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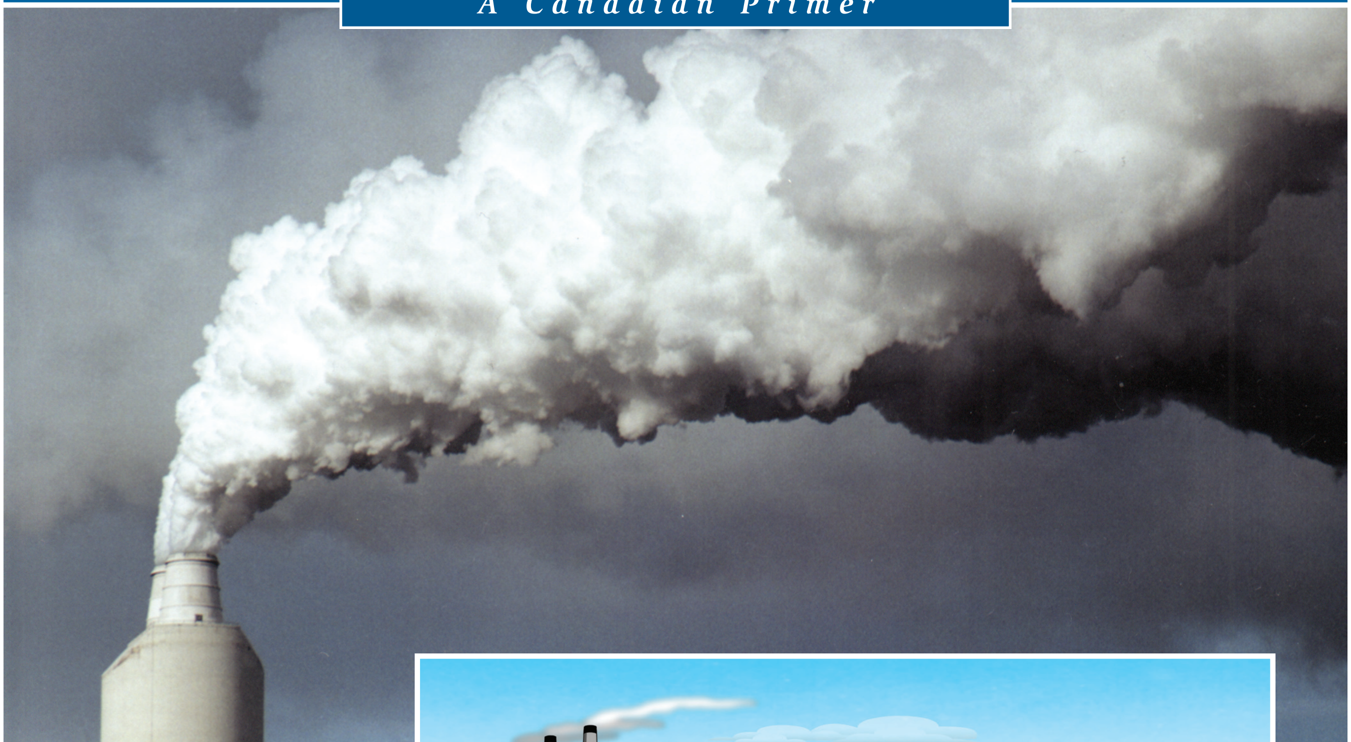
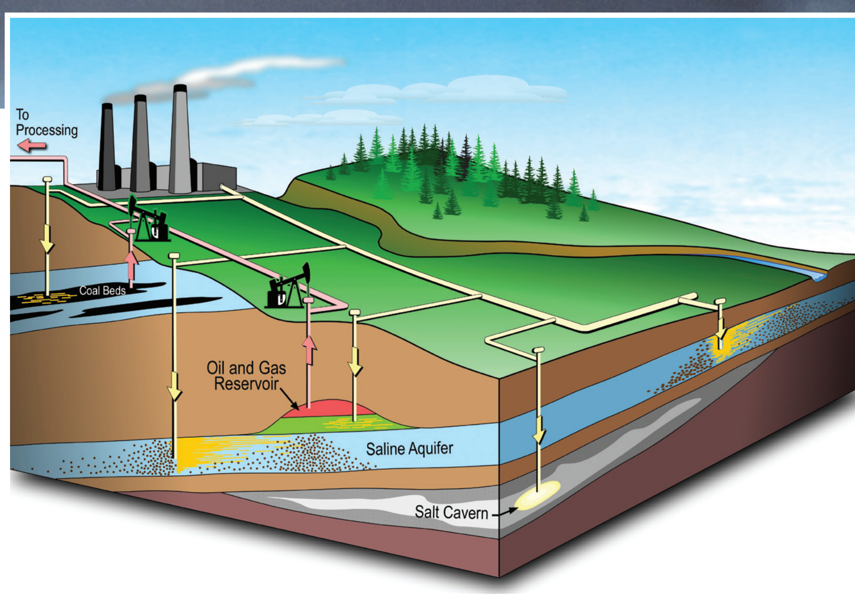
Carbon Capture and Storage:

An arrow in the quiver or a silver bullet to combat climate change?

A Canadian Primer





Mary Griffiths • Paul Cobb • Thomas Marr-Laing

the PEMBINA institute

Sustainable Energy Solutions

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[1] Papers on carbon capture and storage that David Keith has co-authored can be found at http://www.ucalgary.ca/~keith/ccs.html.

About the Pembina Institute

The Pembina Institute creates sustainable energy solutions through research, education and advocacy. It promotes environmental, social and economic sustainability in the public interest by developing practical solutions for communities, individuals, governments and businesses. The Pembina Institute provides policy research leadership and education on climate change, energy issues, green economics, energy efficiency and conservation, renewable energy and environmental governance. More information about the Pembina Institute is available at http://www.pembina.org or by contacting: info@pembina.org

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Executive Summary

Governments, industry and scientists are examining the potential for carbon capture and storage (CCS) to reduce the release of industrial carbon dioxide (CO_2) emissions to the atmosphere as one solution for limiting the increase in atmospheric concentration of greenhouse gases (GHG) and associated climate change.

The International Panel on Climate Change determines what reductions in GHG emissions are required from countries that have ratified the Kyoto Protocol. In its recent *Special Report on Carbon Dioxide Capture and Storage*, the panel recognized CCS as one of the tools that can be used to reduce GHG releases to the environment.[2] CCS is a waste management strategy for carbon dioxide. It does not reduce the production of CO_2, but it provides a depository to keep it from harming the environment.

It is possible to capture CO_2 from large point sources e.g., power plants and cement plants. Research is underway to improve capture methods and to develop processes, such as new forms of fossil fuel combustion, to facilitate capture of the gas. Geological storage of CO_2 involves injecting it into depleted oil and gas reservoirs, coal seams or deep saline aquifers. Storing CO_2 in the water column in the ocean or as a "lake" on the ocean floor has also been proposed. However, many concerns have been raised about potential impacts on ocean ecosystems, and therefore this option is not being widely pursued at the present time.

Several commercial operations are currently storing CO_2 around the world, including EnCana's project at Weyburn in Saskatchewan where the gas is used to enhance the recovery of conventional oil. At this operation, CO_2 from a gasification plant in North Dakota is injected into oil reservoirs to bring more oil to the surface. This location is an international focus for research into how CO_2 can be stored and monitored underground. In Alberta, acid gas — a mixture of CO_2 and hydrogen sulphide (a waste product from treating sour natural gas) — has been injected deep underground since 1990. About 50 acid gas injection sites can now provide an analogue for CO_2 injection. The Western Canada Sedimentary Basin, and especially that part of it lying in southern Alberta and Saskatchewan, is recognized as the most suitable location for geological storage in Canada. There are also many large point sources of emissions in the region, which could limit CO_2 transport costs. Both the Government of Canada and the Alberta government have undertaken initiatives to encourage the development of CCS as a way of limiting the country's GHG emissions.

A summary of the potential for CCS is provided in the following below. It provides selected information on GHG[3] and the physical storage capacity in different geological formations. The figures indicate orders of magnitude and should not be cited out of their context, which is

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[2] International Panel on Climate Change (IPCC). 2005. *Special Report on Carbon Dioxide Capture and Storage: Summary for Policymakers,* p.18, bullet 19, http://www.ipcc.ch.

[3] Greenhouse gases include carbon dioxide, methane, fluorinated hydrocarbons, tropospheric ozone and nitrous oxide. Emissions or concentrations of GHGs other than CO_2 are converted into "CO_2 equivalent" terms by multiplying by factors known as "Global Warming Potentials," which are calculated by the Intergovernmental Panel on Climate Change (IPCC). A rule of thumb used in the literature is to add 100 ppm to the CO_2 concentration to obtain the corresponding "CO_2 equivalent" (CO_2e) concentration that includes the effects of the other long-lived GHGs. Bill Hare, Potsdam Institute for Climate Impact Research, personal communication, July 2005.

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explained later in the report. Even if CCS is acceptable as a means of storing CO_2, capture is only realistic from large point sources. Thus only a portion of total emissions would be available for storage. The cost of CCS in Canada at present exceeds the federal government's commitment to cap costs of carbon credits at $15/tonne in the Kyoto 2008–2012 term.

Selected statistics on greenhouse gas emissions and the geological storage of carbon dioxide

	Global	Canada	Alberta
Emissions			
Total greenhouse gas emissions	25 Gt/year CO_2 in 2000[4]	740 Mt in 2003 (CO_2 equivalent)[5]	221 Mt in 2002 (CO_2 equivalent)[6]
"Emissions gap" between current emissions and Kyoto requirement for 2008—2012		270 Mt/year (CO_2 equivalent)[7]	97 Mt as of 2001[8]
Emissions target for 2050, if emissions are to be 80% below 1990 levels[9]	N/A	119 Mt[10]	34 Mt[11]
Storage Potential			
Deep saline formations	100–10,000 Gt CO_2	?	4,000 Gt CO_2
Depleted oil and gas reservoirs	100–1,000 Gt CO_2	?	2.8 Gt CO_2
Coal seams	10–100 Gt CO_2	?	?
Acid gas injection 1990–2005			2.5 Mt CO_2 and 2Mt H_2S over 15 years
Capture Potential			
	?	?	Approximately 113 Mt emitted from large point sources in 2001[12]

[4] International Energy Agency (IEA). 2004. *Prospects for CO_2 Capture and Storage*, p. 48.

[5] Environment Canada. 2005. *Canada's 2003 Greenhouse Gas Inventory*, http://www.ec.gc.ca/pdb/ghg/2005summary/2005summary_e.cfm.

[6] Environment Canada. 2004. *Canada's Greenhouse Gas Inventory 1990-2002*, http://www.ec.gc.ca/pdb/ghg/1990_02_report/ann10_e.cfm.

[7] Government of Canada. 2005. *Project Green – Moving Forward on Climate Change: A Plan for Honouring our Kyoto Commitment*, *http://www.climatechange.gc.ca/kyoto_commitments/default.asp*.

[8] Government of Alberta. 2002. *Albertans and Climate Change: Taking Action*, p.11, shows the projected emissions for 2010 are 258 Mt., http://www3.gov.ab.ca/env/climate/plan.html Alberta's CO_2 emissions in 1990 were 171 Mt. (Environment Canada. 2004. *Canada's Greenhouse Gas Inventory 1990-2002*, http://www.ec.gc.ca/pdb/ghg/1990_02_report/ann10_e.cfm). The Kyoto objective is 6% below the 1990 level (i.e., 171 x 0.94), which is 161 Mt. This is 97 Mt less than the projected emissions for 2010 — 258 Mt. This volume may be an under-estimate, because additional oil sands projects have been announced since the Alberta Climate Change plan was introduced in 2002.

[9] A target of 80% reduction from 1990 greenhouse gas emission levels by 2050 is in line with what industrialized countries will need to achieve to stabilize greenhouse gas concentrations at a level sufficiently low to prevent dangerous climate changes. See Bramley, M. 2005. *The Case for Deep Reductions: Canada's Role in Preventing Dangerous Climate Change.* David Suzuki Foundation and Pembina Institute, http://www.pembina.org. To be published November, 2005.
On June 1, 2005, Gov. Arnold Schwarzenegger issued an Executive Order to implement strategies to reduce the state's GHG emissions to year 2000 levels by 2010, 1990 levels by 2020 and 80% below 1990 levels by 2050. Office of the Governor of the State of California. 2005. *Governor Schwarzenegger Establishes Green House Gas Emission Reduction Targets*, search on Executive Orders, June 1 at http://www.governor.ca.gov/state/govsite/gov_homepage.jsp.

[10] Canada's CO_2 equivalent emissions on 1990 were 596 Mt. An 80% reduction is 119 Mt.

[11] Alberta's CO_2 equivalent emissions were 171 Mt in 1990. An 80% reduction is 34 Mt.

[12] Bachu, Stefan and S. Stewart. 2002.*Geological Sequestration of Anthropogenic Carbon Dioxide in the Western Canada Sedimentary Basin: Suitability Analysis. Canadian Journal Petroleum Technology*, vol. 41, no. 2, p.32-40. February. See also a graph *CO_2 Emissions by Alberta's Largest Emitters (>100,000 t/yr) in 2001* and interactive map for Western Canada Sedimentary Basin at http://www.ags.gov.ab.ca/activities/CO2/figure2.shtml.

Costs of CCS[13]	US$/t CO_2	Uncertainties
CO_2 capture (including compression)	15[14] to 50 (current) 15 to 30 (future)	Low end for pure streams that only need compression; high end for chemical absorption from gas-fired combined cycles
CO_2 transportation	2 to 20	Depends on scale and distance
CO_2 injection	2 to 50	Low end for Mt size aquifer storage; high end for certain enhanced coalbed methane projects
CO_2 revenues	-60 to 0	No benefits for aquifers; highest benefits for certain enhanced oil recovery projects
Total	-40 to 100	

Although CO_2 has been injected into oil reservoirs for more than 25 years, CCS as a GHG abatement idea is a relatively new development. Major international organizations such as the International Energy Agency and the Carbon Sequestration Leadership Forum recognize that public acceptance will be necessary if CCS is to proceed. It is important for the public to understand not only the risks and benefits of CCS relative to other options for reducing GHG emissions but also the consequences of not taking sufficient measures to limit climate change.

As this report indicates, more information is required and more work is necessary before a decision can be made about the potential role of CCS in a strategy to contain and reduce atmospheric concentrations of GHGs. Some work is underway to address issues that will be of concern to the public, but more needs to be done to

- improve monitoring and understanding of the way in which CO_2 migrates underground;
- evaluate the risk magnitude and timeframe of leakage and clearly identify who is liable for costs and remediation if a leak occurs; and
- develop an appropriate legal and regulatory framework to ensure adequate monitoring, reporting and inspection.

From an industrial perspective, efforts are also being made to address

- high costs and energy penalties of post-combustion capture and separation;
- high capital costs of converting coal-fired power plants to use the gasification process (which enables easier, less costly capture of CO_2 capture) and the electrical sector's lack of experience with gasification; and
- limited experience with large-scale geological storage, including "proving" the estimates of storage capacity in deep saline formations.[15]

CCS is not a silver bullet and even those who support it recognize that it is at best only one arrow in the quiver in the fight to combat climate change. In the immediate future, efforts to reduce energy demand through energy efficiency and the increased use of renewable energy will help

[13] Data for this part of the table is based on IEA. *Prospects for CO_2 Capture and Storage.* Energy Technology Analysis, Table 3.14 Overview of likely CCS costs, p. 98, http://www.iea.org/Textbase/publications/index.asp.

[14] The IEA gives a figure of US$5/t for both current and future low-range costs, but this would be in specific, limited cases.

[15] Benson, Sally. 2004. "Carbon Dioxide Sequestration/Coal Gasification", p.16 in *The 10-50 Solution: Technologies and Policies for Low Carbon Future.* Pew Center for Global Climate Change Workshop Proceedings, March 25-26, http://www.pewclimate.org. Some of the points listed are taken from this paper, which gives an overview of issues that need to be addressed.

move the world's energy system towards a carbon-neutral system. For at least the next 30 years, fossil fuel use is expected to increase, especially in the rapidly growing economies of southeastern Asia (including China and India). CCS provides a technically feasible option to manage a portion of the CO_2 waste from this growth in fossil fuel use.

It is the important for the public to be involved in determining what role CCS should play, if any. The public should be involved in deciding whether they consider CCS should be one of the tools used to combat global climate change and if so, whether taxpayers' money should be used to finance research and development and the costs of implementing CCS. The public should also be engaged in the development of regulations for the management of CCS. Considering industry and government in Canada are already moving ahead with CCS projects, it is important that they engage the public in this debate in the near future.

1 What is Carbon Capture and Storage?

1.1 Introduction

This is an introductory primer to the technology, economics and policy issues associated with carbon capture and storage. Burning fossil fuels releases CO_2 to the atmosphere. Emissions and atmospheric concentrations of CO_2, which is the most important long-lived greenhouse gas, have increased dramatically since pre-industrial times. There is a scientific consensus that increased levels of CO_2 have become the dominant current cause of climate change.

Under Canada's plan to implement the Kyoto Protocol, major Canadian sources of GHGs, notably large industrial facilities, will be required to reduce or compensate for their GHG emissions beginning no later than 2008. Beyond 2012, these constraints are likely to become significantly more stringent. This makes the idea of capturing some of the CO_2 emissions and storing them for long periods deep underground an attractive one for large industrial emitters. Other stakeholders could also conclude that this is an important option for reducing those emissions and helping to stabilize CO_2 concentrations in the atmosphere. But, as with most technologies, there are risks as well as benefits associated with CCS.

The term "carbon capture and storage" refers to the entire process: the capture of carbon from a potential emission source and its purification, compression, transportation and injection into storage, usually in a geological formation. This primer reviews not only the technology associated with CCS but also the development of public policy. Chapter 2 describes the various ways in which carbon can be captured, while Chapter 3 deals with its transportation in pipelines. Chapter 4 outlines the potential for, and issues relating to, CO_2 storage in geological formations and in the oceans. Chapter 5 looks at initiatives that have been undertaken by various government bodies and organizations, and how policy on CCS is developing, internationally and in Canada. Finally, Chapter 6 examines the potential role for CCS in an overall GHG reduction strategy and what issues need to be resolved if CCS is to become an acceptable part of the strategy.

1.2 CCS and climate change

Interest in CCS has grown rapidly in recent years because, in theory, it has the potential to substantially reduce emissions of CO_2 and to be an important tool in the battle to prevent dangerous levels of global climate change.

Atmospheric concentrations of long-lived GHGs (CO_2, methane, chlorinated and fluorinated hydrocarbons, tropospheric ozone, nitrous oxide and sulfur hexafluoride) have increased well above pre-industrial levels because of human activities.[16] The atmospheric concentration of CO_2

[16] Intergovernmental Panel on Climate Change. 2001. *Climate Change 2001: The Scientific Basis, Summary for Policymakers*, p.7, http://www.ipcc.ch.

has risen from 280 parts per million (ppm) in 1750 to 377 ppm[17] today — a level that has not been exceeded during the past 420,000 years, and likely not during the past 20 million years.[18]

The burning of fossil fuels accounted for about 75% of the increase in atmospheric CO_2 during the 1990, with changes in land use responsible for the rest.[19] Global average temperature has increased by approximately 0.6°C over the 20th century, and "most of the observed warming over the last 50 years is likely to have been due to the increase in greenhouse gas concentrations."[20] According to the range of scenarios developed by the Intergovernmental Panel on Climate Change (IPCC), CO_2 concentrations are projected to rise between 485 to 1250 ppm during the 21st century (up to 350% above pre-industrial concentrations). The global average surface air temperature is projected to warm 1.4–5.8°C by 2100 relative to 1990 (see Figure 1.1, left side).[21] Given that the temperature difference between the last ice age and today is only about 4–6ºC, these are enormous changes over a very rapid timeframe.[22] As depicted in Figure 1.1, a global temperature rise in the range of 2–4°C will likely bring more extreme climate events, threaten sensitive ecosystems and lead to rises in sea level, while the 4–6°C range would exacerbate all of the previous adverse impacts and significantly increase the risk of irreversible damage to natural systems such as the melting of glaciers and change weather patterns. The IPCC concluded that "human influence will continue to change the atmospheric composition throughout the 21st century," and that "emissions of CO_2 due to fossil fuel burning are virtually certain to be the dominant influence on the trends in atmospheric CO_2 concentration" over that period of time.[23]

Review of the scholarly scientific literature[24] and public statements by numerous professional scientific societies and national science academies[25] indicates that the vast majority of professional climate scientists concur with the IPCC position.

The IPCC has shown that

1) to stabilize GHG *concentrations* in the atmosphere at any level, it will be necessary to reduce global GHG *emissions* from human activities to a small fraction of their current level; and

2) the longer it takes to achieve those reductions, the higher the level at which GHG concentrations will stabilize.[26,27] The higher the stabilization level, the larger the likely environmental impacts.

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[17] Keeling, C. et al. 2005. *Atmospheric CO_2 concentrations (ppmv) derived from in situ air samples collected at Mauna Loa Observatory, Hawaii*, http://cdiac.esd.ornl.gov/ftp/trends/co2/maunaloa.co2.

[18] IPCC. 2001. *Climate Change 2001: The Scientific Basis, Summary for Policymakers*, p.7, http://www.ipcc.ch.

[19] *Ibid.*

[20] *Ibid.* p.2-3, 10.

[21] *Ibid.* p.3.

[22] Hengeveld, H. 1995. *Understanding Atmospheric Change: A Survey of the Background Science and Implications of Climate Change and Ozone Depletion*. Second Edition, Environment Canada, State of the Environment Report No. 95-2, Cat. No. En1-11/95-2E, p.18, http://www.msc-smc.ec.gc.ca/saib/climate/Climatechange/SOE_95-2_english.pdf.

[23] IPCC. 2001. *Climate Change 2001: The Scientific Basis, Summary for Policymakers*, p.12, http://www.ipcc.ch.

[24] See, for example, Oreskes, N. 2004. "The Scientific Consensus on Climate Change," *Science* vol. 306, 3 December, p.1686.

[25] See, for example, Royal Society. 2001. *Royal Society backs international call for action on climate change* (media release, May 18), http://www.royalsoc.ac.uk/templates/press/releasedetails.cfm?file=318.txt.

[26] IPCC. 2001. *Climate Change 2001: Synthesis Report*, p. 90, http://www.ipcc.ch/pub/syreng.htm.

[27] Intergovernmental Panel on Climate Change. 2001. *Climate Change 2001 – The Scientific Basis*, Technical Summary, p. 75–76, http://www.ipcc.ch/pub/wg1TARtechsum.pdf.

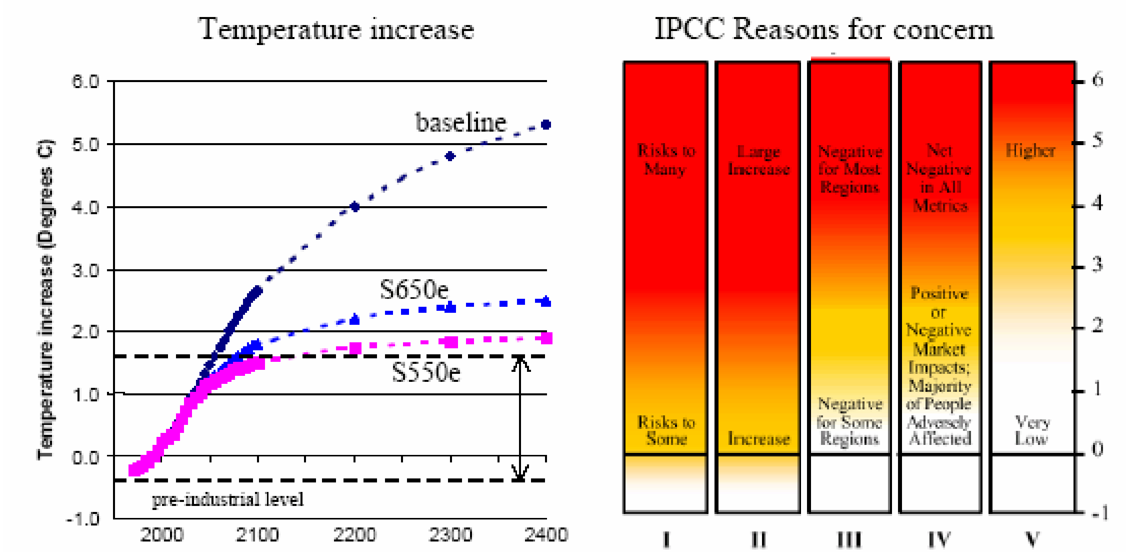

Figure 1.1 Estimates of long-term temperature increase compared to 1990 baseline and emission CO_2 stabilization trajectories and reasons for concern according the IPCC [28]

The right-hand panel summarizes the IPCC's reasons for concern for different levels of temperature increase. The colour white means little or no impacts, yellow indicates moderate impacts and red stands for serious impacts:

I: Risks to unique and threatened ecosystems

II: Risks to extreme climate events

III: Distribution of impacts

IV: Aggregate impacts

V: Risk of future large-scale discontinuities

One hundred and eighty-eight countries,[29] including Canada and the US, have ratified the United Nations Framework Convention on Climate Change (UNFCCC), which entered into legal force in March 1994. The Convention's "ultimate objective" is "to achieve . . . stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system."[30] Recognizing the need for legally binding instruments to achieve the UNFCCC objective, the international community adopted the Kyoto Protocol to the UNFCCC in 1997. The Protocol, which entered into force in February 2005, sets GHG emission targets for the period 2008–2012 for industrialized countries including Canada. Canada ratified the Protocol in December 2002, thereby accepting the Canadian target for reducing its GHG emissions, net of credits for "sinks" and international emissions trades, to 6% below the 1990 level during 2008–2012. The existing targets fall very far short of the

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[28] IPCC. 2001. *Climate Change 2001: Impacts, Adaptation, and Vulnerability*. Cambridge University Press, p.5, http://www.grida.no/climate/ipcc_tar/wg2/008.htm (original source) and Vuuren DP van et al. 2003. *Regional costs and benefits of alternative post-Kyoto climate regimes: Comparison of variants of the Multi-stage and Per Capita Convergence regimes.* RIVM Report 728001025, p.81; http://www.rivm.nl/bibliotheek/rapporten/728001025.pdf Note: The left-hand figure shows the temperature pathways as calculated up to 2100 – extended after 2100 using comparable IPCC scenarios. The two horizontal lines indicate the pre-industrial temperature level (-0.4 degrees Celsius compared to 1990) and the temperature target of a maximum increase of 2 °C compared to pre-industrial).

