible CO_2-EOR in the U.S. as a Function of Crude Oil Price and Delivered CO_2 Cost

Incremental Economic Oil Produced (% OOIP)				
CO_2 Lease-Gate Cost		Oil Price ($ per Barrel)		
$/metric ton	$/Mcf	$30	$70	$100
$ -	$0.00	13.16%	15.56%	16.07%
$ 15.00	$0.79	11.03%	15.22%	15.92%
$ 30.00	$1.59	5.51%	14.82%	15.69%
$ 45.00	$2.38	2.46%	14.21%	15.50%
$ 60.00	$3.17	0.35%	13.48%	15.28%
$ 75.00	$3.97	0.14%	11.73%	14.73%

Source: IEA Greenhouse Gas R&D Programme, *CO_2 Storage in Depleted Oilfields: Global Application Criteria for Carbon Dioxide Enhanced Oil Recovery,* Report IEA/CON/08/155, Prepared by Advanced Resources International, Inc. and Melzer Consulting, August 31, 2009

Relative Location of Industrial CO_2 Sources to Basins Amenable to CO_2-EOR

Up to this point, this assessment has focused on assessing the oil recovery and associated CO_2 storage potential of CO_2-EOR in world oil basins. The third important criterion discussed in this report is the availability of sufficient, affordable and sustainable volumes of CO_2 supplies from industrial sources for use in CO_2-EOR.

In this study, location information for individual fields within each oil basin was generally not available. Therefore, *this assessment was performed based on the proximity of industrial sources of CO_2 emissions to basins containing fields that were amenable to miscible CO_2-EOR.* A high-level assessment was previously performed by Advanced Resources for IEA GHG[40] of the relative contribution that industrial sources of CO_2 could make in facilitating the recovery of the worldwide resource potentially recoverable through the application of CO_2-EOR technologies.

Data on global anthropogenic CO_2 emissions were gathered from the 2010 version of the IEA GHG CO_2 Emissions Database.[41] Data on industrial emissions sources were projected into a GIS map containing the location and spatial extent of the hydrocarbon basins identified as having CO_2-EOR potential. For purposes of this exercise, two sets of analyses were performed. The first just focused on the high purity sources considered in the global technology road mapping exercise for CCS in industry – natural gas processing plants, coal-to-liquids facilities, ethylene plants, and ammonia/fertilizer facilities. The second set includes all sources of industrial emissions, other than power plants. For the purposes of this study, two scenarios were assumed for identifying viable sources of CO_2 near each oil basin: those within 50 kilometres of the boundary of a basin, and those within 100 kilometres of the boundary of a basin.

After screening for distance criteria, each basin's spatial reference information was used to create basin-specific databases of CO_2 emissions. These databases were disaggregated by

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[40] IEA Greenhouse Gas R&D Programme, CO_2 Storage in Depleted Oilfields: Global Application Criteria for Carbon Dioxide Enhanced Oil Recovery, Report IEA/CON/08/155, Prepared by Advanced Resources International, Inc. and Melzer Consulting, August 31, 2009

[41] The IEA GHG CO_2 Emissions Database can be accessed at http://www.co2captureandstorage.info/co2emissiondatabase/co2emissions.htm

CO_2 emissions source and used to develop estimates of the volume of CO_2 emissions that could potentially be captured and used for CO_2-EOR operations in each basin. Then these basins were aggregated by region.

The summary of the results by region are provided in Table 8. For each region, the table summarizes the number of oil basins in the region that may contain fields that are amenable to miscible CO_2-EOR, the potential volume of incremental oil production that could result from the application of CO_2-EOR in the basins in the region, and the volume of CO_2 that would be required to be purchased and ultimately stored to achieve this volume of incremental oil production. The table also shows the portion of that demand that could be met from current industrial sources of CO_2 emissions according to the categories of industrial sources considered – high purity sources, low purity sources, and all industrial sources (the sum the high and low purity sources). These are shown for two cases – those within 50 kilometres of the boundary of a basin, and those within 100 kilometres of the boundary of a basin.

Recall that sufficient field-specific data, including data on location, were not comprehensively available for this study. Consequently, the CO_2 "source-sink matching" was performed using oil producing basins, rather than fields, matched with the individual industrial sources of CO_2 emissions.

Table 8 shows that in all regions, the supply of CO_2 from industrial sources is not sufficient to satisfy the potential demand for CO_2 for CO_2-EOR in all regions. For example, in aggregate, CO_2 from high purity industrial emission sources within 50 kilometres of the oil basins can meet only 4% of the CO_2 requirements for CO_2-EOR; and all CO_2 emissions from industrial sources can meet only 14% of the CO_2 requirements for CO_2-EOR. This numbers increase only slightly if all sources within 100 kilometres are considered.

The regions containing the more developed countries -- like North America, Australia, and Europe -- have the largest portions of industrial emissions that could be a CO_2 supply source for CO_2-EOR, especially from high purity sources. Nonetheless, all of the regions have large volumes of CO_2 emitted from industrial sources that are in relatively close proximity (within 100 kilometres) from basins containing fields that are amenable to the application of CO_2 -EOR.

The same results by basin are provided in Table 9.

Table 8. CO_2 Requirements for CO_2-EOR That Could Be Supplied by Industrial Sources

50 Kilometer Case

Region	Number of Basins	EOR Potential (MMBbls)	Purchased CO_2 Required for EOR (MMmt)	High Purity CO_2 Emissions		Low Purity CO_2 Emissions		Total Industrial CO_2 Emissions	
				(MMmt)	%	(MMmt)	%	(MMmt)	%
Africa	6	35,642	10,474	28	0%	581	6%	609	6%
Australia	1	1,286	324	0	0%	0	0%	0	0%
Canada	2	5,747	1,763	646	37%	1,069	61%	1,714	97%
China Region	3	14,022	3,838	361	9%	530	14%	890	23%
CIS	5	73,018	19,897	254	1%	854	4%	1,108	6%
East Asia	2	3,068	837	0	0%	13	2%	13	2%
Eastern Europe	1	1,939	621	121	20%	340	55%	462	74%
Latin America	6	40,959	13,167	194	1%	606	5%	800	6%
Middle East	8	215,200	65,783	475	1%	1,562	2%	2,037	3%
OECD Europe	1	14,373	4,031	383	9%	39	1%	422	10%
South America	1	3,072	1,095	0	0%	26	2%	26	2%
USA	14	60,204	17,205	2,667	16%	8,678	50%	11,345	66%
Total	**50**	**468,530**	**139,034**	**5,129**	**4%**	**14,298**	**10%**	**19,427**	**14%**

