

TOPIC PAPER #17

CARBON CAPTURE AND SEQUESTRATION (CCS)

On July 18, 2007, The National Petroleum Council (NPC) in approving its report, *Facing the Hard Truths about Energy*, also approved the making available of certain materials used in the study process, including detailed, specific subject matter papers prepared or used by the Task Groups and their Subgroups. These Topic Papers were working documents that were part of the analyses that led to development of the summary results presented in the report's Executive Summary and Chapters.

These Topic Papers represent the views and conclusions of the authors. The National Petroleum Council has not endorsed or approved the statements and conclusions contained in these documents but approved the publication of these materials as part of the study process.

The NPC believes that these papers will be of interest to the readers of the report and will help them better understand the results. These materials are being made available in the interest of transparency.

The attached Topic Paper is one of 38 such working document used in the study analyses. Also included is a roster of the Subgroup that developed or submitted this paper. Appendix E of the final NPC report provides a complete list of the 38 Topic Papers and an abstract for each. The printed final report volume contains a CD that includes pdf files of all papers. These papers also can be viewed and downloaded from the report section of the NPC website (www.npc.org).

**NATIONAL PETROLEUM COUNCIL
CARBON CAPTURE & SEQUESTRATION SUBGROUP
OF THE
TECHNOLOGY TASK GROUP
OF THE
NPC COMMITTEE ON GLOBAL OIL AND GAS**

TEAM LEADER

Michael C. Sheppard
Schlumberger Fellow
Schlumberger Oilfield Services
Schlumberger Cambridge Research

MEMBERS

Michael J. Bowman
Manager
Energy Systems Lab
GE Global Energy

Gardiner Hill
Director
Carbon Capture and Storage Technology
BP Alternative Energy Company

Steven L. Bryant
Assistant Professor
Petroleum and Geosystems Engineering
The University of Texas

Scott M. Klara
Director
Office of Coal & Power R&D
National Energy Technology Laboratory
U.S. Department of Energy

S. Julio Friedmann
Carbon Management Program APL
Lawrence Livermore National Laboratory

Vello A. Kuuskraa
President
Advanced Resources International

Bjørn-Erik Haugan
Executive Director
Gassnova

Arthur Lee
Principal Advisor
Global Policy and Strategy
Chevron Corporation

David Hawkins
Director-Climate Center
Natural Resources Defense Council

Geoffrey Maitland
Professor of Energy Engineering
Department of Chemical Engineering
Imperial College London

Howard J. Herzog
Principal Research Engineer
Laboratory for Energy and
the Environment
Massachusetts Institute of Technology

Thomas Mikus
CO₂ Capture Team Leader
Shell Oil Company

Franklin M. Orr, Jr.
Keleen and Carlton Beal Professor of
Petroleum Engineering
Department of Petroleum Engineering
Stanford University

Robert H. Socolow
Co-Director
The Carbon Mitigation Initiative
Princeton University

T. S. Ramakrishnan
Scientific Advisor
Schlumberger Oilfield Services

John M. Tombari
Vice President North & South America
Schlumberger Carbon Services

Carbon Capture and Sequestration

Team leader: Mike Sheppard
Date submitted: January 24, 2007

I. Executive Summary

It is likely that we are moving into an era of carbon constraint. Oil and gas contribute more than half of the current, energy-related, CO₂ emissions so that in a carbon-constrained world, the use of oil and gas will not remain unaffected by policy measures to reduce carbon emissions. “Carbon management” will involve the combination of a number of measures to reduce CO₂ emissions, including improvements in efficiency of energy use and the use of alternatives to fossil fuels such as biofuels and solar, wind, and nuclear energy. However, to meet the energy needs of the nation, the USA will wish to continue to use fossil fuels, including coal, extensively over the next 50 years or more. In order to do so, and to extend the resource base to include unconventional hydrocarbons such as heavy oil, tar sands, and shale oil, it will be necessary, if carbon constraints are imposed, to capture and sequester a large fraction of the CO₂ produced by burning these fossil fuels.

The technologies required for effective carbon capture and sequestration (CCS) are, by and large, viable. The hurdles to implementation are largely ones of integration at scale; an infrastructure comparable in extent to that used in the pumping of fluids in the existing upstream oil and gas industry will be required to address the needs of effective carbon mitigation. In the event of climate change of the magnitude predicted by the IPCC,¹ the cost worldwide of implementing effective carbon management, including a large dependence on CCS, is expected to be lower than the

¹ Intergovernmental Panel on Climate Change: *Third Assessment Report—Climate Change 2001*, Cambridge University Press. See <http://www.ipcc.ch/>.

ultimate cost of remedying the effects of unconstrained climate change.² Given the exposure to such costs if no measures are taken to abate carbon emissions, we recommend that provision should be made for extensive carbon capture and sequestration. We make a number of key recommendations concerning the development of this technology.

While the technologies for CCS are essentially available, in that capture and storage can be implemented now, there remains extensive scope for improvement. In particular, the capture stage of CCS is key and currently dominates the overall cost. Novel, lower-cost approaches to capture would have a very significant impact on the implementation of CCS and would, in turn, greatly influence the usability of fossil fuels under carbon constraint. As we will discuss further in this report, other areas where continued research is important include:

- Fundamentals of storage
 - Long term physiochemical changes in the storage reservoir
- Characterization and risk assessment (faults, cap rocks, wells)
- Reservoir management for long term storage
- Integration of fit for purpose measurement, monitoring, and verification (MMV)
- Injectivity
- Retention and leakage
 - Leakage through wells.

It is also crucial at this stage to undertake an assessment of the total U.S. capacity for CO₂ sequestration. While it is not unreasonable to expect that the combined capacity of existing hydrocarbon reservoirs and deep, saline formations is large, a detailed understanding of the regional distribution of capacity throughout the USA is of critical importance.

One arena where CO₂ is pumped into reservoirs currently is in enhanced oil recovery (EOR). This provides a proving ground for a variety of techniques of

² Metz B, Davidson O, de Coninck H, Loos M, and Meyer L (eds): IPCC Special Report on Carbon Dioxide Capture and Storage, Intergovernmental Panel on Climate Change, Cambridge University Press (2005). See <http://www.ipcc.ch/>.

relevance to CCS, and we devote a section of this report to a discussion of the role of CO₂-EOR in the development of CCS technologies. At present CO₂-EOR is not directed towards effective storage of CO₂, but the techniques can be modified to improve carbon sequestration.

Finally we discuss at some length the necessity of putting in place a regulatory environment that stimulates and encourages carbon capture and sequestration. Regulation, along with social and political considerations, will play just as much a role as technology development in the effective implementation of CCS sufficient to address the likely future needs.

II. Overview of Methodology

This report was developed from discussion amongst the subtask team members who represent a broad range of expertise across the topic of carbon capture and sequestration.

The team included representation from the Department of Energy, U.S. and UK Academia, U.S. National Labs, the oil and gas industry and the Norwegian Ministry of Petroleum and Energy. A forum was held in Princeton early in October 2006 to establish the key elements of the report, and the subtask team was broken down into smaller teams each with responsibility for writing a particular section. Subsequently, the entire team reviewed the whole document.

The subtask team comprised the following individuals:

Name	Affiliation
T. S. Ramakrishnan	Schlumberger
Julio Friedmann	LLNL
Robert Socolow	Princeton University
Franklin Orr	Stanford University
Steve Bryant	University of Texas
Howard Herzog	MIT
David Hawkins	NRDC
John Tombari	Schlumberger
Mike Bowman	GE Research
Tom Mikus	Shell
Geoff Maitland	Imperial College London
Vello Kuuskraa	Advanced Resources International
Bjorn-Erik Haugan	Norway Ministry of Petroleum and Energy
Arthur Lee	Chevron
Gardiner Hill	BP
Scott Klara	NETL
Mike Sheppard	Schlumberger

Discussions were also conducted with faculty members of the Princeton Carbon Mitigation Initiative and with the representatives of the UK Government Department of Trade and Industry.

This report draws on a number of external reports and publications; key among them are:

- Intergovernmental Panel on Climate Change: *Third Assessment Report—Climate Change 2001*, Cambridge University Press. See <http://www.ipcc.ch/>.
- Metz B, Davidson O, de Coninck H, Loos M, and Meyer L (eds): *IPCC Special Report on Carbon Dioxide Capture and Storage*, Intergovernmental Panel on Climate Change, Cambridge University Press (2005). See <http://www.ipcc.ch/>.
- Pacala S and Socolow R: “Stabilization Wedges: Solving the Climate Problem for the Next 50 Years Using Current Technologies,” *Science* 305 (2004): 986.
- Socolow R: “Can We Bury Global Warming,” *Scientific American* (July 2005). See <http://www.sciam.com>.
- Koonin SE: “Energy for the Coming Decades: Trends and Technologies,” MIT (September 2005). See <http://mitworld.mit.edu/video/299/>.
- Oreskes N: “The Scientific Consensus on Climate Change,” *Science* 306 (December 3, 2004): 1686.
- U.S. Department of Energy: *Climate Change Technology Program Strategic Plan, 2006*, Washington, DC. See <http://www.climatetechnology.gov/>.
- *The Future of Coal*, MIT Press ISBN 978-0-615-14092-6 (2007). Available at <http://web.mit.edu/coal/>.
- International Energy Agency: *World Energy Outlook (WEO) 2006*, IEA, Paris.
- Friedmann SJ: “The ICE framework for CO₂ storage site characterization,” NETL 5th Annual Conference on Carbon Sequestration, Alexandria, VA, ExchangeMonitor Publications (2006).

- Wilson EJ, Friedmann SJ, and Pollak M: “Research for Deployment: Incorporating Risk, Regulation and Liability for Carbon Capture and Sequestration,” *Environmental Science & Technology*, in press.
- “The Stern Review on the Economics of Climate Change.” http://www.hm-treasury.gov.uk/independent_reviews/stern_review_economics_climate_change/sternreview_index.cfm.
- Wilson M and Monea M. (eds.): IEA GHG Weyburn CO₂ Monitoring & Storage Project Summary Report 2000-2004 (2004) 273 p.
- Riddiford F, Wright I, Espie T, and Torqui, A: “Monitoring Geological Storage: In Salah Gas CO₂ Storage Project,” Conference Proceedings, GHGT-7, IEA Greenhouse Gas Programme, Vancouver (2004).
- U.S. Dept. of Energy: “Carbon Sequestration Technology Roadmap and Program Plan for 2006,” Morgantown, WV (2006) 39 p.
- Dooley JJ, Kim SK, Edmond JA, Friedmann SJ, Wise MA: “A First Order Global Geologic CO₂ Storage Potential Supply Curve and Its Application in a Global Integrated Assessment Model,” Conference Proceedings, GHGT-7, IEA Greenhouse Gas Programme, Vancouver (2004).
- Bradshaw J, Allison G, Bradshaw BE, Nguyen V, Rigg AJ, Spencer L and Wilson, P: “Australia’s CO₂ Geological Storage Potential and Matching of Emission Sources to Potential Sinks,” in *Greenhouse Gas Control Technologies: Proceedings of the 6th International Conference on Greenhouse Gas Control Technologies, 1–4 October 2002, Kyoto*, (2003).
- Friedmann SJ, Dooley JJ, Held H, and Edenhofer O: “The low cost of geological assessment for underground CO₂ storage: Policy and economic implications,” *Energy Conversion Management* 47 (2006): 1894–1901.
- Benson SM, Hoversten M, Gasperikova E, and Haines M: “Monitoring Protocols and Life-Cycle Costs for Geological Storage of Carbon Dioxide,” Conference Proceedings, GHGT-7, IEA Greenhouse Gas Programme, Vancouver (2004).

- Ramirez A, et al: “Stochastic Inversion of Electrical Resistivity Changes Using a Markov Chain Monte Carlo Approach,” *Journal of Geophysical Research* 110 (2005): B02101.
- Snodgrass WR: “Physiological and Biochemical Differences between Children and Adults as 5 Determinants of Toxic Exposure to Environmental Pollutants,” in *Similarities and Differences between Children and Adults: Implications for Risk Assessment*, Guzelain PS, Henry CJ, and Olin SS (eds.), ILSI Press, Washington, DC, USA. (1992).
- National Institute for Occupational Safety and Health (NIOSH): *Pocket Guide to Chemical Hazards*. DHHS publication no. 97-140. U.S. Government Printing Office, Washington, 25 DC, USA (1997).
- Gasda SE, Bachu S, and Celia MA: “The Potential for CO₂ Leakage from Storage Sites in Geological Media: Analysis of Well Distribution in Mature Sedimentary Basins,” *Environmental Geology* 46, No. 6-7 (2004): 707–720.
- Ide ST, Friedmann SJ, and Herzog HJ: “CO₂ Leakage Through Existing Wells: Current Technology and Regulatory Basis,” 8th Greenhouse Gas Technology Conference, Trondjheim, Norway, Poster session II (2006).
- Scherer GW, Celia MA, Prevost JH, Bachu S, Bruant R, Duguid A, Fuller R, Gasda SE, Radonjic M, and Vichit-Vadakan W: “Leakage of CO₂ through Abandoned Wells: Role of Corrosion of Cement,” in *The CO₂ Capture and Storage Project (CCP), Volume II*, Thomas DC and Benson SM (eds.) (2005): 823–844.
- Jessen K, Kovscek AR, and Orr FM Jr: “Increasing CO₂ Storage in Oil Recovery,” *Energy Conversion and Management* 46 (2005): 293–311.
- “Proposed Methodology for Construction of a 2006 National Geological Carbon Sequestration Capacity Assessment,” final draft prepared for U.S. Department of Energy, Regional Carbon Sequestration Partnership Program, prepared by Capacity and Fairways Subgroup of the Geologic Working Group of the DOE Carbon Sequestration Regional Partnerships (October 1, 2006).