[29] See http://unfccc.int/essential_background/convention/status_of_ratification/items/2631.php. UNFCCC has had 189 ratifications, but one of these was the EU, not a country.

[30] See http://unfccc.int/resource/docs/convkp/conveng.pdf.

UNFCCC's objective of stabilizing GHG concentrations. Attaining the UNFCCC objective will require either a series of amendments to the Protocol or successor treaties that set increasingly demanding targets for emission reductions for several decades post-2012.

According to the World Business Council for Sustainable Development, stabilizing CO_2 concentrations at levels of less than 500 ppm will prove difficult, as it would require emission reductions below 1990 levels within a few decades. Stabilization at a higher level would be more realistic as "it allows a timeframe in which significant change in our energy infrastructure could take place."[31] But higher levels bring greater risk. The International Symposium on the Stabilisation of GHG Concentrations, convened in February 2005 by the UK government, confirmed that "limiting warming to 2°C above pre-industrial levels with a relatively high certainty requires the equivalent concentration of CO_2 to stay below 400 ppm."[32] Bodies as diverse as the European Council,[33] the German Advisory Council on Global Change,[34] the European Climate Forum[35] and the Climate Action Network International[36] have endorsed the 2°C limit.

Worldwide, governments and industry are now beginning to recognize the need for deep reductions in GHG emissions in order to stabilize the concentration of CO_2 and other GHGs in the atmosphere. The UK government has established a goal of reducing its CO_2 emissions to 60% below the 1990 level by 2050;[37] the French government has adopted the objective of reducing its GHG emissions by 75–80% by 2050,[38] the European Union Environment Council (comprising the environment ministers of all member states) has recommended that "reduction pathways by the group of developed countries in the order of . . . 60–80% by 2050 [below 1990 levels] should be considered,"[39] and California's Governor Schwarzenegger has set the target of limiting state-wide GHG emissions to 80% below the 1990 level by 2050.[40] This is the level by which industrialized countries will need to reduce their emissions in order to stabilize GHG concentrations in the atmosphere at levels sufficiently low to prevent dangerous climate

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[31] World Business Council for Sustainable Development. 2004. *Facts and Trends to 2050 - Energy and Climate Change*, p.2, http://www.wbcsd.ch/web/publications/Basic-Facts-Trends-2050.pdf.

[32] *Avoiding Dangerous Climate Change, International Symposium on the Stabilisation of Greenhouse Gas Concentrations, Hadley Centre, Met Office, Exeter, UK, 1–3 February 2005, Report of the International Scientific Steering Committee*, p.6, http://www.stabilisation2005.com/Steering_Commitee_Report.pdf.

[33] Council of the European Union. 2005. *2647th Council Meeting – Environment*. Press release, March 10, http://ue.eu.int/ueDocs/cms_Data/docs/pressData/en/envir/84322.pdf.

[34] German Advisory Council on Global Change. 2003. *Climate Protection Strategies for the 21st Century: Kyoto and beyond*, p.9–21, http://www.wbgu.de/wbgu_sn2003_engl.html.

[35] European Climate Forum. 2005. *European Climate Forum: The 2 Degrees Strategy*, http://www.european-climate-forum.net/pdf/ECF_strategy_2005.pdf.

[36] Climate Action Network International. 2003. *A Viable Global Framework for Preventing Dangerous Climate Change*, p.1, 14–15, http://www.climatenetwork.org/docs/CAN-DP_Framework.pdf.

[37] Department of Trade and Industry. *Our energy future — creating a low carbon economy*, p.8, http://www.dti.gov.uk/energy/whitepaper.

[38] Ministère de l'écologie et du développement durable. 2004. *Plan Climat 2004*, p.68, http://www.ecologie.gouv.fr/IMG/pdf/PLAN-CLIMAT-2004-2.pdf.

[39] Council of the European Union. 2005. *2647th Council Meeting – Environment*. Press release, March 10, http://ue.eu.int/ueDocs/cms_Data/docs/pressData/en/envir/84322.pdf.

[40] On June 1, 2005, Gov. Arnold Schwarzenegger issued an Executive Order that announced that California is to reduce its GHG emissions to year 2000 levels by 2010, 1990 levels by 2020 and 80% below 1990 levels by 2050. Office of the Governor of the State of California. 2005. *Governor Schwarzenegger Establishes Green House Gas Emission Reduction Targets*, search on Executive Orders, June 1 at http://www.governor.ca.gov/state/govsite/gov_homepage.jsp

change.[41] The CEO of British Petroleum has stated that it is necessary to stabilize the atmospheric GHG concentration in the range of 500–550 ppm and that "stabilization in the range of 500–550 ppm is possible and with care could be achieved without disrupting economic growth."[42]

Such stabilization will not be easy, if the consumption of fossil fuels continues to increase under business-as-usual scenarios. International Energy Agency (IEA) figures indicate that the world's total energy supply was approximately 10,600 million tons of oil equivalent (Mtoe) in 2003 and it is projected to increase to 16,500 Mtoe by 2030 (see Figure 1.2).[43]

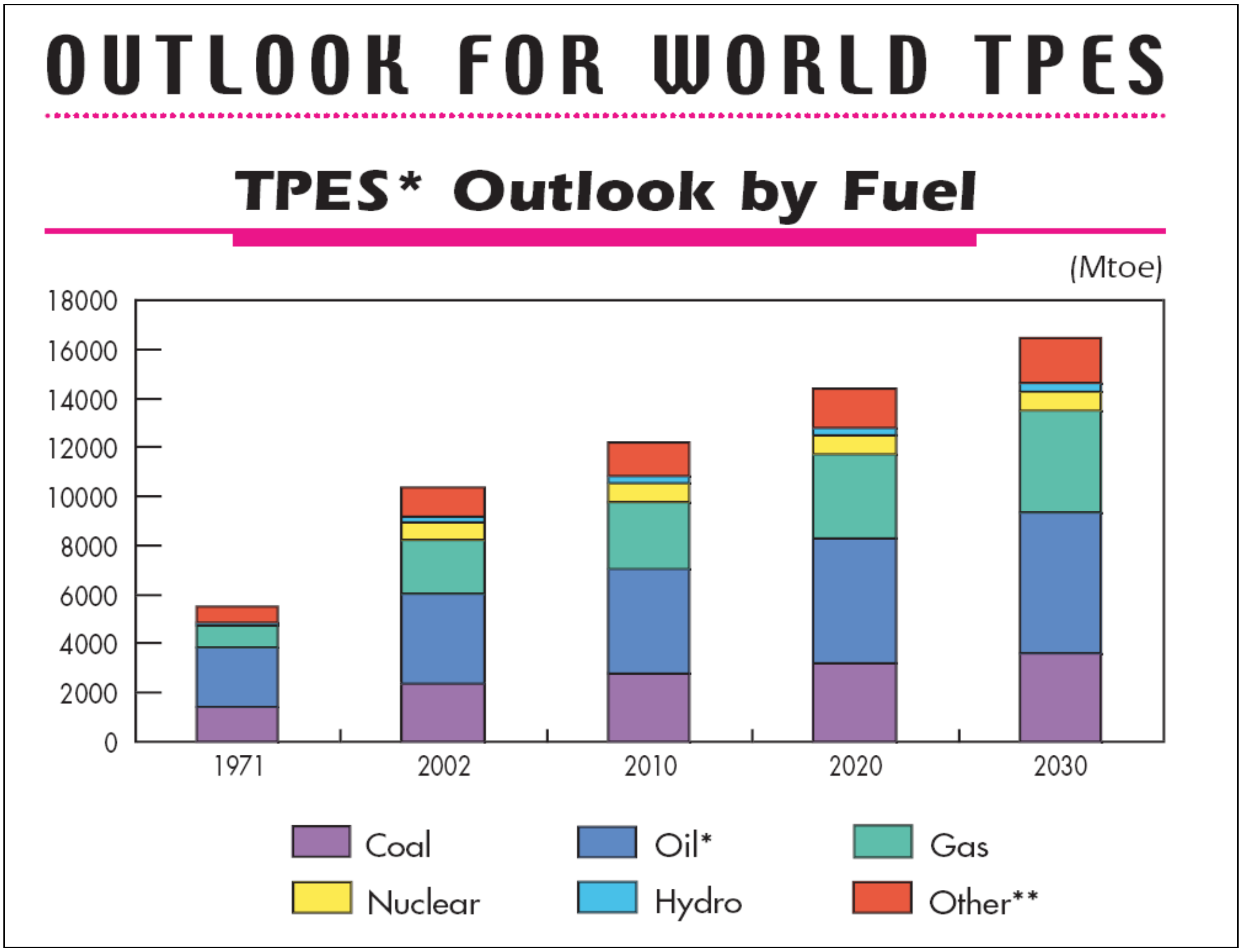

Figure 1.2 Outlook for World Total Primary Energy supply, 1971-2030[44]

A considerable portion of this growth in energy use is anticipated to occur in China and other developing economies, especially parts of Asia (including India), where it is expected that coal

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[41] Bramley, M. 2005. *The Case for Deep Reductions: Canada's Role in Preventing Dangerous Climate Change.* David Suzuki Foundation and Pembina Institute, http://www.pembina.org. To be published November, 2005.

[42] Lord Browne, Group Chief Executive, BP p.l.c. 2003. Speech given to the Institutional Investors Group, Gibson Hall, Bishopsgate, 26th November, http://www.bp.com/genericarticle.do?categoryId=98&contentId=2015334.

[43] IEA. 2005. *Key World Energy Statistics,* p. 6 and 46, http://www.iea.org/.

[44] IEA. 2005. *Key World Energy Statistics,* p.46, http://www.iea.org/. **Other includes combustible renewables and waste, geothermal, solar, wind, tide, etc.

will continue to be a major source of power.[45] The proportion coming from renewable sources (combustible renewables and waste, geothermal, solar, wind, tide, etc.) is expected to remain at approximately 11% of the total.

Canada's total energy supply in 2003 was approximately 260 Mtoe, or 2.4% of the world total, and the country's energy sector is growing rapidly because the demand for energy is growing both in Canada and in the export market. Upstream oil and gas emissions increased 56% between 1990 and 2002, when they accounted for 16% of Canada's total GHG emissions. Overall, 35% of Canada's GHG emissions in 2002 came from industry, 19% from road transportation, 18% from electricity generation, 11% from buildings, 8% from agriculture (non-energy emissions) and 10% from other sources.[46] In 2003, Canada's total CO_2E emissions were 740Mt.[47] If Canada is to achieve the target of an 80% reduction in GHG emissions below 1990 levels by 2050, it will need to reduce its emissions to 119 Mt by that date.[48]

Improvements in energy conservation, energy efficiency and an increase in the use of low-impact renewable energy can lead to important reductions in GHG emissions. However, it will be challenging for Canada to make an equitable contribution to the deep emission reductions needed to reach the objective of the UNFCCC if rapid growth in the oil sands continues and in light of the time likely required to shift from fossil fuels to renewables.

Consequently, capturing CO_2 and storing it in deep geological formations, i.e., CCS, is attracting much attention as a potentially important way to limit CO_2 emissions to the atmosphere. CO_2 can be injected at pressure and stored in depleted oil and gas reservoirs, coal seams or deep saline aquifers. Over time, some of the carbon stored in geological formations will become fixed in a more permanent form.[49] Sometimes the word "sequestration" is used rather than "storage." We use the terms "storage" or "geological storage" in this report, except where the CO_2 is sequestered by a process that fixes it in a permanent form.

What is the potential role for CCS in reducing GHGs? The IPCC *Special Report on Carbon Dioxide Capture and Storage* recently stated that: "CCS has the potential to reduce overall mitigation costs and increase flexibility in achieving greenhouse gas emission reductions."[50] The report makes it clear that CCS is only one element of a broader portfolio of GHG reduction actions that include improvements in energy conservation and efficiency, a switch to less carbon intensive fuels, an increase in renewable energy sources, the enhancement of biological sinks, the reduction of GHGs other than CO_2, and, in the IPCC view, nuclear power. Some policy analysts also see CCS as a way to reconcile the ongoing using of fossil fuels with adequately addressing

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[45] IEA. 2005. *Key World Energy Statistics,* p. 8 and 47, http://www.iea.org/.

[46] Data calculated from Canada's GHG inventory report as submitted to the UNFCCC Secretariat. See United Nation Framework Convention on Climate Change. 2004. *2004 Annex I Party GHG Inventory Submissions*; http://unfccc.int/program/mis/ghg/submis2004.html .

[47] Environment Canada. *Summary Canada's 2003 Greenhouse Gas Inventory, http://www.ec.gc.ca/pdb/ghg/2005summary/2005summary_e.cfm.*

[48] Canada's CO_2 equivalent emissions on 1990 were 596 Mt. An 80% reduction is 119 Mt. If a comparable reduction were applied to Alberta, it would require the province to reduce its emissions to 34 Mt by 2050 (Alberta's CO_2 equivalent emissions were 171 Mt in 1990). This compares with an emission level of 221 Mt in 2002.

[49] While it is normal to use the term "sequestration" to describe carbon stored in plants or the soil, the term is sometimes used to refer to "geological storage." For example, the Carbon Sequestration Leadership Forum, an international body that cooperates on issues relating to carbon capture and storage.

[50] IPCC. 2005. *Special Report on Carbon Dioxide Capture and Storage: Summary for Policymakers,* p.2. The summary in available online at http://www.ipcc.ch.

climate change.[51] For instance, CCS could be used in combination with large-scale production of hydrogen in order to move more quickly to an emissions-free hydrogen economy than would be possible by producing hydrogen solely from renewable sources.

Governments and industry have been investigating the potential of CCS for some years. [52] In Canada, where the country's oil reserves rank second only to Saudi Arabia, government and industry interest in CCS is being driven by the current and projected rapid increase in GHG emissions from the energy sector (especially oil sands) combined with the concentrated, high-volume nature of these point sources. Saskatchewan and Alberta have been the focus of interest in geological carbon storage because they are located in an area of the Western Canada Sedimentary Basin that contains large fossil fuel resources and the geological strata considered most suitable for storage. Electric power generation is the largest point source of emissions in New Brunswick and Nova Scotia, but while these provinces have access to sedimentary formations with potential for CO_2 storage, they are not in a geologically stable area.

Before examining carbon capture and transportation (Chapters 2 and 3) and storage (Chapter 4) in more detail, we will briefly describe some of the main storage projects currently underway.

1.3 What storage projects have been undertaken so far?

CO_2 has been injected and stored in oilfields in the Permian Basin in Texas since the late 1970s This technology was developed to extract greater oil recovery from fields in decline and used natural CO_2 sourced from wells in Wyoming, Colorado and New Mexico. Companies installed CO_2 recycle equipment to recirculate the CO_2 not for environmental reasons but because it was an item they had initially purchased that they wanted to conserve. Currently some 35 Mt/yr of CO_2 is injected into these fields with the majority being permanently stored in the reservoir rock with unrecovered oil

The first major location where CO_2 was stored in geological formations as a climate change strategy was under the North Sea. In 1996, encouraged by high taxes on CO_2 emissions in Norway, StatOil and its partners started removing CO_2 from the raw natural gas recovered from the Sleipner field (using an amine process) and injecting it into a massive saline aquifer in sandstone formations 800–1000 metres under the North Sea.[53]

The leading terrestrial location that is rigorously monitoring CO_2 in an enhanced oil recovery project is an EnCana facility in Weyburn, Saskatchewan. Partners in this International Energy Agency (IEA) project include the Canadian government and several provinces, as well as the U.S. Department of Energy and the European Union.[54] Many other projects are being developed in the U.S. [55]

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[51] See, for example, Mark Jacccard. 2005. *Sustainable Fossil Fuels: The Unusual Suspect in the Quest for Clean and Enduring Energy.* Cambridge University Press.

[52] Natural Resources Canada. 2000. *The Capture and Storage of Carbon Dioxide Emissions: A Significant Opportunity to Help Canada Meet its Kyoto Targets.* This report, which was prepared by D.A. Reeve, for the Office of Energy Research and Development at Natural Resources Canada, provides a good overview of developments and potential in Canada. http://www2.nrcan.gc.ca/es/oerd/english/View.asp?x=649&oid=18

[53] IEA.SACS (Saline Aquifer CO_2 Storage) project. See tab for *CO_2 Capture and Storage* at http://www.ieagreen.org.uk/ and click on "offshore Norway" and "Norwegian" hyperlinks.

[54] The Natural Resources Canada website provides an overview of the Weyburn project and CCS projects in Canada at http://www.nrcan.gc.ca/es/etb/cetc/combustion/co2trm/htmldocs/canadian_r_d_e.html#project6.

[55] A detailed review of CCS in North America is provided in Department of Trade and Industry, UK. 2003. *Carbon Dioxide Capture and Storage.* Report of DTI International Technology Service Mission to the USA and Canada from 27th October to 7th November 2002. (Available in hard copy.)

The third major demonstration site is BP's In Salah project in Algeria, where CO_2 is captured and stored in a gas field. This provides an opportunity to obtain baseline and monitoring data that is not associated with enhanced oil recovery. BP has recently announced another project where it will recover CO_2 from an onshore refinery and transport it offshore for use in an EOR field

BP is one of the companies active in the CO_2 Capture Project (CCP). The CCP brings together the resources of some of the largest energy companies in the world including Suncor Energy of Canada, the U.S. Department of Energy, the European Union and other smaller companies and research centres.[56] This group is leading and funding the evaluation and development of capture and monitoring technologies, as well as increasing public acceptance and awareness of CO_2 capture and storage. Currently in Phase II, the CCP has narrowed the technologies being examined and is moving some of these technologies forward to the pilot plant pre-commercial stage.[57] The CCP is also engaged in policy affairs (see Section 5.1.2), as is the Carbon Sequestration Leadership Forum (see Section 5.1.3).

While there were only three major projects demonstrating CO_2 storage in 2004, others were being planned. There are more than 50 projects capturing CO_2 for re-injection; many of these sites are in Alberta, where acid gas (a mixture of hydrogen sulphide and CO_2, which is a waste-product from the sweetening of sour gas) is injected deep underground (see Section 4.1.3).[58] A full inventory of CCS projects is maintained in the IEA's database.[59] The IEA's Greenhouse Gas R & D Program is focused almost entirely on CCS.[60] The organization provides a good overview of CCS developments in its report, *Solutions for the 21st Century: Zero Emission Technologies for Fossil Fuels,*[61] with further analysis of the issues in *Prospects for CO_2 Capture and Storage.*[62]

Now we examine what is involved in carbon capture in more detail.

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[56] CO_2 Capture Project, http://www.co2captureproject.com/contacts/contacts.htm.

[57] CO_2 Capture Project, Phase 2, http://www.co2captureproject.com/Phase2Index.htm.

[58] EUB. 2005 *Deep Injection of Acid Gas (H2S) in Western Canada*, http://www.ags.gov.ab.ca/activities/CO2/acidgas.shtml.

[59] A database of current CCS projects worldwide can be found on the IEA's Greenhouse Gas R & D Programme website at http://www.co2captureandstorage.info/.

[60] See, for example, the 7th International Conference on Greenhouse Gas Control Technologies, which in 2004 was held in Canada, at http://www.ghgt7.ca/main.html.

[61] IEA. 2002. *Solutions for the 21st Century: Zero Emissions Technology Report,* http://library.iea.org/dbtw-wpd/textbase/papers/2002/tsr_layout.pdf An appendix to the report summarizes the various programs and projects underway in 2002.

[62] IEA. 2004. *Prospects for CO_2 Capture and Storage.* Energy Technology Analysis. This report can be purchased from the IEA at http://www.iea.org/Textbase/publications/index.asp.

2 Carbon Capture

2.1 Concepts and context

CCS has three stages: capture, transportation and storage. In addition, there is the need for monitoring, which should start before injection and continue after the storage site is capped and until stability of injected CO_2 is demonstrated.[63]

Large point sources of CO_2 emissions are the most likely places that CO_2 capture could be implemented. Industries such as oil and gas, electricity production, cement and steel are likely to be the earliest implementers because of economies of scale. Capturing CO_2 from distributed sources, such as the transportation, housing or building sectors, is unlikely to be feasible or economical for the foreseeable future.

The technical capability to remove CO_2 from large point sources has been established; however, at present there are very few large-scale demonstrations of the technology, and in most cases the individual technologies have not been integrated on the large scale envisioned. Advanced technology research is focused on developing low-cost and higher-efficiency methods of capturing CO_2 from large point sources.

Point sources of CO_2 are unique in composition, and therefore no one technology for capture can be applied universally. For example, a natural gas combined-cycle power plant may have flue gas emissions that contain only 3% or 4% CO_2, whereas a coal burning plant may have flue gas emissions in the range of 13%–15%. Industrial emissions (cement or steel) may have concentrations upwards of 30%. Industrial processes, such as ammonia fertilizer production, natural gas processing and hydrogen production for upgrading or refining may already be producing high concentration CO_2 (above 90% in many cases) streams that could be stored with little additional treatment; in some cases only dehydration and compression would be required.[64] Similarly, as CO_2 is removed from raw (sweet or sour) natural gas, a high concentration CO_2 stream is developed that could be easily captured, either as pure CO_2 or as acid gas.

The operation of a capture plant will require additional energy when compared to an equivalent facility with no capture.[65] The result is decreased efficiency or output. Therefore, when comparing a CO_2 capture plant to a plant without capture, it is important to talk about the CO_2 *avoided*, not the CO_2 *captured* because these are different measures. This concept is illustrated below.

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[63] Monitoring may be required for hundreds or thousands of years, depending on site of storage. Transportation, storage and monitoring are discussed in further detail in subsequent sections of this report.

[64] Gale, J. IEA. 2003. *Opportunities for early application of CO_2 sequestration technology.*

[65] The possible exception being gas processing plants where Acid Gas Injection could be used as an alternative to desulphurization.

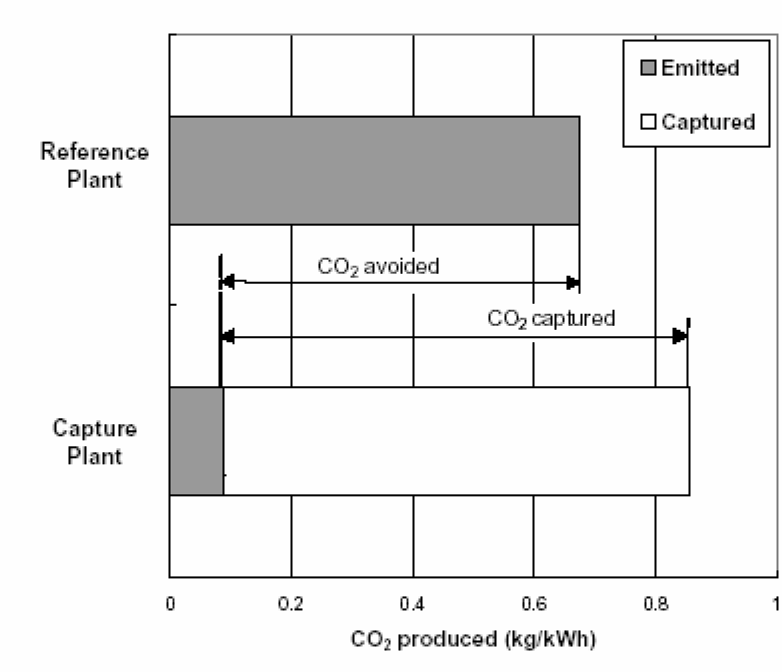

Figure 2.1 CO_2 Captured and CO_2 Avoided[66]

CO_2 capture will, in most cases, be the most expensive stage of CCS. Capture costs will vary depending on the technology and application; transport costs will depend on volume, distance and method of transport; and storage costs will depend on the size and type of storage medium. Furthermore, potential revenue from selling CO_2 for enhanced oil recovery or revenue from carbon credits will affect the economics of CCS.

The IEA produced the following table as a general guideline for costs of CO_2 capture and storage.[67]

Activity	Cost (US$/t CO_2)	Uncertainties
CO_2 capture (including compression)	5[68] to 50 (current) 5 to 30 (future)	Low end for pure streams that only need compression; high end for chemical absorption from gas-fired combined cycles
CO_2 transportation	2 to 20	Depends on scale and distance
CO_2 injection	2 to 50	Low end for megatonne aquifer storage; high end for certain enhanced coalbed methane projects
CO_2 revenues	-55 to 0	No benefits for aquifers; highest benefits for certain enhanced oil recovery projects
Total	-40 to 100	

Table 2.1 Costs of Carbon Capture and Storage[69]

[66] Herzog, H. 1999. *The Economics of CO_2 Separation and Capture.*

[67] IEA. 2004. *Prospects for CO_2 Capture and Storage.* Energy Technology Analysis. Summary available online at http://www.iea.org/Textbase/publications/index.asp.

[68] The Pembina Institute considers the figure of US$5/ t CO_2 to be very low and it likely to be found only in specific limited cases. $15/t CO_2 appears to be the lowest number in Canada.

[69] IEA. 2004. *Prospects for CO_2 Capture and Storage.* Energy Technology Analysis. Summary available online at http://www.iea.org/Textbase/publications/index.asp.

The lowest cost opportunities for capture in Canada are found where there is already a high concentration CO_2 stream available. The upstream oil and gas sector produces high concentration CO_2 streams in the processing of raw natural gas (including acid gas) and in the production of hydrogen for refining and upgrading. Capture costs in this sector could average $20/tonne within the Kyoto timeframe.[70]

2.2 Overview of technology

CO_2 streams can result from both combustion and non-combustion sources. Combustion sources are those gas streams that result from the burning of fossil fuels. These sources generally have low concentrations of CO_2 and are at low pressure. Non-combustion sources include CO_2 streams that are by-products of industrial processes. Examples include the CO_2 removed from raw natural gas and the CO_2 released when natural gas is converted to H_2 for use in refining and upgrading.

There are five main methods for separating CO_2. The selection of method will depend on the concentration, pressure and temperature of the source gas from which CO_2 is to be captured. The methods are

- chemical solvent scrubbing (amine);
- physical solvent scrubbing;
- solid adsorption (physical adsorption);
- membrane separation; and
- cryogenic separation.