100 Kilometer Case

Region	Number of Basins	EOR Potential (MMBbls)	Purchased CO_2 Required for EOR (MMmt)	High Purity CO_2 Emissions		Low Purity CO_2 Emissions		Total Industrial CO_2 Emissions	
				(MMmt)	%	(MMmt)	%	(MMmt)	%
Africa	6	35,642	10,474	28	0%	656	6%	684	7%
Australia	1	1,286	324	0	0%	0	0%	0	0%
Canada	2	5,747	1,763	675	38%	1,169	66%	1,844	105%
China Region	3	14,022	3,838	433	11%	569	15%	1,002	26%
CIS	5	73,018	19,897	267	1%	905	5%	1,172	6%
East Asia	2	3,068	837	83	10%	25	3%	108	13%
Eastern Europe	1	1,939	621	131	21%	430	69%	561	90%
Latin America	6	40,959	13,167	194	1%	754	6%	948	7%
Middle East	8	215,200	65,783	824	1%	1,807	3%	2,632	4%
OECD Europe	1	14,373	4,031	394	10%	47	1%	441	11%
South America	1	3,072	1,095	0	0%	26	2%	26	2%
USA	14	60,204	17,205	3,031	18%	9,976	58%	13,007	76%
Total	**50**	**468,530**	**139,034**	**6,062**	**4%**	**16,363**	**12%**	**22,426**	**16%**

Table 9. Summary by Basin -- CO$_2$ Requirements for CO$_2$-EOR That Could Be Supplied by Industrial Sources