- Advanced Resources International: “Ten Basin-Oriented CO₂-EOR Assessments Examine Strategies for Increasing Domestic Oil Production, Alaska, California, Onshore Gulf Coast, Mid-Continent, Illinois and Michigan, Permian Basin, Rocky Mountains, East and Central Texas, Offshore Louisiana, and Williston Basin,” U.S. Department of Energy, Office of Fossil Energy (February 2006).
- Kuuskraa VA and Koperna GJ: “Assessing and Expanding CO₂ Storage Capacity in Depleted and Near-Depleted Oil Reservoirs,” presented at GHGT-8, Trondheim, Norway (June 19–23, 2006).
- Advanced Resources International: “An Estimate of the Capacity for CO₂ Storage in Depleting Oil Fields in the United States (Updated),” Advanced Resources International as part of the CarBen Model Update for U.S. DOE, National Energy Technology Laboratory, Task Order No. DE-AD26-06NT42752 (October 2006).
- Bachu S and Shaw JC: “CO₂ Storage In Oil And Gas Reservoirs In Western Canada: Effect of Aquifers, Potential For CO₂-Flood Enhanced Oil Recovery And Practical Capacity,” Conference Proceedings, GHGT-7, IEA Greenhouse Gas Programme, Vancouver (2004).
- DOE Fossil Energy Techline: “A Two-For-One Solution.... Alabama Project Plans to Store Carbon Dioxide, Boost Oil Production” (September 6, 2006). See http://www.fossil.energy.gov/news/techlines/2006/06050-DOE_Awards_EOR_Project.html.
- United States Environmental Protection Agency’s draft guidance (deliberative draft) on using Class V wells to regulate pilot geologic sequestration projects (UIC Program Guidance #83).
- G8 International Energy Agency (IEA) & Carbon Sequestration Leadership Forum (CSLF) First Workshop on Near Term Opportunities, held 22–23 August 2006, San Francisco.
- IEA Carbon Sequestration Leadership Forum (CSLF) First Workshop on Legal & Regulatory Issues, held 12–13 July 2004, London and Paris.

- Interstate Oil and Gas Compact Commission: “Carbon Capture and Storage: A Regulatory Framework for States” (2005).
- IPCC Guidelines for National Greenhouse Gas Emissions Inventory 2006 (Pre-Publication Draft). See <http://www.ipcc-nggip.iges.or.jp/public/2006gl/index.htm> (accessed 17 October 2006).
- de Figueiredo MA: *The Liability of Carbon Dioxide Storage*, submitted in partial fulfillment of the requirements for the degree of Doctor of Philosophy in Technology, Management, and Policy, Massachusetts Institute of Technology, February 2007 (Draft 7/21/06).
- Considerations on Regulatory Issues, Carbon Sequestration Leadership Forum (CSLF) report (2004).

III. Background

Carbon capture and sequestration entails the capture of CO₂, at the site where it is generated, and the storage of CO₂ for periods sufficiently long to mitigate the impact of CO₂ on climate. In this report, we will only consider geological sequestration and not discuss possible alternatives such as deep-sea sequestration, which is fraught with environmental concerns and issues of public acceptance. Geological sequestration would target spent oil and gas reservoirs and deep saline formations, the potential capacity of which we will discuss in this document.

By 1996, there was an emerging literature on CCS, including proceedings from five international conferences totaling over 500 papers. With the inception of the Sleipner project in the North Sea, a decade of substantial research and publication followed. Much of this literature and the related experience is captured in the IPCC Special Report on Carbon Storage, which includes chapters on CO₂ capture and

separation, transportation, geological storage, and economics.³ This document was an attempt to gather and integrated the state of CCS knowledge in early 2005.

In addition, several large projects have begun in sequestration, including the Weyburn EOR project in Canada and the In Salah saline formation project in Algeria.^{4,5} Moreover, many governmental and non-governmental entities have published roadmaps, summary documents, national and international frameworks, and strategic documents.⁶ A central conclusion from these documents is that there already exist firm technical and experiential foundations for CCS. These foundations are based in similar or broadly analogous technical endeavors, including operations at scale, comparable physics and chemistry, and availability of technology and experience. These technical analogues are summarized in Table III.1.

Experience basis	Significance	Limitations
CO ₂ enhanced oil recovery (EOR)	>30 years experience injecting >>1 M tons CO ₂ /year	Very limited monitoring programs; questions of applicability of experience to saline formations
Acid gas injection	> 15 years experience injecting CO ₂ and H ₂ S into over 44 geologic formations	Generally small volumes; very little publicly available technical information
Hazardous waste disposal; underground injection control (UIC)	...	Most hazardous waste is not buoyant or reactive
Natural gas storage	~100 years experience injecting natural gas volumes into rocks	Limited monitoring; different chemistry; built for temporary storage
Natural analogs	Several large (>50 Tcf) carbo-gaseous accumulations globally; proof of concept	Most at steady state, transient knowledge unavailable; limited geography and geology
Conventional oil and gas E&P	Nearly 150 years technology and experience in predicting	Hydrocarbon recovery has goals and needs which differ from those of

³ Metz et al, IPCC, reference 2.

⁴ Wilson M and Monea M. (eds.): *IEA GHG Weyburn CO₂ Monitoring & Storage Project Summary Report 2000-2004* (2004) 273 p.

⁵ Riddiford F, Wright I, Espie T, and Torqui, A: "Monitoring Geological Storage: In Salah Gas CO₂ Storage Project," Conference Proceedings, GHGT-7, IEA Greenhouse Gas Programme, Vancouver (2004).

⁶ U.S. Dept. of Energy: "Carbon Sequestration Technology Roadmap and Program Plan for 2006," Morgantown, WV (2006) 39 p.

	and managing buoyant fluids in crust	carbon sequestration
Capture; gas separations tech	>70 years separating CO ₂ and other acid gases from gas streams, including at power plants	Costs still higher than preferred under wide-spread deployment; still no integration of large power plants with CCS
Large CO ₂ storage projects	3 large-scale projects; >6 pending before 2010	Still limited monitoring program; limited geologic representation
CO ₂ pipelines and transportation	>30 years experience at large scale; existing regulations likely to apply	None

Table III.1: Basis for experience relevant to commercial CCS.

It is important to note that there is no experience available of full-process integration, i.e. a coupled large-scale coal-fired power plant with CCS. Several projects world-wide, most notably FutureGen in the USA and Zero-Gen in Australia, are in the process of designing and constructing an integrated large-scale power-CCS operation. Successful operation of such facilities is central to understanding the true economics and operational requirements for large-scale CCS.

IV. Tables of Advances

A. Advances currently being pursued.

Technology	Significance	Brief discussion
CO ₂ -EOR	Natural arena for exploring CCS	Provides a direct commercial incentive to pumping CO ₂ into a reservoir
Evaluation of CCS in association with coal-fired plant	Development of integration of required technologies	Projects in USA, Australia and China to develop CCS with coal plant
Improved Ccapture technologies	Key determinant of cost of CCS	Significant efforts in USA, Europe and Japan to drive down cost of capture
Injection of CO ₂ into subsurface formations	Demonstration of injection and test of storage	CO ₂ currently injected at the Mt/yr level
Development of models for migration of CO ₂ subsurface	Understanding of migration behavior underpins characterization and MMV	Combination of modeling and experiment (e.g. Sleipner) to establish CO ₂ migration
Reservoir characterization for storage	Reservoir characterization techniques migrate to CO ₂ storage estimates	Available techniques tested at several sites
Measurement, monitoring and verification (MMV)	Available MMV technologies applied to CO ₂ injection and storage	Available techniques tested at several sites
Development of CO ₂ resistant cements	Primary leakage path is likely to be existing wells	Improvements in resistance of cements to corrosion are currently being pursued

Table IVA.1. Summary of technologies in priority order.

B. Advances that might be in commercial use by 2010, 2020, and 2030.

Technology	Significance	Commercial use (by 2010, 2020, 2030)
Extensive CO ₂ -EOR with substantial CO ₂ sequestration	Enhanced security of supply through better recovery	2010
Measurement, monitoring and verification techniques	Necessary prerequisite for implementation	2010
Site characterization and risk assessment	Determination of site suitability for sequestration	2010
CO ₂ leak remediation technology	Necessary for implementation of CO ₂ storage	2010
Demonstration of coal-fired power with CCS	Establish precedent for the technology	2010
Assessment of U.S. CO ₂ sequestration capacity	Primary requirement for siting power stations	<2020
Novel, inexpensive capture technology	Key cost determinant of CCS	<2020
Next generation CO ₂ EOR with maximum CO ₂ storage	Increases usable CO ₂ storage capacity in structurally confined geologic settings by three to ten fold	2020
Ubiquitous coal-fired power with CCS	Extensive power generation without CO ₂ emissions	2020
Rig-site or sub-surface hydrocarbon processing to generate low carbon fuels or feedstocks and recycle CO ₂ within the reservoir or field for EOR followed by CCS	Keeping most of the carbon in or near the reservoir, simplifying CCS logistics and costs, enabling low carbon fuels, heat, and power from oil and gas	2030

Table IVA.2. Summary of technologies in time and priority order.

V. Discussion

A. Two scenarios: a world with, or without, carbon constraint

Because of the likely link between anthropogenic CO₂ and undesirable climate change, use of fossil fuels in the coming decades may be significantly impacted by constraints on CO₂ emissions. We do not discuss the possible links between CO₂ emissions and climate (this is a separate debate), nor do we discuss the mechanisms whereby carbon constraint is imposed (tax, capping, trading, etc.). We are concerned here with proposing the best course of action, from the point of view of energy security, in the event that a significant carbon constraint applies.

In the current mix, oil accounts for 39% of hydrocarbon-related CO₂ emissions and gas for 20%, with coal accounting for the remaining 41%.⁷ Absent societal and market responses to climate change, oil and gas will continue to play a major role in energy supply over the next many decades. In particular, because of their high energy density and the convenience of using fluids, hydrocarbons will continue to dominate transportation. Conventional oil, heavy oils, and, to a lesser extent, biofuels, liquids derived from gas, and liquids derived from coal, will ensure continuity of supply for transportation at relatively low cost. At the same time, heat and power will be dominated by coal (providing security of supply) and natural gas (with its benefits as a clean fuel). Hydrogen power will only emerge in response to increasing carbon constraints, nuclear power will remain fixed or grow only slowly, and renewables will keep their secondary role.⁸

What happens to this picture if there is a significant constraint on emissions of CO₂? Given that more than half of the global energy-related emissions of CO₂ come

⁷ International Energy Agency: *World Energy Outlook (WEO) 2006*, IEA, Paris.

⁸ Koonin SE: "Energy for the Coming Decades: Trends and Technologies," MIT (September 2005). See <http://mitworld.mit.edu/video/299/>.

from oil and gas, the use of these resources cannot remain unaffected in such a world. If we are to continue to use hydrocarbons in a carbon-constrained world, then the CO₂ generated by burning fossil fuels must, to some substantial degree, be prevented from reaching the atmosphere. Carbon capture and sequestration (CCS) encompasses those technologies which achieve this. In a carbon-constrained world, CCS will play a crucial role amongst a portfolio of measures deployed to control the emissions of CO₂ to the atmosphere. In particular, in such a world, CCS will largely determine the degree to which we can continue to exploit hydrocarbons as sources of energy.

1. Carbon Capture and Sequestration: Enabling Acceptable Continued Use of Oil and Natural Gas in a Carbon-Constrained World

Carbon capture and sequestration entails the capture of CO₂, at the site where it is generated, and the storage of CO₂ for periods sufficiently long (several thousand years) to mitigate the impact of CO₂ on climate. We will consider only geological sequestration, which is probably sufficient, at least in magnitude if not in distribution, for the potential needs of the USA. We will not discuss possible alternatives such as deep sea sequestration, which is fraught with environmental concerns as well as being more costly. Geological sequestration would target spent oil and gas reservoirs and deep saline formations, the potential capacity of which we will discuss in this report.

In brief, carbon capture and sequestration will allow us to sustain many of the benefits of access to hydrocarbons even in a carbon-constrained world. Even where the CO₂ generated by burning hydrocarbon cannot be captured easily (as in the case of oil used for transportation), sequestration of CO₂ from other sources (such as coal-fired power stations) can help create, to some degree, the “headroom” needed to allow for the volumes of CO₂ that escape capture. Because of the likely continuing competitive (direct) cost of hydrocarbons, and in light of the huge investment already made in infrastructure to deliver them, under carbon constraint, the combination of fossil fuel use with CCS is likely to be emphasized as a strong complement to strategies involving alternative, non-hydrocarbon sources of energy supply. If we

wish to sustain the use of oil and gas to meet U.S. energy demands in a carbon-constrained world, and reduce the pace at which we would otherwise need to move towards alternative energy sources, then it will be necessary to plan for, and implement, CCS over the coming decades.⁹ Subsequently, we should expect a continued need for CCS beyond the end of the century. There is now a scientific consensus that anthropogenic CO₂ is driving detrimental climate change.¹⁰ Moreover, the IPCC Special Report on CCS indicates that including CCS in a mitigation portfolio could reduce the cost of stabilizing CO₂ concentrations in the atmosphere (to double the pre-industrial level) by 30% or more compared to other approaches.¹¹ The IPCC Special Report states:

“Models indicate that CCS systems will be competitive with other large-scale mitigation options such as nuclear power and renewable energy technologies. These studies show that including CCS in a mitigation portfolio could reduce the cost of stabilizing CO₂ concentrations by 30% or more. One aspect of the cost competitiveness of CCS technologies is that they are compatible with most current energy infrastructures.”

More recently, the UK Stern Review estimated, based on detailed macroeconomic modeling—but not without dissenting voices—that the cost of meaningful mitigation (aimed at maintaining atmospheric levels of CO₂ at no more than double the pre-industrial levels) would amount to about 1% of global GDP.¹² Doing nothing, on the other hand, would likely incur a cost of greater than 5% of world GDP (with a worst-case figure of 20%) to ameliorate the damage caused by a deteriorating climate. There is a basis to conclude that the financial risk to the nation of delaying action is now so high that a concerted emphasis on CCS is already strongly warranted.

⁹ The EU has an agreement with the Chinese government to fund and build in China a coal-fired power station, with full CO₂ capture and sequestration, to come on stream within the next five years.

¹⁰ Oreskes N: “The Scientific Consensus on Climate Change,” *Science* 306 (December 3, 2004): 1686.