Hybrid processes can also be developed. An example is the Sleipner project in the North Sea where they are capturing CO_2 from natural gas using a membrane/amine technology.

Capture plants can generally be divided into three technology categories or applications: post-combustion, pre-combustion and oxyfuel combustion.

Post-combustion facilities remove carbon *after* combustion. A post-combustion capture plant treats emissions at the tail end of the plant. Removing CO_2 at this point is an established technology, but it is expensive and energy intensive. This technology is also used to remove CO_2 from produced (or raw) natural gas sources that have unacceptably high levels of CO_2.

Pre-combustion facilities remove the carbon *before* combustion. The source fuel — natural gas, coal, coke, oil or biomass — can be converted to syngas (primarily CO and H_2) in established gasification processes. The energy carrier (H_2) and CO_2 can then be isolated.

Oxyfuel cycles are similar to the post-combustion process in that the carbon is removed after combustion. Typically combustion occurs in atmospheric air, which results in high volumes of N_2 and NO_x in exhaust gases that dilute the concentration of CO_2. If combustion takes place in a pure oxygen environment, the main product of combustion is CO_2. Therefore, the exhaust stream of an oxyfuel cycle requires very little treatment before it can be delivered for storage.

[70] Keith, D.W. 2002. *Towards a Strategy for Implementing CO_2 Capture and Storage in Canada.* Prepared by D.W. Keith, Carnegie Mellon University, Pittsburgh, Pennsylvania, for the Oil, Gas and Energy Branch, Environment Canada, Ottawa, Ontario.

Acid Gas Injection (AGI), where the CO_2 and hydrogen sulphide (H_2S) removed from a sour natural gas stream is re-injected into a geological formation, is often used in place of conventional flaring or desulphurization. AGI eliminates SO_x emissions while also storing CO_2.

Each of these technologies — post-combustion, pre-combustion and oxyfuel combustion — are discussed in more detail below.

2.3 Post-combustion

2.3.1 Technologies

Post-combustion capture of CO_2 is a well-established industrial process. It is commonly used in the food industry to produce CO_2 and is used in gas processing to remove CO_2 from extracted natural gas.

A conventional CO_2 absorption process uses a lean amine solvent to selectively scrub CO_2 from a gas stream in an absorber column, thereby yielding a rich amine and a CO_2 -depleted gas stream. The CO_2 rich amine is then regenerated by the addition of heat, releasing a high purity CO_2 stream. The amine can then be recycled to the absorber column.

The most common amines for capture are monoethanol amines (MEA), but other proprietary, commercial amines are also available.[71] Developments in the areas of amine performance (reduced degradation, reduced energy for regeneration, waste generation, operation costs) will improve the viability and cost effectiveness of post-combustion capture at large scale. However, it is anticipated that solvent development will yield only minor performance improvements and/or marginal reductions in cost.

Integrating membranes into the post-combustion process can improve efficiency and reduce costs by decreasing the volume of amine required and increasing the percentage of CO_2 removed from the source gas stream. Currently, the Sleipner project in the North Sea uses an amine/membrane hybrid process.[72] A further benefit in this case is the reduced footprint and weight compared to a standard amine capture plant.

Physical adsorption processes represent an alternative to amine absorption processes. Physical processes, however, are more efficient for high pressure and high concentration streams and will not likely find use in strictly post-combustion capture scenarios unless emissions have very high concentrations of CO_2 (>30% CO_2). Physical adsorption will more likely be used as part of a pre-combustion or oxyfuel capture process. Pressure Swing Adsorption (PSA) is a common physical adsorption process.[73]

2.3.2 Applications

Post-combustion processes are common in the oil and gas industry as well as the food industry because they can be applied to most gas streams that require CO_2 removal.[74] This technology can be applied as a retrofit to existing facilities such as large power generation facilities.

[71] Fluor Daniel Ltd, ABB Lummus both have commercial MEA amines for CO_2 capture. Mitsubishi Heavy Industry has developed a proprietary amine with better performance than conventional amines in the areas of energy consumption and degradation, but it is more expensive per unit.

[72] The Sleipner project processes off-shore natural gas laden with CO_2. The CO_2 removed is re-injected into a saline aquifer below the seabed.

[73] PSA is emerging as a common method of separating H_2 from syngas in the production of H_2 for upgrading and refining.

[74] Post-combustion processes are used in oil and gas industry to remove CO_2 from raw natural gas, and it is used to produce CO_2 for enhanced oil recovery in some applications.

The technology required for post-combustion capture is established and mature; therefore, implementation is feasible in a short time frame. However, the costs to implement post-combustion capture to existing facilities on a large scale in a rapid time frame will lead to high costs.[75]

2.3.3 Gaps

The energy requirements for post-combustion capture significantly affect the efficiency of a plant because of the large amount of energy required for regeneration of the solvent. Reducing energy requirements for solvents is necessary if post-combustion technology is to be competitive with other CCS options. The strong bonding of the solvent with CO_2 requires significant energy input to break the bond for the regeneration process. New solvents that have much weaker bonds with CO_2 are being developed because these will require less energy for regeneration.

A concern with amine solvent capture is the generation of toxic amine waste. Impurities in the gas stream, such as sulphur or nitrogen oxides, produce heat-stable salts that degrade the performance of the amine. Consequently, degraded amine must constantly be removed and disposed of, and replaced with fresh solution. At the scale envisioned for large-scale implementation of CCS, "this technology has yet to prove acceptable in terms of energy consumption and levels of toxic waste effluent."[76]

Although integration of membrane technology will improve the performance and decrease the size of the required infrastructure, a post-combustion plant "overwhelms existing plant infrastructure."[77]

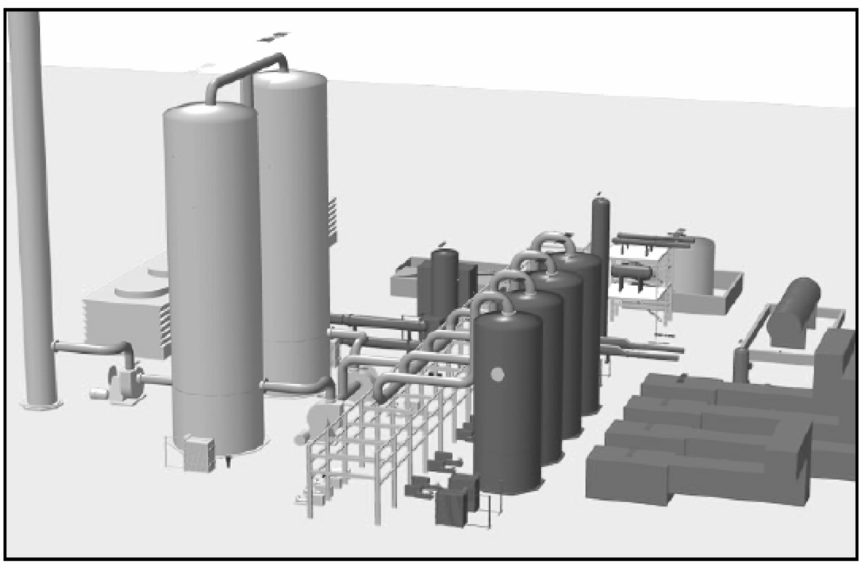

Figure 2.2 Visualization of CO_2 Capture Plant. The person standing in front of the two large absorber columns gives an impression of scale. [78]

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[75] Keith, D.W. 2002. *Towards a Strategy for Implementing CO_2 Capture and Storage in Canada.* Prepared by D.W. Keith, Carnegie Mellon University, Pittsburgh, Pennsylvania, for the Oil, Gas and Energy Branch, Environment Canada, Ottawa, Ontario.

[76] Bolland, O. and H. Undrum. 2003. "A novel methodology for comparing CO_2 capture options for natural gas combined cycle plants." *Advances in Environmental Research*. 7: 901-911.

[77] Simmonds, M., P. Hurst, M.B. Wilkinson, C. Watt and C.A. Roberts. 2002. *Amine Based CO_2 Capture from Flue Gas.* Paper presented at the Gas Processors Association of Europe, Annual Meeting, September.

Because of their drawbacks, chemical and physical scrubbing technologies will most likely not be used for post-combustion applications; they are more likely to find application in non-combustion sources such as CO_2 removal from raw natural gas, to purify high concentration streams of CO_2 prior to transport, or as part of a pre-combustion facility.

2.4 Pre-combustion

2.4.1 Technologies

The pre-combustion process removes carbon from the source fuel before combustion. This requires the gasification of the fuel i.e., conversion of the fossil fuel to a synfuel (CO and H_2). The gasification process can be applied to most fuels, including natural gas, coal and biomass.[79]

The most common method used for the conversion of fossil fuels to a mixture of hydrogen and CO_2 is a two-step process. The fossil fuel is first converted to a syngas composed mainly of carbon monoxide (CO) and hydrogen (H_2). This first step is called Steam Methane Reforming (SMR). The CO and H_2 syngas then undergoes a water-gas shift, converting the CO to CO_2 and forming more H_2. Lastly, the H_2 is separated from the CO_2.[80] The CO_2 can be compressed for transport and storage.

The generic process steps are shown below. In some cases, a pure oxygen stream is used for syngas generation.

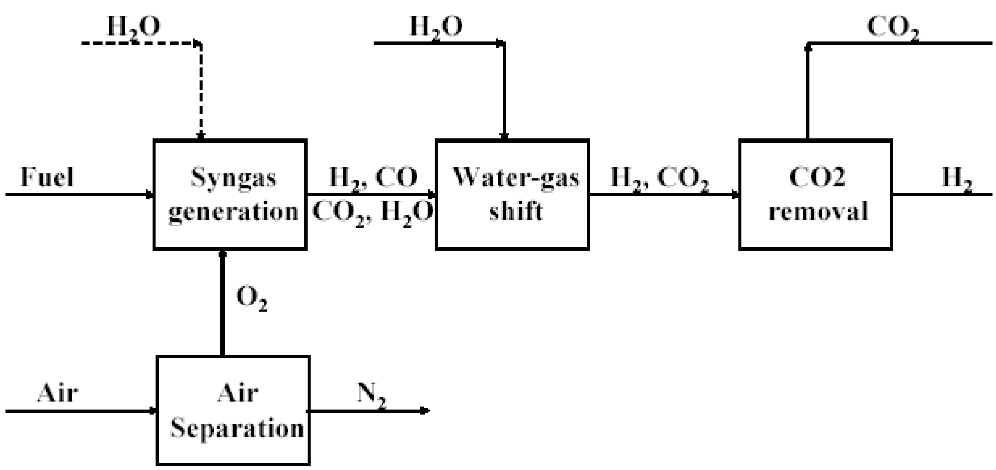

Figure 2.3 Pre-Combustion Process Steps[81]

The CO_2 separation step can be accomplished with absorption or adsorption technologies.[82] The key difference in the pre-combustion separation step is that the CO_2 stream being separated is at high pressure and temperature, allowing for more efficient capture.

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[78] Simmonds, Hurst, Wilkonson, Watt and Roberts. *Amine Based CO_2 Capture from Flue Gas.* Paper presented at the Gas Processors Association of Europe, annual meeting 2002.

[79] Biomass energy in combination could actually remove carbon from the atmosphere. Since biomass absorbs CO_2 from the atmosphere, if the biomass were combusted and the CO_2 from emissions sequestered, the process would effectively create 'negative' emissions.

[80] Davison, J. and K. Thambimuthu. 2004. *Technologies for Capture of Carbon Dioxide.* Invited technical overview for 7th Greenhouse Gas Control Technologies Conference.

[81] The CO_2 Capture Project. Capture Technology Overview. EU Roll-out. Bruxelles, June 2nd, 2004.

Much of the current research into pre-combustion technologies focuses on improving the efficiency of the hydrogen production process. By developing new adsorbents (more energy efficient removal of CO_2), integrating novel membranes (efficient and continuous separation of CO_2 and H_2) or combining process steps, researchers hope to develop an efficient, low-cost alternative to current multi-step processes.

For example, the CO_2 Capture Project funded research into several pre-combustion processes, including the Hydrogen Membrane Reformer (HMR). The HMR membrane continuously removes H_2 from the product gas, thus driving equilibrium-limited reactions towards completion and providing the separation step simultaneously. For a power generation facility, the CCP anticipates the overall efficiency compared to a post-combustion amine capture would improve 6% and the cost of capture would be reduced by nearly 60%.[83] CCP also is developing the Sorption Enhanced Water Gas Shift (SEWGS) and the Membrane Water Gas Shift (MWGS). Both are H_2 production processes with a reduced number of steps. The MWGS process combines the final two steps in Figure 2.3 (water gas shift and CO_2 separation) by using a membrane that selectively removes the H_2 from the reaction, allowing the water-gas shift reaction to be continuous.[84]

2.4.2 Applications

Pre-combustion may have wide applications, as both the source fuel and end uses can be diverse. The gasification of fuels can be applied to coal, coke, oil, natural gas and biomass. The product of gasification (H_2) can be used in industrial processes as the primary energy carrier for power generation and in distributed systems providing energy to buildings or fuel for transportation.

“Clean coal” is a concept that is receiving attention as an option for the supply of significant amounts of emissions-free energy. Coal is a cheap, abundant and domestic source of energy in North America. Concepts for Advanced Zero Emissions Plants (AZEP) are being developed, including the U.S. “FutureGen”, based on pre-combustion concepts of converting fossil fuels to H_2 and capturing CO_2.[85]

Three Integrated Gasification Combined Cycle (IGCC) coal demonstration plants are already operating in the U.S. to generate electricity (the largest is 330 MWe), and numerous others are operating in Europe.[86] The International Test Centre in Weyburn, Saskatchewan is using CO_2 delivered from a gasification unit in North Dakota for enhanced oil recovery.

In the oil sands regions of Western Canada and other refining and upgrading areas, hydrogen is primarily produced from natural gas using SMR and water-gas shift. The use of this process will allow the capture of CO_2 from these facilities at a relatively low cost. Of concern, however, is that while new facilities are starting to integrate the hydrogen production process to improve efficiencies, many are planning to use PSA technologies that increase the difficulty of capturing

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[82] Absorption reactions occur throughout the bulk of the absorbent, whereas adsorption is confined to the surface of the adsorbent.

[83] CO_2 Capture Project. Results from the CCP 2000–2004. Lars Ingolf Eide. Hydro Oil and Energy. Presented at the Second Trondheim Conference on CO_2 Capture, Transport and Storage. Oct 25th, 2004.

[84] CO_2 Capture Project. Results from the CCP 2000–2004. Lars Ingolf Eide. Hydro Oil and Energy. Presented at the Second Trondheim Conference on CO_2 Capture, Transport and Storage. Oct 25th, 2004.

[85] U.S. Department of Energy, http://www.fossil.energy.gov/programs/powersystems/futuregen/. The FutureGen project is based on coal gasification. See also the Canadian Clean Power Coalition, http://www.canadiancleanpowercoalition.com/. Other advanced zero emission concepts based on natural gas have been developed, see AZEP-MCM in Section 2.5.

[86] IEA. http://www.iea-coal.org.uk/content/default.asp?PageId=74.

CO_2. Given the necessary expansion of hydrogen production capacity in the area in the very near term, if CO_2 capture is going to be adopted in Canada as a GHG mitigation measure, oil and gas companies should plan their facilities with the expectation they will be required to capture the CO_2 produced as a byproduct of H_2 production.

Compared to facilities where CO_2 mitigation is the driver for hydrogen production (example, H_2 used as energy carrier for power generation), a facility that already requires H_2 as an end product in an industrial process (e.g., upgraders) will have lower additional costs ($/tonne captured).

As fuel cell technology becomes more cost effective, it will be applied to a broad range of stationary and mobile applications, and this will expand the market for carbon free hydrogen fuel sources.[87]

2.4.3 Gaps

Each process step for pre-combustion capture is widely used in different industrial applications, but the use and integration of these processes for CO_2 capture is not well established. In Phase 1, the CO_2 Capture Project (CCP) evaluated several prospective low energy pre-combustion processes; their research focused on the development of low-cost hydrogen production combined with CO_2 separation.

The membranes developed for advanced pre-combustion processes (HMR, SEWGS, MWGS) often suffer from low stability, insufficient selectivity or intolerance to impurities. For example, the MWGS membrane developed in Phase 1 was sufficiently stable at high temperature and pressure, but researchers were unsuccessful in developing a membrane that could demonstrate sufficient selectivity and tolerance to H_2S simultaneously.[88]

A further barrier to implementation of pre-combustion technology is the capability of industrial equipment to combust H_2. High temperature metals are required to withstand the temperatures achieved when combusting H_2. For this reason, pre-combustion processes require a more significant change to power plant or boiler design.[89] Current capability of hydrogen use in turbines is limited to 45% of total fuel; further development is required before electricity can be produced from turbines that use only H_2 as fuel.[90]

Water use is a concern for pre-combustion plants, as high volumes of steam are required for the SMR process. One study found that water requirements for SMR were 14 times greater than an equivalent plant with non-capture, and a 3-fold increase in water consumption was required for post-combustion capture.[91]

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[87] IEA. 2004. *Prospects for CO_2 Capture and Storage.* Energy Technology Analysis.

[88] Researchers were able to demonstrate perfect selectivity for H_2, but this membrane was not tolerable to H_2S. Source: CO_2 Capture Project. Capture Technology Overview. EU Roll-Out. Bruxelles. June 2nd, 2004.

[89] Davison, J. and K. Thambimuthu. 2004. *Technologies for Capture of Carbon Dioxide*. Invited technical overview for 7th Greenhouse Gas Control Technologies Conference.

[90] IEA. 2004. *Prospects for CO_2 Capture and Storage.* Energy Technology Analysis.

[91] Clerici, G., et al. 2003. *Environmental Analysis of Different Options of CO_2 Capture in Power Generation from Natural Gas.* In J. Gale and Y. Kaya (Eds.), Proceedings of the 6th Greenhouse Gas Technologies Conference.

2.5 Oxyfuel combustion

2.5.1 Technologies

Typically fuel is combusted with atmospheric air, the composition of which is approximately 80% N_2 and 20% O_2. The flue gas stream therefore consists of large amounts of N_2 and NO_x components mixed with CO_2.

By combusting fuel in an oxygen-rich environment (oxyfuel combustions), instead of atmospheric air, the CO_2 concentration of flue gas can be increased significantly, resulting in a simple and less expensive capture of CO_2 compared to post-combustion capture. These capture methods could be physical processes, which would eliminate the need for most solvents and their associated waste streams. Furthermore, NO_x emissions, a significant air quality contaminant, is suppressed because nitrogen is never introduced into the combustion process.[92]

However, the combustion of fuel in pure oxygen drives the combustion temperature above the limits of conventional metals and turbines. Therefore, either specialized materials must be developed, or the temperature in the combustion chamber must be moderated. One method for moderating temperature is an O_2/CO_2 cycle; this involves the recycle of CO_2 from flue gas to the combustion chamber. Steam or water can also be used in place of CO_2 for moderating temperature.

The production of pure oxygen for oxyfuel processes requires an Air Separation Unit (ASU) that separates O_2 from other components typically found in air. Current industry standard for air separation is cryogenic separation, which is the progressive cooling of atmospheric air to the point where constituent components can be isolated. This established technology requires a significant amount of energy input.

Advanced concepts based on oxygen firing are being developed but will not be commercially available until early in the next decade, according to industry estimates. These concepts include

- Advanced Zero Emission Plants (AZEP) uses a high pressure mixed conducting membrane (MCM), which separates oxygen for combustion with gas; and
- Chemical Looping Combustion (CLC) plants, which use a metal oxide to transfer oxygen to fuel without fuel and air ever mixing.

The AZEP-MCM technology uses a membrane reactor instead of the combustion chamber of a standard gas turbine. Air compressed by the turbine is delivered to the MCM where O_2 is permeated at high pressure through the membrane and picked up by a recycled CO_2 and H_20 stream. This stream is then compressed and delivered to a combustion chamber to react with fuel. Combustion products are delivered to an absorption column, or other post-combustion technology, to remove all, or an economically desired amount, of the CO_2. Because there is a higher pressure and concentration, the post-combustion efficiency is much greater than for a standard natural gas combustion facility with post-combustion capture.[93]

CLC systems do not require external capture devices, and there is no significant energy penalty. The technology is based on the transfer of oxygen from the combustion air to the fuel by means

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[92] Flue gas desulpherization may still be required.

[93] Personal communication with, Sven Gunnar Sundkvist, 2004.

of a metal oxide oxygen carrier. Like oxyfuel cycles, the combustion products are CO_2 and H_2O. A secondary reactor regenerates the metal oxide through a reaction with air.

Since fuel and combustion air never mix, the combustion products (CO_2 and H_2O) are not diluted with N_2. Consequently, a high purity CO_2 stream can be obtained by condensing out the H_2O.[94]

Proof of feasibility for AZEP-MCM has been accomplished, and a pilot unit is to be operational by 2008 with commercialization expected by 2012.[95]

2.5.2 Applications

Oxyfuel combustion could be applied to boilers and fired heaters in industrial processes. In particular, boilers could be designed or modified to use O_2/CO_2 as working fluid in lieu of atmospheric air.

In terms of power generation, retrofitting existing turbines to operate on a O_2/CO_2 recycle is difficult because a redesign of turbines is required.[96] Advanced oxyfuel processes, such as AZEP-MCM and CLC, are feasible and relatively efficient power generation options.

2.5.3 Gaps

At the present time, oxygen production is an energy- and cost-intensive process; in one study of a natural-gas-fired oxyfuel cycle with flue gas recycle, oxygen production alone represented a 12% loss of net plant efficiency.[97] Current oxygen production technology may be replaced in the coming decade by membrane technologies, which could significantly reduce the cost of oxygen production.

Oxyfuel combustion in gas turbines or use of recycled CO_2 with oxygen will require development of new turbines substantially different from existing models. Until clear market demand is established, manufacturers are unlikely to invest in the development of this technology.[98,99]

Catalytic Membrane Reactors (CMR) and Ion Transport Membranes (ITM) are advanced concepts for low energy oxygen production, but both require further testing before commercialization.

For CLC, different oxygen carriers have been studied, including copper, iron, manganese and nickel-based carriers. Although the carriers all proved the feasibility of the concept, there were

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[94] Ryden & Lyngfelt. 2004. *Hydrogen and power production with integrated carbon dioxide capture by chemical looping reforming.* Proceedings of 7th Greenhouse Gas Technologies Conference.

[95] CO_2 Capture Project. Capture Technology Overview. EU Rollout. Bruxelles. June 2004.

[96] Thambimuthu, K. Invited Technical Overview for publication in the Proceedings of the 7th International Conference on Greenhouse Gas Control Technologies, 5-9 Sept 2004. Vancouver, Canada.

[97] Bolland, O. and H. Undrum. 2003. "A novel methodology for comparing CO_2 capture options for natural gas-fired combined cycle plants." *Advances in Environmental Research*. 901-911.

[98] Bolland, O. and H. Undrum. 2003. "A novel methodology for comparing CO_2 capture options for natural gas-fired combined cycle plants." *Advances in Environmental Research.* 901-911.

[99] Davison, J. and K. Thambimuthu. 2004. *Technologies for Capture of Carbon Dioxide.* Invited technical overview for 7th Greenhouse Gas Control Technologies Conference.

problems with reliability and durability of the material.[100] The *Grace Project*, part of the larger CCP, developed a 10kW design based on a nickel compound.

Other unresolved issues include the impact of chemical and thermal cycling on the metal oxide oxygen carrier. The Grace Project estimates that despite attrition, material costs will be low, in the order of one euro per ton of CO_2 captured.[101] There are no estimations for capital or CO_2-avoided costs at this point.

2.6 Efficiency

CO_2 capture facilities will result in a net loss of plant efficiency,[102] an increase of capital and operating costs, and an increase of energy and material use (e.g., solvents) in the capture process.

According to Herzog, Pulverized Coal, Integrated Gasification Combined Cycle (IGCC) and Natural Gas Combined Cycle (NGCC) power generation facilities with currently available capture technology can expect net efficiency losses of 20%, 14% and 16% respectively compared to equivalent plants with no capture.[103] The IGCC plant has the best efficiency because the gas stream is at high pressure following gasification, allowing a more efficient physical adsorption process to be used for capture in place of chemical amine scrubbing.[104]

A benchmark study[105] completed in 2004 compared different capture concepts for natural-gas-fired power plants. The basis for the study was a 400 MW electricity generation plant. The results show that the emerging (advanced) concepts (AZEP-MCM, Membrane Reforming and fuel cells) have the highest efficiency, while currently available technologies (amine, oxyfuel) suffer from low efficiency. See Table 2.2 for results.

Table 2.2 Natural Gas Power Plant Benchmark Study

		Net efficiency
	Base Case (no capture)	56.7
Oxyfuel	AZEP-MCM 85% capture	54.3
Oxyfuel	AZEP-MCM 100% capture	51.1
Pre-combustion	Membrane reforming	50.6
Oxyfuel	Solid oxide fuel cell	66.5
Oxyfuel	Oxyfuel combined cycle	44.1
Post-combustion	Amine capture	48.1

Simulation models have demonstrated that integration and optimization of a capture plant with the overall facility can significantly improve net efficiency.[106]

[100] Adanez et al. 2004. *Characterization of oxygen carriers for chemical looping combustion.* Proceedings of 7th Greenhouse Gas Technologies Conference.

[101] Lyngfelt et al. 2004. The Grace Project. *Development of oxygen carrier particles for chemical looping combustion. Design and operation of a 10 kW chemical looping combustor.* Proceedings of 7th Greenhouse Gas Technologies Conference.

[102] The exception here is the use of fuel cells, where net efficiency compared to power produced through combustion actually increases.

[103] Herzog, H. 1999. *The economics of CO_2 separation and capture*. Massachusetts Institute of Technology.

[104] Herzog, H. and D. Golomb. 2004. "Carbon capture and storage from fossil fuel use." Contribution to *Encyclopedia of Energy*.

[105] Kvamsdal, H., O. Bolland, O. Maurstad, and K. Jordal. 2004. *Benchmarking of Gas-Turbine Cycles with CO_2 Capture.* Presented at 7th Greenhouse Gas Control Technologies Conference. Available online at http://uregina.ca/ghgt7/PDF/papers/peer/076.pdf.