Basin Name	Region	EOR Potential		50 Kilometers									100 Kilometers								
				High Purity			Low Purity			Total			High Purity			Low Purity			Total		
		Tertiary Recovery (MMBbls)	CO$_2$ Required for EOR (MMmt)	#	Emissions (MMmt)	%	#	Emissions (MMmt)	%	#	Emissions (MMmt)	%	#	Emissions (MMmt)	%	#	Emissions (MMmt)	%	#	Emissions (MMmt)	%
Sirte Basin	Africa	11,765	3,368	1	24	1%	5	166	5%	6	190	6%	1	24	1%	5	166	5%	6	190	6%
Niger Delta	Africa	10,448	3,132	0	0	0%	4	101	3%	4	101	3%	0	0	0%	5	111	4%	5	111	4%
Trias/Ghadames Basin	Africa	5,185	1,481	0	0	0%	2	17	1%	2	17	1%	0	0	0%	4	44	3%	4	44	3%
West-Central Coastal	Africa	4,057	1,261	0	0	0%	3	71	6%	3	71	6%	0	0	0%	4	77	6%	4	77	6%
Red Sea Basin	Africa	3,072	973	1	4	0%	8	226	23%	9	230	24%	1	4	0%	9	258	27%	10	262	27%
Illizi Basin	Africa	1,114	259	0	0	0%	0	0	0%	0	0	0%	0	0	0%	0	0	0%	0	0	0%
Gippsland Basin	Australia	1,286	324	0	0	0%	0	0	0%	0	0	0%	0	0	0%	0	0	0%	0	0	0%
Alberta Basin	Canada	4,724	1,449	27	613	42%	14	967	67%	41	1,581	109%	31	635	44%	16	1,012	70%	47	1,647	114%
Williston Basin, Canada	Canada	1,024	314	6	32	10%	6	102	32%	12	134	43%	7	40	13%	7	158	50%	14	198	63%
Bohaiwan Basin	China Region	7,443	2,039	9	204	10%	14	337	17%	23	541	27%	10	239	12%	17	376	18%	27	614	30%
Songliao Basin	China Region	4,495	1,189	4	91	8%	6	159	13%	10	250	21%	5	129	11%	6	159	13%	11	288	24%
Junggar Basin	China Region	2,084	609	1	66	11%	2	34	6%	3	99	16%	1	66	11%	2	34	6%	3	99	16%
West Siberian Basin	CIS	43,683	11,654	1	10	0%	3	248	2%	4	258	2%	1	10	0%	3	248	2%	4	258	2%
Volga-Ural Region	CIS	19,130	5,219	5	134	3%	11	318	6%	16	451	9%	5	134	3%	11	318	6%	16	451	9%
Timan-Pechora Basin	CIS	3,943	1,051	0	0	0%	1	12	1%	1	12	1%	0	0	0%	1	12	1%	1	12	1%
North Caspian Basin	CIS	3,226	1,100	0	0	0%	2	88	8%	2	88	8%	0	0	0%	2	88	8%	2	88	8%
Middle Caspian Basin	CIS	3,036	874	4	111	13%	4	188	22%	8	299	34%	5	124	14%	6	239	27%	11	363	42%
Baram Delta/Brunei-Sabah B	East Asia	1,895	559	0	0	0%	1	13	2%	1	13	2%	0	0	0%	1	13	2%	1	13	2%
Malay Basin	East Asia	1,173	278	0	0	0%	0	0	0%	0	0	0%	3	83	30%	1	12	4%	4	95	34%
Carpathian-Balkanian Basin	Eastern Europe	1,939	621	10	121	20%	20	340	55%	30	462	74%	11	131	21%	27	430	69%	38	561	90%
Maracaibo Basin	Latin America	14,307	4,518	1	39	1%	4	31	1%	5	69	2%	1	39	1%	6	64	1%	7	102	2%
Villahermosa Uplift	Latin America	12,333	4,140	0	0	0%	1	18	0%	1	18	0%	0	0	0%	2	26	1%	2	26	1%
East Venezuela Basin	Latin America	8,707	2,716	2	155	6%	7	394	15%	9	550	20%	2	155	6%	8	405	15%	10	561	21%
Putumayo-Oriente-Maranon	Latin America	1,945	614	0	0	0%	1	6	1%	1	6	1%	0	0	0%	5	101	16%	5	101	16%
Llanos Basin	Latin America	1,867	648	0	0	0%	7	99	15%	7	99	15%	0	0	0%	7	99	15%	7	99	15%
Tampico-Misantla Basin	Latin America	1,799	531	0	0	0%	2	59	11%	2	59	11%	0	0	0%	2	59	11%	2	59	11%
Mesopotamian Foredeep Bas	Middle East	89,069	27,228	6	360	1%	11	555	2%	17	916	3%	6	360	1%	14	616	2%	20	977	4%
Greater Ghawar Uplift	Middle East	43,348	13,152	1	8	0%	8	385	3%	9	393	3%	4	286	2%	12	405	3%	16	690	5%
Zagros Fold Belt	Middle East	39,274	11,802	2	22	0%	12	202	2%	14	224	2%	2	22	0%	16	238	2%	18	260	2%
Rub Al Khali Basin	Middle East	27,977	8,782	2	45	1%	18	184	2%	20	230	3%	2	45	1%	23	209	2%	25	254	3%
Widyan Basin-Interior Platfo	Middle East	7,068	2,276	1	11	0%	0	0	0%	1	11	0%	3	83	4%	4	94	4%	7	177	8%
South Caspian Basin	Middle East	5,697	1,715	1	23	1%	4	67	4%	5	89	5%	1	23	1%	5	72	4%	6	95	6%
Interior Homocline-Central A	Middle East	1,421	431	1	6	2%	18	169	39%	19	176	41%	1	6	2%	19	173	40%	20	179	42%
Fahud Salt Basin	Middle East	1,346	396	0	0	0%	0	0	0%	0	0	0%	0	0	0%	0	0	0%	0	0	0%
North Sea Graben	OECD Europe	14,373	4,031	55	383	9%	1	39	1%	56	422	10%	57	394	10%	2	47	1%	59	441	11%
Campos Basin	South America	3,072	1,095	0	0	0%	3	26	2%	3	26	2%	0	0	0%	3	26	2%	3	26	2%
Permian Basin	USA	13,428	4,103	1	24	1%	5	68	2%	6	92	2%	3	41	1%	7	110	3%	10	151	4%
North Slope	USA	11,373	3,084	0	0	0%	2	9	0%	2	9	0%	0	0	0%	2	9	0%	2	9	0%
East/Central Texas Basins	USA	9,392	2,415	38	1,523	63%	39	1,502	62%	77	3,025	125%	39	1,565	65%	41	1,662	69%	80	3,227	134%
Mid-Continent Basins	USA	6,359	1,609	9	133	8%	21	360	22%	30	492	31%	11	143	9%	32	516	32%	43	659	41%
LA Offshore	USA	4,594	1,629	9	281	17%	18	766	47%	27	1,047	64%	15	431	26%	23	944	58%	38	1,374	84%
Gulf Coast Basins	USA	4,131	1,319	16	411	31%	26	980	74%	42	1,391	105%	18	519	39%	28	995	75%	46	1,514	115%
Rockies Basins	USA	2,625	742	1	4	1%	27	410	55%	28	414	56%	3	21	3%	32	481	65%	35	502	68%
San Joaquin Basin	USA	2,164	536	0	0	0%	6	72	13%	6	72	13%	0	0	0%	7	98	18%	7	98	18%
Williston Basin, US	USA	1,827	492	1	13	3%	18	208	42%	19	221	45%	2	34	7%	21	224	46%	23	258	52%
Coastal California Basin	USA	1,179	338	7	49	14%	8	316	93%	15	364	108%	7	49	14%	14	394	117%	21	443	131%
Los Angeles Basin	USA	1,096	292	7	49	17%	10	384	131%	17	433	148%	7	49	17%	14	472	162%	21	521	178%
Appalachia	USA	856	290	5	46	16%	26	815	281%	31	862	297%	5	46	16%	30	944	325%	35	990	341%
Cook Inlet	USA	670	215	0	0	0%	1	21	10%	1	21	10%	0	0	0%	1	21	10%	1	21	10%
Illinois Basin	USA	512	141	10	134	96%	63	2,768	1970%	73	2,903	2065%	10	134	96%	70	3,107	2211%	80	3,241	2306%
Total		**468,530**	**139,034**	**245**	**5,129**	**4%**	**473**	**14,298**	**10%**	**718**	**19,427**	**14%**	**280**	**6,062**	**4%**	**577**	**16,363**	**12%**	**857**	**22,426**	**16%**

CURRENT ACTIVITIES AND PROJECT PLANS FOR CO_2-EOR AND CCS

In addition to the more than 120 CO_2-EOR projects being pursued around the world, as described earlier, a number of research, development, and demonstration efforts are underway focused on the potential of CO_2-EOR, primarily in combination with CO_2 storage.

In March 2011, the Global CCS Institute published its update[42] on the global status of large-scale integrated[43] CCS projects for input into the International Energy Agency (IEA), Carbon Sequestration Leadership Forum (CSLF) and the Global CCS Institute (the Institute) Report to the Muskoka 2010 G8 Summit.[44] The CCS Institute reports that active collaboration between government and industry has led to 77 large-scale integrated projects (LSIPs) at various stages of the asset life cycle, a net increase of 13 projects since 2009. These include eight operating projects and a further four projects in the execution phase of the project life cycle. The vast majority of the projects are advancing in developed countries. The Institute also notes that a number of LSIPs have progressed through various development phases in 2010, encouraged by a range of factors including government funding programs and by the potential revenue from supplying anthropogenic CO_2 to oil producers for EOR (this is especially the case in North America).

Of the 77 LSIPs, 34 (44%) are targeted for EOR applications. Five of the eight LSIPs and three of the four in execution are injecting CO_2 for EOR.

A list of the LSIPs targeting EOR opportunities is provided in Table 10. As shown, all but four are in the U.S. and Canada, and all in the execution or operation phase are in North America.

Interest has also been expressed in establishing a 'backbone' CO_2 supply system for North Sea oil fields -- the CENS (CO_2 for EOR in the North Sea) project.[45] In fact, a considerable amount of work has been done identifying the best CO_2-EOR prospects in the North Sea. Oil majors like BP, Shell, ConocoPhillips, and Statoil have investigated CO_2-EOR potential at fields like Forties, Miller, Draügen and Gullfaks; but have not pursued these opportunities. Initial evaluations of these prospects have tended to conclude that CO_2-EOR oil yields are disappointing, and together with escalating capital costs for the conversion of offshore installations, including facilities and wells for CO_2 injection, and thus these prospects were determined unlikely to be economic.