¹¹ Metz et al, IPCC, reference 2

¹² “The Stern Review on the Economics of Climate Change.” http://www.hm-treasury.gov.uk/independent_reviews/stern_review_economics_climate_change/sternreview_index.cf

More generally, ensuring security of energy supply for the USA will involve a combination of a variety of approaches including: improving the efficiency of energy usage; reductions in dependence on conventional oil and gas; moves towards low carbon alternatives, and moves towards other fossil fuel sources (coal, unconventional oil and gas, etc.). However, the exploitation of heavy oil, tar sands, oil shales, and coal comes with a significantly heavier burden of CO₂ than conventional oil and gas. Yet, in the interests of energy security, there will likely be strong pressure to use them. CCS has the potential to mitigate some of this extra CO₂ burden. Here we are confronted with the interplay between concerns about energy security and concerns about climate. BP's Chief Scientist, Steve Koonin, elucidates this issue in Figure VA1.1 showing, in particular, the impact of CCS on this interplay between energy security and climate change.¹³

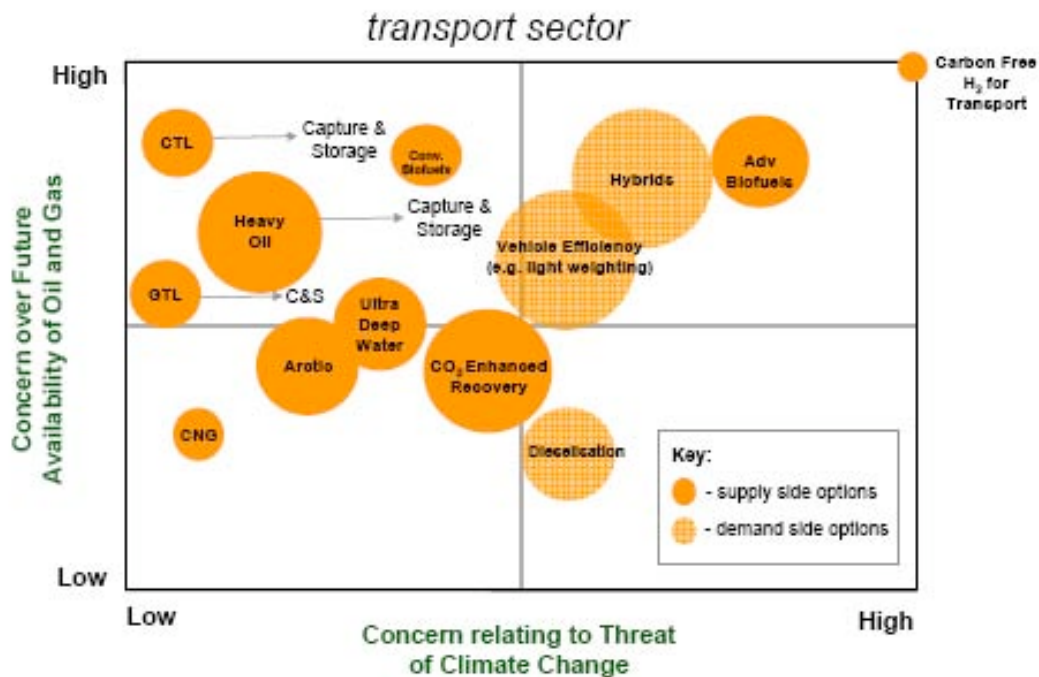


Figure VA1.1. Impact of CCS on interplay between energy security and climate change [reference 13].

¹³ Koonin, reference 8.

CCS will help mitigate extra CO₂ associated with heavy oil, coal-to-liquids (CTL) and gas-to-liquids (GTL) technologies and, thereby, help render these resources more readily usable even under carbon constraint.

2. The Role of the Oil and Gas Industry in CCS

The degree of CCS required in a carbon-constrained world is not inconsiderable. By the year 2056, based on current possible scenarios for climate change it will be necessary to mitigate at least 7 billion tons of carbon per year.^{14, 15} Sequestering a billion tons of carbon each year would entail pumping about 80 mbbls/day of supercritical CO₂ into secure geological formations. This amounts to about a quarter of the volume of water currently pumped worldwide for secondary oil recovery. At the local level, sequestering CO₂ from a 1 GW coal-fired power station would require pumping into the ground around 150,000 bbls/day of supercritical CO₂.^{16, 17}

The technologies and expertise needed to sequester such volumes already reside within the oil and gas industry. Sequestration of carbon dioxide is largely a modification of what the industry currently does to ensure the supply of oil and gas. The required knowledge of the subsurface is well-established and the pumping technologies are already ubiquitous. We will spend some time discussing the current status of this technology and any gaps that emerge in particular association with CCS but, by and large, the effective implementation of carbon sequestration does not critically depend on the development of currently unknown technologies.

a. The particular case of petroleum coke

The expectation is that electric power production with carbon capture will be matched largely to the combustion of solid fuels, rather than to natural gas. The reason is that natural gas power requires relatively little fuel processing, and therefore

¹⁴ Pacala S and Socolow R: "Stabilization Wedges: Solving the Climate Problem for the Next 50 Years Using Current Technologies," *Science* 305 (2004): 986.

¹⁵ IPCC *Third Assessment Report*, reference 1.

¹⁶ Socolow R: "Can We Bury Global Warming," *Scientific American* (July 2005). See <http://www.sciam.com>.

¹⁷ 6 MtCO₂/yr per 1 GW = 17,000 tCO₂/day = 150,000 bbl CO₂/day at 9 bbl per ton (specific gravity of 0.7).

the additional capital cost for CO₂ capture is a large percent of the total capital cost and a large number in \$/t CO₂. Solid-fuel power plants require considerably higher capital cost per kW, whether they be steam plants or gasification plants, but some of this capital does double duty when the task of capture is added; this is especially true for gasification, where the CO₂ is captured upstream of the turbine, as an add-on to gas cleaning. Moreover, starting with solid fuels provides more CO₂ to capture per unit of power. For both reasons, the cost of capture, in \$/t CO₂, should be considerably less for solid fuels.

The issues and choices presented by capture from a coal power plant are very similar for other solid fuels, notably including petroleum coke, but also biomass. For this report, we highlight petroleum coke (petcoke), and its analogues, that are the residual “bottom of the barrel” across the world’s refineries. Petcoke is essentially identical to a good quality coal, as far as capture is concerned. Its cost at the refinery is very low and sometimes even negative (one has to pay to get rid of it). In countries where air pollution rules are strict and enforced, it cannot be burned for power (it is often as high in sulfur as the highest-sulfur coals). The result is a largely opaque international trade in petcoke that has considerable risk for the petroleum industry, as concern for the export of pollution to poor countries becomes less and less socially acceptable. Petcoke-fueled power combined with CCS has the potential to transform a cost center and a political risk into a cutting edge, environmentally friendly, jobs-generating, and profitable technology. Gasification, along with capture, makes it possible to burn polluting fuels like petcoke, since the removal of pollutants when a gas is at high pressure is much cheaper than in a stack. Consequently, 6% sulfur petcoke (a typical figure) can be readily accommodated.

The Carson project announced early in 2006 by BP and Edison Mission Group (a power-plant operator in California) exemplifies this kind of venture. At BP’s 260,000 bbl/day Carson refinery near Long Beach, California, 4,500 t/day of petroleum coke will be gasified, creating a synthesis gas consisting mostly of CO and H₂. Subsequently, the gas will be “shifted” with steam to produce a gas consisting mostly of CO₂ and H₂. These two gases will be separated, the H₂ will be burned to generate

510 MW, and 4 Mt CO₂ /yr will be compressed and sent offsite for sequestration (in this case, twinned with enhanced oil recovery). The gasifier, shift reactor, gas cleaning technology, gas separation technology, CO₂ compressor, and hydrogen turbine are exactly the systems one envisages for coal power with CCS.

The petroleum industry, because of petcoke, is not a bystander to the early years of CO₂ capture, just as, because of EOR, it is not a bystander to the early years of CO₂ storage. For both aspects of CCS, the petroleum industry has the opportunity to lead the world as familiarity is gained and costs are reduced in a critical environmental endeavor. And it has the opportunity to operate profitably in domestic power markets and at domestic oil fields—in some cases even without the inducements generated by a CO₂ emissions price, and in many more cases when this price has arrived and become significant.

3. Outline of the Remainder of the Discussion

In this report we discuss the current status of carbon capture and sequestration technologies and make recommendations for future developments. We start with a discussion of the current status of these technologies and review the requirements for further development. We follow this with a discussion of the use of CO₂ for enhanced oil recovery. This represents an activity where we already inject significant quantities of CO₂ into oil reservoirs with a view to recovering more oil. This established activity provides an arena where we can test and develop many of the necessary approaches needed to make carbon sequestration a widespread technology. Finally we discuss issues of regulation of CCS since the regulatory environment will play a key role in encouraging the adoption or rejection of large scale carbon capture and sequestration.

B. R&D Requirements for Carbon Capture and Sequestration

There are many similarities between conventional oil and gas exploration and production, and geological carbon sequestration, including similarities in methodologies, tools, and technical concerns. Consequently, there is a high degree of

technical readiness for CCS. It should be stressed, though, that many of the experiences in analogous operations (e.g. CO₂-EOR) do not automatically translate into CCS rubrics. This section aims to clarify the points of similarity and difference from a technical perspective.

1. CO₂ Capture and Separation

The technologies for capturing CO₂ from pre- and post-combustion gas streams are available, although the costs are somewhat uncertain and there remain constraints on the levels of oxygen, of particulates, and of SO_x for effective extraction using the current amine solvents (MEA and MDEA). Current capture technologies also prefer steady-state conditions that do not always prevail in the power-generation arena. However the capture technologies broadly exist and are not critically dependent on new technology breakthroughs. They do require substantial heat to release the CO₂ and reconstitute the sorbent, and multiple pathways to low-cost, high-efficiency fuel conversion with CO₂ capture continue to be pursued.

The three main approaches involve post-combustion capture, pre-combustion separation, and combustion in a pure oxygen environment. Each approach could be accomplished through many technical pathways (e.g. sorbents, membranes). There are many projects in the USA, Europe, and Japan to reduce costs of CO₂ separation, including substantial industrial and governmental efforts. Several nations (e.g. Canada, Norway, and Japan) have created special testing facilities for new separation technologies, and the United States currently invests \$15 million per year on novel capture technologies, of a total of \$65 million per year invested in sequestration R&D through the Department of Energy. At present, each approach appears to be competitive in the correct context, and it is too early to select a preferred approach.¹⁸ There would appear to be considerable scope for greatly reducing the operating costs for carbon capture.¹⁹

¹⁸ *The Future of Coal*, MIT Press ISBN 978-0-615-14092-6 (2007). Available at <http://web.mit.edu/coal/>.

¹⁹ Metz et al, IPCC, reference 2.

2. CO₂ Transportation

Commercial CO₂-EOR has created a U.S. pipeline infrastructure and experience base for the transportation and distribution of large CO₂ volumes.²⁰ As such, the technology for CO₂ transportation is well established, as is the regulatory framework and siting criteria. Several issues remain, including concerns about corrosion, coordination of transportation with power plants, and issues of classification associated with transportation of component gases (e.g. H₂S, SO₄).

3. CO₂ Storage Capacity

A central question to CO₂ storage at a single site, for a commercial enterprise, or for a nation, is the likely CO₂ storage capacity. This question will affect project economics and viability as well as policy framework.^{21, 22} Methodologies to estimate risked pore volumes are well-tested and understood in the oil and gas industry and serve as a basis for reserves estimation. Workers have applied these approaches to capacity estimates, most notably in Australia and U.S. EOR provinces (see Section V.C).²³ Nonetheless, several outstanding questions or concerns remain regarding CO₂ storage-capacity estimation.

Even given a discrete pore volume estimate, the resource of storage capacity varies as a function of trapping mechanism. Many estimates use an assumed maximum solubility for a brine of given composition, whereas others look at physical trapping of pore volumes. Residual-phase trapping by capillary forces within the pores could trap CO₂ in as much as 20% of the pore volume, but the mechanism is very difficult to estimate theoretically and is sensitive to pore geometry and injection

²⁰ Metz et al, IPCC, reference 2.

²¹ Dooley JJ, Kim SK, Edmond JA, Friedmann SJ, Wise MA: "A First Order Global Geologic CO₂ Storage Potential Supply Curve and Its Application in a Global Integrated Assessment Model," Conference Proceedings, GHGT-7, IEA Greenhouse Gas Programme, Vancouver (2004).

²² Friedmann SJ, Dooley JJ, Held H, and Edenhofer O: "The low cost of geological assessment for underground CO₂ storage: Policy and economic implications," *Energy Conversion Management* 47 (2006): 1894–1901.

²³ Bradshaw J, Allison G, Bradshaw BE, Nguyen V, Rigg AJ, Spencer L and Wilson, P: "Australia's CO₂ Geological Storage Potential and Matching of Emission Sources to Potential Sinks," in *Greenhouse Gas Control Technologies: Proceedings of the 6th International Conference on Greenhouse Gas Control Technologies, 1–4 October 2002, Kyoto, (2003)*.

design. At present, no standards exist for capacity estimation. The USGS and the DOE are both developing such methodologies and these will help provide the basis of a well-vetted and broadly accepted approach that can be used to make investment decisions at the project, state, or federal level.

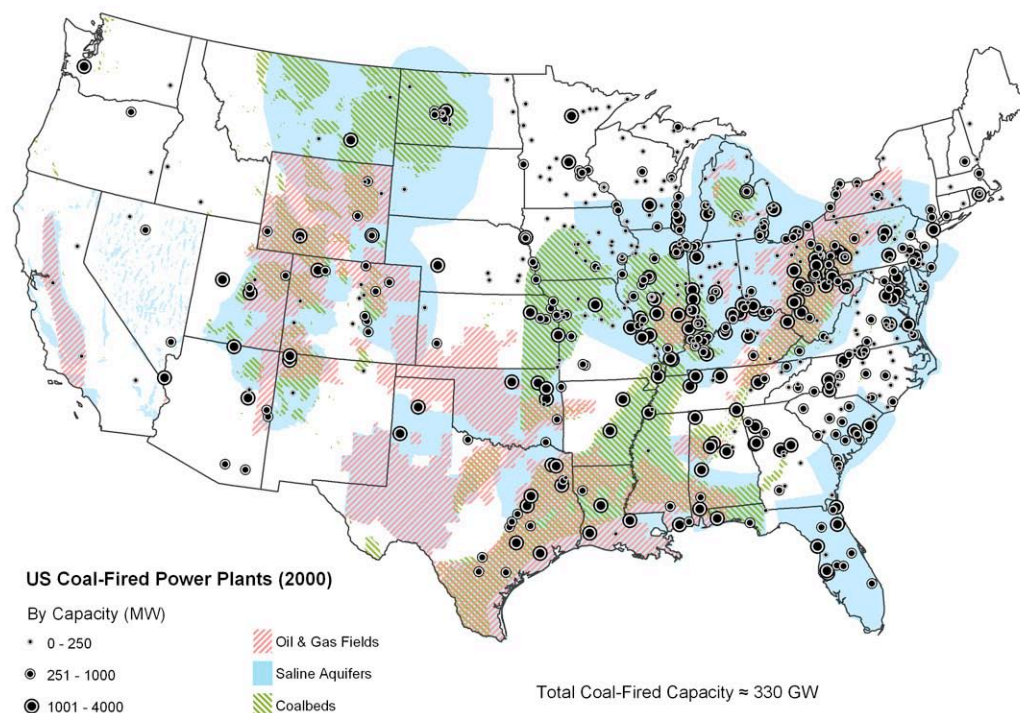


Figure VB3.1. Map comparing location of existing coal-fired power plants in the USA with potential sequestration sites. This information is not equivalent to local risked capacity volumes. Some shaded areas above may prove inappropriate, while detailed surveys may show sequestration potential in places that are currently not identified [Reference 18].