[106] In one model, the Carbon Capture Project found that integration of a capture process, along with implementation of low-cost strategies, decreased cost per tonne of CO_2 avoided by 43% when compared to a non-integrated retrofit application of amine capture technology.

2.7 Costs

In most cases for the power generation sector, CO_2 capture will increase fuel consumption, and therefore fuel costs, by about 25%; the increase in specific capital costs (in $/kW) is estimated to be in the 20–25% range for coal plants but much higher (70–75%) for natural gas plants. [107] Emerging technologies could limit electricity cost increases to 1–2 ¢/kWh.[108]

Because new IGCC plants already have the hydrogen production process in place, the incremental cost of capture in these scenarios could be as low as US$10–US$15 per tonne of CO_2 avoided, including compression but not including transport or storage.[109]

For existing Canadian coal facilities, a Canadian study[110] comparing post-combustion oxyfuel capture options found that post-combustion would cost US$53/tonne CO_2 avoided, and electricity prices would increase by 3.3 ¢/kWh; by contrast, figures for CO_2/O_2 recycle were US$35/tonne CO_2 avoided and 2.4 ¢/kWh. The cost increases represent a 20–30% increase compared to current electricity prices.

For natural-gas-fired electricity plants the estimated capture costs range from $24–$90/tonne CO_2 avoided.[111] The lowest cost estimate was for a newly built 400 MW natural gas combined cycle facility with advanced membrane reforming pre-combustion technology. The high cost estimate is for a post-combustion capture facility retrofitted to an existing single cycle gas turbine facility.

Current estimates of carbon prices under the Kyoto Protocol range from $5–$20/tonne. For power generation facilities with current technology, cost estimates for capture are $30 and up per tonne; market carbon prices are not enough to completely offset the cost of capturing and storing CO_2. Other economic uses of CO_2, such as enhanced oil and gas recovery, may improve the economic viability of CCS, particularly for early implementation.

For non-combustion sources of CO_2, costs for CCS could be less than those anticipated for the power generation sector, mainly because there are CO_2 streams available at high concentration and pressure that require little treatment before they can compressed for transport and storage. CO_2 streams resulting from natural gas processing or hydrogen production could allow offset costs in the range of $13–$20/tonne.[112]

The IEA report *Prospects for CO_2 Capture and Storage* (2004) indicates that emerging technologies (membrane development, chemical looping combustion and fuel cells) could cut capture costs by 50% compared to current technologies.

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[107] Davison, J. and K. Thambimuthu. 2004. *Technologies for Capture of Carbon Dioxide.* Invited technical overview for 7th Greenhouse Gas Control Technologies Conference.

[108] IEA. 2004. *Prospects for CO_2 Capture and Storage.* Energy Technology Analysis.

[109] CO_2 Capture Project. 2004. Project Results: Co-operating for a better environment.

[110] Singh, D., E. Croiset, P. Douglas and M. Douglas. 2003. “Techno-Economic study of CO_2 capture from an existing coal-fired power plant: MEA Scrubbing vs. O_2/CO_2 recycle combustion”. *Energy Conversion and Management*. 44, 3073–3091.

[111] CO_2 Capture Project. 2004. Project Results: Co-operating for a better environment.

[112] Keith, D.W. 2002. *Towards a Strategy for Implementing CO_2 Capture and Storage in Canada*. Prepared by D.W. Keith, Carnegie Mellon University, Pittsburgh, Pennsylvania, for the Oil, Gas and Energy Branch, Environment Canada, Ottawa, Ontario.

2.8 Other environmental issues

As mentioned above, post-combustion amine technology "has yet to prove acceptable in terms of energy consumption and levels of toxic waste effluent."[113] Should CCS be implemented on a large scale and achieve high market penetration, this waste production could become a significant issue.

Water consumption at post-combustion and pre-combustion capture plants is also a concern because of the volume required for diluting amines and steam reforming, respectively. One study found that total water consumption, compared to a natural gas combined cycle plant baseline, would more than triple for an amine post-combustion plant and increase 14-fold for a pre-combustion plant.[114]

The IEA cautions in their 2004 report *Prospects for CO_2 Capture and Storage*:

> From an environmental policy perspective, it is worth bearing in mind that CCS may not always be the complete answer to the problem of CO_2. Past experience suggests that shifting from one medium to another can create new unforeseen environmental problems.

2.9 The Canadian context

Canada is diverse in its distribution and types of large point source CO_2 emissions. From the coal power generation of the Maritimes, through the manufacturing bases in Ontario, to the rapidly growing oil and gas industry in Alberta and the existing pulp mills in BC, large quantities of industrial point sources of CO_2 are being emitted from coast to coast.

In the Canadian context, Western Canada is geographically unique in that there is an abundance of large point sources within a reasonable distance to suitable storage sites. Also, there are opportunities to derive income from CO_2 in the developing enhanced oil recovery sector.[115]

Although attention is often focused on the electricity sector for possible early application of CCS, there are opportunities in the upstream oil and gas sector that may provide lower cost mitigation, within the Kyoto timeframe.

2.9.1 Electricity sector

Canadian power generation facilities are responsible for 19% of Canada's total GHG emissions.[116] Electricity generation facilities are among the largest point sources of emissions in Canada, and technological capability exists to capture carbon at existing and new facilities. Two of the advantages of using CCS in the power generation sector are that little or no change in the infrastructure for the supply and delivery of energy is needed, and the sizing and ease of dispatch[117] of capture plants compared to the status quo can be maintained.

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[113] Bolland, O. and H. Undrum. 2003. A novel methodology for comparing CO_2 capture options for natural gas combined cycle plants. *Advances in Environmental Research.* 7: 901-011.

[114] Clerici, G., E. D'Addario, M. Musicanti, M. Pulvirenti, S. Serenellini and M.G. Vadiserris. 2003. "Environmental Analysis of Different Options of CO_2 Capture in Power Generation from Natural Gas." In Gale J. and Kaya Y. (Eds.), *Proceedings of 6th Greenhouse Gas Technologies Conference.*

[115] Enhanced oil recovery involves injecting CO_2 into conventional oil (and gas) reservoirs to increase production of existing wells. CO_2 would become trapped in the reservoir when the site is depleted and capped, thus removing CO_2 from the atmosphere.

[116] Keith, D.W. 2002. *Towards a Strategy for Implementing CO_2 Capture and Storage in Canada.* Prepared by D.W. Keith, Carnegie Mellon University, Pittsburgh, Pennsylvania, for the Oil, Gas and Energy Branch, Environment Canada, Ottawa, Ontario.

[117] Fossil fuel plants can be dispatched to produce power when there is demand.

The Carbon Capture Project determined that a newly built gasification plant, optimized for capture, could achieve capture costs lower than natural gas plants (in $/tonne terms) primarily because the gasification step required for an IGCC plant produces a CO_2 that needs very little treatment or compression. Gasification plants also incur the lowest increase in specific capital costs ($/kW) when compared to other coal or natural gas power generation facilities.[118,119] The capital costs for a newly built natural gas plant with capture is however approximately two-thirds of the cost of a newly built coal facility with capture.[120]

As the timeline for the construction of a new pulverized coal power plant is five to six years, it is reasonable to assume that new capture-ready IGCC plants would take at least this long.[121] Capture facilities at power generating stations would likely not be available in time to support Canada's Kyoto commitments.

2.9.2 Industrial sector

Industrial emissions from the chemical, cement, iron and pulp sectors account for 23% of worldwide CO_2 emissions.[122]

Cement production worldwide accounts for 5% of global CO_2 emissions.[123] CO_2 concentrations in flue gas are typically 15–30%, making post-combustion capture processes attractive. Oxyfuel combustion is another option, but further technology development and testing would be required.[124]

Iron and steel production are also significant point sources of emissions, often with CO_2 flue gas concentrations near 20%. New processes in iron ore industry are well suited for CO_2 capture.[125]

2.9.3 Upstream oil and gas sector

Two areas of immediate relevance for CCS in the upstream oil and gas sector, and to benefit of CCS in Canada generally, are non-combustion sources:

- CO_2 produced from natural gas processing. Natural gas in most reservoirs has a percentage of CO_2 that must be removed by processing stations before the natural gas can be moved downstream. Typically, this CO_2 stream is vented to the atmosphere. Often, both H_2S and CO_2 must both be removed.
- CO_2 stream from hydrogen production. Hydrogen is used in the oil and gas sector to upgrade heavy oil and bitumen and to produce refined petroleum end products. The oil

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[118] CCP Economics and Case Studies. Tom Brownescombe, Shell. March 24th, 2004. Presentation at Mayflower Hotel, Washington, D.C.

[119] Thambimuthu, K. Invited Technical overview for publication in the Proceedings of the 7th International Conference on Greenhouse Gas Control Technologies. 5-9 September 2004. Vancouver, Canada.

[120] Keith, D.W. 2002. *Towards a Strategy for Implementing CO_2 Capture and Storage in Canada*. Prepared by D.W. Keith, Carnegie Mellon University, Pittsburgh, Pennsylvania, for the Oil, Gas and Energy Branch, Environment Canada, Ottawa, Ontario.

[121] Keith, D.W. 2002. *Towards a Strategy for Implementing CO_2 Capture and Storage in Canada*. Prepared by D.W. Keith, Carnegie Mellon University, Pittsburgh, Pennsylvania, for the Oil, Gas and Energy Branch, Environment Canada, Ottawa, Ontario.

[122] IEA. 2004. *Prospects for CO_2 Capture and Storage.* Energy Technology Analysis.

[123] Thambimuthu, K. Invited Technical overview for publication in the Proceedings of the 7th International Conference on Greenhouse Gas Control Technologies. 5-9 September 2004. Vancouver, Canada.

[124] Thambimuthu, K. Invited Technical overview for publication in the Proceedings of the 7th International Conference on Greenhouse Gas Control Technologies. 5-9 September 2004. Vancouver, Canada.

[125] Thambimuthu, K. Invited Technical overview for publication in the Proceedings of the 7th International Conference on Greenhouse Gas Control Technologies. 5-9 September 2004. Vancouver, Canada.

sands in particular, require as much as 10 times more hydrogen per barrel than conventional oil reservoirs.[126] Hydrogen is produced from natural gas, creating an H_2 stream and a CO_2 stream.

Natural gas recovery in Western Canada's oil and gas sector is expected to increase in the next decade by as much as 50%. During this period, marginal sources of gas may become economical as conventional reserve production decreases.[127] Currently, the average concentration of CO_2 in raw natural gas produced in Canada is 2.4%; this could possibly rise to 3.5%, implying that in combination with production increases, emissions of CO_2 from natural gas could rise from current levels of 9 Mt-CO_2/year to 20 Mt-CO_2/year.[128]

Currently, gas processing facilities remove CO_2 and H_2S from raw gas. H_2S is converted to elemental sulphur while the CO_2 is released to atmosphere. The CO_2 could be captured at this point, or as in the case of Acid Gas Injection, both the CO_2 and H_2S could be re-injected into geographical formations together.[129]

Hydrogen is used in the upstream oil and gas sector to upgrade heavy oil and bitumen and to produce refined petroleum end products. New projects in the oil sands will require up to 1000 scf-H_2/bbl[130] of synthetic crude produced. Since hydrogen is derived from natural gas, each 3.5–4 units of hydrogen produced results in one unit of CO_2. Hydrogen requirements in the upstream sector are expected to increase fourfold in the next decade — up to 2 billion scf-H_2/day. This capacity would produce 13 Mt CO_2 year in the sector, 20% of the world total resulting from hydrogen production.

Recently, OPTI/Nexen received regulatory approval for a gasification unit to supply syngas to its upgrader. Suncor is seeking approval for a gasification unit and proposes to utilize 25% of the coke waste by-product generated by its new upgrader as a fuel source. In both cases, the CO_2 waste stream could be captured.

With hydrogen capacity expected to increase so drastically in the next decade, it is important that if CCS is to become a reality in Canada, plants currently in the planning stage be prepared to capture CO_2 for storage.

As the expansion of the oil sands region continues, using natural gas as the source fuel for the rapid growth in hydrogen requirements will become more expensive as demand in North America and the oil sands region continues to rise. Pre-combustion processes in combination with coke or coal fuel supplies may become the fuel of choice for the required hydrogen.

[126] Keith, D.W. 2002. *Towards a Strategy for Implementing CO_2 Capture and Storage in Canada.* Prepared by D.W. Keith, Carnegie Mellon University, Pittsburgh, Pennsylvania, for the Oil, Gas and Energy Branch, Environment Canada, Ottawa, Ontario.

[127] Marginal sources of gas include those that are sour (presence of H_2S) or have high concentrations of CO_2.

[128] Keith, D.W. 2002. *Towards a Strategy for Implementing CO_2 Capture and Storage in Canada.* Prepared by D.W. Keith, Carnegie Mellon University, Pittsburgh, Pennsylvania, for the Oil, Gas and Energy Branch, Environment Canada, Ottawa, Ontario.

[129] Acid Gas Injection is currently occurring in over 30 facilities in Alberta at negative cost (i.e., it is less expensive than treating raw natural gas by removing the sulphur and releasing the CO_2). Source: Keith, D.W. 2002. *Towards a Strategy for Implementing CO_2 Capture and Storage in Canada.* Prepared by D.W. Keith, Carnegie Mellon University, Pittsburgh, Pennsylvania, for the Oil, Gas and Energy Branch, Environment Canada, Ottawa, Ontario.

[130] scf-H_2/bbl = standard cubic feet of hydrogen per barrel.

3 Transportation

Transport by tanker ship, pipeline and truck is technically feasible, although the latter is likely not economical or feasible because of the large volumes involved.

Apart from the economic cost and environmental impacts associated with the construction of a new pipeline, there are unlikely to be many technical issues relating to transportation that are not encountered in other pipeline operations. Since CO_2 is corrosive, the risk of leaks may be greater than with other substances transported by pipeline. As with sulphur dioxide, the gas must be dried to reduce the risk of corrosion. Alternatively, H_2S can be reinjected with CO_2, as is done in Canadian Acid Gas Injection facilities.

The risk of leaks in low-lying areas where the CO_2 would not dissipate (since it is heavier than air) may be a concern in some locations. A leak of CO_2 is a public safety concern because unlike sour gas, it does not have an odour and therefore would not be immediately detected and ignited.

Since there are limited geographical locations where both the source of CO_2 and an acceptable storage site coincide, an infrastructure to transport CO_2 from source to storage will need to be developed. For example, a CO_2 "backbone" pipeline connecting potential storage locations in the southwestern region of the province of Alberta to large point sources in the Edmonton (coal plants) and Fort McMurray (oil sands) areas would be needed. The CANiCAP report prepared by the Alberta Research Council identified potential CO_2 "Hubs"[131] and areas that could serve to store the CO_2 generated there (see Figure 3.1). One or several hubs would be connected to a backbone CO_2 pipeline to transport the CO_2 to appropriate storage locations.

The cost of CO_2 transportation infrastructure required to implement CCS on a large scale in Alberta is "unlikely to be higher than $10/tonne CO_2" if a volume of approximately 5Mt/year is transported.[132] Internationally, the IEA reports that large-scale pipeline transportations costs are likely to range between US$1 and $5 per tonne per 100 km, but if CO_2 is shipped over long distances, the cost can be as low as US$15–$25/tonne for 5,000 km.[133] Local conditions, such as a requirement to situate a pipeline above ground because of geological conditions, may increase the costs.

Following the resolution of capture and storage issues, transportation development could proceed rapidly.[134] Siting of pipeline right-of-ways and assessing the impact of pipeline development may present barriers to development because consultation with stakeholders will be required.

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[131] Hubs are identified as clusters of Large Final Emitters, producing large volumes of CO_2 in concentrated geographic areas.

[132] Keith, D.W. 2002. *Towards a Strategy for Implementing CO_2 Capture and Storage in Canada.* Prepared by D.W. Keith, Carnegie Mellon University, Pittsburgh, Pennsylvania, for the Oil, Gas and Energy Branch, Environment Canada, Ottawa, Ontario.

[133] IEA. 2004. *Prospects for CO_2 Capture and Storage,* p.18.

[134] Keith, D.W. 2002. *Towards a Strategy for Implementing CO_2 Capture and Storage in Canada.* Prepared by D.W. Keith, Carnegie Mellon University, Pittsburgh, Pennsylvania, for the Oil, Gas and Energy Branch, Environment Canada, Ottawa, Ontario.

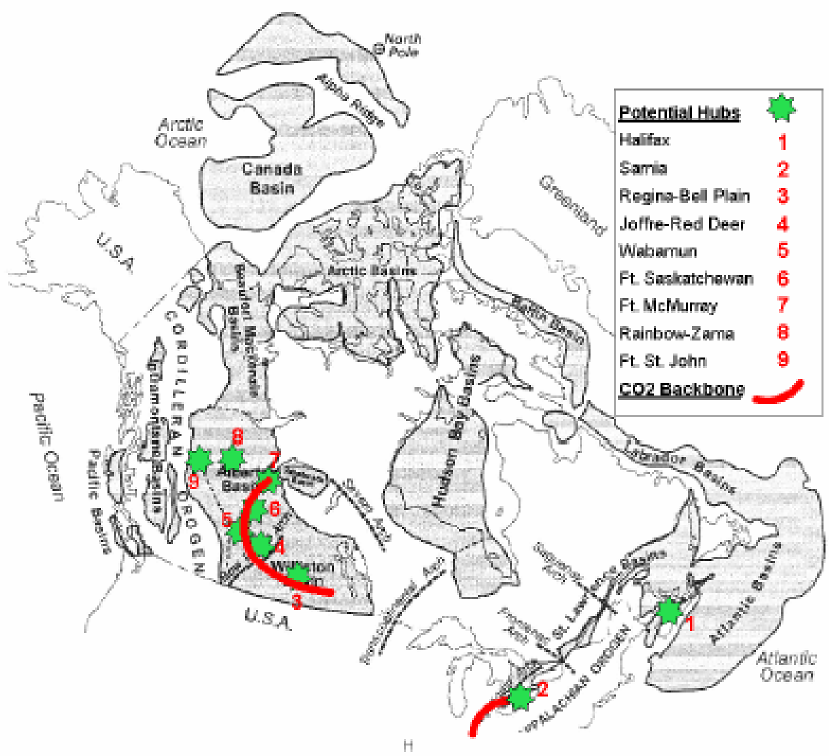

***Figure J-2:** A CO_2 backbone scheme for Canada. Canada's sedimentary basins are those areas of Canada that appear in grey stripping. Note a backbone between Sarnia and the Maritime Provinces may be justifiable in the future, once the Maritime gas and oil industry matures and depleted pools become available..*

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Figure 3.1 CO_2 hubs and backbones[135]

If CCS were to be implemented on a global scale, the volume of CO_2 to be transported would equal or surpass the combined volume of shipments of oil, coal, cement and cereals. The IEA cautions that: "In the long run, total CO_2 shipment could be of the same order of magnitude as shipments of all existing commodities put together. Therefore, the challenge of putting in place an appropriate transportation system for CO_2 should not be underestimated."[136]

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[135] Alberta Research Council Inc. 2005. *The CANiCAP Program: Planning Options for Technology and Knowledge Base Development for the Implementation of Carbon Capture and Transportation Research, Development and Deployment in Canada.* Report prepared for Alberta Environment by Bill Gunter, ARC; Bob Mitchell, Inspired Value Inc.; Ian Potter, ARC; Brent Lakeman, ARC; Sam Wong, ARC, http://www.nrcan.gc.ca/es/etb/cetc/combustion/co2network/htmldocs/aboutus_e.html.

[136] IEA. 2004. *Prospects for CO_2 Capture and Storage.* Energy Technology Analysis.

4 Storage of CO_2

4.1 The geological storage of CO_2

CO_2 can be stored in porous sedimentary formations such as depleted gas, oil and bitumen reservoirs, coal seams, deep saline aquifers and salt caverns using normal drilling techniques. The suitability of these reservoirs for long-term storage will depend on the nature and depth of the formation, the presence of suitable overlying cap rock formations, the number and integrity of existing well bores, and many other factors.

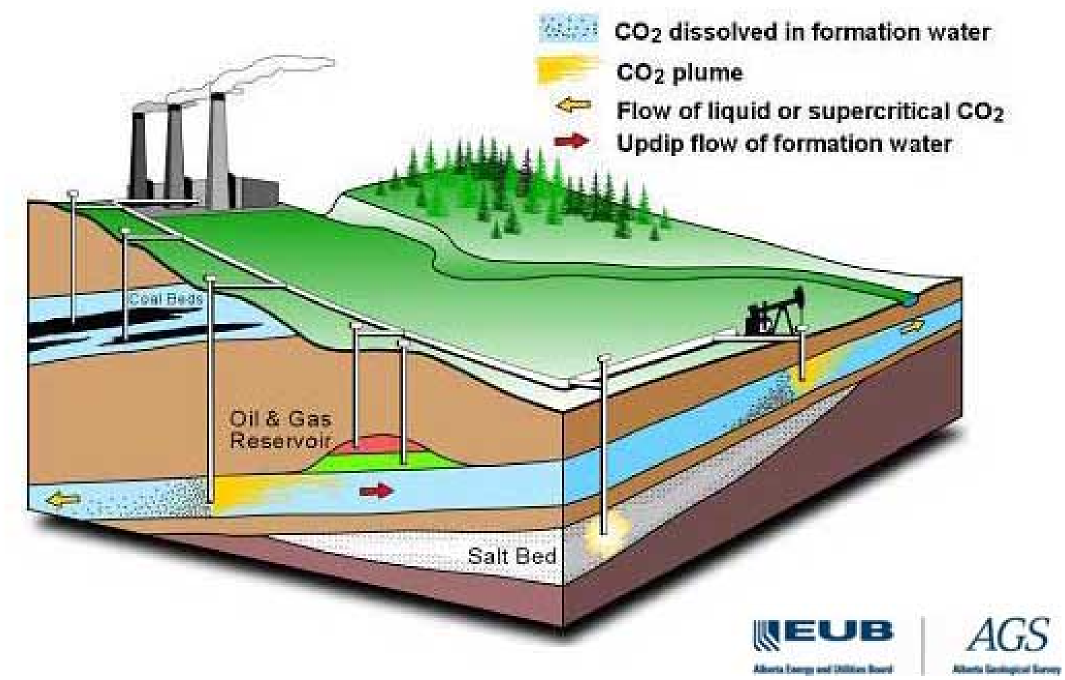

Figure 4.1 Potential Methods for Geological Storage of CO_2[137]

4.1.1 Deep saline aquifers

Deep saline aquifers are currently considered to be the most suitable long-term storage location. Water-filled strata (aquifers) are distributed widely below many major landmasses and under the oceans, usually in carbonate or sandstone formations. The water in these deep aquifers is saline (often much more salty than the sea). If CO_2 is compressed to its liquid state, it can be injected into these deep aquifers where (usually at depths of one kilometer or more), the temperature and pressure will ensure that the CO_2 stays as a dense fluid (rather than in its gaseous state).[138] At

[137] Alberta Geological Survey website at http://www.ags.gov.ab.ca/activities/CO2/means_of_storage.shtml.

[138] Bachu, Stefan. 2004. "Evaluation of Sedimentary Basins in Canada for CO_2 Storage: A Proposed Role for the Federal and Provincial Geological Surveys," Appendix A, p.20, in *Planning Options and Concepts for the Evolution of Geological Storage Research in Canada,* prepared by Bill Gunter and R. Chalaturnyk, http://www.nrcan.gc.ca/es/etb/cetc/combustion/co2network/pdfs/canistore_final_report.pdf.

such depths, “Once injected, evidence from natural CO_2 reservoirs and from numerical models suggests that CO_2 can — in principle — be confined in geological reservoirs for time scales well in excess of 1000 yr and that the risks of leakage from geological storage can be small.”[139]

By contrast, if CO_2 is injected into shallow or intermediate flow systems, it will probably be unstable, i.e., change from its liquid or supercritical state to a gas, and it could escape into adjacent groundwater or to the atmosphere (as explained below).

When CO_2 is injected into deep saline aquifers it should be hydrodynamically trapped for geological periods of time. Some of the injected CO_2 will dissolve in the water (although the solubility of CO_2 in water decreases with the increasing salinity of water); the rest will form a plume that lies at the top of the aquifer. Over very long periods, geochemical reactions could take place that would permanently sequester the carbon in the sedimentary rock.[140] While this process may take from 100 to 10,000 years under natural conditions, the CO_2 will dissolve more rapidly if the brine is circulated through pumping. It has been calculated that pumping can increase the rate of dissolution so that 80% of the injected CO_2 is dissolved in 100 years, thus reducing the long-term risk of leaks.[141] The energy used for pumping would produce less than 1% of the amount of CO_2 stored. After dissolving, the CO_2 may further react with the saline water and the surrounding rocks and become permanently sequestered as carbonates. If geologically stable, thick sedimentary formations are selected: “Injection and storage of CO_2 in deep saline aquifers characterized by long-range, regional-scale flow systems ensure extremely long residence time (thousands to millions of years); hence these are suitable for CO_2 hydrodynamic and mineral trapping.”[142]

The first commercial-scale CO_2 storage project in a deep saline aquifer is being undertaken by Norway at its Sleipner gas field under the North Sea, where 1 Mt CO_2 per year is being injected.[143]

4.1.2 Enhanced oil recovery

Approximately 100 enhanced oil recovery projects around the world are underway where CO_2 is being injected into oil reservoirs to increase the mobility of the oil.[144] Some of this CO_2 returns to the surface with the oil, but some stays underground. The proportion retained varies between 20%–67%.[145] At the Weyburn project in Saskatchewan, where about 2Mt of CO_2 per year has

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[139] Wilson, E.J., T.L. Johnson and D.W. Keith. 2003. “Regulating the Ultimate Sink: Managing the Risks of Geologic CO_2 Storage”. *Environmental Science and Technology,* Vol.37, No.16. Citation from p. 3476. Publication #54 at http://www.ucalgary.ca/~keith/ccs.html/

[140] One definition of “geological sequestration” is *“the process of injecting CO_2 into deep (greater than ~ 1 km) geologic formations for the explicit purpose of avoiding atmospheric emission of CO_2.* Wilson, E.J., T.L. Johnson and D.W. Keith. 2003. “Regulating the Ultimate Sink: Managing the Risks of Geologic CO_2 Storage,” *Environmental Science and Technology,* Vol.37, No.16, p .3476-3483. Citation from p. 3476. Publication #54 at http://www.ucalgary.ca/~keith/ccs.html/

[141] Keith, David W., Hassan Hassanzadeh and Mehran Pooladi-Darvish. 2004. *Reservoir Engineering to Accelerate Dissolution of Stored* CO_2 *in Brine.* In press. To appear in Proceedings of 7th International Conference on Greenhouse Gas Control Technologies, IEA Greenhouse Gas Program, Cheltenham, UK.