Further studies by Herriot Watt University and the Norwegian Petroleum Directorate (NPD) concluded that CO_2-EOR development in the North Sea area uneconomic without financial incentives.[46] The authors cite as causes a lack of market incentives, regulatory guidance, poor sweep efficiency (and hence oil recovery) high oil recovery rates from secondary recovery techniques (compared to onshore fields), high costs of offshore platform retrofits, the lack of availability of sufficient and cheap volumes of CO_2, and the costs to establish a region-wide CO_2 supply infrastructure.

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[42] Global CCS Institute, *Global Status of CCS: 2010*, 2011 (http://www.globalccsinstitute.com/global-status-ccs-2010)

[43] An 'integrated' CCS project links together the whole CCS chain of capture, transport, and storage of CO_2.

[44] *IEA/CSLF Report to the Muskoka 2010 G8 Summit, Carbon Capture and Storage: Progress and Next Steps*, 2010

[45] http://www.co2.no/default.asp?uid=56&CID=56

[46] See, for example, Guntis Moritis , "Norway study finds CO_2 EOR too expensive, risky" *Oil and Gas Journal*, Volume 103, Issue 30, August 8, 2005

Table 10. CCS Institute Identified Projects Targeting CO_2-EOR

Project Name	Location	Capture Facility	Scale (MM metric tons per year)	Planned Start
IDENTIFICATION STAGE				
CO2 Global- Project Viking	US	Oxyfuel Combustion	1.2	2014
Good Spring IGCC	US	IGCC Power Plant	1	2015
EVALUATION STAGE				
Bow City Power Plant CO2 Capture Project	Canada	Coal Power Plant	1	2016
Cash Creek	US	IGCC Power Plant	2	2015
Faustina H2 Project	US	Coal-to-Liquids	1.5	By 2020
Freeport Gasification	US	Petcoke to SNG Plant	2	2013
South Heart IGCC	US	IGCC Power Plant	2.1	2017
GreenGen IGCC Project	China	IGCC Power Plant	2	2013
Indiana Gasification	US	Coal-to-SNG	1	By 2020
Leucadia Mississippi	US	Petcoke to SNG Plant	4	2014
Swan Hills	Canada	Coal Gasification Faciltiy	1.5	2015
Sweeney Gasification	US	IGCC Power Plant	3	2015
Taylorsville IGCC	US	IGCC Power Plant	1.9	2015
DEFINITION STAGE				
Air Liquide	Netherlands	Hydrogen Power Plant	0.55	2012
Air Products	US	H2 at Oil Refinery	1	2015
Coffeeville Resources N2 Plant	US	Fertilizer Plant	0.6	by 2020
Entergy Nelson 6 CCS Project	US	Post-combustion	2	2016
Masdar CCS Project	UAE	Steel & Aluminum Plants	4.3	2013
SaskPower Boundary Dam	Canada	Coal Power Plant	1	2013
Hydrogen Energy California Project	US	IGCC Power Plant	2	2016
Hydrogen Power Abu Dhabi	UAE	Hydrogen Power Plant	1.7	2015
Lake Charles Gasification Plant	US	Petcoke to SNG Plant	4	2014
Summit Texas Clean Energy CCS Project (NowGen)	US	IGCC Power Plant	2.7	2014
Tenaska Trailblazer Energy Center	US	Supercritical PC Power Plant	5.75	2016
Transalta Project Pioneer	Canada	Post-combustion	1	2015
Lost Cabin Gas Plant Capture Project	US	Natural Gas Processing	1	2014
EXECUTION AND OPERATION STAGE				
Weyburn-Midale CO2 Project	Canada	Great Plains Synfuel Plant	3	2000
Oxy Gas Processing Plant	US	Natural Gas Processing	9	2011
Salt Creek EOR	US	Natural Gas Processing	2.4	2004
Enid Fertilizer	US	Fertilizer Plant	0.7	2003
Sharon Ridge EOR	US	Natural Gas Processing	1.3	1999
Rangely Weber CO2 Injection Project	US	Natural Gas Processing	1	1986
Enhance Energy EOR Project	Canada	Fertilizer & Oil Refining	1.8	2012
Southern CO2 IGCC	US	IGCC Power Plant	2.5	2014

The Bellona Foundation, however, did not accept the conclusions NPD's report; and believes that the NPD's opinion "… is based on flawed technical, economical and industrial arguments and assessments.[47] A more recent study by researchers at Durham University concludes that that using CO_2 to enhance the recovery from existing North Sea oil fields could yield an extra three billion barrels of oil over the next 20 years, and lead to economic benefits worth £150 billion ($240 billion U.S.) -- but only if the current infrastructure is enhanced now.[48]

In China, the GreenGen project, located in Tianjin's Binhai New Area, will be China's first commercial-scale IGCC power plant, being deployed with CCS. This $1 billion project is a joint effort of seven Chinese state-owned companies led by China Huaneng (China's largest electric utility). U.S. coal magnate Peabody Energy has a 6% share in the project. The project is located near the Dagang oil fields, so the captured CO_2 is planned for use in CO_2-EOR operations.[49]

The governments of Japan and China are implementing a project to inject CO_2 emitted from a thermal power plant in China into an oil field.[50] According to the project plan, from 1 to 3 million tonnes of CO_2 will be captured annually from the Harbin Thermal Power Plant in Heilungkiang Province and potentially other plants. The captured CO_2 will then be transported by pipeline nearly 100 kilometres to the Daqing Oilfield to be injected and stored. The project is estimated to cost 20 to 30 billion yen ($216 million to $324 million). According to the Ministry of Economy, Trade, and Industry (METI), if realized, it will be the first case of injecting CO_2 from a thermal power plant into an oil field in China.