Unlike Alberta and Australia, the rest of the world including the USA lacks comprehensive maps of risked volumes by formation. The U.S. DOE has, however, initiated a substantial effort through the seven Carbon Sequestration Regional Partnerships which have been established across the states. The partnerships have developed a internet based, GIS system called “NATCARB” that is constantly updated as data are gathered on potential sequestration sites.²⁴ The partnerships are also developing a regional atlas that will form the initial foundation for establishing

²⁴ www.natcarb.org.

the locations of sources and sinks across the country (see Figure VB3.1). The USGS and other organizations have critical expertise that will contribute to creating a United States atlas on sequestration sites. Efforts should be directed and integrated for the entire nation at the federal level, and encouraged in other nations, including rapidly developing economies such as China and India. The combination of an accepted methodology and national formation-level maps would provide the basis to develop a resource pyramid that could underlie macroeconomic models of CCS deployment. It is worth noting that this effort represents the lowest initial-cost step in commercial CCS deployment with the highest likely return.²⁵

4. CO₂ Storage-Site Characterization

Proper siting of plants, infrastructure, and pipelines is essential to maximize use of capital and subsurface capacity. For CO₂ storage to succeed, a site must have three characteristics.²⁶

- Sufficient *injectivity* to sequester point-source volumes at a rate commensurate with the CO₂ production rate of the source (order of millions of tons CO₂/year)
- Sufficient *capacity* to store the total emissions of an injection project over its lifetime (order of 100s of millions of tons CO₂)
- *Effective* storage, such that the overwhelming majority of injected CO₂ will be kept from the biosphere and atmosphere for a long time.

This last characteristic (effectiveness) is the most difficult to define, and there is no current consensus on what constitutes effective storage. The IPCC Special Report on CCS considers it likely that 99% could be stored successfully for 1,000s of years and describes key components to a successful site.²⁷ The Weyburn project used a 5,000 year standard with over 99% storage.²⁸ The Australian government is

²⁵ Friedmann et al, reference 22.

²⁶ Friedmann SJ: "The ICE Framework for CO₂ Storage Site Characterization," NETL 5th Annual Conference on Carbon Sequestration, Alexandria, VA, ExchangeMonitor Publications (2006).

²⁷ Metz et al, IPCC, reference 2.

²⁸ Wilson and Monea, reference 4.

considering adoption of a standard of 99.9% over 1,000 years. At present, no U.S. project, state, or federal entity has published a proposed standard.

For the framework of injectivity, capacity, and effectiveness (ICE) to be commercially viable, conventional geological, geophysical, and petrophysical approaches must suffice for characterization. While injectivity is fairly straightforward, capacity characterizations must assume different storage mechanisms for a given pore volume (e.g. CO₂ dissolution, residual-phase trapping, and physical trapping) and will consequently require special analysis of cores and rock samples. Effectiveness characterizations will require understanding of caprock continuity and integrity, geomechanical and wellbore hazards, and regional hydrodynamics (see section VB5 below). Ultimately, conventional tools and approaches such as well-logs, core samples, stress-tensor information, 2D and 3D seismic surveys, and structural and stratigraphic analyses should be able to provide enough information to execute a successful site characterization. However, the appropriate level of due diligence is likely to vary from site to site as a function of data density, analog or correlative information, and scale of project.²⁹

5. CO₂ Storage Monitoring and Verification

Once injection begins, a program of measurement, monitoring, and verification (MMV) of CO₂ distribution is required in order to:

- understand key features, effects, and processes needed for risk assessment
- manage the injection process
- delineate and identify leakage risk and surface escape
- provide early warnings of failure near the reservoir
- verify storage for accounting and crediting.

For these reasons, MMV is a focus of many CCS research efforts.³⁰ Because research and demonstration projects are attempting to establish the scientific basis for

²⁹ Friedmann, reference 26.

³⁰ U.S. DOE, reference 6.

geological sequestration, they will require more involved MMV systems than future commercial projects.

Perhaps surprisingly, there has been little discussion of what are the most important parameters to measure and in what context (research or pilot vs.

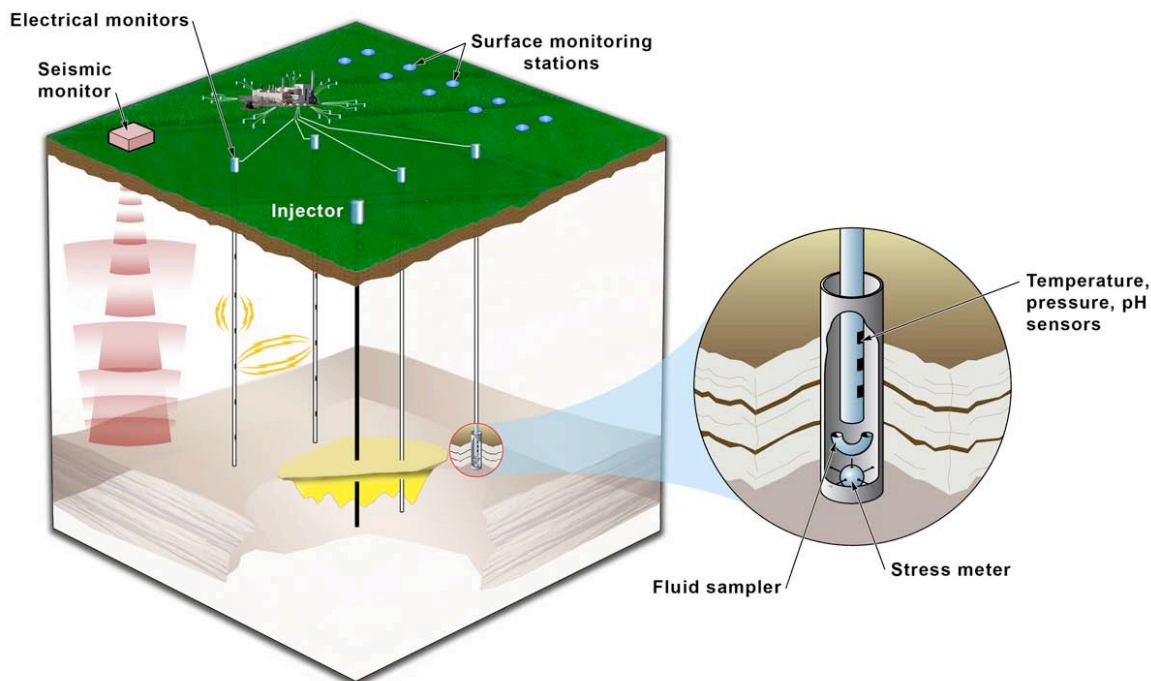


Figure VB5.1. Schematic diagram of a monitoring array providing insight into all key parameters.

Note both surface and subsurface surveys, and downhole sampling and tool deployment. A commercial monitoring array would probably be much larger [Reference 18].

commercial).³¹ Rather, the literature has focused on the current ensemble of tools and their costs.³² Time lapse (4D) seismic has emerged as the standard for comparison, with 4D surveys deployed at Sleipner and Weyburn and likely to be deployed at In Salah. While this technology excels at delineating the boundaries of a free-phase CO₂ plume, and can detect small saturations of conjoined free-phase bubbles that might be an indicator of leakage, time-lapse seismic does not measure all the relevant parameters and has limits in some geological settings. Key parameters for research

³¹ MIT, reference 18.

³² Benson SM, Hoversten M, Gasperikova E, and Haines M: "Monitoring Protocols and Life-Cycle Costs for Geological Storage of Carbon Dioxide," Conference Proceedings, GHGT-7, IEA Greenhouse Gas Programme, Vancouver (2004).

and validation of CO₂ behavior and fate involve both direct detection of CO₂ and detection through proxy data sets. Table VB5.1 describes the most important parameters for monitoring.

Parameter	Viable tools
Fluid composition	Direct sample at depth (e.g. U-tube), surface sampling
Field-wide temperature and pressure	Thermocouples, pressure transducers, fiber-optic Bragg grating
Subsurface pH	Down hole pH sensors
CO ₂ distribution	Time-lapse seismic, tilt, ERT*, EMIT [‡] , microseismic
CO ₂ saturation	ERT*, EMIT [‡] , advanced seismic methods, well-logging
Stress changes	Tri-axial tensiometers, fiberoptic Bragg grating
Surface detection	Eddy towers, soil gas, FTIRS [†] , PFC and noble gas tracers
* Electrical-resistivity tomography ‡ Electromagnetic-induction tomography † Fourier-transform infrared spectrometers	

Table VB5.1 Key parameters for CO₂ monitoring and verification.

Importantly, even in the fields where multiple monitoring techniques have been deployed (e.g. Weyburn), there has been little attempt to integrate the results. This was identified as a research gap from the Weyburn effort. There are few formal methods to integrate and jointly invert multiple data streams; however, past studies have demonstrated that formal integration of orthogonal data often provides robust and strong interpretations of subsurface conditions and characteristics.^{33, 34} It is highly likely that the integration will improve robustness and accuracy of inference while at the same time it will reduce the cost of monitoring operations. As such, the absence of integration of measurements represents a major gap in current MMV capabilities and understanding.

At present, there is no standard accepted approach (e.g. best practices) to the operation of MMV networks. This is particularly important in future commercial projects, where a very small MMV suite focused on leak detection may suffice.

³³ Benson et al, reference 32.

³⁴ Ramirez A, et al: "Stochastic Inversion of Electrical Resistivity Changes Using a Markov Chain Monte Carlo Approach," *Journal of Geophysical Research* 110 (2005): B02101.

Within the context of a large-scale deployment, it is likely that determination and execution of monitoring will involve a four-phase approach.³⁵

Assessment and planning: During this phase, the site is characterized geographically, geologically, geophysically, and geochemically.

Baseline monitoring: Before injection takes place, baseline surveys must be collected to understand the background and provide a basis for difference maps.

Operational monitoring: During injection, injection wells are monitored to look for circulation behind casing, failures within the well bore, and other operational problems or failures.

Array monitoring during and after injection: This phase will involve active surface and subsurface arrays, with the potential for additional tools around high-risk zones. Ideally, MMV data would be formally integrated to reduce operational cost and complexity and to provide higher fidelity.

Ultimately, practices in CO₂ monitoring and verification will lead to the development of protocols and eventually standards for operation. This must include a fit-for-purpose monitoring rubric with low cost and high reliability and accuracy. This issue cannot be answered without testing and research at large-scale projects and without formal data integration.

6. CO₂ Leakage Hazards and Risks

Since supercritical CO₂ is buoyant in most geological settings, it will seek the earth's surface. Therefore, despite the fact that the crust is generally well configured to store CO₂, there is the possibility of leakage from storage sites. Leakage of CO₂ would negate some of the benefits of sequestration.³⁶ If the leak is into a contained environment, CO₂ may accumulate in high enough concentrations to cause adverse health, safety, and environmental consequences.^{37,38} For any subsurface-injected

³⁵ MIT, reference 18.

³⁶ Gasda SE, Bachu S, and Celia MA: "The Potential for CO₂ Leakage from Storage Sites in Geological Media: Analysis of Well Distribution in Mature Sedimentary Basins," *Environmental Geology* 46, No. 6-7 (2004): 707–720.

³⁷ Snodgrass WR: "Physiological and Biochemical Differences between Children and Adults as 5 Determinants of Toxic Exposure to Environmental Pollutants," in *Similarities and Differences between*

fluid, there is also the concern for the safety of drinking water.³⁹ Based on experience analogous to CO₂ injection, such as acid-gas disposal and EOR, these risks appear small. However, the state of science today does not provide quantitative estimates of the (site-specific) risk associated with CCS operations.

It is worth bearing in mind for the future evolution of risk that, although sequestration in reservoirs or saline formations is the immediate option, and that risk, monitoring, etc., should all be based around this, over the coming decades CO₂ will probably become more safely and permanently sequestered, for example through the development of accelerated mineralization processes, microbial sequestration, and hydrate formation where conditions allow. In other words, improvements in sequestration techniques will lower the risks of leakage with time; the technology will not remain static and will be applicable retrospectively to already sequestered CO₂.

The list of potential earth and atmospheric hazards that could present substantial risk is short. Each fundamental hazard—atmospheric release, groundwater contamination, and crustal deformation—is associated with a characteristic set of potential injection-triggered processes (risk elements) that may alone or in combination result in hazard realization. Table VB6.1 summarizes these hazards and their risk elements.

Atmospheric release hazards	Groundwater degradation hazard	Crustal deformation hazards
Well leakage	Well leakage	Well failure
Fault leakage	Fault leakage	Fault slip/leakage
Caprock leakage	Caprock leakage	Caprock failure
Pipeline/ops leakage		
Pink = highest priority		Induced seismicity

Children and Adults: Implications for Risk Assessment, Guzelain PS, Henry CJ, and Olin SS (eds.), ILSI Press, Washington, DC, USA. (1992).

³⁸ National Institute for Occupational Safety and Health (NIOSH): *Pocket Guide to Chemical Hazards*. DHHS publication no. 97-140. U.S. Government Printing Office, Washington, 25 DC, USA (1997).

³⁹ Wilson Wilson EJ, Friedmann SJ, Pollak M: "Research for Deployment: Incorporating Risk, Regulation and Liability for Carbon Capture and Sequestration," *Environmental Science & Technology*, in press.

Orange = high priority Yellow = moderate priority		Subsidence/tilt
--	--	-----------------

Table VB6.1. CCS-related earth and atmospheric hazards and component risk elements.

For each hazard class, the prioritization hierarchy assigned to developing protocols for underlying risk elements reflects *a priori* perception of relative importance, which has a significant component of site dependency; e.g. Table VB6.1 prioritizations are based on a hypothetical CCS project in the Los Angeles basin. Such prioritizations would likely be different for cases in the Illinois basin, coastal Gulf of Mexico, or offshore New Jersey.