[142] Bachu, Stefan. 2004. “Evaluation of Sedimentary Basins in Canada for CO_2 Storage: A Proposed Role for the Federal and Provincial Geological Surveys,” Appendix A, p.21, in *Planning Options and Concepts for the Evolution of Geological Storage Research in Canada,* prepared by Bill Gunter and R. Chalaturnyk; http://www.nrcan.gc.ca/es/etb/cetc/combustion/co2network/pdfs/canistore_final_report.pdf.

[143] IEA. 2004. *Prospects for* CO_2 *Capture and Storage,* p. 8.

[144] IEA. 2004. *Prospects for* CO_2 *Capture and Storage,* p. 84.

[145] IEA. 2004. *Prospects for* CO_2 *Capture and Storage,* p. 81.

been stored since 2001,[146] the volume is carefully measured and monitored. Seismic surveys show how the CO_2 moves through the formation. The total volume of CO_2 stored during EOR will be relatively small, compared with other storage options, but CO_2 storage associated with EOR will probably be the first major development of CCS because the revenue from the oil offsets some of the capture and storage costs.[147] When the EOR is complete, the CO_2 is left in the reservoirs, and additional CO_2 can be added to fill up the storage capacity (see Section 4.1.3).

It is possible that CO_2 could be injected into gas fields (enhanced gas recovery) to extend gas production and store the CO_2, but this is still being investigated.

4.1.3 Depleted gas, oil and bitumen reservoirs

Once gas, oil or bitumen reservoirs are depleted, they may be used for long-term CO_2 storage. These reservoirs are of immediate interest for storage because their characteristics and extent are well known. In addition, pipeline and injection well facilities are already in place. However, depleted oil and gas reserves have a smaller total volume than deep saline aquifers, and there may be a greater potential for leakage. It is recognized that: "Such leakage is a concern because it may contaminate existing energy, mineral, and/or groundwater resources, it may pose a hazard at the ground surface, and it will contribute to increased concentrations of CO_2 in the atmosphere."[148]

Leakage could occur through natural seepage, either through some undetected weakness in the cap rock or because the gas is injected at excessively high pressure that opens up fissures in the rock. CO_2 may also leak as a result of a well casings failure, which could provide an unintended route to the surface. Experience with underground gas storage facilities (where natural gas is stored for future sale) indicates the type of problem that might be encountered with the injection of CO_2. In gas storage facilities, mechanical flaws in wells and abandoned wells have been the most common cause of leaks.[149] For example, a natural gas explosion in 2001 in the central Kansas town of Hutchinson (which killed two people and destroyed two businesses) is thought to have occurred because of a failure in the pipe that went into the salt cavern where the gas was stored. It is thought that the highly pressured methane gas escaped from a hole in the pipe and moved up the formation (which was slightly tilted) until it came to two old wells and then to the surface, where it exploded.[150]

Potential pathways for leakage in an existing well are between the cement and the casing, through the cement, through the casing, through fractures, and between the cement and the formation.[151] More than one million wells have been drilled in Texas and more than 350,000 in Alberta, and many have already been abandoned (closed down), which means they are no longer

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[146] IEA. 2004. *Prospects for* CO_2 *Capture and Storage.* p. 8. Two Mt is equivalent to about 0.3% of Canada's total CO_2 emissions in 2003.

[147] See IEA. 2004. *Prospects for* CO_2 *Capture and Storage,* p. 85, 87 for a discussion of costs and revenues associated with EOR.

[148] Celia, Michael A., Stefan Bachu, Jan Martin Nordbotten, Sarah E. Gasda and Helge K. Dahle. 2004. *Quantitative Estimation of* CO_2 *Leakage from Geological Storage: Analytical Models, Numerical Models and Data Needs.* 7th International Conference on Greenhouse Gas Technology. http://uregina.ca/ghgt7/PDF/papers/peer/228.pdf.

[149] IEA. 2004. *Prospects for* CO_2 *Capture and Storage,* p.96.

[150] Kansas Geological Survey. 2001. "Survey Responds to Hutchinson Natural Gas Explosion," *The Geologic Record, Vo. 7.2,* http://www.kgs.ku.edu/Publications/GeoRecord/2001/vol7.2/Page1.html .

[151] Celia, Michael A., Stefan Bachu, Jan Martin Nordbotten, Sarah E. Gasda and Helge K. Dahle. 2004. *Quantitative Estimation of CO2 Leakage from Geological Storage: Analytical Models, Numerical Models and Data Needs, p.2.* 7th International Conference on Greenhouse Gas Technology. http://uregina.ca/ghgt7/PDF/papers/peer/228.pdf/

monitored. Even if old oil and gas wells were properly plugged when they were abandoned, they may provide routes to the surface because CO_2 is corrosive and can weaken the cement casing or plugs.

As CCS is new, experience with monitoring and reporting of actual physical leakage rates of CO_2 is limited. However, acid gas injection into deep saline formations is considered a commercial-scale analogue for CO_2 injection. Acid gas, a mixture of CO_2 and H_2S, is a waste product from sour gas processing. Acid gas injection is primarily intended to avoid recovering and transporting or storing sulphur (all of which have associated infrastructure costs) and to reduce incineration of sulphur-containing gases. However, it also reduces CO_2 emissions. Since 1989, gas plants in Western Canada (mainly Alberta) have not been allowed to flare or incinerate large volumes of sulphur, so some companies now inject the waste acid gas deep underground. By the end of 2003, 2.5 Mt of CO_2 and 2.0 Mt of H_2S had been injected into deep hydrocarbon reservoirs and saline aquifers, and injection was underway at 41 sites.[152] At approximately two-thirds of the sites, the acid gas is injected into deep saline aquifers, while at the remainder it is injected into depleted oil or gas reservoirs.

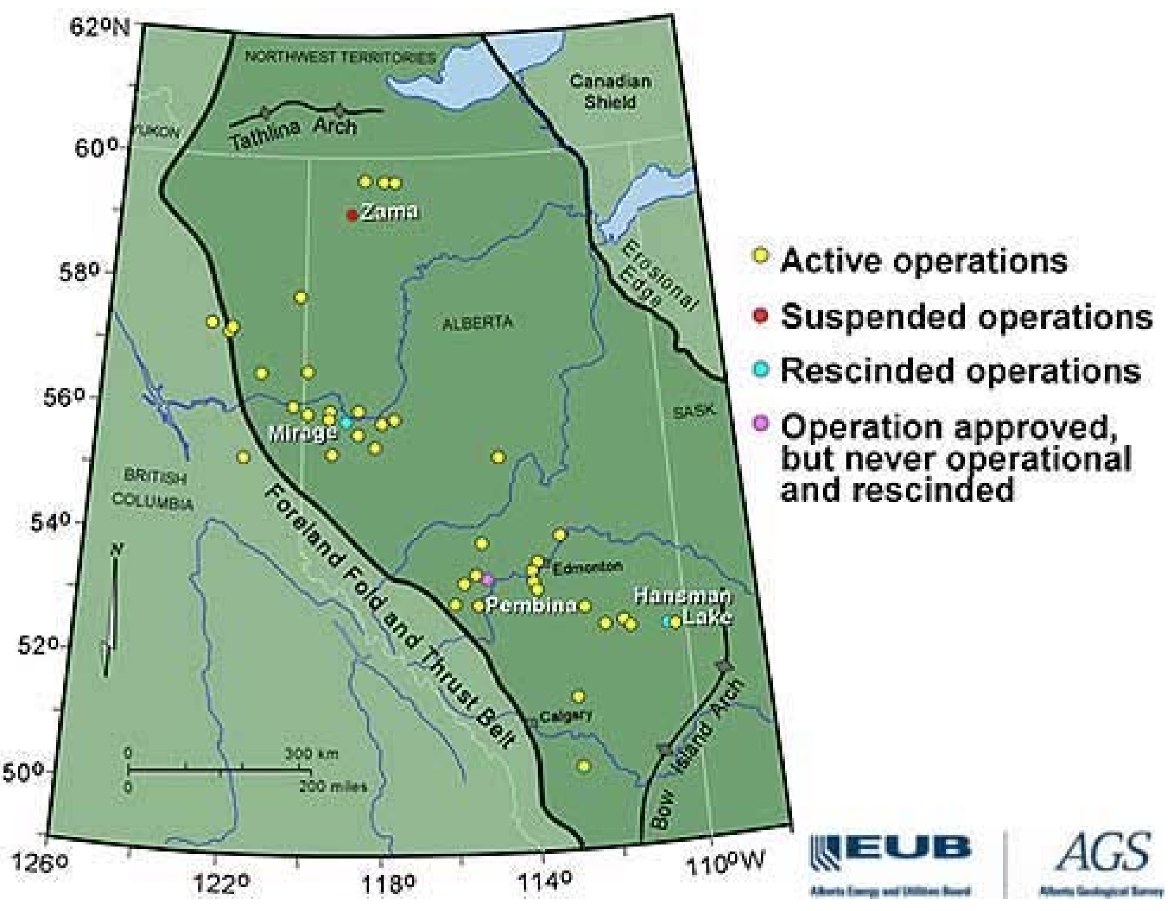

Figure 4.2 Acid gas injection sites in Western Canada[153]

[152] Bachu, Stefan and William D Gunter. 2004. *Overview of Acid-Gas Injection Operations in Western Canada.* In Proceedings of 7th International Conference on Greenhouse Gas Control Technologies. Vol. 1: Peer-Reviewed Papers and Plenary Presentations. Online at http://www.ghgt7.ca.

[153] Alberta Geological Survey website at http://www.ags.gov.ab.ca/activities/CO2/means_of_storage.shtml.

When selecting sites for acid gas injection, it is necessary to consider the same issues as for CO_2 injection, including the confinement of the injected gas, the effect it will have on the rock, protection of groundwater, well bore integrity and public safety. Injection pressures are kept below the initial reservoir pressure to avoid fracturing the rocks because that would create pathways for leaks. There are often oil and gas wells nearby, so it is important to assess the potential for upward leakage along improperly completed and/or abandoned wells. Analytical methods have been developed to estimate the movement of the acid gas plume in the formation in Western Canada. The model indicated that by the end of 2003 (up to 15 years since injection started) "acid gas plumes have probably spread at distances that, depending on the particular case, range from approximately 150 m to less than 2100 m from the injection well. This method allows for the easy identification of existing wells that may be reached by a plume of injected CO_2 or acid gas."[154] It has been pointed out that: "No safety incidents have been reported in the 15 years since the first operation in the world started injecting acid gas into a depleted reservoir on the outskirts of the city of Edmonton, Alberta."[155] However, the potential for a leak is higher where there are many oil and gas wells.

The evaluation of a specific formation in Alberta indicated that a typical CO_2 plume could contact several hundred wells in an area of high well density, while in an area with a lower well density about 20 would be reached by the plume.[156] Models are being developed that estimate where leakage may occur, but some monitoring would be required to detect actual leaks. While it has been suggested that depleted oil and gas reservoirs could potentially store CO_2 for hundreds of thousands or millions of years,[157] the risk of leaks must be evaluated.

4.1.4 Enhanced coalbed methane

CO_2 may be stored in coal seams. CO_2 has an affinity with coal that is almost twice as high as that of methane found in the coal seams. Therefore, when CO_2 is pumped into coal seams, it replaces the methane gas that is held in the coal and becomes sequestered through sorption in the coal. The methane (which is the same as conventional natural gas, except that it comes from a coal seam) can be piped for use. The injection process would normally take place at depths between 300 and 1500 metres. Once sorption has occurred, the carbon is permanently removed from the atmosphere, provided the coal seams are not later mined (since mining the coal would change the pressure, releasing methane to the atmosphere).

Research is still underway to determine the potential for this form of sequestration, including a pilot project in Alberta.[158] Coal seams to be used for enhanced coalbed methane recovery must

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[154] Bachu, Stefan, Jan M. Nordbotten and Michael A. Celia. 2004. *Evaluation of the Spread of Acid-Gas Plumes Injected in Deep Saline Aquifers in Western Canada as an analogue for CO_2 Injection into Continental Sedimentary Basins.* In Proceedings of 7th International Conference on Greenhouse Gas Control Technologies. Vol. 1: Peer-Reviewed Papers and Plenary Presentations. Online at http://www.ghgt7.ca.

[155] Bachu, Stefan and William D Gunter. 2004. *Overview of Acid-Gas Injection Operations in Western Canada.* In Proceedings of 7th International Conference on Greenhouse Gas Control Technologies. Vol. 1: Peer-Reviewed Papers and Plenary Presentations. Online at http://www.ghgt7.ca.

[156] Celia, Michael A., Stefan Bachu, Jan Martin Nordbotten, Sarah E. Gasda and Helge K. Dahle. 2004. *Quantitative Estimation of CO2 Leakage from Geological Storage: Analytical Models, Numerical Models and Data Needs, p.2.* 7th International Conference on Greenhouse Gas Technology. http://uregina.ca/ghgt7/PDF/papers/peer/228.pdf.

[157] Wong, Sam, William D. Gunter and Stefan Bachu. 1999. "Geological Storage for CO_2: Options for Alberta" in Proceedings of the Conference on *"Combustion and Global Climate Change: Canada's Challenges and Solutions"* Calgary, AB, May 26-28, 1999, Table 1. http://www.ags.gov.ab.ca/activities/CO2/CO2_journal_publications.shtml.

[158] Alberta Research Council. 2004. A*lberta Field Pilot to Test CO_2 Enhanced Coalbed Methane Recovery,* http://www.arc.ab.ca/energy/Coalbed_pilot.asp.

meet various criteria.[159] They must, for example, be sufficiently permeable and homogeneous, with little faulting and folding. This means that only a small proportion of coal seams that could produce commercial quantities of coalbed methane will be suitable for enhanced methane recovery. A key issue, which is being studied in the Alberta pilot project, is the potential swelling of coals when CO_2 replaces methane, and whether this would close off fractures and prevent effective filling of the coal reservoir.

4.1.5 Salt caverns

Salt caverns could also provide long-term storage of CO_2. Salt mining has created caverns in both Saskatchewan and Alberta, and the caverns are already used for storing liquified petroleum gas (LPG) in central Alberta.[160]

Salt caverns are probably the most expensive form of geological storage, and it is unlikely that they will be used on a large scale, except in regions where there are no other storage options.[161] In northern Alberta, for example, where the extraction of bitumen creates large quantities of CO_2, the options for storage are limited because the area lies at the eastern edge of the sedimentary deposits, close to the Canadian Shield. While there are no deep saline aquifers or depleted oil and gas reservoirs in the region, there are several extensive, thick salt beds. Calculations show that a single salt cavern could hold 0.5 Mt CO_2, and it would be possible to construct an array of caverns in this area, and in other similar regions. The technology for creating salt caverns is well developed for mining salt or for storing petroleum and natural gas.[162] However, considerable volumes of water are required for the construction of salt caverns, and the resultant brine requires disposal (in a deep formation) or treatment prior to use (with the resultant wastes being sent for landfill).

4.2 Other storage options

4.2.1 Ocean storage

CO_2 can be injected into the ocean using either a fixed pipeline or a moving ship. There are two possible ways of storing it: either in the water column or on the ocean floor. If CO_2 were injected into the water column (usually at depths below 1,000 metres), it would dissolve in the water. If liquid CO_2 were piped onto the ocean floor (usually at depths below 3,000 metres), it would be denser than the water and form a "lake." Model calculations suggest that if CO_2 were injected at depths greater than 3,000 metres, 80-90% of it would remain in the ocean for more than 500 years, with more rapid release to the atmosphere than if the injection had taken place at shallower depths. The IEA recognizes that oceanic storage is the most controversial option and problematic "given the unknown environmental impacts."[163] In the IEA report on *Prospects for*

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[159] IEA. 2004. *Prospects for CO_2 Capture and Storage*, p.88.

[160] IEA. 2002. *Opportunities for Early Application of CO2 Sequestration Technology.* Greenhouse Gas R & D Programme. File Note. See link under http://www.cslforum.org/publications.htm

[161] Bachu, Stefan and L. Rothenburg. 2003. "Carbon Dioxide Sequestration in Salt Caverns: Capacity and Long Term Fate" in *Proceedings of the Second Annual Conference on Carbon Dioxide Sequestration* (CD-ROM), Alexandria, VA, May 5-8. Available online at http://www.ags.gov.ab.ca/activities/CO2/CO2_journal_publications.shtml.

[162] Bachu and Rothenburg do not discuss the availability of water for the construction of salt caverns. Construction of a salt cave requires considerable volumes of water for several years. Unless they can be created using waste water from the oils ands extraction process, the need for water could limit the number of caverns created in northern Alberta where the extraction of bitumen already places a heavy toll on the region's water resources.

[163] IEA. 2004.*Prospects for CO_2 Capture and Storage*, p.16.

CO_2 Capture and Storage, oceanic storage is relegated to a short section on "Other storage options."

The direct impact of CO_2 on the ocean would be a change in water acidity, which could seriously affect ocean chemistry if large volumes of CO_2 were injected. It is not known what implications this would have for marine ecosystems nor how this could be effectively monitored. Proposals for two pilot projects off Hawaii and Norway were abandoned because of public protests.[164]

It is also not clear if CO_2 could legally be stored in the ocean. The 1972 *Convention on the Prevention of Marine Pollution by Dumping of Waters and Other Matters* (usually known as the London Convention) prohibits storage of CO_2 in the water column, if it is considered an industrial waste. However, "According to the Office for the London Convention . . . there is no unanimity on the issue of whether fossil fuel-derived CO_2 should be regarded as industrial waste."[165] It can be argued that if the source is a waste from an industrial process, such as power plant emissions, it should be banned. The London Convention also requires that the precautionary approach should be adopted, if there is reason to believe that substances could harm the marine environment.

The *OSPAR Commission on the Protection of the Marine Environment in the North East Atlantic*, which usually sets strict standards on marine protection, held a meeting and workshop to determine its position on the storing of CO_2 in or under the sea.[166] The meeting of legal experts discussed the placement of CO_2 in the water column, on the seabed and under the seabed, either for storage or for enhanced oil or gas recovery.[167] The experts developed a matrix of their initial conclusions, showing that some activities are permissible, subject to authorization, while others are prohibited. In general, experimental schemes are permitted. CO_2 placements to mitigate climate change or for disposal are sometimes banned, but the conclusions vary, depending on whether the placement is from a pipeline, via a shipment or from a structure in the maritime area, and whether the CO_2 is from an offshore activity or other activity.

The OSPAR workshop examined the placement of CO_2 in geological formations under the sea and concluded that this was a technically feasible option, with significant potential in the OSPAR maritime area.[168] Subsequently, some delegates at an OSPAR biodiversity committee meeting "stressed the need to take all possible measures to avoid CO_2 emissions at source (energy efficiency, use of renewable energy) before the storage of CO_2 in deep geological formations is considered," while others felt that "all weapons in the armory to combat climate change needed to be developed." A "pragmatic approach" was recommended that would allow use of reservoirs currently accessible from offshore installations that would cease to be accessible when the installations were no longer used and decommissioned.

The IPCC has clearly stated the risks of putting CO_2 into ocean waters: "Adding CO_2 to the ocean or forming pools of liquid CO_2 on the ocean floor at an industrial scale will alter the local

[164] IEA. 2004. *Prospects for CO_2 Capture and Storage,* p.94.

[165] UNESCO. 2003. *Capturing Carbon?* Media Services, Online at http://portal.unesco.org/en/ev.php-URL_ID=10326&URL_DO=DO_TOPIC&URL_SECTION=201.html.

[166] IEA. 2004. *Prospects for CO_2 Capture and Storage,* p. 196.

[167] OSPAR Convention for the Protection of the Marine Environment of the North-east Atlantic. 2004. *Report from the Group of Jurists and Linguists on Placement of Carbon Dioxide in the OSPAR Maritime Area.* Meeting of the OSPAR Commission. Reykjavik, 28 June – 1 July. This document was e-mailed to the author by OSPAR.

[168] OSPAR. 2005. Meeting of the Biodiversity Committee. Summary Record, p.29. Bonn, 21-25 February. This meeting included a report on the workshop.

chemical environment. Experiments have shown that sustained high concentrations of CO_2 would cause mortality of ocean organisms. CO_2 effects on marine organisms will have ecosystem consequences. The chronic effects of direct CO_2 injection into the ocean on ecosystems over large ocean areas and long time scales have not yet been studied."[169] The IPCC also indicated that if CO_2 were stored in the ocean, there would be a gradual release to the atmosphere, occurring over hundreds of years.[170]

The environmental community has protested the ocean storage of CO_2. Climate Action Network Europe, which unites about 80 non-governmental organizations working on climate change and energy issues in Western Europe, opposes ocean disposal of CO_2 for several reasons.[171] They believe that the practice would put the oceans at unnecessary risk and, since the oceans are poorly understood, biological impacts would be difficult to anticipate. They believe that ocean disposal contradicts established international law, and they find the evidence for certain, long-term retention is unconvincing. The group called for an end to efforts to develop pilot projects because they do little to address the important issues of biological impacts or long-term, large-scale retention times.

Some countries are not actively pursuing ocean storage because they have the potential for storage in geological formations. Japan, however, is conducting research into ocean storage because of its lack of suitable geological storage sites.[172]

4.2.2 Surface mineralization of carbon

The concept of surface mineralization of carbon is based on the fact CO_2 reacts with magnesium and calcium silicate to form carbonates.[173] Serpentine and olivine rock, which can be ground to provide magnesium or calcium silicate, are abundant, although they do not occur naturally in the sedimentary basins where most of the fossil fuel energy projects are located. The proposed process would mix CO_2 and magnesium-rich silicates, giving magnesium carbonate (the magnesium analog of limestone), silica (quartz), water and heat. It would require between 1.6 and 3.7 tonnes of silicate rock to fixate one tonne of CO_2, and the impacts would be the same as for a large mining operation.[174] Not only would the volumes of rock required be enormous, the process would also create huge piles of solid waste. The concept has not been developed beyond lab scale, and there is no process that gives realistic reaction times.[175] Thus it seems very unlikely that this process will be used, unless other storage options are unavailable (e.g., because of other environmental concerns).

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169 IPCC. 2005. *Special Report on Carbon Dioxide Capture and Storage. Summary for Policymakers,* p. 22, bullet 23, http://www.ipcc.ch.

170 IPCC. 2005. *Special Report on Carbon Dioxide Capture and Storage. Summary for Policymakers,* p. 23, bullet 26, http://www.ipcc.ch.

171 Climate Action Network Europe. Undated, but 2002 or later. *Common Position on Ocean Disposal of* CO_2. http://www.climnet.org/CTAP/CTAP.htm.

172 IEA. 2004. *Prospects for* CO_2 *Capture and Storage,* p. 190.

173 Mineral carbonation is promoted by the ZECA Corporation (formerly the Zero Emission Coal Alliance). See http://www.zeca.org/overview/carbon_dioxide.html.

174 IPCC. 2005. *Special Report on Carbon Dioxide Capture and Storage: Summary for Policymakers,* p.22, bullet 24, http://www.ipcc.ch.

175 IEA. 2004. *Prospects for* CO_2 *Capture and Storage,* p. 93.

4.2.3 Sequestration of carbon dioxide in oil sands tailings streams

Research is being conducted into understanding the chemistry of oil sands tailings, with the objective of sequestering CO_2.[176] Tailings are the waste stream (mainly water with some hydrocarbons) that result from the upgrading of mined bitumen. The concept involves mixing CO_2 with the mature fine tailings, gypsum and coarse tailings, with the intent of eventually reclaiming them as land. The process would enable the recovery of some bitumen from the tailings and also store CO_2. The CO_2 would initially be dissolved in the process water and then become chemically sequestered by converting to carbonate and bicarbonate. A summary of the research indicates that: "Although preliminary results are very encouraging, long term tailings deposit stability has to be determined, along with the long-term water quality."[177] It has been suggested that if the results are satisfactory, between 0.3 and 3 Mt/year CO_2 might be stored in mature, fine tailings in the Fort McMurray area of Alberta.

4.3 Global geological storage potential

The total worldwide anthropogenic emissions of CO_2 were almost 25 gigatonnes (Gt) in 2000.[178] The IPCC indicates that worldwide the potential storage capacity in geological formations is likely to be at least 2,000 Gt CO_2.[179] This is the technical potential, using a technology or practice that has already been demonstrated. The IPCC recognizes that there may be a much larger potential for geological storage in saline formations "but the upper limits are uncertain due to lack of information and an agreed methodology."

The relative capacity of different storage sites is given in Table 3.1.

Table 3.1 Worldwide Capacity of Potential CO_2 Storage Sites

Sequestration Option	Worldwide Capacity for CO_2
Oceans	1,000s Gt
Deep saline formations	100s–10,000 Gt[180]
Oil and gas reservoirs	100–1,000 Gt[181]
Coal seams	10–100 Gt[182]
Terrestrial ecosystems	10s Gt
World emissions of CO_2 for 2000	25 Gt

Source: *Prospects for CO_2 Capture and Storage* (IEA. 2004) and *Solutions for the 21st Century: Zero Emissions Technologies for Fossil Fuels* (IEA. 2002).[183]

[176] Natural Resources Canada. 2005. *Summary of Canadian CO_2 Capture and Storage Technology Initiatives*, Canadian CO_2 Capture and Storage Technology Network (CCCSTN), http://www.nrcan.gc.ca/es/etb/cetc/combustion/co2network/htmldocs/projects_e.html#oilsands.

[177] Natural Resources Canada. 2005. *Summary of Canadian CO_2 Capture and Storage Technology Initiatives*, Canadian CO_2 Capture and Storage Technology Network (CCCSTN), http://www.nrcan.gc.ca/es/etb/cetc/combustion/co2network/htmldocs/projects_e.html#oilsands.