In the United Arab Emirates, the Masdar project includes post-combustion capture of CO_2 from power generation and steel and aluminium production facilities. The CO_2 captured (4.3 million metric tons per year) will potentially be used for EOR. The front-end engineering and design (FEED) study for the power and aluminium capture sites is set to be completed by 2011; the full-scale operation are is expected to start by 2013-2016. The Hydrogen Power Abu Dhabi (HPAD) will be operational in 2014 and will use pre-combustion technology to convert natural gas to produce hydrogen and CO_2. The hydrogen rich synthesis gas will be used as a fuel for a 400 MW power plant, and the CO_2 will be transported by pipeline for EOR. Finally, Abu Dhabi Company for Onshore Oil Operations (ADCO) has initiated a CO_2-EOR project in a carbonate reservoir in the MENA region of Abu Dhabi. The pilot began operations in the fourth quarter of

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[47] Jakobsen Viktor E, Frederic Hauge, Marius Holm, and & Beate Kristiansen, *Environment and value creation - CO_2 for EOR on the Norwegian shelf, – a case study*, Bellona report, August 2005

[48] "North Sea Oil Recovery Using Carbon Dioxide Is Possible, but Time Is Running Out, Expert Says", *Science Daily*, October 29, 2010 (http://www.sciencedaily.com/releases/2010/10/101013193533.htm)

[49] http://switchboard.nrdc.org/blogs/jqian/taking_the_carbon_out_of_coal.html

[50] Nikkei financial news, May 3, 2008

2009. A continuous supply of 60 metric tons per day of CO_2 is being provided to ADCO and is being injected into one of the pilot wells.[51]

Saudi Aramco, the world's biggest oil producer, as part of its long term strategy to reduce its greenhouse gas emissions, is in the planning stages for a project to capture CO_2 from otherwise emitted from its Hawiyah and Uthmaniyah gas-processing plants, and inject the CO_2 in a pilot test in its Ghawar oil field, the world's largest.[52]

In Brazil, Petrobras recently started injecting high-pressure CO_2 into the Miranga onshore field in the state of Bahia in Brazil to test technologies that might contribute to future development projects in the Santos Basin. As much as 370 metric tons of CO_2 per day of CO_2 injection and eventual geological storage is anticipated for the project, with the intention of also increasing oil recovery efficiency.[53] Petrobras, in partnership with international institutions and Brazilian universities, including CEPAC/PUCRS, is developing a series of research projects, including pilot and demonstrating CO_2 geological storage projects in coal seams, oil fields and saline aquifers, in several sedimentary basins in Brazil.[54]

In the United States, RD&D is being pursued by the U.S. Department of Energy, National Energy Technology Laboratory's (DOE/NETL's) Carbon Sequestration Program to ensure that the stored CO_2 remains isolated from the atmosphere and the biosphere and that the storage process remains as safe and economically viable as possible.[55] As part of the DOE/NETL Regional Carbon Sequestration Partnerships (RCSPs), the seven partnerships in the Program are moving into their third phase, which involves large-scale injection tests. About half of the nine scheduled projects for Phase III already have started field activities or are in the final design stages. The rest are finalizing their site selections. Only one of these large-scale tests – to be conducted in the Williston Basin of North Dakota – is examining opportunities associated with CO_2 storage in combination with CO_2-EOR.[56]

In addition, in 2009, as part of economic stimulus funding in the U.S. under the American Recovery and Reinvestment Act, $1.5 billion was targeted as part of a two-part competitive solicitation for large-scale CCS from industrial sources. In September 2010, DOE announced the selection of 24 additional projects that will accelerate CCS R&D for industrial sources, funded at a level of $635 million.[57] However, only two of these projects were assessing the CO_2 storage potential of industrial source CO_2 in combination with CO_2-EOR.

Finally, several additional projects in the U.S. were also under consideration, but were not among those identified in the CCS Institute's report. Baard Energy's Ohio River Clean Fuels project, a 53,000 barrels per day coal- and biomass-to-liquids project, plans to market the

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[51] http://www.pennenergy.com/index/petroleum/display/0080149715/articles/pennenergy/petroleum/exploration/2010/04/adco-starts_co2_injection.html

[52] http://www.arabianbusiness.com/saudi-aramco-use-co2-boost-ghawar-oil-field-output-by-2013-383900.html

[53] "Petrobras' CO_2 Injection Project to Serve As Test for Pre-Salt," *Rigzone*, October 02, 2009 (http://www.rigzone.com/news/article.asp?a_id=80962)

[54] http://www.pucrs.br/cepac/index_e.php?p=sequestro_carbono

[55] http://www.netl.doe.gov/publications/factsheets/program/Prog053.pdf

[56] Dittrick, Paula, "DOE partnerships testing CO_2 EOR, sequestration synergies," *Oil and Gas Journal*, April 12, 2010

[57] http://www.fossil.energy.gov/recovery/projects/iccs_projects_0907101.pdf

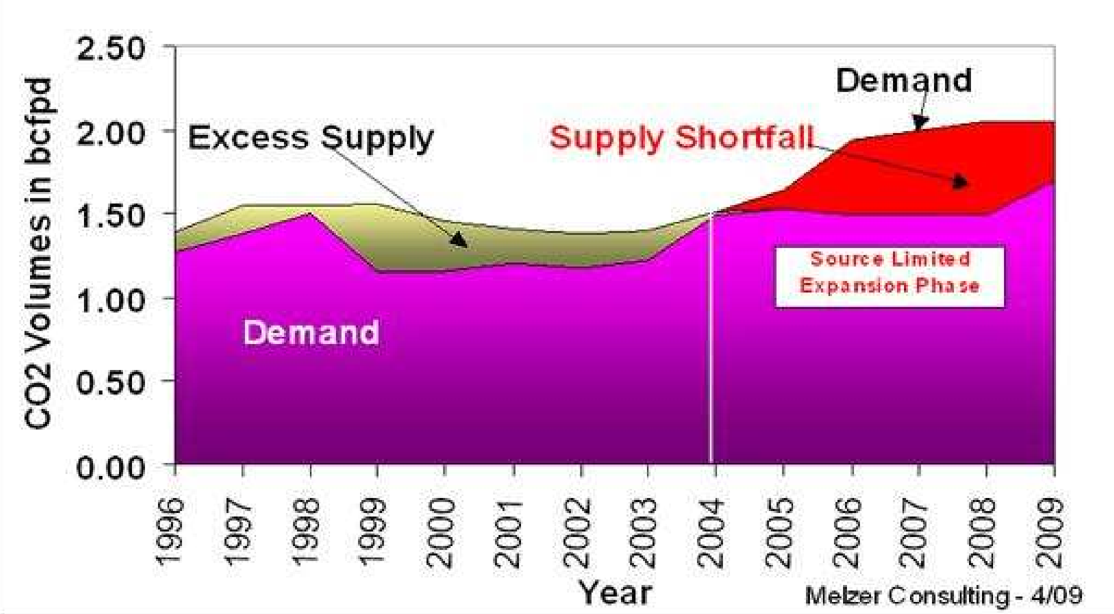
plant's CO_2 for EOR.[58] Rentech's 30,000 barrel per day coal- and biomass-to-liquids plant in Natchez, Mississippi, plans to market the plant's CO_2 for EOR. The first phase of the project is expected in 2011.[59] And DKRW Energy's 15,000 to 20,000 barrel per day coal-to-liquids plant in Medicine Bow, Wyoming, also plans to also market its CO_2 for EOR. The project is expected to begin operation in 2013.[60]