Wells almost certainly present the greatest risk to leakage to all cases, because they are drilled to bring large volumes of fluid quickly to the earth's surface, removing the aspects of the rock volume that prevent buoyant migration.⁴⁰ Well casing and cements are susceptible to corrosion from carbonic acid. When wells are adequately plugged and completed, they trap CO₂ at depth effectively; however, large numbers of orphaned or abandoned wells may not be adequately plugged, completed, or cemented, and such wells represent potential leak points for CO₂.⁴¹ From a practical standpoint, well failure provides a clear trail of liability and exposure to a specific operator or company. Little is known about the specific probability of escape from a given well, the likelihood of such a well existing within a potential site, or the risk such a well presents in terms of potential leakage volume or consequence.⁴²

A proper risk assessment would focus on several key elements, including both likelihood and potential impact. Efforts to quantify risks should focus on scenarios with the greatest potential economic or health and safety consequences. An aggressive risk-assessment research program would help financiers, regulators, and policy makers decide how to account accurately for leakage risk. Ultimately, as with

⁴⁰ Gasda et al, reference 36.

⁴¹ Ide ST, Friedmann SJ, and Herzog HJ: "CO₂ Leakage Through Existing Wells: Current Technology and Regulatory Basis," 8th Greenhouse Gas Technology Conference, Trondheim, Norway, Poster session II (2006).

⁴² Scherer GW, Celia MA, Prevost JH, Bachu S, Bruant R, Duguid A, Fuller R, Gasda SE, Radonjic M, and Vichit-Vadakan W: "Leakage of CO₂ through Abandoned Wells: Role of Corrosion of Cement," in *The CO₂ Capture and Storage Project (CCP), Volume II*, Thomas DC and Benson SM (eds.) (2005): 823–844.

monitoring and verification, large-scale projects will be central to understanding the full suite of hazards and their risk profile.

7. Summary: Technical Issues

- The USA lacks a national CO₂ storage-capacity assessment. This greatly inhibits potential CCS users in making key investment decisions. A national assessment should be resolved as a policy priority.
- The USA needs to undertake multiple large-scale storage projects that vet key representative national geological settings. These are central to providing science and technology inputs to development of regulatory frameworks, central to public acceptance of CCS, and central to development of an industrial business model. Opportunities in EOR will be critical in the near term for both commercial-scale deployment and technology development—however, long term deployment will require large projects in saline formations.
- There is currently a substantial effort in reducing capture costs, much of it outside the USA. Substantial reduction in capture costs would help increase deployment and industrial growth in CCS. This is a global effort; the USA needs to increase international participation and its research efforts.
- Technology today is well understood and effective and can probably deliver what is needed. However, there are some outstanding technical concerns.
 - Novel, lower-cost capture technologies
 - Integration and fit-for-purpose deployment of monitoring and verification
 - Well leakage characterization and mitigation
 - Protocols for site characterization
 - Technical basis for operational protocols and risk characterization.

8. Summary: Non-Technical Issues

Given the scope of commercial CCS, there are many issues that are not technical per se but relate to technical readiness and maximizing early investment.

- There is a high likelihood of a critical gap in human capital. Currently, workers who can execute CCS are the same as those employed in oil and gas exploration and production. In a carbon-constrained economy, there will not be enough skilled workers to go around. This is particularly true of geoscientists, but also true of chemical and mechanical engineers.
- Development of regulations is critical to providing the certainty needed to make investment decisions. This is discussed in greater depth in Section V.D.
- The legislative and regulatory framework within which CCS is conducted will have a major impact on how rapidly the technology is implemented and ultimately will determine whether CCS can effectively mitigate carbon emissions and provide access to future hydrocarbon supplies. A section of this report is devoted to regulatory issues and details the various aspects of regulation that will be critical to the success of CCS.
- It is not clear that the science and technology programs in place today will provide the answers that regulators and decision makers need. Greater dialogue between individuals in technology and regulatory-framework development would help to reduce unnecessary regulation and guide R&D goals to serve the most immediate needs.
- Infrastructure to transport CO₂ (e.g. pipelines) is a key enabler to commercial deployment. However, there is concern that pipelines for early project opportunities will not be able to carry additional future projects. Incentives and government action for this infrastructure are needed to build networks sufficient for large-scale commercial CCS deployment in the USA.

9. Recommendations

- The DOE should invest in integrated large-scale demonstrations that serve an R&D function in capture and in storage. These projects should be appropriately supported both in terms of the volumes of CO₂ involved and in terms of the scientific program. This will extend the DOE's current activity

on large-scale injection which they are pursuing through Phase III of the Carbon Sequestration Regional Partnerships.

- The USA needs to undertake a national capacity assessment as a policy priority, building on the existing efforts being undertaken by the DOE Regional Partnerships.
- Incentives of many kinds are critical to accelerated deployment of CCS and limit waste and redundancy. Such incentives might include:
 - Pipeline construction, permit streamlining, and appropriate scaling
 - Training of human capital
 - Regulatory clarity
 - Limitations to liability, particularly for early pilots
 - Severance or royalty tax relief for anthropogenic CO₂ storage
 - Increased R&D in carbon capture and storage.

C. Integrating CO₂ Sequestration with CO₂ Based Enhanced Oil Recovery

Enhanced oil recovery using CO₂ (CO₂-EOR) has the potential to play a key role in the early commercialization of CCS and, as such, will provide an important technology bridge to more extensive carbon sequestration. CO₂-EOR is already used extensively as one of the main techniques for increasing the fraction of oil that can be recovered from a reservoir, and is becoming an increasingly valuable technology in mature reservoirs. Currently about 40 Mt of CO₂ is pumped each year to improve recovery in U.S. oil fields. Ironically, most of this CO₂ comes from natural sources (about half from the McElmo Dome alone). We should, in future, expect carbon-constraint policy to emphasize anthropogenic sources of CO₂ for EOR and to discourage the extraction of CO₂ already naturally sequestered safely underground. We should also expect that as CO₂ becomes more readily available because of the pressure to mitigate carbon, then greater use will be made of anthropogenic CO₂ to improve recovery in young fields at earlier stages of production, when it is even more

effective at enhancing ultimate recovery. In each case CO₂-EOR has the potential to significantly increase the supply of oil and delay the ultimate decline of the resource.

Although currently CO₂-EOR is not optimized for sequestration, with the emphasis on removing oil rather than on CO₂ storage, it has the potential to play a significant role in CO₂ sequestration.⁴³ In future, it will be necessary to assert an additional focus on CO₂ storage and modify approaches to CO₂-EOR with this in mind. Ultimately the size of the market for CO₂-EOR is not large enough to approach the full needs of carbon mitigation, but it will be through CO₂-EOR that many of the CCS technologies will be driven and refined. At the same time, of course, CO₂-EOR will continue to help augment the supply of oil. Consequently we will devote considerable attention in this report to the discussion of CO₂-EOR and its potential impact on security of supply in a carbon-constrained world.

1. Oil Reservoirs as Preferred Sites for Storing CO₂

Large oil reservoirs have numerous attributes that make them ideal candidates for safely and securely storing CO₂.

- **Established trap and seal:** The oil reservoirs that are candidates for combined CO₂ sequestration and EOR have accumulated and held fluids for millions of years, providing confidence in the integrity of the reservoir seal and the permanence of the fluid trap. As such, CO₂ injected into an oil reservoir remains securely trapped and stored.
- **Well-defined local and regional geologic settings:** Decades of geological and geophysical studies have lead to valuable data and understandings on the subsurface conditions in major oil reservoirs. As such, greater confidence exists for using these reservoirs for securely storing CO₂.
- **Potential for value-added products:** In geologically favorable settings, injecting CO₂ into an oil reservoir can recover a significant portion of the oil that is left behind after primary and secondary oil recovery. As such, CO₂-

⁴³ Jessen K, Kovscek AR, and Orr FM Jr: "Increasing CO₂ Storage in Oil Recovery," *Energy Conversion and Management* 46 (2005): 293–311.

EOR could provide revenues to offset some (or all) of the costs of storing CO₂. Many parts of the world have large oil fields with reservoir properties favorable for combining CO₂ storage with EOR. Advances in technology could increase the rate at which oil can be recovered while maximizing the storage of CO₂.

- **Use of existing infrastructure:** In many cases, much of the essential infrastructure already exists at oil fields for injecting and storing CO₂. As such, the capital requirements for establishing a CO₂ storage facility could be considerably lower than for alternative CO₂ storage sites. In addition, the permitting, land-disturbance and public-acceptance aspects of initiating a CO₂ storage project would be more readily accepted in areas already developed for and comfortable with injection of fluids into the subsurface. Extending CO₂ injection into the aquifers below an oil reservoir could significantly increase storage capacity at relatively low cost.
- **Establish procedures for compensating surface and mineral owners:** The established practice of royalty payments and prior actions involving unitization of oil fields will help overcome one of the most difficult barriers to geological storage of CO₂—gaining acceptance by site owners for the use of their property for injecting and storing CO₂.

2. CO₂ Storage Capacity Offered by Oil Reservoir

While large oil fields are an attractive, near-term option for storing CO₂, particularly when these fields may also provide significant “value-added” oil production, considerable uncertainty surrounds the question—*how much CO₂ is required and could be geologically sequestered in oil fields as part of CO₂-EOR?* Addressing this question requires addressing three underlying topics.

- 1) *How should one estimate the technically available CO₂ storage capacity in oil fields amenable to miscible and immiscible CO₂-EOR?*
- 2) *How much of this technical storage capacity becomes actually used as part of CO₂-EOR, given the way it is currently applied?*

3) *How much additional CO₂ storage could be achieved by providing incentives and advances in technology for integrating CO₂-EOR and CO₂ storage?*

The recent guidelines developed for the 2006 National Geological Carbon Sequestration Capacity Assessment provide a standard methodology for estimating the technical CO₂ storage capacity for oilfields.⁴⁴ According to these guidelines, this capacity is to be set equal to the volume of hydrocarbons produced from the reservoir. This can be established by adding: (1) past conventional oil (and associated gas) production; (2) remaining reserves; and (3) oil produced by enhanced oil recovery. (However the total technical CO₂ storage volume offered by oil reservoirs and their associated structures is considerably larger than the above estimate when one includes the transition, residual oil zone below the main oil pay zone and the underlying saline aquifer.)

Using the above guidelines, the technical CO₂ storage capacity offered by discovered U.S. oil reservoirs is on the order of 50 billion metric tons of CO₂. This estimate assumes an ultimate recovery of 300 billion barrels of stock tank oil (equal to 400 billion barrels of reservoir oil), a conversion factor of 2.25 Mcf of CO₂ per barrel of available reservoir pore space, and a conversion factor of 18.9 Mcf of CO₂ per metric ton. An additional 20 billion metric tons of CO₂ storage capacity exists in the reservoir strata below the main pay zone.

However, under current CO₂-EOR practices, only a portion of this technically available CO₂ storage capacity would become productively used, estimated at 5 to 8 billion metric tons under the economic assumptions set forth in the study (see Tables VC2.1 and VC2.2).⁴⁵

⁴⁴ "Proposed Methodology for Construction of a 2006 National Geological Carbon Sequestration Capacity Assessment," final draft prepared for U.S. Department of Energy, Regional Carbon Sequestration Partnership Program, prepared by Capacity and Fairways Subgroup of the Geologic Working Group of the DOE Carbon Sequestration Regional Partnerships (October 1, 2006).

⁴⁵ Advanced Resources International: "Ten Basin-Oriented CO₂-EOR Assessments Examine Strategies for Increasing Domestic Oil Production, Alaska, California, Onshore Gulf Coast, Mid-Continent, Illinois and Michigan, Permian Basin, Rocky Mountains, East and Central Texas, Offshore Louisiana, and Williston Basin," U.S. Department of Energy, Office of Fossil Energy (February 2006).

Basin or Area	Technically Recoverable Oil (billion barrels)	Demand for Purchased CO ₂ (Tcf)
1. Alaska	12.4	51.4
2. California	5.2	23.9
3. Gulf Coast	6.9	33.3
4. Mid-Continent	11.8	36.3
5. Illinois and Michigan	1.5	5.7
6. Permian	20.8	95.1
7. Rockies	4.2	27.5
8. Texas, East and Central	17.3	62
9. Williston	2.7	10.8
10. Louisiana offshore (shelf)	5.9	31
Total	88.7	377.1

Table VC2.1. U.S. CO₂-EOR technical market for purchased CO₂ (ten basins or areas).

	Recoverable Oil (billion barrels)	Purchased CO ₂		Stored CO ₂ (billion tonnes)
		(Tcf)	(billion tonnes)	
Technically recoverable	89	377	20	10–16
Economically recoverable*	47	188	10	5–8
*Assumes \$40 per bbl oil price, CO ₂ cost of \$0.80/Mcf and a rate of return of 15% before tax.				

Table VC2.2. U.S. CO₂-EOR technical and economic market for purchased CO₂ (ten basins or areas).

Currently, about 2 Bcf/d of CO₂ is injected for CO₂-EOR, with one-quarter of this from industrial sources, Table VC2.3.

State or Province (storage location)	Source Type (location)	CO ₂ Supply MMcf/d	
		Natural	Industrial*

Texas-Utah-New Mexico	Geologic (Colorado-New Mexico) Gas processing (Texas)	1,300	75
Colorado-Wyoming	Gas processing (Wyoming)	0	240
Mississippi	Geologic (Mississippi)	400	0
Michigan	Ammonia plant (Michigan)	0	15
Oklahoma	Fertilizer plant (Oklahoma)	0	35
Saskatchewan	Coal gasification (North Dakota)	0	145
TOTAL		1,700	510**
*Source: ARI, reference 46.			
**Equal to 10 million metric tons per year.			

Table VC2.3. Volumes of natural and industrial CO₂ injected for EOR.⁴⁶

The IPCC Special Report on Carbon Dioxide Capture and Storage recognized the global limitations in using and storing CO₂, as CO₂-EOR is currently practiced, by stating:⁴⁷

“Enhanced oil recovery operations have the lowest capacity of all forms of CO₂ geologic storage, estimated globally at 61 to 123 billion (metric) tons of CO₂.”

In addition, the IPCC report recognized that changes in CO₂-EOR operating practices could lead to more efficient use of the CO₂ storage capacity offered by oil fields:

“ . . . it is important to note that CO₂ EOR, as practiced today, is not engineered to maximize CO₂ storage. In fact, it is optimized to maximize revenues from oil production, which in many cases requires minimizing the amount of CO₂ retained in the reservoir. In the future, if storing CO₂ has an economic value, co-optimizing CO₂ storage and EOR may increase capacity estimates.”