[178] IEA. 2004. *Prospects for CO_2 Capture and Storage*, p.48. The IEA gives a total figure of almost 30 Gt, but this includes approximately 5 Gt from biomass combustion, which is not usually taken into account in the calculation of CO_2 emissions. The IEA agrees that excluding biomass CO_2 is acceptable if the CO_2 in plants and soil recovers to its original level prior to combustion. However, they point out that there is no physical difference between CO_2 from fossil fuels and CO_2 from biomass. CO_2 capture could be applied to both cases.

[179] IPCC. 2005. *Special Report on Carbon Dioxide Capture and Storage: Summary for Policymakers*, p.18, bullet 18, http://www.ipcc.ch .The IPCC says there is a 66%–90% probability that the 2,000 Gt CO_2 figure is correct.

[180] IEA. 2004. *Prospects for CO_2 Capture and Storage*, p.91. This includes offshore aquifers.

[181] IEA. 2004. *Prospects for CO_2 Capture and Storage*, p. 84-85 indicates that depleted gas reservoirs have a much larger storage potential than depleted oil fields. The world capacity for gas fields is estimated at 1,000 Gt of CO_2. Estimates for storage in enhanced oil recovery vary widely from a few GT to several hundred Gt, depending on how many of the cost and geological constraints are considered.

[182] IEA. 2004. *Prospects for CO_2 Capture and Storage*, p. 89 indicates that the world potential in un-mineable coal seams is 148 Gt CO_2, with about 60 Gt being available at a cost of less that US$50/t CO_2.

The figures show a wide range because this is a relatively new field, and criteria for assessing site acceptability and storage potential in different formations have not yet been fully determined. As the IEA says with respect to capacity in geological formations (i.e., excluding oceans): "Many uncertainties remain and capacity estimates and the associated methodologies used by researchers vary significantly. But these formations have the potential to store all energy related CO_2 emitted within next decades."[184] Far more is known about the potential storage capacity in depleted oil and gas fields and coal basins, where there are hydrocarbon resources, than about deep on-shore or off-shore saline reservoirs (i.e., in geological saline formations deep under the sea). The capacity of deep saline formations far exceeds that of depleted oil pools, gas basins and coal basins.[185] At a regional level there may occasionally be limitations on capacity, but modeling suggests that the geological reservoir capacity is more than would be required for CO_2 storage over the next century.[186]

The extent to which storage can be used depends not only on the suitability of the geological formations but also on their proximity to large CO_2 sources that can be captured. As the cost of CO_2 transportation is low relative to the cost of capture, it may be possible to move CO_2 as far as 500-1000 km to secure an appropriate storage location. An examination of opportunities for the early application of CO_2 storage technologies found that there are approximately 420 sites worldwide where there is a high purity CO_2 source within about 100 km of locations where the gas could be used for enhanced oil recovery; 329 of those sites are in the U.S. and 22 are in Canada.[187] Nearly 80 locations were identified globally for enhanced coalbed methane (CBM) recovery. The EOR locations are likely to be used first because the net sequestration costs were negative i.e., the recovery of the oil more than compensates for the cost of storage, while there were net positive costs for enhanced CBM.

4.4 Geological capacity for storage in the U.S. and Canada

As noted earlier, deep saline aquifers are one of the best sites for CO_2 storage. An analysis of CO_2 storage capacity within North America found that deep saline formations account for 97% of the total identified onshore capacity and are capable of holding more than 3,700 Gt CO_2.[188] Depleted oil reservoirs account for only 0.3% of the North American storage capacity and could hold 13 Gt. This compares with an estimated storage requirement for the U.S. in the 21st century of 62.5 Gt CO_2, in a stringent scenario that would stabilize CO_2 in the atmosphere at 450 ppm.

[183] IEA. 2004. *Prospects for CO_2 Capture and Storage*, p.81-93 is the source for the figures on deep saline aquifers, oil and gas reservoirs and coal seams. Other figures in the table are based on data from H. Herzog reproduced in IEA. 2002. *Solutions for the 21st Century: Zero Emissions Technologies for Fossil Fuels, p.15.* Further estimates are summarized by Sally Benson. 2004. "Carbon Dioxide Sequestration/Coal Gasification", p.8 in *The 10-50 Solution: Technologies and Policies for Low Carbon Future.* Pew Center for Global Climate Change Workshop Proceedings, March 25-26, http://www.pewclimate.org.

[184] IEA. 200. *Legal Aspects of Storing CO_2,* p.15, http://www.iea.org/Textbase/publications/index.asp.

[185] Dooley, J.J., S.H. Kim, J.A. Edwards, S.J. Friedman and M.A. Wise. 2004. *A First-order Global Geological CO_2 -Storage Potential Supply Curve and its Application in a Global Integrated Assessment Model.* See Table 1 in this paper: Geological CO_2 –storage potential by region. Online at *http://uregina.ca/ghgt7/PDF/papers/peer/281.pdf.*

[186] Dooley, J.J., S.H. Kim, J.A. Edwards, S.J. Friedman and M.A. Wise. 2004. *A First-order Global Geological CO_2 -Storage Potential Supply Curve and its Application a Global Integrated Assessment Model,* p.9.

[187] IEA. 2002. *Opportunities for Early Application of CO_2 Sequestration Technology.* Greenhouse Gas R & D Programme. File Note. See link under http://www.cslforum.org/publications.htm.

[188] Dooley, J.J., R.T. Dahowski, C.L. Davidson, S. Bachu. N. Gupta and J. Gale. 2004. *A CO_2-storage Supply Curve for North America and its Implications for the Deployment of Carbon Dioxide Capture and Storage Systems, p7, http://uregina.ca/ghgt7/PDF/papers/peer/282.pdf.* This paper includes two maps, showing the distribution of large CO_2 point sources and candidate CO_2 storage reservoirs in N. America.

Deep saline aquifers have a large areal extent so they are within close proximity to many CO_2 sources, which will minimize the transportation requirements.

To make use of this capacity, it will be necessary to drill a large number of injection wells. Referring to U.S. emissions, Sally Benson, from the Lawrence Berkeley National Laboratory, says: "In the United States alone, CCS for our 2 billion tons of CO_2 emissions from electrical generation from fossil fuels could require 200 projects, each 10 times larger than the Sleipner project."[189]

However, "The constraints on CCS will not be whether sufficient storage capacity exists but rather factors such as the costs of alternative emissions-mitigation options and the nature of the future regulatory regime that will govern the use of CCS systems."[190]

The costs associated with CCS are mainly those associated with capture and compression, for piping and injection (see Chapter 2). By comparison, the costs of storage are small (see Section 4.5).

A review of Canada's major sedimentary basins (see hatched areas in Figure 4.3) ranked the basins according to their geological suitability for CCS.[191] The most suitable area in the country, which is located in southwestern Alberta, was given a score of one, and other basins were ranked relative to that region. The Western Canada Sedimentary Basin, which includes the Alberta and Williston basins, received a score of 0.95. For comparison, the St. Lawrence River basins scored 0.33. "This cursory analysis indicates that the primary targets for CO_2 sequestration in Canada should be the Alberta and Williston basins (i.e., northeastern B.C., Alberta and Saskatchewan). Second-order targets should be basins in Nova Scotia and the shallow edge of the Williston basin in Manitoba." [192] While the east coast has aquifers and deep coal seams that could be used to store CO_2, the region is also more liable to seismic activity.[193] The sedimentary strata in southwestern Ontario and southern Quebec are considered to be third-order targets. Most areas outside the Western Canada Sedimentary Basin need further study to evaluate their potential.

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[189] Benson, Sally. 2004. "Carbon Dioxide Sequestration/Coal Gasification," p.15 in *The 10-50 Solution: Technologies and Policies for Low Carbon Future.* Pew Center for Global Climate Change Workshop Proceedings, March 25-26, http://www.pewclimate.org.

[190] Dooley, J.J., R.T. Dahowski, C.L. Davidson, S. Bachu. N. Gupta and J. Gale. 2004. *A CO_2 -storage Supply Curve for North America and its Implications for the Deployment of Carbon Dioxide Capture and Storage Systems,* p.7.

[191] Bachu, Stefan. 2004. "Evaluation of Sedimentary Basins in Canada for CO_2 Storage: A Proposed Role for the Federal and Provincial Geological Surveys," Appendix A in Alberta Research Council Inc. *The CANiSTORE Program: Planning Options for Technology and Knowledge Base Development for the Implementation of Geological Storage, Development and Deployment in Canada.* Report prepared for Alberta Environment by Bill Gunter, Alberta Research Council and Rick Chalaturnyk, University of Alberta, http://www.nrcan.gc.ca/es/etb/cetc/combustion/co2network/htmldocs/aboutus_e.html.

[192] Bachu, Stefan. 2004. "Evaluation of Sedimentary Basins in Canada for CO_2 Storage: A Proposed Role for the Federal and Provincial Geological Surveys," Appendix A in Alberta Research Council Inc. p.22. *The CANiSTORE Program: Planning Options for Technology and Knowledge Base Development for the Implementation of Geological Storage, Development and Deployment in Canada.* Report prepared for Alberta Environment by Bill Gunter, Alberta Research Council and Rick Chalaturnyk, University of Alberta, http://www.nrcan.gc.ca/es/etb/cetc/combustion/co2network/htmldocs/aboutus_e.html.

[193] Alberta Geological Survey. *CO_2 Sequestration Program Components,* http://www.ags.gov.ab.ca/activities/CO2/program_components.shtml.

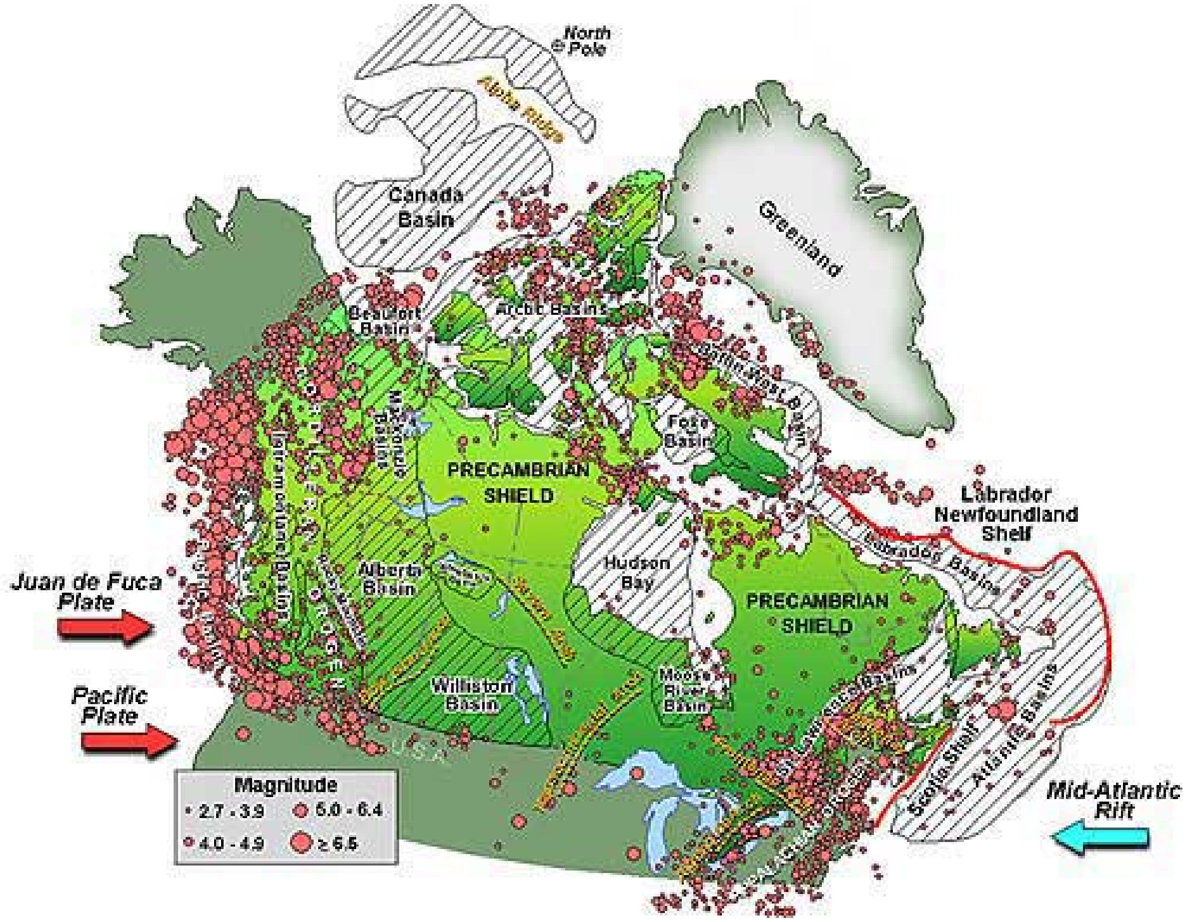

Figure 4.3 Distribution of Sedimentary Basins and Location and Magnitude of Earthquakes in Canada[194]

The Western Canada Sedimentary Basin is considered to be geographically and geologically suitable for CO_2 storage because it is tectonically stable and contains a range of suitable formations so CO_2 can be stored in several ways: through enhanced oil recovery, by storage in depleted oil and gas reservoirs, through replacement of methane in deep coal beds (enhanced coalbed methane recovery), by injection into deep saline aquifers and by storage in salt caverns.[195] As mentioned above, CO_2 is being used for EOR at Weyburn in Saskatchewan; this is a commercial enterprise, as well as a major research project. The CO_2 for the Weyburn operation is being piped to the operation from a gasification plant in North Dakota, but Western Canada has a considerable number of major CO_2 producers. Once capture mechanisms become economic, many point sources could find storage locations in close proximity.

The total potential for geological CO_2 sinks in Alberta was initially estimated grossly to be 55 Gt CO_2, but it was recognized that the figure would be refined by a more careful study of rock permeability and porosity, which determine injectivity and volumes.[196] Recent figures indicate that deep saline aquifers are much more extensive than originally estimated. The ultimate

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[194] Alberta Geological Survey. *CO_2 Sequestration Program Components,* http://www.ags.gov.ab.ca/activities/CO2/program_components.shtml.

[195] Bachu, Stefan and S. Stewart. 2002. "Geological Sequestration of Anthropogenic Carbon Dioxide in the Western Canada Sedimentary Basin: Suitability Analysis," *Canadian Journal Petroleum Technology,* vol. 41, no. 2, p.32-40. February.

[196] Bachu, Stefan. 1999. *The Potential for Carbon Dioxide Sequestration in Geological Media in Alberta,* http://www.ags.gov.ab.ca/activities/CO2/abstracts/bachu.pdf.

potential for CO_2 in storage in solution in deep saline aquifers at depths greater than 1,000 metres is estimated to be 4,000 Gt.[197] By comparison, the practical capacity for storage in depleted gas reservoirs is about 2.7 Gt CO_2, while in oil reservoirs it is 115 Mt. Even the capacity in depleted oil and gas reservoirs would be sufficient to accept the CO_2 from major point sources for a few decades.[198]

One early evaluation suggested that the available capacity in Alberta could last for approximately 1,000 years at the following rates of storage: 2.2 Mt CO_2/year in EOR applications, 18 Mt CO_2/year in coal beds, 13 Mt CO_2/year in depleted oil and gas reservoirs, and 20 Mt CO_2/year in deep aquifers (for a total of 53 Mt CO_2 stored per year).[199] This would be sufficient to store the CO_2 emissions from electrical power generation in Alberta in 2000 (47 Mt) each year for more than 1,000 years. Alternatively, this capacity would allow emissions equivalent to those from all sectors in Alberta in 2000 to be stored annually for approximately 200 years. Using the recent figure of 4,000 Gt for deep saline aquifers, it is evident that Alberta's potential for CO_2 storage is much greater than indicated in this paragraph.

The Alberta Geological Survey has determined the pressure and temperature of each of the major geological formations and units in the Western Canada Sedimentary Basin, to identify which locations would be suitable for CO_2 injection (see Figure 4.4).[200] The southwestern region (western Alberta, between the U.S. border and 55^{o} N) is considered to be very suitable because there is a large thickness of sedimentary rocks at depths where the CO_2 would be in a liquid or supercritical state, and the deep saline aquifers are confined by regional-scale aquitards (that restrict flow). The region also contains salt beds and many oil and gas reservoirs at depths where the CO_2 would be in a supercritical state. The northwestern region (NW Alberta) and the southern region, which extends across southern Saskatchewan to the U.S.-Manitoba border, are considered suitable, while other parts of the basin have somewhat more limitations. Having determined the general suitability of the area, the next stage will be to determine the capacity of the formations, match the formations with the available CO_2 sources and undertake a safety assessment.

The areas with large storage capacity are also the areas where large CO_2 producers, such as coal-fired power plans, petrochemical plants, cement plants, and pulp and newsprint mills, are located (see Figure 4.4). However, major producers of CO_2 in the Fort McMurray oil sands region are without readily accessible geological storage. Therefore, a major pipeline would be needed to transport the CO_2 to the most appropriate storage sites,[201] unless salt caverns are developed in the

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[197] Bachu, Stefan and J.J. Adams. 2003. "Sequestration of CO_2 in Geological Media in Response to Climate Change: Capacity of Deep Saline Aquifers to Sequester CO_2 in Solution," in *Energy Conversion and Management, v. 44, no. 20, p. 3151-3175.* Abstract at http://www.ags.gov.ab.ca/activities/CO2/abstracts/ECM_Solubility.shtml.

[198] Bachu, Stefan and J. Shaw. 2003.Evaluation of the CO_2 sequestration Capacity in Alberta's Oil and Gas Reservoirs at Depletion and the Effect of Underlying Aquifers. *Journal of Canadian Petroleum Technology,* vol. 42, no. 9, p. 51-61. Abstract available at http://www.ags.gov.ab.ca/activities/CO2/abstracts/JCPT_2003_CO2.shtml The practical capacity is less than the theoretical, due to water invasion. The figures cited are for the largest reservoirs where the individual capacity at the most suitable depths is greater than 1 Mt.

[199] Wong, Sam, William D. Gunter and Stefan Bachu.1999. *Geological Storage of CO_2: Options for Alberta*, http://www.ags.gov.ab.ca/activities/CO2/abstracts/wong.pdf The paper was published in Proceedings of the Conference "Combustion and Global Climate Change: Canada's Challenge and Solutions" (CD-Rom), Calgary, AB, May 26-28, 2002;

[200] Bachu, Stefan and S. Stewart. 2002.*Geological Sequestration of Anthropogenic Carbon Dioxide in the Western Canada Sedimentary Basin: Suitability Analysis. Canadian Journal Petroleum Technology, v*ol. 41, no. 2, p.32-40. February.

[201] Bachu, S., 2002. "Sequestration of CO_2 in geological media in response to climate change: road map for site selection using the transform of the geological space into the CO_2 phase space," *Energy Conversion and Management 43*, p. 87-102. Bachu points out (p.100) that the oil and gas reservoirs in northeast Alberta are the least suitable for storage since the CO_2 will be in the gaseous phase. They thus have less storage capacity and there is greater potential for CO_2 migration and escape. "However, these reservoirs, such as Liege, could be the only option available for the giant oil sands plants at Ft. McMurray that are major CO_2 producers. . . "

area (see above, Section 4.1.5) or current research is successful and leads to storage in tailings ponds.

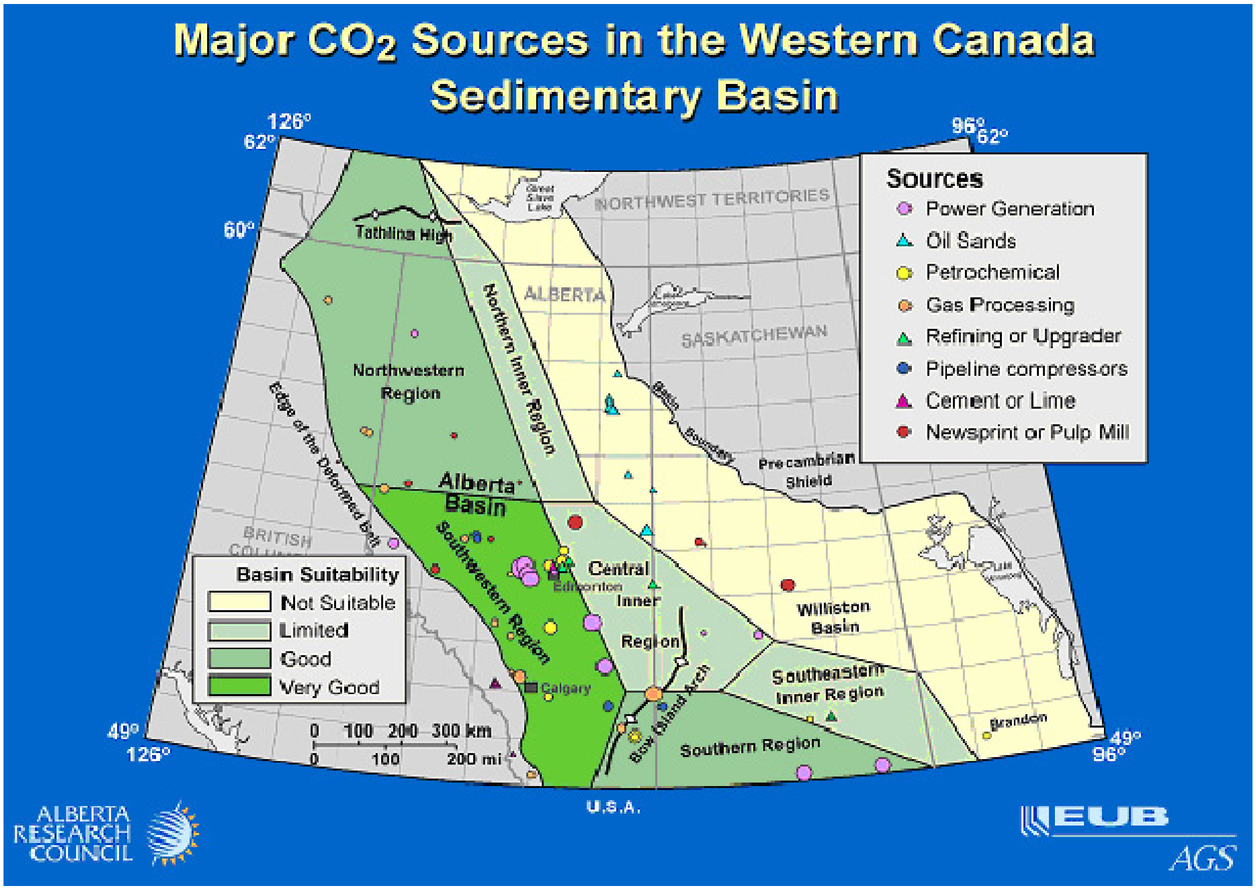

Figure 4.4 Source of CO_2 point sources and location of storage basins according to suitability[202]

Research is also underway in Canada to assess the carbon storage potential in the country's coal seams.[203] Again, the initial focus is on the Western Plains, since they contain the largest concentration of widespread thick coal seams in Canada that directly underlie point sources.

4.5 Cost of storage

The cost of CO_2 storage is usually considered to be low, relative to the cost of capture. This assumes that the cost of compression in included in the capture phase. The main storage cost is usually the cost of drilling an injection well, which increases exponentially with depth. At a

[202] Source: "CO_2 Emission Hubs across Canada and Proximity of Geological Sinks (onshore and offshore)." Brent Lakeman, Alberta Research Council, p.35, in Appendix A in *The CANiCAP Program: Planning Options for Technology and Knowledge Base Development for the Implementation of Carbon Capture and Transportation Research, Development and Deployment in Canada*. Report prepared for Alberta Environment by Bill Gunter, Ian Potter, Brent Lakeman, Sam Wong of the Alberta Research Council, Bob Mitchell, Inspired Value Inc. 2004. See also Bachu, Stefan. 2004. "Evaluation of Sedimentary Basins in Canada for CO_2 Storage: A Proposed Role for the Federal and Provincial Geological Surveys," http://www.nrcan.gc.ca/es/etb/cetc/combustion/co2network/htmldocs/aboutus_e.html.

[203] Natural Resources Canada. 2005. *Project: Monitoring methods and assessment of carbon sequestration over Canada's landmass. Activity: Assessment of geological carbon sequestration potential*, http://rcvcc.nrcan.gc.ca/j31/4_e.php.

depth of 3,000 metres, a well will usually cost in the range of US$1 million, while for a well at 4,000 metres it might cost around US$1.5 million.[204] In the case of enhanced oil recovery or injection into depleted oil or gas reservoirs, it may be possible to use existing wells and in the case of EOR there will be revenue to offset the costs.

While capture costs may range between US$30 and $70 per tonne — depending on the capture process — storage cost has been estimated to lie between US$2–$12 per tonne.[205] One study uses a cost of US$5/tonne as an approximation.[206]

The cost associated with different monitoring techniques has been estimated, and the cumulative cost for various monitoring scenarios (including both the geographical extent and the frequency of monitoring from pre-development to closure) has been calculated for both enhanced oil recovery and for storage in saline formations.[207] The discounted cost of monitoring for 1,000 years has been estimated to range between 5–16 cents per tonne (depending on the storage method monitored and whether enhanced monitoring is used). This is a small part of the estimated capture costs. The IEA has estimated the undiscounted cost for seismic monitoring (pre-operational, operational and closure) to be US$/0.19–0.31 per tonne of CO_2.[208] However, even if the overall costs of monitoring are not significant relative to other CCS costs, it is essential to ensure that those who benefit from storing the CO_2 (presumably those who obtain the CO_2 credits) also make provision to pay for these costs, into the post-closure period.

4.6 Risks of leakage

Risks associated with ocean storage were discussed in Section 4.2.1. This section focuses on geological storage. There are two types of risk associated with leakage of CO_2: leaks that could pose a risk to life and slow leaks that reduce the effectiveness of storage for reducing GHG emissions.

CO_2 poses a risk if it replaces the oxygen in air that is needed for breathing. A sudden, large release of CO_2 would pose a risk to human health and life if the volume in air exceeded 7–10%. Since CO_2 has no odour and is heavier than air, a large-scale leak in a low-lying area (e.g., because of a pipeline break or a leak from underground into a basement) might cause asphyxiation because the gas would not dissipate. This has occurred with a natural CO_2 leak.[209]

The risk of leaks during capture and transport can probably be addressed through the mechanisms currently used to manage hazardous substances. The IPCC states that: “The local

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[204] IEA. 2004. *Prospects for CO_2 Capture and Storage*, p.82. Dollar estimates interpolated from Figure 3.11.