BARRIERS TO GREATER CO_2-EOR IMPLEMENTATION

Lack of CO_2 Supplies for CO_2-EOR

Today, the main barrier to reaching higher levels of CO_2-EOR production, both in the U.S. and worldwide, is insufficient supplies of affordable CO_2.[61] The establishment of CO_2 sources and the growth of CO_2 flooding in West Texas, Wyoming, and Mississippi in the U.S. provide three independent case histories as support. Today, all three areas are constrained by CO_2 supply, and CO_2 production from current supply sources is fully committed. As an example, as shown in Figure 8, after nearly a decade where CO_2 supplies in the Permian Basin outpaced demand in CO_2-EOR projects, since 2004 there has been a shortfall of CO_2 supply.

Figure 8. CO_2 Supply and Demand in the Permian Basin



Efforts have been underway to alleviate to some degree this CO_2 supply shortage for CO_2-EOR in the Permian Basin. Three pump stations have been added to the Cortez CO_2 pipeline from McElmo Dome natural CO_2 field to upgrade throughput to enable transport of up to 25 million metric tons per year of CO_2. The Doe Canyon CO_2 source field, just north of McElmo

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[58] http://www.baardenergy.com/orcf.htm

[59] http://www.rentechinc.com/natchez.php

[60] http://www.dkrwenergy.com/fw/main/Overview-46.html

[61] Hargronve, Brian, L. Stephen Melzer, and Lon Whitman, "A Status Report on North American CO_2 EOR Production and CO_2 Supply," presented at the 16th Annual CO_2 Flooding Conference, Midland Texas, December 9-10, 2010

Dome, was drilled and volumes from that field were added to the enhanced volumes at McElmo Dome to keep the CO_2 pipeline full.[62] In addition, a new area of Bravo Dome was developed by the Hess Corporation, called West Bravo Dome, and some upgrades at Bravo Dome were completed by Oxy to keep their CO_2 supplies from these natural source fields from declining, and to keep the CO_2 pipeline from this region full.

All these projects were completed by the end of 2009 and the aggregated Permian Basin CO_2 deliveries reached 34 million metric tons per year. These new supplies were absorbed quickly in the marketplace, and a significant shortage still remains.

In fact, given this situation, the Permian Basin may be the world's first example of a "demand pull" on anthropogenic CO_2 capture.[63] Legislative and regulatory activity in the State of Texas is evolving to support increasing CO_2 supplies from anthropogenic sources to serve the CO_2-EOR market. This combination of unmet demand for CO_2 and a supportive political/regulatory climate has stimulated several new projects to increase anthropogenic CO_2 supplies for the West Texas CO_2-EOR market:

- The SandRidge/Oxy gas separation plant in Pecos County, Texas plans to provide more than three million metric tons per year of by-product CO_2 to be utilized by Oxy for CO_2-EOR.[64]
- Summit Energy's 400 MW integrated gasification combined cycle (IGCC) power/poly-gen plant in the Permian Basin plans to provide three million metric tons per for CO_2-EOR.[65]
- The Tenaska Trailblazer Energy Center plans to generate 600 MW net using best available supercritical steam, pulverized coal technology to provide as much 4.5 million metric tons per year of CO_2.[66]

Barriers Specific to CO_2-EOR Project Implementation

Review of the history of CO_2-EOR shows that the process is generally successful in fields that meet the criteria for achieving miscibility of the injected CO_2 with the oil (defined primarily in terms of reservoir depth and oil viscosity), that have a relatively large volume of remaining unrecovered oil, and where there is a source of sustainable volumes of pure CO_2 supplies at affordable costs. Other factors that contribute to success are operator knowledge, comfort and willingness to pursue CO_2-EOR technologies; the willingness and ability of the regulatory regime to permit CO_2-EOR projects, and, often, the availability of government financial incentives to promote CO_2-EOR.[67] In contrast, where these conditions have not existed, they often represented barriers to the successful implementation of CO_2-EOR projects.

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[62] 2009 Annual Report and 10-K (pp. 24-25) for Kinder Morgan Energy Partners, Press Release, "Kinder Morgan Energy Partners Announces the Development of New CO_2 Source Field and Major Expansions to Existing CO_2 Operations" January 24, 2007, and 2010 KMP Analyst Conference Presentation, January 28, 2010, Tim Bradley presentation on "CO_2"

[63] Tom Doll, Tracy Evans, L. Stephen Melzer, "North American CO_2 Status," presented at the EORI 3rd Annual CO_2 Conference, Casper, WY, June 2009

[64] SandRidge Energy, Presentation at Investor/Analyst Meeting, March 3, 2009 and Sandridge Energy, Inc., 2009 Annual Report

[65] "Summit Power begins FEED study for Texas IGCC-CCS project," *Carbon Capture Journal*, July 22,2010 (http://www.carboncapturejournal.com/displaynews.php?NewsID=603)

[66] http://www.tenaskatrailblazer.com/

[67] IEA Greenhouse Gas R&D Programme, *CO_2 Storage in Depleted Oilfields: Global Application Criteria for Carbon Dioxide Enhanced Oil Recovery,* Report IEA/CON/08/155, Prepared by Advanced Resources International, Inc. and Melzer Consulting, August 31, 2009

Refurbishing depleted oil fields for CO_2-EOR requires a significant commitment of up front capital, as shown previously in the examples presented in Table 3. This often represents a constraint, especially for smaller producers.