⁴⁶ Advanced Resources International: “An Estimate of the Capacity for CO₂ Storage in Depleting Oil Fields in the United States (Updated),” Advanced Resources International as part of the CarBen Model Update for U.S. DOE, National Energy Technology Laboratory, Task Order No. DE-AD26-06NT42752 (October 2006).

⁴⁷ Metz et al, IPCC, reference 2.

3. Expanding CO₂ Storage Capacity Offered by Oil Reservoirs

Providing incentives for storing CO₂ and demonstrating integrated CO₂-EOR and CO₂ storage technology could lead to a much larger portion of the CO₂ storage capacity available in oil reservoirs (and their underlying storage space) being productively used. While considerable work remains to be done to provide a reliable estimate, preliminary analyses indicate that the usable storage capacity in U.S. oil fields can be increased by six to ten fold to 50 billion metric tons.^{48, 49}

By analogy, the equivalent global storage capacity in oil reservoirs offered by integrating CO₂-EOR and CO₂ storage and assuming incentives exist that defray the costs of storing additional CO₂ would also increase by six to ten fold. This would increase the capacity of CO₂ storage with enhanced oil recovery operations to a range of 400 to 1,200 billion metric tons.

Developing a more-rigorous estimate of global CO₂ storage capacity offered by oil fields and CO₂-EOR requires answering: *how many of the world's oil fields are technically and economically amenable to CO₂-EOR; how many of the technically amenable oil fields are favorably located with respect to large sources of industrial CO₂; and how many of these favorable oil reservoirs will use integrated CO₂-EOR and CO₂ storage?* The near-term feasibility of using geological storage for managing carbon depends greatly on the answers to these questions.

4. Role of CO₂-EOR as a Bridge to Carbon Management

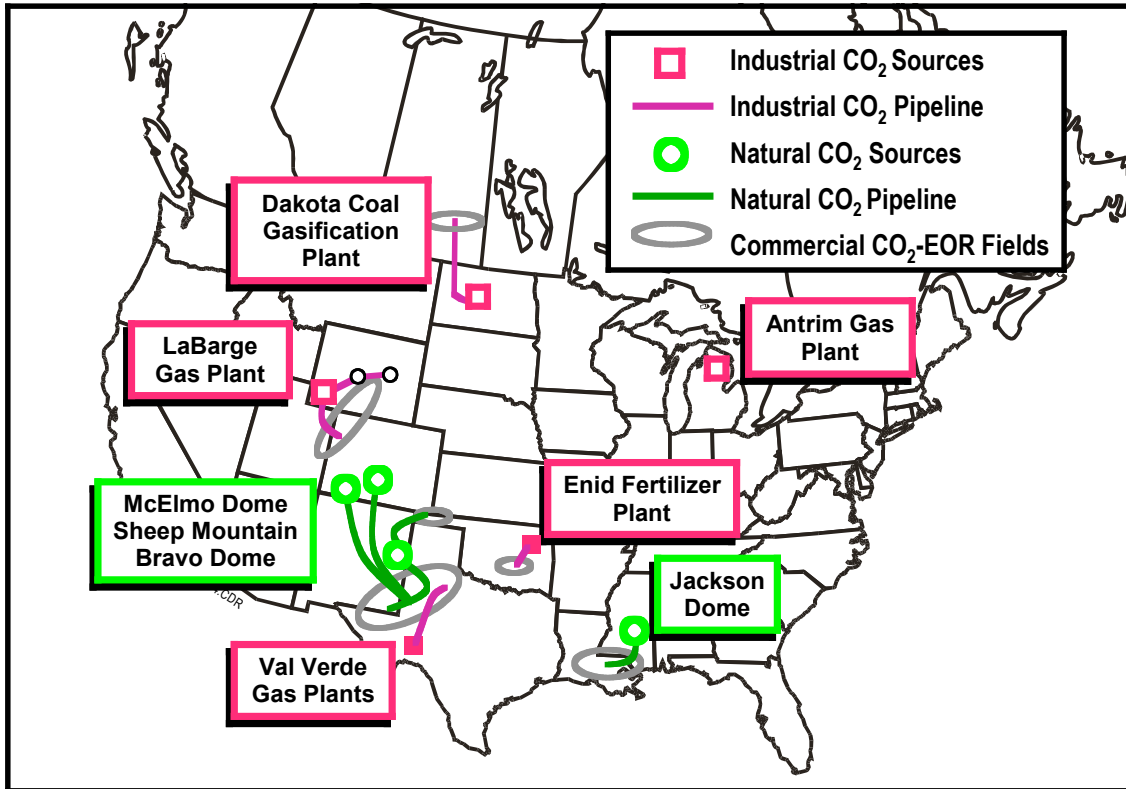
In addition to offering secure locations for storing CO₂, CO₂-EOR could serve as a most valuable near-term “bridge” toward longer-term CO₂ management.

- CO₂-EOR can help build portions of the essential CO₂ storage and transportation infrastructure for facilitating larger-scale, longer-term storage of CO₂. A number of pipelines already transport industrial CO₂ for EOR, notably the 200-mile CO₂ pipeline from the Northern Great Plains

⁴⁸ Kuuskraa VA and Koperna GJ: “Assessing and Expanding CO₂ Storage Capacity in Depleted and Near-Depleted Oil Reservoirs,” presented at GHGT-8, Trondheim, Norway (June 19–23, 2006).

⁴⁹ Advanced Resources International, reference 46.

Gasification Plant in North Dakota to the Weyburn CO₂-EOR project in Saskatchewan, Canada. Other CO₂ pipeline systems link industrial CO₂ with oil fields in Michigan, Oklahoma, West Texas and Wyoming. Figure VC4.1 provides a diagram of existing CO₂ pipelines, with emphasis on pipelines transporting industrial CO₂ for EOR.



JAF02594.PPT

Figure VC4.1. Domestic CO₂-EOR pipeline system and projects [ARI, reference 46].

- CO₂-EOR can also help establish protocols, experience, and public confidence on safely and securely storing CO₂ in geological formations. A broader base of experience in integrating CO₂-EOR and CO₂ storage, particularly in portions of the USA and other parts of the world lacking prior experience with handling, transporting and injecting CO₂ deep into the earth, could facilitate public and regulator acceptance of this important CO₂ management option.

5. Identifying and Overcoming Barriers to Integrating CO₂-EOR and CO₂ Storage

In spite of its potential, a number of barriers impede wide-scale integration of CO₂-EOR and CO₂ sequestration. This section of the report identifies the most important of these barriers and discusses actions that could accelerate the removal of these barriers.

- **Lack of incentives for storing CO₂:** The most significant of the barriers is the lack of revenue or incentives for storing industrial CO₂. For an oil producer, the purchase, injection and recycling of CO₂ is the single largest cost for an enhanced oil recovery project. Injecting and storing large volumes of CO₂, beyond the optimum volumes required for CO₂-EOR, could make a project uneconomic. A well-formulated set of incentives, sufficient to cover the costs of injecting and storing industrial CO₂, beyond the standards of conventional EOR, is required if industry is to fully utilize the secure CO₂ storage capacity offered by oil reservoirs.
- **Limitations in current knowledge of CO₂ trapping and storage mechanisms:** Very limited information exists yet on alternative geologic structures and how these alternative geologic settings would securely trap CO₂. A robust R&D program on fundamental CO₂ storage mechanisms, such as capillary trapping, characterization of pore geometrics, density inversion, and mineralization, would greatly improve the current knowledge base on how to maximize CO₂ storage capacity and assure its secure, long-term containment.⁵⁰

⁵⁰ Bachu S and Shaw JC: "CO₂ Storage In Oil And Gas Reservoirs In Western Canada: Effect of Aquifers, Potential For CO₂-Flood Enhanced Oil Recovery And Practical Capacity," Conference Proceedings, GHGT-7, IEA Greenhouse Gas Programme, Vancouver (2004).

6. Limitations in Current CO₂-EOR and CO₂ Storage Design and Technology

CO₂-EOR, as currently practiced, uses very little (about 10%) of the storage capacity available in oil reservoirs. A robust set of field demonstrations of applying integrated CO₂-EOR and CO₂ storage in alternative geological and geographic settings is needed for overcoming this barrier. This would help field operators establish optimum well and flood designs at project initiation to achieve increased CO₂ storage. One such field demonstration effort that has the potential for integrating CO₂-EOR storage has recently been funded at the Citronelle Oil Field in Alabama by the U.S. DOE.⁵¹ Other essential technological advances would involve using “smart wells” and real-time process control to manage gravity-stable CO₂-EOR (as further discussed in section VC7 below).

7. Increasing, or Reducing Global CO₂ Emissions?

A question often asked is: *would wide-scale use of integrated CO₂-EOR and CO₂ sequestration further contribute to or help solve global CO₂ emissions problems?* The concern is that by applying CO₂-EOR (or any EOR), more of the oil in the ground (and its associated carbon) is produced and consumed, contributing to higher CO₂ emissions.

One response to this question is that additional liquid fuel consumption and thus production, at some level, will be needed to support the world economy. As such, answering this question requires addressing the related question: *what will be the CO₂ emissions footprint of the alternative sources of liquid transportation fuels?*

- Some of the proposed alternative sources of liquid fuels, such as coal-to-liquids, oil shale and oil sands, will likely have a much larger CO₂ emissions footprint than CO₂-EOR.

⁵¹ DOE Fossil Energy Techline: “A Two-For-One Solution.... Alabama Project Plans to Store Carbon Dioxide, Boost Oil Production” (September 6, 2006). See http://www.fossil.energy.gov/news/techlines/2006/06050-DOE_Awards_EOR_Project.html.

- Other proposed alternatives, such as corn-based ethanol or hydrogen, involve major energy inefficiencies, have less visible but still substantial CO₂ emissions, and still face significant economic constraints.

A more positive response is that it is technically possible to use innovative CO₂-EOR designs that would sequester a greater quantity of CO₂ in the reservoir than that quantity of CO₂ that would be emitted from burning the produced oil. In general, 0.4 metric tons of CO₂ would be released in consuming one barrel of produced crude oil.

- A typical CO₂-EOR project, operated to optimize oil recovery, will inject about 0.25 to 0.30 metric tons of purchased CO₂ per barrel of recovered oil. At the end of the project, from 0.15 to 0.20 metric tons of CO₂ per barrel of oil will remain in the reservoir, depending on trapping mechanisms inherent to the reservoir and operator practices. As such, the oil produced by today's typical application of CO₂-EOR, assuming the use of industrial CO₂, provides an offset for 40% to 50% of the CO₂ emissions in the produced oil.
- Integrated application of CO₂-EOR and CO₂ storage, assuming appropriate incentives exist for storing additional CO₂ beyond the requirements of the EOR project, could lead to storing more CO₂ in the oil reservoir than the CO₂ content in the produced oil.
- In one such application, using a "next generation" CO₂-EOR and CO₂ storage design (involving a gravity-stable CO₂ flood, Figure VC7.1), approximately 0.6 metric tons of CO₂ is stored per barrel of produced oil. This design involves utilizing the entire reservoir structure, including the underlying residual oil zone (TZ/ROZ) and saline formation, for storing CO₂. Such a design would provide an offset for 150% of CO₂ emissions, enabling the produced oil to become more than "fully green."⁵²

⁵² Kuuskraa and Koperna, reference 48.

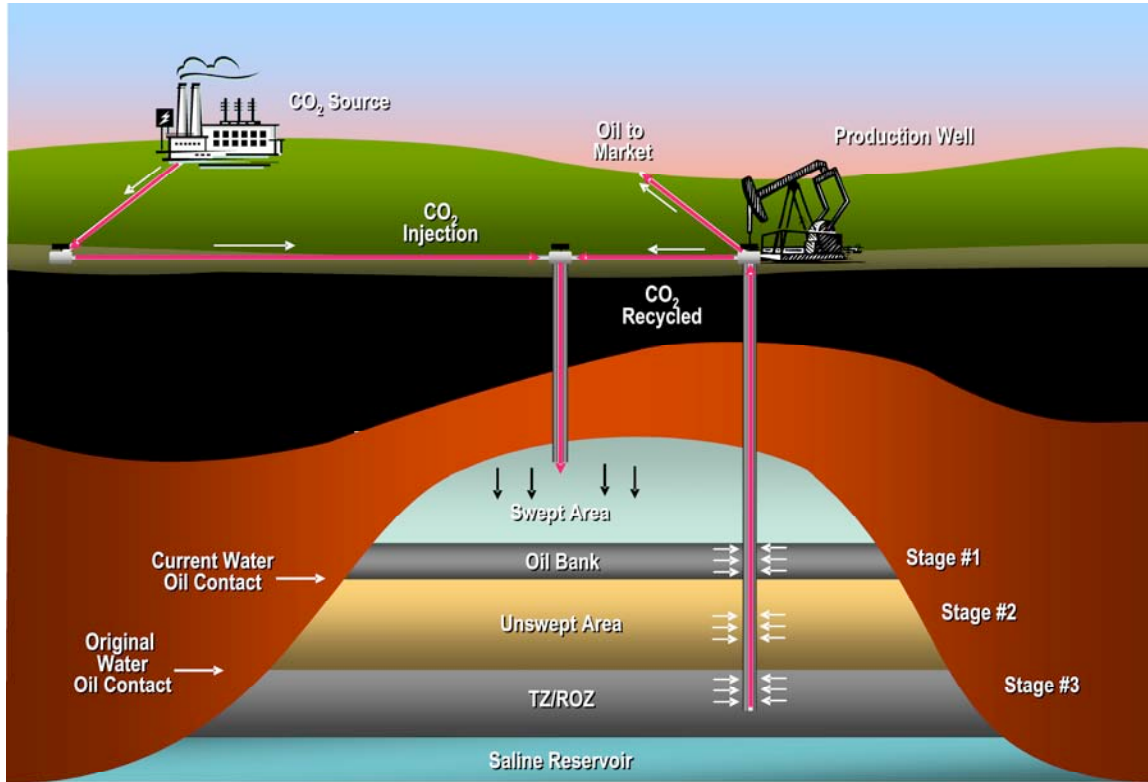


Figure VC7.1. Integrating CO₂-EOR and CO₂ storage with gravity-stable design.