[205] Benson, S. 2004. *Monitoring Protocols and Life-Cycle Costs for Geologic Storage of Carbon Dioxide*, http://www.cslforum.org/documents/benson_sally_wed_Pal_AB_0915.pdf. This presentation also refers to the monitoring techniques that may be used.

[206] Rubin, E.S. et al. 2004. *Comparative assessment of fossil fuel power plants with CO_2 capture and storage*. Department of Engineering and Public Policy, Carnegie Mellon University, http://uregina.ca/ghgt7/PDF/papers/peer/475.pdf.

[207] Benson, S. 2004. *Monitoring Protocols and Life-Cycle Costs for Geologic Storage of Carbon Dioxide*, http://www.cslforum.org/documents/benson_sally_wed_Pal_AB_0915.pdf This presentation also refers to the monitoring techniques that may be used.

[208] IEA. 2004. *Prospects for CO_2 Capture and Storage*, p.96.

[209] A natural example of CO_2 leakage occurred at Lake Nyos in Cameroon. CO_2 from numerous sodium bicarbonate springs accumulated at the bottom of the lake, which sits in a former volcanic crater. In 1986 some event, perhaps a mudslide or wind blowing across the lake, disturbed the water and released about 100 kt of CO_2. This gas cloud spilled over the lake’s outlet and down the valley, killing more than 1,700 people, See Keith, David and Malcolm Wilson. 2002. *Developing Recommendations for the Management of Geologic Storage of CO_2 in Canada*, University of Regina, PARC, Regina, SK, p. 3, http://www.ucalgary.ca/~keith/ccs.html Also: *Degassing Lake Nyos*, http://www.mala.bc.ca/~earles/nyos-feb01.htm.

risks[210] associated with CO_2 pipeline transport could be similar to or lower than those posed by hydrocarbon pipelines in operation."[211]

The risks associated with geological storage depend on the formation where it is stored and on the integrity of the injection system. Until CO_2 is actually sequestered, it might move to lower pressure areas and migrate to the surface through fractures and cracks in the surrounding geosphere. The CO_2 could also move to the surface through older wells that have been improperly sealed or where the seals have weakened over time. Mining or a seismic event (e.g., an earthquake or volcanic activity) could also disturb the strata and allow the CO_2 to move upwards. However, the risk of leakage from deep saline aquifers is considered to be lower than for other geological storage options. The relative safety of a storage site will depend not only on the geological formation, but on the way storage is implemented (e.g., pressure at which the gas is injected) and the way in which it is managed (e.g., identification of possible leakage routes and tests for well integrity). The scientific community is only just beginning to quantitatively evaluate the probability of accidents and failures.

A large leak would be most likely to occur soon after the CO_2 is injected, through undetected weakness (fault or fracture) in the cap rock or through old, abandoned oil or gas wells. If CO_2 is injected at too high a pressure, it could open up fractures and fissures in the cap rock. As noted earlier, mechanical flaws in wells and abandoned wells have been the most common cause of leaks in underground gas storage facilities.[212] Even if wells have been correctly capped when abandoned,[213] the CO_2 may react with the cement seal and leak. Stringent control of injection and monitoring is thus required to minimize the risk and identify and remediate any leaks that occur.

Slower leaks of CO_2 are more difficult to detect but they are less likely to present acute danger to people, livestock or crops. Leakage creates safety concerns and makes storage less effective as a way of reducing the climate change impact of CO_2 emissions. The cumulative impact of even small leaks could be significant if CO_2 is leaking from various points over a wide area. A leakage rate of up to 0.1% per year has been proposed as acceptable for an effective storage policy.[214]

The careful selection of storage sites and control of the CO_2 injection process can reduce the risk of leaks but not eliminate them. "So far, there is very little experience with long-term CO_2 storage and no proof that storage can be safely guaranteed over a period of centuries."[215] Given the time frames involved in CO_2 storage, site monitoring could be necessary for very long periods.[216]

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[210] IPCC footnote: In discussing the risks, we assume that risk is the product of the probability that an event will occur and the consequences of the event if it does occur.

[211] IPCC. 2005. *Special Report on Carbon Dioxide Capture and Storage: Summary for Policymakers,* p.21, bullet 21, http://www.ipcc.ch.

[212] IEA. 2004. *Prospects for CO_2 Capture and Storage,* p.96.

[213] The term "abandonment" refers to the process which aims to close down the well in such a way that it can be left indefinitely without further attention. It includes capping the well and may involve plugging of the well bore, to prevent damage to fresh water aquifers, potential oil and gas reservoirs or the environment.

[214] IEA. 2004. *Prospects for CO_2 Capture and Storage,* p.95.

[215] IEA. 2004. *Prospects for CO_2 Capture and Storage,* p.42.

[216] IPCC. 2005. *Special Report on Carbon Dioxide Capture and Storage: Summary for Policymakers,* p.21, bullet 22, http://www.ipcc.ch .

4.7 Permanence and monitoring

The permanence of carbon storage depends on the way in which it is stored. A distinction can be made between physical methods of trapping CO_2 in its gaseous, liquid or supercritical state and chemical trapping.[217]

In physical trapping, the CO_2 is stored in pore spaces in sedimentary basins (e.g., sandstones and limestone) and will usually be held in place by the cap rocks that prevented the escape of oil and gas for millions of years. However, leaks might occur through faults, fractures or abandoned wells that have not been properly sealed.

Chemical trapping may occur in various ways:

1. CO_2 may be dissolved in formation water or in the unrecoverable portion of oil that remains in an oil formation. This is known as solubility trapping.
2. CO_2 can become fixed in solution, when it forms bicarbonate ions. This ionic trapping process is usually regarded as permanent (although it could potentially be reversed if there were a change in the pH of the water due to some unforeseen external disturbance).
3. In coal seams, CO_2 replaces the methane gas and becomes adsorbed on the coal. This bonding can occur fairly quickly and, assuming there are no pressure changes and the coal seams remain undisturbed, the CO_2 is permanently sequestered.
4. Mineral trapping occurs when CO_2 bonds to the rock, that is, it becomes geochemically fixed, or precipitated, onto the rock. The chemical reaction process is very slow and depends on the proportion of reactive minerals in the rock. It could take thousands of years for all the CO_2 to become precipitated, but it will then be permanently sequestered.

Except when CO_2 is brought to the surface during enhanced oil or gas recovery, it might stay underground for a very long time and become permanently sequestered. However, leaks are possible while the CO_2 is in a liquid or gaseous phase.

To ensure that the CO_2 actually remains underground, it is essential to have the technology to monitor CO_2 movement. Monitoring must be accurate enough to minimize the risk to humans and ecosystems of unexpected rapid leaks or slower leaks. Various monitoring techniques may be used, and these will vary according to the development stage (pre-operational, operational and closure).[218] During the operational phase, monitoring requirements include testing wellhead pressure, injection and production rates; monitoring for CO_2 at the wellhead; measurement for microseismicity; and seismic surveys. Seismic imaging techniques that can monitor the dynamic response of geological reservoirs are being developed at Weyburn in Saskatchewan.[219] To assess the seismic results, data obtained by seismic monitoring is compared with statistics on production and injection wells. While the work undertaken at Weyburn and at Norway's Sleipner site suggests that seismic imaging can detect larger leaks, it is uncertain whether smaller leaks (e.g., 0.1% of the volume stored per year) could be detected.

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[217] Alberta Geological Survey. 2004. *Mechanisms, Means and Duration of CO_2 Sequestration in Geological Media*. Online at http://www.ags.ab.ca/activities/CO2/means_of_storage.shtml

[218] Benson, Sally. 2004. *Monitoring Protocols and Life-Cycle Costs for Geologic Storage of Carbon Dioxide*, http://www.cslforum.org/documents/benson_sally_wed_Pal_AB_0915.pdf

[219] Natural Resources Canada. 2005. *Project: Monitoring methods and assessment of carbon sequestration over Canada's landmass. Activity: In-situ monitoring methods for geological carbon sequestration,* http://rcvcc.nrcan.gc.ca/j31/3_e.php

Other techniques that might be used both during the operational phase and post-closure include gravity surveys, electromagnetic surveys, continuous CO_2 flux monitoring, and pressure and water quality monitoring above the storage formation. Leaks into water might be indicated by a higher concentration of bicarbonate ions, significantly altered pH, or the presence of heavy metal ions in drinking well water (released from the surrounding bedrock as a result of pH changes). Slow leaks through the soil, which can kill soil microorganisms, can be identified by the death of vegetation in the area.

In addition it will be necessary to determine:

- Who conducts the monitoring;
- Who provides oversight, verifies the results and keeps the records; and
- Who is responsible for remediation.

These issues must be resolved through the regulatory process in the near future if CCS is to proceed because strict monitoring requirements will be needed both to gain public confidence in the technology and to enable geologic storage of CCS to qualify for formal credits. It is important to ensure that the monitoring is not only technically reliable but also environmentally acceptable.[220]

A framework for the regulation of CCS in Canada suggests what monitoring and reporting to regulatory agencies might be required.[221] It covers not only reporting of injection pressures and volumes and the mechanical integrity of the well, but also information to indicate potential impacts from the injection of CO_2. This could include:

- Monitoring for ground displacement or seismic movement (earth tremors);
- Seismic surveys to show how the CO_2 is migrating;
- Testing of fresh water aquifers and soils near the well bore for possible CO_2 leaks; and
- Testing at the surface, if geological formations or abandoned wells suggest that they may provide a pathway for CO_2 to migrate.

A process will also be needed to ensure consistent reporting on stored CO_2 volumes (and for deducting any CO_2 that returns to the surface). This requires the development of national and international policy to ensure consistent standards.

[220] "Environmentally acceptable" monitoring means monitoring that does not in itself have a harmful effect on the environment (e.g., frequent surface seismic surveys to monitor for leaks could be harmful to the land surface and disrupt wildlife.)

[221] Keith, David and Malcolm Wilson. 2002. *Developing Recommendations for the Management of Geologic Storage of CO_2 in Canada.* University of Regina, PARC, Regina, SK, http://www.ucalgary.ca/~keith/ccs.html. Appendix 2 of the report summarizes some of the existing regulations in place in Alberta and Saskatchewan. The authors point out that their recommendations are applicable in most geological settings, with the exception of caverns and disused mines, which are the only geological locations where rapid, catastrophic release of stored gas could occur.

5 Policy Initiatives

5.1 International groups involved in CCS

5.1.1 The International Panel on Climate Change

As the international body that determines what reductions in GHGs emissions are required by countries that have ratified the Kyoto Protocol, the IPCC has a considerable influence on policy with respect to CCS. Since the publication of its Special Report in September 2005, it is clear that the IPCC recognizes CCS as one of the tools that can be used to reduce GHG emissions. This suggests that the next stage will be to provide a process for those who have verified GHG reductions to obtain credit for their actions. It may take a while to set up the framework for an internationally recognized set of criteria for the geological storage, monitoring and verification of CCS. However, several international bodies have shown an interest in this because they recognize that sound policy is essential if CCS is to proceed in a safe and responsible manner.

5.1.2 The Carbon Capture Project

The CO_2 Capture Project (CCP) is a group of eight leading energy companies (including BP, Chevron Texaco, Shell, Suncor, ConocoPhillips and Norway's Hydro), the U.S. Department of Energy, the European Union (through CACHET) and Klimatek NorCap (from Norway). This international group seeks to reduce the cost of CO_2 capture from combustion sources and to limit GHG emissions by developing methods for the geological storage of CO_2. They believe that part of their distinctive approach to CCS is that they emphasize collaboration and partnerships, not only with industry and government but also with non-governmental organizations and other stakeholders. In addition to working on capture technology, the CCP group pays attention to monitoring and verification, as well as policy and legal issues surrounding CCS.

The CCP group provides a good overview of policy relating to CCS in its 2004 report *Policies and Incentives Developments in CO_2 Capture and Storage Technology*.[222] They found that individual countries have little specific policy relating specifically to CCS although some, including Canada, Norway and the U.S., are developing initiatives. For example, the U.S. Department of Energy is planning guidelines to encourage industry to establish monitoring and verification processes for CCS. The CCP identified a general need for a monitoring and verification framework to enable CCS to obtain credits for GHG reductions. The report also found that the London Convention and the OSPAR Commission may also apply to geological storage under the ocean (i.e., similar to Norway's Sleipner project), not only to storage **in** the ocean itself (which was discussed above in Section 4.2.1).

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[222] CO_2 Capture Project. 2004. *Policies and Incentives Developments in CO2 Capture and Storage Technology: A Focused Survey by the CO_2 Capture Project.* Reports section: http://www.co2captureproject.com/reports/reports.htm#. See also *Update and Studies of Selected Issues Related to Government and Institutional Policies and Incentives Contributing to CO_2 Capture and Geological Storage* that was published earlier in 2004. For phase 2 see: http://www.co2captureproject.com/Phase2index.htm.

5.1.3 Carbon Sequestration Leadership Forum

Although the U.S. has not ratified the Kyoto Protocol, it is actively involved in the development of CCS and played a major role in setting up the Carbon Sequestration Leadership Forum (CSLF). The first meeting was held in Washington in 2003, and the U.S. funds the CSLF secretariat. The CSLF describes itself as an international climate change initiative that is focused on development of improved cost-effective technologies for the separation and capture of CO_2, for its transport and for its long-term safe storage.[223]

The CSLF now has 21 member countries including Australia, Canada, China, the European Commission, France, Germany, Japan, Norway, the Russian Federation and the United Kingdom. Some have expressed concern that the CSLF is a parallel process outside the Kyoto framework, but it provides a forum that involves the U.S.

The CSLF uses the term "sequestration" as synonymous with "storage." While some organizations focus on the geological storage of CO_2 (recognizing the opposition to ocean storage), the CSLF takes a very broad view of carbon sequestration, which it defines as:

> The capture, from power plants and other facilities, and storage of carbon dioxide (CO_2) and other greenhouse gases that would otherwise be emitted to the atmosphere. The gases can be captured at the point of emission and can be stored in underground reservoirs (geological sequestration), injected in deep oceans (ocean sequestration), or converted to rock-like solid materials (advanced concepts).[224]

The CSLF has two working groups, each chaired by the U.S.: the Technical Group and the Policy Group. Australia is also providing strong leadership within the CSLF, but the level of interest in other countries varies, as does their focus. While Japan is interested in ocean sequestration, the European Union is focused on public outreach and stakeholder involvement.

The CSLF encourages cooperation between members in the development of CCS and has endorsed 10 projects. Canada is involved in four of them:[225]

- Weyburn II CO_2 Storage Project
- Natural Resources Canada's CANMET Energy Technology Centre R & D Oxyfuel Combustion for CO_2 Capture
- ITC CO_2 Capture with Chemical Solvents
- Alberta Research Council Enhanced Coalbed Methane Recovery Project.

At the CSLF's 2004 meeting, members recognized that before CCS can be widely adopted, it will be necessary to address

- the technical conditions that must be met;
- the regulations for storage;
- the role of CCS in the broader energy system; and
- technology transfer.[226]

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[223] CSLF web site at http://www.cslforum.org/.

[224] CSLF web site at http://www.cslforum.org/WhatIsCS.htm.

[225] CSLF. 2004. Ministerial Communique, Meeting of the CSLF Ministers, September 14, p.2.

The ministers attending also recognized that it is important to encourage public outreach programs on CCS because "public acceptance and support based on a clear and accurate understanding of all aspects of these technologies, including the safety and environmental dimensions, is vital."[227] Canada has agreed to coordinate public engagement efforts for the CSLF and solicit best practices from others dealing with this issue.[228]

To obtain input from others in Canada, Natural Resources Canada (NRCan) and Environment Canada invited stakeholders to a meeting prior to the CSLF 2004 meeting, to discuss Canada's input.[229] Canada's position on CO_2 storage is evident from the Ministerial Statement made at the 2004 CSLF meeting, which stated:

> In Canada, the case for CO2 capture and storage is clear. Fossil fuels will continue to be an important part of our energy mix for many years to come. Reducing emissions arising from electricity generation, oil sands development and upgrading operations remains a serious challenge. Finding ways to reduce the emissions associated with the production of hydrogen and from other industrial activities such as petrochemical plants and fertilizer production are equally daunting.230

The statement went on to say that Canada is trying to find ways to reduce the costs associated with CO_2 capture and treatment technologies and referred to the Alberta government's royalty incentive program for enhanced oil recovery projects using CO_2[231] It mentioned research on monitoring and verification, such as that being undertaken at Weyburn, "where estimates have been made of the storage integrity and the long term fate and distribution of the injected CO_2 over the next 5000 years."[232] Commercial demonstration projects are seen as a way to develop the CO_2 market in Canada, although the statement also recognized that one of the issues of common interest to those at the CSLF is "improving public confidence."[233]

5.2 International work on legal aspects of CCS

Various international organizations involved in technological developments concerning CCS have been working to improve policy because they recognize that many legal aspects of storing CCS also need to be resolved. Although each country has some domestic laws that apply to wastes and other substances, several issues are unique to the long-term storage of CO_2.

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[226] CSLF. 2004. Stakeholder Wrap-Up Session Report. http://www.cslforum.org/documents/Morvell_Gerry_Wed_Pal_AB_1330.pdf. It was also recognized that the CSLF is not a substitute for Kyoto and that it is only one of several complementary forums to address climate change.

[227] CSLF. 2004. Ministerial Communique, Meeting of the CSLF Ministers, September 14, p.3.

[228] Anne-Marie Thompson, Environment Canada, in her presentation to a CSLF meeting on January 12, 2005.

[229] At this meeting a representative from both the Pembina Institute and from Climate Action Network Canada were present. Later Natural Resources Canada provided an opportunity for stakeholder feedback on the draft document that was prepared by the CSLF Legal, Regulatory and Financial Issues Task Force, entitled *Considerations on Regulatory Issues for Carbon Capture and Storage Projects.*

[230] Natural Resources Canada. 2004. Ministerial Statement, 2nd Carbon Sequestration Leadership Ministerial Forum, Melbourne 2004. This message was delivered by George Anderson, Deputy Minister at Natural Resources Canada. A copy of this two-page statement was provided by Anne-Marie Thompson, Environment Canada to individuals interested in the CSLF Melbourne meeting.

[231] Alberta Energy. 2003. *CO_2 Credits Royalty Credit Program*, http://www.energy.gov.ab.ca/cod/docs/CO2_Projects_Credit_Prog.pdf.

[232] The storage integrity study was reported at the Seventh IEA Greenhouse Gas Technologies Conference, held in Vancouver, September, 2004. See W. Zhou et al, *The IEA Weyburn CO_2 Monitoring and Storage Project – Modeling of the Long-term Migration of CO_2 from Weyburn*, http://www.ghgt7.ca/papers_posters.php?format=peer. The study examined movement in the geosphere and as a result of leakage from abandoned wells. The authors conclude that *"if the Weyburn CO_2 storage system evolves as expected, the goal of storing greenhouse gas CO_2 can be achieved."*

[233] Natural Resources Canada. 2004. Ministerial Statement, 2nd Carbon Sequestration Leadership Ministerial Forum, Melbourne 2004.

In 2004, a joint workshop held by the IEA and the CSLF identified a number of legal and regulatory gaps and uncertainties. Following this "Paris Workshop" the IEA published *Legal Aspects of Storing CO_2*, which provides a good overview of the policy issues as well as a summary of the legal framework in the main countries engaged in CCS.[234] Issues to address, both at a national and international level, include

- criteria for site selection, including site integrity with respect to leakage;
- ownership of the storage site, which will vary between and within countries;
- monitoring and reporting systems to identify who is responsible for conducting the monitoring for both short-term and long-term leaks;
- long-term liability for leakage and migration of CO_2 — to identify who is responsible for any damage to aquifers, the environment or human health, if leaks occur and who will pay for monitoring and remediation; and
- creating a level playing field with other climate change mitigation options. This means explicitly allowing CCS in various mitigation mechanisms and agreeing on accounting principles (e.g., who owns any GHG emission credits and how are they discounted for leaks).

The IEA's report also indicates that more work needs to be done on the precautionary principle approach. This means that: "The risks associated with the *status quo* (not capturing and storing CO_2 emissions), even when using more carbon efficient technologies, should be taken into consideration when analyzing countries' or actors' obligations under various instruments."[235]

Workshop participants clearly supported the development of CCS but indicated that: "The first challenge facing CCS development today is to carry out the scientific trials, demonstration and monitoring that are necessary for further legal and regulatory development and for gaining public acceptance." [236]

Five priority areas were identified at the Paris Workshop. They are listed here as they indicate what actions some of the lead players in CCS consider important. They want action to

- increase the number of CO_2 storage demonstration projects. This includes EOR and focusing on long-term storage and monitoring;
- set appropriate national legal and regulatory frameworks for more demonstration projects, perhaps by initially adapting existing legal requirements. Over the longer term, national frameworks should be based on empirical knowledge about the conditions and the risks of long-term storage;
- take a proactive approach to clarifying the legal status of carbon storage in the marine environment protection instruments. This applies to those countries that are contracting parties to international agreements;[237]

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[234] IEA. 2005. *Legal Aspects of Storing CO_2*, http://www.iea.org/Textbase/publications/index.asp.

[235] IEA. 2005. *Legal Aspects of Storing CO_2*, p. 38, http://www.iea.org/Textbase/publications/index.asp.

[236] IEA. 2005. *Legal Aspects of Storing CO_2*, p. 41, http://www.iea.org/Textbase/publications/index.asp.

[237] A few issues relating to ocean storage are described in section 4.2.1 of the current report.

- create a level playing field for CCS with other climate change mitigation technologies, including market-oriented emission trading schemes; and
- increase public awareness and work on gaining public acceptance of CCS. This would be done by those engaged in CCS increasing the transparency of their activities and making the information about projects available to the public.

When the legal framework is being developed, it may be necessary to distinguish between different types of projects. The IEA report identifies

- experimental projects;
- CO_2 enhanced resource recovery (oil, coalbed methane or potentially enhanced gas recovery);
- disposal or permanent storage, where CO_2 is injected into a formation with the intent that it stays there permanently; and
- storage that has a temporary objective, such as storing CO_2 in a formation where it can be retrieved e.g., for use in EOR projects.

Each category may have different requirements for regulatory purposes.

5.3 Canadian initiatives

5.3.1 Government of Canada

As was seen in Section 5.1.3, Canada strongly supports the development of CCS and is a member of the CSLF. The federal government believes that CCS has an important role in the country's climate change plan and is "capable of playing a major role in reducing Canada's greenhouse gas emissions while enabling Canada to make use of its abundant fossil fuel resources." [238] It is suggested that over the long term, 50Mt/year could potentially be captured and stored. In the *Climate Change Plan for Canada* the government indicated that it would work with the provinces and the private sector to explore the transportation needs associated with CCS, since a backbone pipeline system could accelerate development of an effective CO_2 capture and storage market. Three years later, the government announced its Partnership Fund and envisages using some of this fund to contribute to the costs of a CO_2 pipeline.[239]

NRCan is actively engaged in CCS research and initiated the CO_2 Capture and Storage Technology Roadmap to plan future development.[240] The Technology Roadmap website provides a good overview of the projects that have been completed or are underway in Canada.[241] They include research on

- suitability of Canada's sedimentary basins for CO_2 sequestration;

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[238] Government of Canada. 2002. *Climate Change Plan for Canada*, p. 35, http://www.climatechange.gc.ca.

[239] Government of Canada. 2005. *Moving Forward on Climate Change: A Plan for Honouring our Kyoto Commitment*, p. 25 and 39, http://www.climatechange.gc.ca It is estimated that a reduction of 20Mt/year in CO_2 emissions could be achieved from clean coal, CO_2 capture and storage, and east-west transmission projects over 2008-2012, but what proportion is expected to come from CCS is not indicated.

[240] Natural Resources Canada. CO_2 Capture and Storage Technology Roadmap; http://www.nrcan.gc.ca/es/etb/cetc/combustion/co2trm/htmldocs/mission_e.html The draft report for the Third Workshop is online at http://www.nrcan.gc.ca/es/etb/cetc/combustion/co2trm/htmldocs/events_workshop_co2trm3_e.html.

[241] More information on the projects and links to websites can be found at http://www.nrcan.gc.ca/es/etb/cetc/combustion/co2trm/htmldocs/canadian_r_d_e.html.

- sequestration of CO_2 in Alberta's oil and gas reservoirs;
- storage of CO_2 in coal seams via the CSEMP pilot project;[242]
- assessment of CO_2 storage capacity of deep coal seams in the vicinity of large CO_2 point sources in central Alberta and Nova Scotia;
- use of amines for CO_2 capture at the International Test Center, University of Regina;
- oxy-fuel combustion undertaken by the CANMET CO_2 Consortium;
- oxy-fuel field demonstration project;
- closed gas turbine cycle project;
- The Zero Emission Coal Alliance;
- Canadian Clean Power Coalition;
- IEA Weyburn CO_2 monitoring and storage projects;
- enhanced coalbed methane recovery for zero greenhouse gas emissions (see section below);
- acid gas re-injection in Alberta and British Columbia (see Section 4.1.3. above);
- sequestration of CO_2 in oil sands tailings streams; and
- geological sequestration of CO_2 and simultaneous CO_2 sequestration/methane production from natural gas hydrate reservoirs.

In addition to supporting research, NRCan has provided funding to companies engaged in CCS.[243]

NRCan also coordinates the Clean Coal Technology Roadmap, which focuses on new ways to obtain the energy from coal while minimizing pollution and emissions of CO_2.[244] There is clearly a relationship between the clean coal work and the work on CCS, since there is an expectation that where CO_2 storage conditions are suitable, the emissions will be stored or sequestered.

While NRCan is actively promoting technology, Environment Canada is monitoring the situation and is engaged in the public policy aspects. Environment Canada participated in various workshops, including one to develop a CO_2 Storage Protocol, and the department commissioned a report entitled *Towards a Strategy for Implementing CO_2 Capture and Storage in Canada,*[245] which identified both the opportunities and the risks of CCS. The report points out the

[242] The CO_2 Storage/Enhanced Methane Production (CSEMP) project is briefly described at http://www.coal-seq.com/Proceedings2003/Law&Gunter.pdf.