Several additional aspects are of importance when considering the technical challenges in matching individual sources of CO_2 and specific, individual prospective fields for the application of CO_2-EOR:[68]

- The demand for CO_2 by an individual CO_2-EOR project is not constant: the injection profile requires much more CO_2 to be used initially than in the later stages of recovery as the reservoir is saturated and the CO_2 produced with the oil is recycled back into the reservoir.
- The timing of the availability of the CO_2 is crucial. Once an oil field has been abandoned, it is generally not economical to reopen it for CO_2-EOR
- CO_2-EOR activities have traditionally not been optimized for CO_2 storage, but for oil recovery; this could change, however, with policies designed to encourage CO_2 emissions reductions.

Moreover, CO_2 off-take agreements with CO_2 sources can be difficult to execute to meet the requirement that large volumes of CO_2 be taken on a continuous basis. Industrial emitters are likely to desire take-away contracts for CO_2 that guarantee continuous take away without interruption. Today, pipeline construction for large CO_2 transport relies on contracts for firm transportation, and does not now function under an “open access” or “common carrier” model.

Nevertheless, while the business case for an individual CO_2-EOR project matched with a single industrial CO_2 source may be limited; applying CCS to a cluster of CO_2 sources matched to a cluster of CO_2-EOR prospects may provide the necessary economies of scale for successful deployment.[69] There have been a number of proposals for industrial collaborations on CCS in the U.S., Canada, Europe and Australia which seek to exploit such opportunities.

Quality Specifications for Industrial CO_2 Use for CO_2-EOR

CO_2-EOR fundamentally works on a very simple principle; namely, that given the right physical conditions, CO_2 will mix miscibly with oil, acting much like a thinning agent. As described above, after miscible mixing, the fluid is generally displaced by a chase phase, typically water.

To achieve miscibility, flooding a reservoir with CO_2 for CO_2-EOR must meet a specific combination of conditions defined by reservoir temperature, reservoir pressure, injected gas composition, and oil chemical composition.[70] Thus, the exact conditions for achieving miscibility are reservoir-specific. Impurities in the injected CO_2 stream in a CO_2-EOR project could hinder the ability of the injected fluid to meet the criteria for achieving miscibility.

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[68] United Nations Industrial Development Organization, *Carbon Capture and Storage in Industrial Applications: Technology Synthesis Report Working Paper*, November 2010

[69] McKinsey & Company, Carbon Capture and Storage: Assessing the Economics, 2008 (http://www.mckinsey.com/clientservice/ccsi/pdf/ccs_assessing_the_economics.pdf)

[70] See Holm L.W., “Miscibility and Miscible Displacement”, *Journal of Petroleum Technology*, August 1986, p. 817-818; and Haynes Jr. S. and R.B. Alston, “Study of the Mechanisms of Carbon Dioxide Flooding and Applications to More Efficient EOR Projects”, SPE/DOE Enhanced Oil Recovery Symposium, Tulsa, Oklahoma, October 22-25, 1990, SPE 20190-MS.

Moreover, the design of CO_2 pipeline and the safe, reliable, and cost effective transport of the CO_2 through that pipeline also generally require that the CO_2 stream meet certain specifications. Impurities in the CO_2 stream can impact the transport capacity of the pipeline, the potential for micro-fractures in the pipeline, and other safety and operational considerations. Meeting such pipeline standards has permitted the CO_2 pipeline industry to safely transport CO_2 with no demonstrated examples of substantial leakage, rupture, or incident. In fact, CO_2 pipelines in the U.S. have a safety record which is better than that of comparable natural gas pipelines.[71] Thus, meeting the specifications for CO_2-EOR should also allow for the safe, reliable, and economical transport of CO_2.[72]

In general, for CO_2 used for CO_2-EOR applications, the following represents a typical CO_2 pipeline quality specification:

Constituent	Standard	Reason
CO_2	95% minimum	MMP
Nitrogen	4% maximum	MMP
Hydrocarbons	5% maximum	MMP
Water	480 mg/cubic meter max	Corrosion
Oxygen	10 ppm max	Corrosion
H_2S	10-200 ppm max	Safety
Glycol	0.04 ml/cubic meter max	Operations
Temperature	65 °C max	Material Integrity

Barriers Specific to CO_2-EOR with CO_2 Storage

Since storing CO_2 in association with EOR can substantially offset some of the costs associated with CCS,[73] it can encourage its application in the absence of other incentives for CCS deployment. However, significant expansion of oil production utilizing CO_2-EOR will require volumes of CO_2 that cannot be met by high purity sources alone. Nonetheless, industrial sources of CO_2 will still need to play a critical role. This is resulting in a *fundamental change in the CO_2-EOR project paradigm; that is, not only does CCS need CO_2-EOR to help provide economic viability for CCS, but CO_2-EOR needs CCS in order to ensure adequate CO_2 supplies to facilitate growth in the number of and production from new and expanded CO_2-EOR projects.*

In addition to adequate supplies of affordable CO_2, critical to any significant growth in production from CO_2-EOR projects will be programs that create economic incentives for reducing emissions, through emissions trading programs, carbon taxes, or other mechanisms. The importance of CO_2-EOR as a facilitator for CCS is particularly significant where there is no established financial or regulatory incentive for sequestering GHG emissions.

Within any established framework for regulating and/or incentivizing emissions reductions from wide-scale deployment of CCS (with or without CO_2-EOR), storage must be established as a certifiable means for reducing GHG emissions. The inability to date of the

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[71] Gale, John and John Davidson, "Transmission of CO_2 - Safety and Economic Considerations," *Energy,* Vol. 29, Nos. 9-10 (July-August 2004): 1326

[72] Mohitpour, Mo, Andy Jenkins, and Gabe Nahas, "A generalized overview of requirements for the design, construction, and operation of new pipelines for CO_2 sequestration," *Journal of Pipeline Engineering,* Vol. 7, No. 4, December 2008, pp. 237-252

[73] Favreau, Didier, "Economics act against CCS retrofits," *Oil and Gas Journal*, October 4, 2010

United States to pass climate legislation hinders CCS project deployment within its borders. In developing countries, the Clean Development Mechanism (CDM) is currently the only potential incentive for greenhouse gas emission reduction options, and CCS. The controversy around CCS in the CDM and therefore absence of a CCS project methodology has made pursuing CCS and CO_2-EOR project deployment in developing countries less attractive.[74] Without the potential incentives given by the CDM, CO_2-EOR in developing countries will only take place sporadically in niche sectors.