- In a second example, CO₂ could continue to be injected into a reservoir after the oil production phase has been completed. Assuming the announced CO₂ injection design for the Weyburn Project is implemented, this CO₂-EOR project would store about 0.35 metric tons of CO₂ per barrel of produced oil, providing an offset of over 80% of the CO₂ emissions in the produced oil, Figure VC7.2.

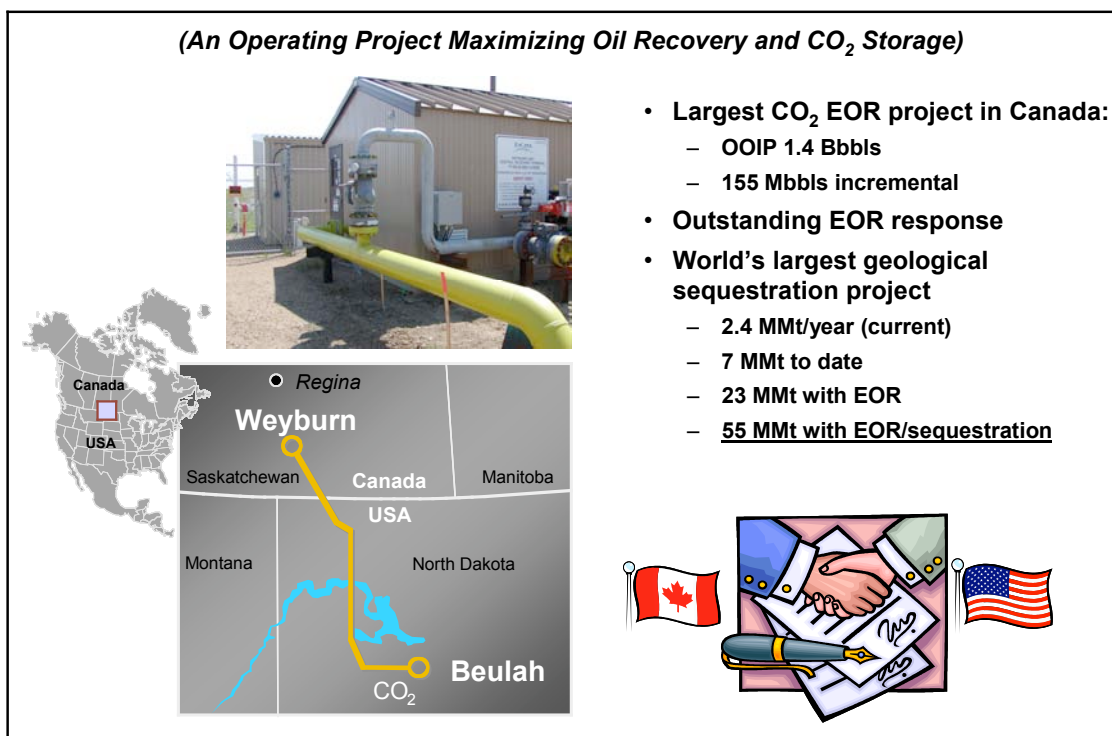


Figure VC7.2. Weyburn enhanced oil recovery project.

D. Regulation

The technological hurdles to effective implementation of CCS are surmountable. However, the regulatory framework within which CCS is deployed and, closely linked to that, public opinion will play equally important roles in determining the future of carbon sequestration. The legislative framework within which CCS is conducted will have a major impact on how rapidly the technology is implemented and ultimately determine whether CCS can effectively mitigate carbon emissions and provide access to future hydrocarbon supplies.

During the G8 International Energy Agency Carbon Sequestration Leadership Forum Workshop on Near Term Opportunities for Carbon Dioxide Capture and Storage (22-23 August 2006), more than 120 participants from 15 nations identified

the following five critical areas to be in need of resolution if near-term deployment of CCS projects is to be facilitated.⁵³

- Ownership and liability of CO₂ along the value chain
- Regulatory treatment of CO₂ and other gases in the CO₂ stream
- Monitoring, verification and remediation
- Property rights and intellectual property
- Jurisdictional and trans-boundary issues.

Earlier, in 2004, the Carbon Sequestration Leadership Forum (CSLF) described several overarching considerations on regulatory issues.⁵⁴ Their consideration #1 states: “A regulatory framework should be soundly based, publicly stated, instill public confidence and provide predictability for stakeholders.”

Features could include:

- adequate opportunities for public participation and information sharing
- drawing upon existing legislation and regulatory provisions, where relevant
- establishment of new legislation or regulatory provisions, where necessary
- consistency with international law
- flexibility to allow a range of technologies for carbon dioxide capture and storage
- consistency with environmental, health, and safety regulations
- consistency with economic considerations, while avoiding over-regulation as appropriate
- appropriate monitoring and verification
- ensure the appropriate standards for operations and monitoring based on transparency and sound analysis
- provision of mechanisms for community consultation
- clarification of the legal status of CO₂ within legislation and regulations.

For the purposes of this National Petroleum Council report we will focus on the issues of legal and regulatory frameworks from a United States perspective, though

⁵³ G8 International Energy Agency (IEA) & Carbon Sequestration Leadership Forum (CSLF) First Workshop on Near Term Opportunities, held 22–23 August 2006, San Francisco.

⁵⁴ Considerations of Regulatory Issues, Report of the Carbon Sequestration Leadership Forum, 2004.

many of the issues have been and are continuing to be discussed in international forums. This section of the chapter draws upon and highlights existing and ongoing work, including:⁵⁵

- United States Environmental Protection Agency's draft guidance (deliberative draft) on using Class V wells to regulate pilot geologic sequestration projects (UIC Program Guidance #83)
- Intergovernmental Panel on Climate Change Special Report on Carbon Dioxide Capture and Storage, 2005
- G8 International Energy Agency (IEA) and Carbon Sequestration Leadership Forum (CSLF) First Workshop on Near Term Opportunities, held 22-23 August 2006, San Francisco
- IEA CSLF First Workshop on Legal and Regulatory Issues, held 12-13 July 2004, London and Paris
- IEA CSLF Second Workshop on Legal and Regulatory Issues, held 17 October 2006, Paris
- Interstate Oil and Gas Compact Commission's report "Carbon Capture and Storage: A Regulatory Framework for States," 2005.
- Considerations on Regulatory Issues, CSLF report, 2004.

This discussion will be organized under the following headings:

- 1) Ownership of resources and of CO₂
- 2) Definition of CO₂ as a waste and the regulatory treatment of other gases in the CO₂ stream
- 3) Risk management, site selection and approval
- 4) Operational monitoring and verification
- 5) Long term liability
- 6) Jurisdictional clarity of emerging policies and regulations

⁵⁵ As some of these are on-going efforts and contain material that are not to be quoted, cited, or distributed, ideas from the discussions or draft materials are taken without citation but are noted here to identify their source.

7) Policies to facilitate initial infrastructure development.

1. Ownership of Resources and of CO₂

a. The CO₂ value chain

At the first G8 IEA CSLF Workshop on Near Term Opportunities for Carbon Dioxide Capture and Storage, participants identified ownership and liability of CO₂ along the value chain as the first critical issue requiring resolution in the near term.⁵⁶

The workshop participants highlighted three key attributes:

- Accounting for ownership, transfer of custody, and transfer of liability of CO₂ along the value chain; that is, from capture of the CO₂, through transportation, to injection and storage
- Retroactive liability
- Insurance to address the liability of developers of near term projects, along the entire value chain.

While the three aspects of the ownership of and liability for the CO₂ is not unique to CCS, with many similarities to the initial deployment of other technologies, the resolution of these aspects will have an important influence on the rate at which near-term CCS projects are deployed. The workshop participants deemed this a “critical” issue, meaning: “Progress on near-term opportunities cannot be made unless this issues is resolved.”

As yet, only a handful of projects have been announced by oil and gas companies, power generators, and technology providers. Business models in these projects are nascent, and ownership and liability for the CO₂ are far from clear. Currently the partners in a particular project tend to set out ownership and liability in contractual terms. Outside the USA, emerging government regulations are starting to play a role. The European Union emissions trading scheme, for example, is already capping emissions from over 10,000 facilities in the EU. The required reduction in CO₂ is the responsibility of each permitted emitter. If CCS is to be included into the

⁵⁶ G8 forum, reference 53

trading scheme, future EU regulations may choose to prescribe CO₂ ownership and liability, or alternatively choose to remain silent on the issue while ascribing ultimate liability to the emitter, allowing for contractual arrangements to govern the rest.

Obtaining insurance for such projects has also been raised as a critical aspect of developing and operating the CO₂ value chain in the near term. This may be a matter for the markets to decide, but there is a need for government policy to prescribe and clarify the role of an insurance mechanism, limit liabilities, and provide indemnities for the operation of such projects along the CO₂ value chain.

b. CO₂ storage resources

The G8 IEA CSLF Workshop on Near Term Opportunities also identified “CO₂ storage” as giving rise to critical issues of property rights, including the rights of other resource owners such as petroleum title holders.⁵⁷ In the United States, natural gas storage appears to be an appropriate analog for CO₂ storage, given the extent of natural gas storage and the history of ownership issues across different states. Moreover, the technical framework for characterizing natural gas storage sites, include aspects of permeability, porosity, thickness, caprock integrity, and rock types, are all relevant to the characterize of CO₂ storage sites.

Natural gas storage already raises the issue of “property interests” that influence the cost of geologic storage through the cost of acquisition of the necessary geologic reservoir property rights, and the value of storage through ownership of the injected gas. Mark de Figueiredo (MIT) proposes in his doctoral thesis that for CCS, the CO₂ property-rights regime should emulate the natural gas property-rights regime.⁵⁸ In the United States, the issue of property rights is largely an issue of state law. Ownership of the land (“surface interests”) and ownership of the subsurface (“mineral interests”) can be held by a single owner, or can be severed through a mineral deed or oil and gas lease. While a CO₂ storage-site operator would probably only need a small area

⁵⁷ G8 Forum, reference 53.

⁵⁸ de Figueiredo MA: *The Liability of Carbon Dioxide Storage*, submitted in partial fulfillment of the requirements for the degree of Doctor of Philosophy in Technology, Management, and Policy, Massachusetts Institute of Technology, February 2007 (Draft 7/21/06): 251–258.

for installing and operating surface facilities, the subsurface formation requirement would be much more extensive and would require the acquisition of mineral interests from a variety of landowners. To complicate the issue, state rules for property ownership differ, when the mineral and surface interests are severed, as to whether the geologic formation is owned by the mineral owner or by the surface owner. Moreover, property rights also differ depending on whether the reservoir is, or is not, depleted of the minerals. In the majority of states, case law over the years has resulted in the following picture outlined in Table VD1b.1.⁵⁹

	Unsevered Mineral Interest	Severed Mineral Interest
Non-depleted reservoir	Surface owner	Mineral owner
Depleted reservoir	Surface owner	Surface owner

Figure VD1b.1. Relevant property interests (in a majority of states) for acquisition of a geological reservoir.

Technically, the geologic formation will never be fully depleted of minerals. In the future, new methods of mineral extraction could be developed to exploit the presently unrecoverable minerals. It seems likely that a prospective CO₂ storage operator will have to purchase both surface and mineral interests, as is the case with the natural gas storage regime currently, thus increasing the transaction costs of storage. Purchasing these interests is necessary to avoid trespass.

Figueiredo argues that there is potential for both federal and state legislation to further clarify property interests and liability in the CO₂ context. Although property interests and the liability for mineral rights have traditionally been addressed by common law, there exists the potential for legislation to define the circumstances of ownership and trespass:

From a state perspective, state legislation could be used to clarify property interests and liability. For example, the IOGCC report 2005 contains a conceptual

⁵⁹ de Figueiredo, reference 58: 251-258.

framework for a CO₂ geological-storage statute designed for the states.⁶⁰ In this framework, CO₂ storage operators would be allowed to exercise the state's eminent-domain power over any subsurface stratum or formation found to be suitable for geologic storage of CO₂ and thereby rendered a matter of public interest. The property interest provided is essentially an easement to the subsurface.

From a federal perspective, eminent-domain legislation and property-rights clarification could also be exercised at the federal level, although federal legislation would be limited to those circumstances where the CO₂ storage is deemed to be within interstate commerce or having a substantial effect on interstate commerce.⁶¹

2. Definition of CO₂ as a Waste and the Regulatory Treatment of Other Gases in the CO₂ Stream

The issue of defining CO₂ as a waste or pollutant, or as a resource and product, or some other category of substance, is discussed as a high priority issue in many international forums. Such treatment can increase the regulatory burden for the operator of the CO₂ capture and storage project along the entire value chain, as regulations that were promulgated without considering CO₂ explicitly would be triggered if CO₂ were defined to be a waste or pollutant.

For example, the U.S. Environmental Protection Agency released a draft program guidance memorandum #83 under the Underground Injection Program of the Safe Drinking Water Act (SDWA) to address the regulation of pilot geologic sequestration projects.⁶² The EPA makes clear that the guidance is only addressing pilot geologic sequestration projects and that any commercial-scale projects will be subject to further developing regulations. In the draft guidance, the EPA states:

“While CO₂ is not an identified pollutant under SDWA, it has the potential to endanger public health. Additionally, injected CO₂ may potentially contain contaminants that could adversely affect underground sources of drinking water

⁶⁰ Interstate Oil and Gas Compact Commission (IOGCC): “Carbon Capture and Storage: A Regulatory Framework for States” (2005).

⁶¹ de Figueiredo, reference 58: 178–179.

⁶² United States Environmental Protection Agency (EPA) draft guidance (deliberative draft) on using Class V wells to regulate pilot geologic sequestration projects (UIC Program Guidance #83).

(USDWs). Furthermore at the commercial-scale, displacement of native fluids and chemical constituents, movement of possibly hazardous impurities in injected fluids, and potential leaching and mobilization of naturally occurring minerals in the injection and confining formations associated with CO₂ injection may potentially endanger USDWs, if not properly regulated. It is up to the Director to determine, on a case-by-case basis, whether endangerment of USDWs could occur as a result of the proposed injection.”