Within any established framework for regulating and/or incentivizing emissions reductions (e.g., the CDM, the EU Emissions Trading Scheme, the Regional Greenhouse Gas Initiative (RGGI) in the U.S. Northeast), in order for geologic storage to achieve wide-scale deployment, it must be established as a certifiable means for reducing GHG emissions. In this regard, standards, guidelines, etc. need to be established to provide consistency and market acceptability about the reality of the reductions claimed. These uncertainties are also hindering the pursuit of CO_2-EOR, particularly because of the lack of regulatory clarity regarding the process and requirements associated with the transition from EOR operations to permanent geologic storage.[75,76]

As one step in this direction, the recent international meeting in Cancun of the Conference of Parties to the U.N. Framework Convention on Climate Change recognized that CCS "…is a relevant technology for the attainment of the ultimate goal of the Convention and may be part of a range of potential options for mitigating greenhouse gas emissions…" and asked that specific conditions and modalities for its eligibility under the CDM be developed.[77]

However, the storage of CO_2 with CCS, especially if deployed in conjunction with CO_2-EOR, still faces many challenges in order to be adopted within the CDM. As noted by de Coninck,[78] "…debate around CCS in the CDM has developed into a highly polarised discussion, with a deep divide between proponents and opponents and no view on reconciliation between the various perspectives." Obviously, on one extreme, fossil-fuel dependent companies, associations, and countries tend to be more supportive of including CCS in the CDM. On the other extreme, organizations and countries that believe that a rapid transition from dependence on fossil fuels as essential feel CCS in the CDM will only prolong this dependence. A number of others are somewhere between these two extremes.

With respect to CO_2-EOR, one conviction held by many is that CO_2-EOR will lead to more greenhouse gas emissions. This conviction is based on the fact that incremental oil recovered will be combusted, generating about two times as many CO_2 emissions as the CO_2 injected. If these emissions are accounted for, the CO_2 emissions of the CDM project would be even higher than the emissions without the CDM project. This, the opponents say, must lead to the conclusion that CO_2-EOR should in no case be allowed under the CDM.

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[74] ERM, *Carbon Dioxide Capture and Storage in the Clean Development Mechanism*, Report No. 2007/TR2, prepared for IEA GHG Programme, April 2007 (http://www.co2captureandstorage.info/techworkshops/2007%20TR2CCS%20CDM%20methodology%20.pdf)

[75] Marston, Phillip M., and Patricia A. Moore, "From EOR to CCS: The Evolving Legal and Regulatory Framework for Carbon Capture and Storage," *Energy Law Journal*, July 1, 2008 (http://txccsa.org/From%20EOR%20to%20CCS.pdf)

[76] Carbon Capture and Sequestration: *Framing the Issues for Regulation, An Interim Report from the CCSReg Project,* January 2009 (http://www.ccsreg.org/pdf/CCSReg_3_9.pdf)

[77] http://unfccc.int/files/meetings/cop_16/application/pdf/cop16_cmp_ccs.pdf

[78] de Coninck, Heleen, "Trojan horse or horn of plenty? Reflections on allowing CCS in the CDM," *Energy Policy*, Volume 36, pp. 929–936, 2008

On the other hand, a recent study sponsored by the U.K Department of Energy and Climate Change reports that some approaches for CO_2-EOR that attempt to better increase CO_2 storage can store more CO_2 than is associated with the CO_2 emissions over the life cycle of the incremental oil produced from CO_2-EOR, including emissions from consumption.[79]

Moreover, proponents argue that even if only half of the emissions resulting from incremental oil production from CO_2-EOR are stored, and thus offset, this is still considerably better than none, which would be the case otherwise. CO_2-EOR contributes to permanently sequestering CO_2 that would otherwise be emitted to the atmosphere, and has other environmental benefits over oil produced by most other means.

Finally, numerous regulatory and liability issues and uncertainties are currently associated with CCS that are hindering wide-scale deployment. These uncertainties are also hindering the pursuit of CO_2-EOR, particularly because of the lack of regulatory clarity regarding the process and requirements associated with the transition from EOR operations to permanen geologic storage.[80,81]

To facilitate investment in the rapid scaling up of infrastructure necessary to support large scale deployment of CCS, the IEA's technology roadmap for CCS recognizes that policies are needed to pave the way for technology development to be able to effectively take advantage of early opportunities for CCS with enhanced oil and gas recovery.[82]

Financing of the necessary CO_2 transport infrastructure may also be necessary. In addition, governments may need to subsidize or take ownership of CO_2 transport pipelines in some manner.[83]

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[79] Advanced Resources International, Inc. and Melzer Consulting, *Optimization of CO2 Storage in CO2 Enhanced Oil Recovery Projects*, report prepared for the U.K. Department of Energy & Climate Change (DECC), Office of Carbon Capture & Storage, November 30, 2010 (http://www.decc.gov.uk/en/content/cms/what_we_do/uk_supply/energy_mix/ccs/ccs.aspx)

[80] Marston, Phillip M., and Patricia A. Moore, "From EOR to CCS: The Evolving Legal and Regulatory Framework for Carbon Capture and Storage," *Energy Law Journal*, July 1, 2008 (http://txccsa.org/From%20EOR%20to%20CCS.pdf)

[81] Carbon Capture and Sequestration: *Framing the Issues for Regulation, An Interim Report from the CCSReg Project,* January 2009 (http://www.ccsreg.org/pdf/CCSReg_3_9.pdf)

[82] International Energy Agency, *Technology Roadmap: Carbon Capture and Storage*, 2009

[83] International Energy Agency, *CO_2 Capture and Storage: A Key Carbon Abatement Option*, 2008