Defining CO₂ as a waste or pollutant is a highly controversial issue and is central to numerous lawsuits in the United States. One high profile example was *Massachusetts v. US EPA*, No. 05-1120 (2006), which was decided by the Supreme Court on April 2, 2007. The central issue is whether EPA has the authority to list CO₂ as a criteria pollutant under section 108 of the Clean Air Act. In simple terms, the plaintiffs argued that EPA has the authority, and therefore once listed as a criteria pollutant the EPA must follow all other relevant provisions of the Clean Air Act to promulgate regulation of CO₂. The EPA, in turn, argued that it does not have the authority and even if it did it chooses not to exercise that authority because there is a range of other actions that the President has initiated to address climate change. The Supreme Court rejected all of EPA's arguments and ruled that the EPA has the authority to regulate CO₂ as an air pollutant.⁶³

On the other hand, recent developments in Europe eased the situation with regard to treating CO₂ as waste when a new amendment to the London Protocol was signed in Brussels that now allows for CO₂ to be stored in rocks below the sea, essentially removing one of the highest legal hurdles to the implementation of large-scale CCS projects in the North Sea.

3. Risk Management, Site Selection and Approval

Secure storage of CO₂ for several thousands of years will depend on many factors. Key amongst these will be: identification of environmental, health, and safety

⁶³ <http://www.supremecourtus.gov/opinions/06pdf/05-1120.pdf>.

risks; management of these risks; and determination of criteria for site selecting that would sufficiently attenuate such risks.

The CSLF report on regulatory issues emphasized site evaluation. The #8 overarching consideration is: “... [a] regulatory framework which adopts a science-based approach to site evaluation that takes into account environmental, health, safety and community concerns to be used for identification of appropriate sites for the injection of CO₂.”⁶⁴ Features could include:

- Encouraging the development and use of new technologies in the identification of sites
- Compliance with domestic and international legal obligations when selecting sites and applying environmental impact and assessment procedures for evaluating projects for injecting CO₂
- Where appropriate, including consideration of the effect of leakage on ecosystems and humans
- Requiring a level of proof on performance standards that is in line with “best available technology”
- Developing criteria for the various formations to mitigate investment, environmental, safety, and health risk.

The IPCC Inventory Guidelines on CCS offers national governments a proposed series of steps for estimating, verifying, and reporting CO₂ emissions from storage sites. Among these steps, the document provides proposals for site evaluation, which states:⁶⁵

“Determine whether an adequate geological site characterization report has been produced for each storage site. The site characterization report should characterize and identify potential leakage pathways such as faults and pre-existing wells, and quantify the hydrogeological properties of the storage system, particularly with respect to CO₂ migration. The site characterization report should include

⁶⁴ IEA Carbon Sequestration Leadership Forum (CSLF) First Workshop on Legal & Regulatory Issues, held 12–13 July 2004, London and Paris.

⁶⁵ IPCC Guidelines for National Greenhouse Gas Emissions Inventory 2006 (Pre-Publication Draft). See <http://www.ipcc-nggip.iges.or.jp/public/2006gl/index.htm> (accessed 17 October 2006).

sufficient data to represent such features in a geological model of the site and surrounding area. It should also include all the data necessary to create a corresponding numerical model of the site and surrounding area for input into an appropriate numerical reservoir simulator. Proper site selection and characterization can help build confidence that there will be minimal leakage, improve modeling capabilities and results, and ultimately reduce the level of monitoring needed.”

In the Underground Injection Program draft guidance #83, the EPA states:⁶⁶

“The appropriateness of injection sites selected for pilot CO₂ injection will depend on the goals of the project. Possible experimental goals may include testing the effectiveness of various geologic formations in receiving or trapping CO₂ (e.g. short-term and long-term relations between trapping mechanisms, structural and stratigraphic considerations, and formation impacts such as solubility and mineralization); failure scenario testing or testing or validating the accuracy of models in certain geologic conditions. In general, to prevent endangerment of [underground sources of drinking water], CO₂ injection sites should have an adequate receiving and confining system, which may consist of:

- A receiving zone of sufficient depth, areal extent, thickness, porosity, and permeability;*
 - A trapping mechanism that is free of major non-sealing faults;*
 - A confining system of sufficient regional thickness and competency; and*
 - A secondary containment system which could include buffer aquifers and/or thick, impermeable confining rock layers.*
- A site that is deemed to be appropriate for pilot CO₂ injection may not necessarily meet future requirements for commercial-scale operations. Therefore, owners or operators intending to eventually expand their pilot projects to commercial-scale operations should understand that additional requirements may apply to the project after the conversion to full-scale commercial operation.*

⁶⁶ EPA, reference 62.

Directors should consider some of the following factors in assessing the appropriateness of proposed pilot CO₂ injection sites:

- *Some leakage of CO₂ from the injection zone may occur, and in fact may be the experimental goal of certain research projects that are designed to test monitoring methods. However, in no case, should leakage endanger [underground sources of drinking water] or the health of persons.*
- *Potential reactions between injected CO₂ and the rocks and fluids in the injection zone may impact injectivity. Permeability may be reduced (by chemical precipitates blocking pore throats or coal swelling) or increased (if matrix minerals dissolve).*
- *Other types of reactions include gas release due to injectate-fluid reactions and selective adsorption and desorption reactions of the minerals in a reservoir.*
- *Pressures needed for CO₂ injection may impact receiving and confining formations (e.g. fracture pressure).*
- *Thermal effects (e.g. thermal shock) on receiving formations and cement should be considered.*
- *Vertically transmissive geologic features (e.g. faults or fractures), which may facilitate the upward movement of CO₂, should be delineated.*
- *Testing and validation of analytical or numerical models of CO₂ containment or transport. (This model testing will provide valuable information on the selection of proper time frames for the modeling of commercial-scale projects. The modeled time frames may vary to reflect the project goals and objectives.)”*

At the time of drafting of this NPC report the U.S. EPA draft guidance document is the clearest indication of the United States’ intent to regulate CO₂ injection and storage underground, using the underground injection control program. As commercial-scale projects develop, the U.S. EPA is already signaling its intent to further develop a new classification of wells for CO₂, which would also appear to define CO₂ not as a waste (as in Class I) within the underground injection control

program. Such regulations will be forthcoming in future years. The current draft guidance will serve as the basis for permitting CO₂ injection and storage activities by the U.S. DOE Regional Carbon Sequestration Partnership, and the elements of the site selection criteria will probably serve as the basis for future regulations of commercial-scale projects.

The Interstate Oil and Gas Compact Commission (IOGCC), tasked by the DOE to craft initial regulatory guidelines for potential sequestration projects, made several recommendations in its 2005 report that are also relevant to storage-site evaluation.⁶⁷ The report states, in part:

“ ...

- States and provinces with natural gas storage statutes should utilize their existing natural gas regulatory frameworks, with appropriate modifications, for [carbon capture and geological storage].
- Should the U.S. Environmental Protection Agency (EPA) recommend that injection of CO₂ for non-EOR purposes be regulated under the Underground Injection Control (UIC) program, the Task Force strongly recommends reclassifying such wells either as a subclass of Class II or a new classification. The Task Force strongly believes that inclusion of non-EOR [carbon capture and geological storage] wells under Class I or Class V of the UIC program would not be appropriate.
- States and provinces with regulations for acid gas injection should utilize their regulatory frameworks, with appropriate modifications, for [carbon capture and geological storage].
- Review existing CO₂ EOR, natural gas storage and acid gas regulations to ensure that operational plans for addressing public health and safety, as well as release or leakage mitigation procedures, are adequate.
- Regulations governing permitting processes should adequately address reservoir properties relative to the interaction of CO₂ with rock matrix and reservoir fluids. ...”

⁶⁷ IOGCC, reference 60.

The IPCC Special Report on Carbon Dioxide Capture and Storage provides further insight on managing risks associated with CO₂ storage.⁶⁸ The report states:

“For geological storage, effective risk mitigation consists of four interrelated activities:

- Careful site selection, including performance and risk assessment and socio-economic and environmental factors;
- Monitoring to provide assurance that the storage project is performing as expected and to provide early warning in the event that it begins to leak;
- Effective regulatory oversight;
- *Implementation of remediation* measures to eliminate or limit the causes and impacts of leakage.”

Taken together, the principles and concepts outlined in the two IPCC documents, the U.S. EPA draft guidance, the IOGCC report, and the CSLF report on considerations of regulatory issues can form a basis for developing elements that would be required for risk management, site selection and approval.

4. Measurement, Monitoring and Verification

A regulatory framework is required to establish suitable measurement, monitoring, and verification (MMV) practices to ensure health, safety, and environment protection throughout the entire carbon capture and storage chain. Moreover, MMV is required to provide accurate accounting of stored CO₂ and to establish confidence that the CO₂ remains sequestered for a sufficient period of time. This last consideration has independent importance when emissions-reduction credits are at stake and, all in all, contributes to the economic viability of carbon capture and storage projects.

MMV in the storage environment will depend on measurements that can detect the presence and motion of CO₂ as well as its physical and chemical state, and will include seismic data, well log data, testing data, hydrogeology data, and mapping

⁶⁸ Metz et al, IPCC, reference 2.

data. A regulatory framework for MMV in the storage environment will also need to address potential leakage mechanisms including:

- Wellbores
- Caprock penetration
- Hydrologic flow
- Trapping mechanism breach.

These data should enable the prediction and verification of migration and chemical reactions of CO₂ in the reservoir and will determine the permanence of storage and the environmental impacts within the reservoir, as well as impacts on the local environment including human health.

Verification entails the construction of predictive models for the expected behavior of the underground storage site and comparison between these predictions and a suitable set of measurements.

Best practices and procedures will be developed through the U.S. DOE Regional Carbon Sequestration Partnerships as well as those currently being developed through other CCS projects around the world (e.g. Weyburn CO₂ Monitoring Project, which is co-funded by the U.S. DOE).

5. Long-Term Liability

Long term liability must be considered in any policy framework since it will have significant impact on industry's willingness to participate in the deployment of CCS technology. Long-term liability encompass those liabilities which occur some time after a site undergoes transition from its operational phase (i.e. closure of injection facilities) to a post-closure phase characterized by long-term environmental monitoring.

A site could be deemed to have reached this post-closure phase when it achieves a pre-agreed state when the gap between modeling and observation is negligible or predictable (verification). At this point in time, subsurface conditions have become relatively static and our confidence of effective storage is high. Depending on the long-term liability regime to be developed, a government authority may take over site

management at this stage. Government, in cases where liabilities of negligence, trespass, nuisance and other common-law concerns exist, may also choose to indemnify or otherwise limit the long-term liability of the site operator. Without such indemnification or limit on long-term liability, a potential developer of CCS projects is likely to find the long-term liability prohibitive.

To transition to this post-closure stage, there will need to be agreement on the long term environmental monitoring program in terms of:

- Design
- Acceptable modeling techniques and methodologies
- Frequency of monitoring
- Required level of confidence of storage effectiveness
- Funding.

Provision for funding this long term monitoring plan is an issue requiring consideration.

The Interstate Oil and Gas Compact Commission made several recommendations on the issues of long term liability, abandoned wells, long term monitoring, mitigation, and the funding of such monitoring and potential mitigation.⁶⁹ The 2005 report recommends, in part:

- Given the long time frames proposed for CO₂ storage projects, innovative solutions to protect against orphaned sites will need to be developed. The current model used by most oil and natural gas producing states and provinces—whereby the government provides for ultimate assurance in dealing with orphaned oil and natural gas sites—may provide the only workable solution to this issue. This can be accomplished through state and provincial government administration of federally guaranteed industry-funded abandonment programs.
- Establish technical standards for well abandonment and site closure accounting for specialized concerns dealing with the unique properties of

⁶⁹ IOGCC, reference 60.

CO₂ impacts on reservoir characteristics, well construction, and cementing techniques normally used in the oil and natural gas industry.

- Establish procedures for long-term reservoir management and monitoring. A new framework will need to be established to address the long-term monitoring and verification of emplaced CO₂ to confirm that injected volumes remain in place.
- Establish a regulatory threshold requiring mitigation procedures be initiated.

6. Jurisdiction Clarity of Emerging Policies and Regulations

Clarity of the roles of the federal government and states, and clarity of which authority is responsible for which regulation or permitting process will be required to best attract commercial players into the carbon capture and storage market. This jurisdictional clarity is considered one of five “critical issues” by the participants of the G8 International Energy Agency Carbon Sequestration Leadership Forum Workshop on Near Term Opportunities for Carbon Dioxide Capture and Storage who felt that “progress cannot be made on near term opportunities if this issue is not resolved.”⁷⁰

Aside from laws on property rights and liability issues, in the context of CCS U.S. federal and state governments play important roles in the protection of health, environment, and safety, as well as roles in trade and commerce. Clarity in the boundaries of these authorities is critical. Moreover, the government plays important roles in encouraging research and development for CCS and providing incentives for CCS deployment. Finally, both federal and state governments have roles to play in educating the public about the role of CO₂ capture and storage in a portfolio of approaches (e.g. renewable energy, non-fossil energy) to appropriately address issues of climate change.

⁷⁰ G8 Forum, reference 53.

a. Federal

The federal role should include the consideration of national and international implications of CO₂ policy, as well as the long time frames associated with storage. The federal government also plays a role when CO₂ capture and storage occurs on federal lands. Furthermore, issues on infrastructure in interstate commerce, including pipelines, will inevitably entail a federal role.

b. States

State natural resource, oil and gas, and mineral commissions have experience that gives them competencies for handling the specifics of policies, especially where there might be local impacts within their borders. Precedence exists in other areas for allowing state primacy to create differences in regulation from state to state as long as minimum safeguards are consistent throughout.

7. Policies to Enable and Encourage Initial Infrastructure Development

CCS will require large initial investments in infrastructure. In the Climate Change Technology Program Strategic Plan, released in September 2006, the following statement is made in the context of geologic storage in the United States:⁷¹

“The goal of geologic storage R&D portfolio is to advance technologies that would enable development of domestic CO₂ underground storage repositories capable of accepting around one billion tons of CO₂ per year.”

A potential FutureGen power plant of 275 MW would emit approximately one million metric tons of CO₂ per year.⁷² This would translate into approximately one thousand such power plants for CO₂ capture and storage, hence requiring a large infrastructure development to connect these power plants to their geologic storage sites.

⁷¹ U.S. Department of Energy: *Climate Change Technology Program Strategic Plan, 2006*, Washington, DC. See <http://www.climatechange.gov/>.

⁷² The FutureGen Project is a proposed cooperative project between the USA and a consortium of companies and other non-government organizations to demonstrate a coal-fired power plant with CO₂ capture and geologic storage.

The scale of such infrastructure development is substantial; it has been estimated to rival the current natural gas supply infrastructure in the United States. It will take appropriate policy to encourage early movers to develop parts of this infrastructure. Financial incentives and liability limitations will need to be considered. A plan to provide these may include their phase out once the market for carbon management matures.