[243] Natural Resources Canada. 2005. *Carbon Dioxide Capture and Storage Project Receive Funding.* Media release. January 17. Four companies received $10.8 million for projects in Alberta. They are Anadarko Canada Corporation, Apache Canada Ltd, Penn West Petroleum Ltd. and Suncor Energy Inc. An additional $4.2 million was available.

[244] Natural Resources Canada. Canadian Clean Coal Technology Roadmap at http://www.nrcan.gc.ca/es/etb/cetc/combustion/cctrm/htmldocs/roadmapping_e.html.

[245] Environment Canada. 2002. *Towards a Strategy for Implementing CO_2 Capture and Storage in Canada.* EPS/2/IC/1-Dec. 2002. Oil, Gas and Energy Branch, Air Pollution Prevention Directorate, Environmental Protection Service. This report, which was written by David Keith, was posted at the first meeting of the CO_2 Technology Roadmap Workshop, September 18-19 2003, at http://www.nrcan.gc.ca/es/etb/cetc/combustion/co2trm/pdfs/co2trm1_dkeith_paper.pdf.

importance and the difficulty in building a system to regulate CO_2 storage and poses a number of questions that regulators need to consider, such as: Should the median lifetime of CO_2 storage facilities be 500 years or 10,000? What fraction of early failures are we willing to accept?[246]

The report says that the federal government must assume a central role in building a robust regulatory environment for CCS and proposes that Environment Canada should

- facilitate an assessment of the risks of CO_2 storage;
- set goals for CO_2 management, including tools for monitoring storage; and
- clarify international commitments.

In 2004, the IEA noted that although the existing legal frameworks in Canada could be adapted to cover capture, transport and possibly injection of CO_2, there are serious gaps with respect to monitoring and liability.[247] This is true both at the national and provincial level.

5.3.2 Developments in Western Canada

Apart from the activity of the federal government, most of the interest in CCS has come from Western Canada. As may already be apparent, there are several reasons for this:

- The Western Canadian Sedimentary Basin is geologically suited to CO_2 storage;
- The extraction and use of fossil fuels (oil, gas and coal) creates large CO_2 emissions;
- CO_2 can be used to enhance the recovery of oil, and possibly gas; and
- The Alberta government has encouraged research and pilot projects into CCS.

Several years ago, with federal government plans to ratify the Kyoto Protocol and the awareness that CCS could play a role in reducing GHG emissions, some of those engaged in the Weyburn project in Saskatchewan and in research and policy development in Alberta recognized the need to examine social and policy issues. The University of Regina, Saskatchewan Energy and Mines, and Alberta Environment initiated discussions on the storage of CO_2 in 2002, by sponsoring a workshop on *Ensuring Credible Geological Storage of CO_2: Real, Measurable and Verifiable Tonnes.*

A number of action items were identified and resulted, indirectly, in various meetings and papers. A good overview of the issues that need to be addressed is provided in *Developing Recommendations for the Management of Geologic Storage of CO_2 in Canada.*[248] As indicated in Section 4.7, this report provides draft recommendations for potential regulations. No new regulations have yet been announced. While the departments of energy in Saskatchewan and British Columbia have attended various meetings, and the Saskatchewan government is investigating the geological storage potential in the south of the province,[249] Alberta is the province that has been most actively involved in CCS.

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[246] Environment Canada. 2002. *Towards a Strategy for Implementing CO_2 Capture and Storage in Canada,* p. 16. Reference is also made to p.22.

[247] IEA. 2004. *Prospects for CO_2 Capture and Storage,* p.193.

[248] Keith, D. and M. Wilson. 2002. *Developing Recommendations for the Management of Geologic Storage of CO_2 in Canada.* University of Regina, PARC, Regina, SK, http://www.ucalgary.ca/~keith/ccs.html.

[249] For documents on carbon storage and sequestration, in Saskatchewan, see http://www.publications.gov.sk.ca/details.cfm?p=8762.

5.3.3 The Alberta government

Alberta's position on CCS is set out in the province's strategy for dealing with climate change: *Albertans and Climate Change: Taking Action.*[250] The three-phase carbon management strategy involves enhanced recovery of fossil fuels, building the CO_2 market in Alberta and, post 2007, commercially testing zero-emission coal plants. Various bodies are engaged in implementing the plan.

- The Alberta Geological Survey has provided information on the potential for storage in the Western Canada Sedimentary Basin where there are extensive formations that are considered geologically suitable for CO_2 storage.[251]
- The Alberta Energy Research Institute (AERI) is working on cleaner coal technology and reducing GHG emissions.[252] The goal set in the Action Plan was to reduce the cost of capture and compression of CO_2 by 50% for retrofit operations and 75% for new facilities. AERI was also the starting point for the EnergyINet, the Energy Innovation Network, where one of the objectives is to develop ways to capture emissions from power plants and use them for enhanced oil recovery combined with CO_2 storage.[253]
- The Alberta Research Council Inc. (ARC) is participating in a pilot project to inject CO_2 into coal seams.[254] The ARC has been the lead on two projects to identify the potential for CCS in Canada: The CANiSTORE Program[255] and the CANiCAP Program.[256]
- The Alberta government plans to work with industry to develop infrastructure, such as pipelines, to make CO_2 a marketable product. [257] Enbridge Pipelines Inc. has expressed interest in building a 400-km pipeline to transport 4,000 tonnes of CO_2 per day,[258] but the company has no public plans at present.[259]
- Alberta Energy announced a royalty program to encourage the development of EOR using $CO_{2,}$[260] and projects from four companies qualified for the program.[261]

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[250] Government of Alberta. 2002. *Albertans Climate Change: Taking Action*, http://www3.gov.ab.ca/env/climate/plan.html.

[251] Alberta Geological Survey. 2005. See website and publications at http://www.ags.gov.ab.ca/activities/CO2/CO2_main.shtml.

[252] Alberta Energy Research Institute, http://www.aeri.ab.ca/.

[253] EnergyINet. 2005. *Unlocking Tomorrow's Energy*, http://www.energyinet.com/.

[254] The project is described on the Alberta Research Council website at http://www.arc.ab.ca/Index.aspx/ARC/2629.

[255] Alberta Research Council Inc. 2004. *The CANiSTORE Program: Planning Options for Technology and Knowledge Base Development for the Implementation of Geological Storage, Development and Deployment in Canada.* Report prepared for Alberta Environment by Bill Gunter, Alberta Research Council and Rick Chalaturnyk, University of Alberta, http://www.nrcan.gc.ca/es/etb/cetc/combustion/co2network/htmldocs/aboutus_e.html.

[256] Alberta Research Council Inc. 2005. *The CANiCAP Program: Planning Options for Technology and Knowledge Base Development for the Implementation of Carbon Capture and Transportation Research, Development and Deployment in Canada.* Report prepared for Alberta Environment by Bill Gunter, ARC; Bob Mitchell, Inspired Value Inc.; Ian Potter, ARC; Brent Lakeman, ARC; Sam Wong, ARC, http://www.nrcan.gc.ca/es/etb/cetc/combustion/co2network/htmldocs/aboutus_e.html.

[257] Government of Alberta. 2004. *Strategic Business Plan*, p. 18, http://www.finance.gov.ab.ca/publications/budget/budget2004/govbp.html.

[258] Edmonton Journal. 2004. *Work is underway on transforming one of Alberta's worst environmental headaches, carbon dioxide emissions, into a bonus.* January 20, http://www.nrcan.gc.ca/es/etb/cetc/combustion/co2network/htmldocs/news_story.html.

[259] Personal communication between Jim Rennie, Enbridge Pipelines Inc. and Mary Griffiths, October 5, 2005.

[260] Alberta Energy. 2003. *New oil and gas recovery program tackles CO_2 emissions.* News release, Mary 16, http://www.gov.ab.ca/acn/200305/14414.html.

[261] Alberta Energy. 2004. *Companies named for pilot CO_2 storage projects.* News release. April 30, http://www.gov.ab.ca/acn/200404/16359.html. Over $14 million in royalty credits was approved for four enhanced oil recovery projects. The four

- Alberta Environment commissioned the reports on the CANiSTORE Program and the CANiCAP Program, which were written by the Alberta Research Council. Alberta Environment has produced a short brochure for the public about CCS[262] and, with Environment Canada, is currently developing plans for further communication on CCS issues. Since the CO_2 Storage Protocol Workshop in 2002, the department has participated in various meetings and sent a delegate to CSLF meetings (see Section 5.1.3).

Alberta does not have a specific regulatory system for CCS. The Alberta Energy and Utilities Board requirements for acid gas injection provide the basic process for CO_2 storage.[263]

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companies selected are Anadarko Canada Corporation, Apache Canada Ltd, Penn West Petroleum and Devon Energy. The first three companies later received federal funding (see above).

[262] Alberta Environment. 2004. *Capture and Storage of Carbon Dioxide in Western Canada.* This brochure is from the Alberta Climate Change: Taking Action series.

[263] EUB. 2004. *Directive 065. Resources Applications for Conventional Oil and Gas Reservoirs,* regulates acid gas injection and underground gas storage. See also EUB. 2001. Guide 7. *Production Accounting Handbook* See also the list of regulatory requirements in Keith, David and Malcolm Wilson. 2002. *Developing Recommendations for the Management of Geologic Storage of CO_2 in Canada.* University of Regina, PARC, Regina, SK, http://www.ucalgary.ca/~keith/ccs.html. Appendix 2 lists the major relations in Alberta (and Saskatchewan).

6 What is the Role of CCS in a GHG Reduction Strategy?

6.1 Environmental and public interest groups' views on CCS

Industry and government bodies are enthusiastic about CCS as a way of reducing GHG emissions, but they recognize that if CCS is to succeed, it must be acceptable to the public. However, there are various issues that could cause public concern. The IEA states that: "A number of potential environmental, health, and safety risks associated with CO_2 sequestration are broadly acknowledged and require additional research to allow for a comprehensive risk assessment, particularly with regard to geologic storage."[264] They also realize that the viability of CCS will depend on meaningful public dialogue, but the public is currently not well informed on the subject. In fact, most members of the public are not aware of issues relating to CCS and may only become involved when specific projects are reviewed for permitting or licensing. When the public does show interest, it is likely that non-governmental organizations (NGO) will play a key role in determining the acceptance of this technology.

When the CO_2 Capture Project conducted a survey and workshops involving NGOs in 2001, they found that although most groups were open-minded, they also believed that CCS would extend the use of fossil fuels and divert resources from the development of renewable energy.[265] The survey noted that some NGOs are developing a more supportive attitude because they realize that it may be some time before renewable energy sources are widely implemented, and CCS may play a role in the transition to a hydrogen economy. This is reflected in the positions expressed by some members of the environmental community in North America, Europe and Australia.

The Union of Concerned Scientists regards CCS as one potential way to reduce CO_2 levels in the atmosphere but cautions against viewing it as the "silver bullet."[266] Its paper identifies a series of potential risks to humans and the environment and notes that many policy issues are unresolved, including the long-term intergenerational questions that arise because of the uncertainty about long-term retention of stored carbon.

Climate Action Network Europe has focused on key concerns about whether CO_2 storage can be made truly permanent, the potential effects on health and human ecosystems from slow or rapid

[264] IEA. 2002. *Solutions for the 21st Century: Zero Emissions Technologies for Fossil Fuels*, p. 26.

[265] CO_2 Capture Project. *Policies and Incentives Developments in CO_2 Capture and Storage Technology: A Focused Survey by the CO_2 Capture Project.* Available online at http://www.co2captureproject.com/reports/reports.htm#.

[266] Union of Concerned Scientists. 2001. *USC Position on Geologic Carbon Sequestering*, http://www.ucsusa.org/global_environment/global_warming/page.cfm?pageID=529.

leakage, and the fact CCS will continue the focus on fossil fuels, which could delay the uptake of renewable technologies.[267] They expand on these issues as follows:

- Doubts as to whether CO_2 storage can really be made permanent. While oil and gas fields are reasonably well understood over periods of a few decades, the long-term performance of seals and the character of other formations such as saline aquifers are much less well understood. CO_2 would need to be trapped permanently — meaning at a minimum for tens of thousands of years.
- Continuing our dependence on fossil fuels. There are many other problems associated with fossil fuels, from the exploitation of developing countries to health problems from air pollution, from oil spills to the propping up of dangerous regimes. Even if CCS helps solve the climate problem, it may delay the implementation of renewable energy sources that offer a more sustainable future.
- Health effects. Slow leakage through ground and catastrophic leaks from CO_2 extraction plants, pipelines and wells can all affect human and ecosystem health.

Climate Action Network Europe also sees potential benefits, which include reduced air pollution from vehicles and more modern fossil power plants (IGCCs for instance), and thus improvements to human health. It also realizes that CCS, combined with biomass fuel, may offer the only opportunity to return to pre-industrial levels of atmospheric CO_2 concentrations.[268]

Climate Action Network Australia (CANA) has been critical of CCS.[269] CCS is an important issue in Australia because about 80% of Australia's electricity is supplied by coal-fired power stations, which create about 30% of Australia's total GHG emissions.

Scientists from Greenpeace in England reviewed the potential environmental impacts of CCS at the IPCC meeting in Weyburn in 2002.[270] Citing another paper, the authors pointed out that the potential for leakage depends on cap rock integrity, the security of well capping and the degree to which CO_2 is eventually trapped through solubility. They noted that, "Even in formations with adequate nominal capacity some of the injected CO_2 is expected to leak as a result of the buoyancy of the separate phase carbon dioxide, the induced pressure gradients from the injection and the variable nature of strata that, in theory, act as barriers to upward migration."[271] The paper identifies ten research needs relating to the long-term containment of CO_2 that must be addressed. At the 2004 CSLF meeting, Greenpeace Germany expressed concern that storing large volumes of CO_2 underground is not sustainable and should not be used solely to prolong

[267] CAN Europe. *Carbon Dioxide Capture and Storage: Introduction* at http://www.climnet.org/CTAP/CTAP.htm See, also the Climate Technologies Assessment Workshop, May 2004, http://www.climnet.org/CTAP/workshop2004/PresentationsWS2.htm.

[268] IGCC stands for "integrated gasification combined cycle" and refers to a process that gasifies a combustible substance (e.g., coal or coke) and then uses the gas to generate electricity.

[269] Climate Action Network Australia, CSLF Melbourne, *Australian NGO Perspective*, Julie-Anne Richards, CANA Coordinator (Power Point presentation). The group is a non-profit alliance of 30 Australian environmental, public health, social justice and research organizations.

[269] Saddler, H., C. Riedy and R. Passey. 2004. *Geosequestration: What is it and how much can it contribute to a sustainable energy policy for Australia?* The Australia Institute.Discussion Paper 72, September, http://www.tai.org.au

[270] IPCC. 2002. Proceedings of the Workshop for Carbon Capture and Storage, http://arch.rivm.nl/env/int/ipcc/pages_media/ccs2002.html The paper can be found at: http://www.greenpeace.to/pdfs/ccs02-07.pdf.

[271] Johnston, P. and D. Santillo. 2002. *Carbon Capture and Sequestration: Potential Environmental Impacts,* section 2(ii), citing Bruant et al, 2002. IPCC Workshop on Carbon Dioxide Capture and Storage, Weyburn.

the use of fossil fuels.[272] It wants open and transparent discussion of the issues, as well as research and development into CCS to close the gaps in knowledge; it does not want any shift of money or priorities away from renewable energy and energy efficiency. It identifies the need for careful site selection, involving the public and NGOs, resolution of liability issues (including adoption of the polluter pay principle and plans for remediation), long-term monitoring and reporting to the public.

Also speaking at the CSLF meeting, David Hawkins from the U.S. Natural Resources Defense Council pointed out that the countries that are the biggest CCS proponents are also the biggest opponents to legally binding emission cuts.[273] He noted that CSLF countries are responsible for 86% of global coal consumption and for 74% of world CO_2 emissions (based on data from IEA 2002). He emphasized the need to

- integrate CCS with a serious plan to cut GHG emissions;
- promote renewables and efficiency more strongly; and
- build confidence in CCS as means of permanent isolation of CO2.

The position expressed by ENGO delegates to the CSLF meeting in 2004 has been summarized as follows. ENGOs

1) do not support disposal of CO_2 in the ocean (i.e., dissolved in the water or on the ocean floor);
2) do not support EOR applications that simply prolong the use of fossil fuels;
3) only accept CCS if it is linked to deeper GHG reductions;
4) only accept CCS if it is part of a basket of approaches that includes the development of renewable energy and does not divert funding away from renewables; and
5) do not accept CCS as a replacement for Kyoto (they are suspicious of the U.S. and Australia in this regard).[274]

Additional NGO concerns include the fact CCS leads to additional energy use (and thus the need to capture yet more CO_2) and the risk of CO_2 leaking from storage sites.[275] At the local level there may be concern about the surface impacts of additional well sites. It is not known exactly how many wells would be required to inject 50Mt/year (the approximate volume that it was suggested earlier might potentially be injected in Alberta). In the case of EOR or storage in a depleted oil reservoir, a company may be able to convert existing oil wells for CO_2 injection or

[272] von Goerne, G., 2004. *Carbon Capture and Storage; NGOs hope? and concern!* http://www.cslforum.org/documents/von_Goerne_Gabriella_mon_Pal_AB_1330.pdf.

[273] Hawkins, David. 2004. *CSLF- the Path Ahead,* http://www.cslforum.org/documents/Hawkins_David_Mon_Pal_AB_0955.pdf.

[274] This summary is taken from an unpublished report from a government official from Canada who attended the CSLF.

[275] IEA. 2004. *Prospects for CO_2 Capture and Storage*, p.190.

construct new wells on the same pad.[276] The number of wells required will depend on the permeability of the formation.[277]

A recent study of public perception on the geological disposal of CO_2 in Canada indicated that knowledge on this subject is low, although higher than in the U.S.[278] Also the vast majority of those who had heard of geological disposal could not correctly identify what environmental problem it was meant to address. The most important benefit seen was its use as a bridging technology while long-term climate change solutions are being developed. "However, the risks were considered more important than the benefits, with the public most concerned about unknown future impacts, contamination of groundwater, the risk of a CO_2 leak, and harm to plants and animals."[279] The report indicates that overall the public surveyed was mildly supportive of geological disposal, and over half would include it in a climate change strategy, although it was less popular than energy efficiency and renewable energy programs. It was found that public support could increase significantly if various policy recommendations are implemented. This includes strict regulation and monitoring, with the federal or provincial governments taking an active role in the management of the technology, together with independent experts and NGOs. Public education about climate change is considered to be critical, as is more information about the role that geological disposal could play in addressing it.

The IEA has recognized the importance of the public perception in CCS. "The single most important hurdle which CCS must overcome is public acceptance of storing CO_2 underground. Unless it can be proven that CO_2 can be permanently and safely stored over the long term, the option will be untenable, whatever its additional benefits."[280]

6.2 What could be the role for CCS in a comprehensive GHG reduction strategy?

The IPCC sees a role for CCS as one tool for helping to reduce global climate change. They state that in a least-cost portfolio of mitigation options, CCS could economically contribute 220–2,200 Gt CO_2 (60–600 GtC) in the period to 2100 (and there could be a much larger potential in saline formations).[281] This would represent 15%–55% of the cumulative GHG reductions up to that time. In most scenario studies, the role that CCS plays increases over the century, but over that period, adoption of CCS could reduce the costs of stabilizing CO_2 concentrations in the atmosphere by 30%.[282]

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[276] EnCana uses approximately 30 wells to inject 2 Mt/year at its Weyburn EOR operation. Following pressure tests to ensure the integrity of the well, an oil well may be converted for the injection of CO_2. If a well fails to meet the pressure tests, a new injection well will be constructed, probably on the same pad. The well lease will be approximately 100 x 100 metres, although the actual area used may typically be about 15 metres in diameter, plus an access road. Personal communication, Dave Hassan, EnCana, October 17, 2005.

[277] In a permeable formation, e.g., some deep saline aquifers, one well might be able to handle 10 to 1000 times the volume handled by an injection well at the EnCana Weyburn operation, where the oil is in a tight (low permeability) formation. Personal communication, Dave Hassan, EnCana, October 17, 2005.

[278] Sharp, Jaqueline, Mark Jaccard and David Keith. 2005. *Public Attitudes Toward Geological Disposal of Carbon Dioxide in Canada: Final Report.* This study was conducted as part of a degree in Master of Resource and Environmental Management, Simon Frazer University.

[279] Sharp, Jaqueline, Mark Jaccard and David Keith. 2005. *Public Attitudes Toward Geological Disposal of Carbon Dioxide in Canada: Final Report,* p. 2.

[280] IEA. 2004. *Prospects for CO_2 Capture and Storage*, p. 20.

[281] IPCC. 2005. *Special Report on Carbon Dioxide Capture and Storage: Summary for Policymakers,* p.18, bullet 19, http://www.ipcc.ch.

[282] IPCC. 2005. *Special Report on Carbon Dioxide Capture and Storage: Summary for Policymakers,* p.18, bullet 20, http://www.ipcc.ch.

To help identify how a range of mitigation measures might achieve stabilization below a doubling in CO_2 levels in the atmosphere, Stephen Pacala and Robert Socolow from Princeton University have developed the concept of "stabilization wedges."[283] A wedge is a strategy to reduce carbon emissions in which the wedge grows in 50 years from zero to 1 GtC/year. Cumulatively, over the 50-year period, a wedge redirects a total of 25 GtC.[284] To achieve stabilization in the next 50 years requires about seven wedges of 1 Gt, which would avoid 175 billion tons of carbon emissions.

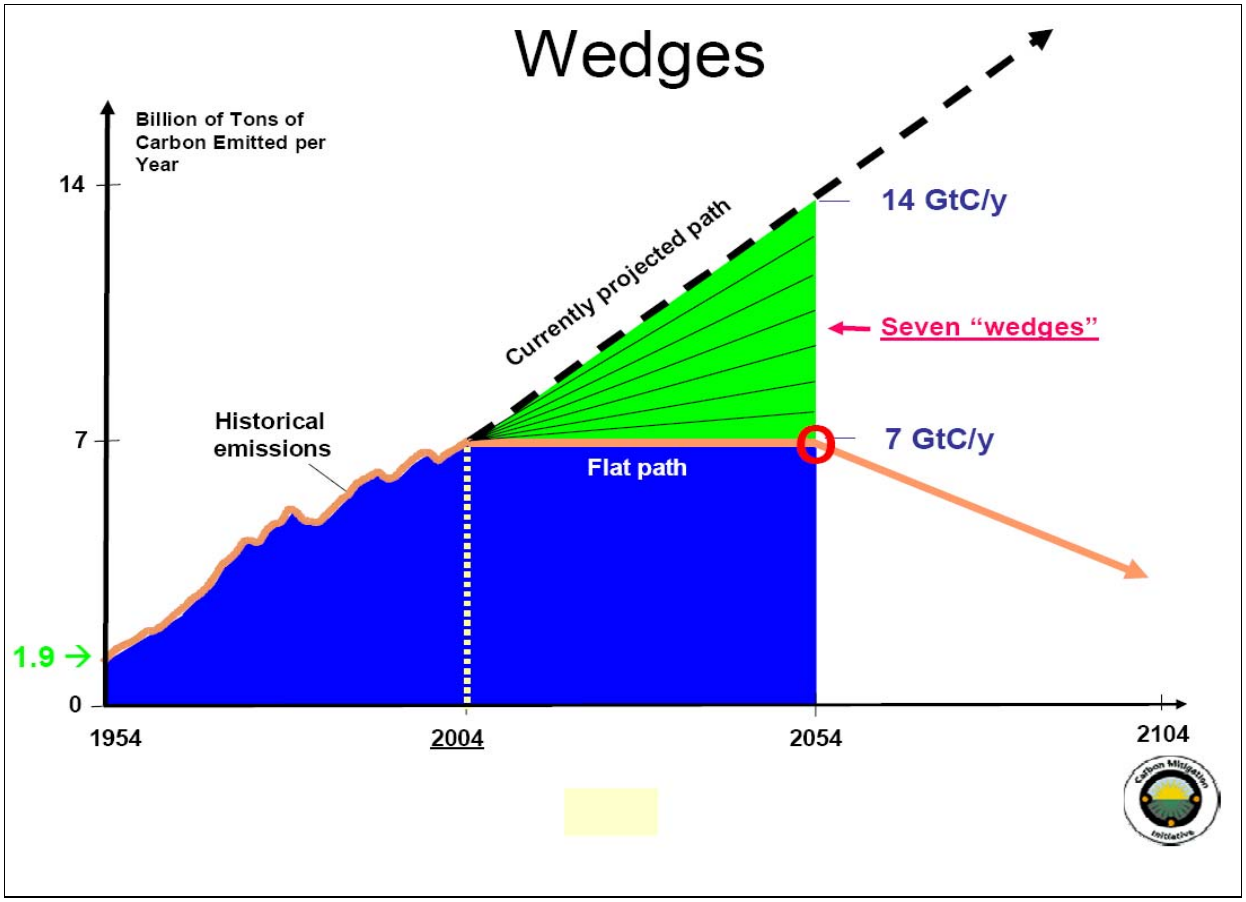

Figure 6.1 Stabilization wedges, as proposed by Pacala and Socolow[285]

The authors suggested 15 actions that could each give a 1Gt wedge, relative to the 14 GtC/y business-as-usual scenario. These include energy efficiency and conservation, use of renewable energy, a fuel shift from coal power plants to gas plants, nuclear fission and CCS. The wedges that relate to CCS are reproduced in Table 6.1. They indicate the magnitude of the actions that

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283 Pacala, Stephen and Robert Socolow. 2004. "Stabilization Wedges: Solving the Climate Problem for the Next 50 Years with Current Technologies," *Science*, vol. 305, p. 968-971.

284 To convert from carbon to CO_2, multiply the carbon value by 3.67.

285 Figure taken from "Stabilization Wedges: Mitigation Tools for the Next Half-Century," presented by Robert Socolow at *Avoiding Dangerous Climate Change: A Scientific Symposium on Stabilization of Greenhouse Gases,* Met Office, Exeter, UK, February 3, 2005, online at www.stabilisation2005.com/day3/Socolow.pdf.

will be necessary and that a range of actions will be required to stabilize and then reduce GHG emissions.

Table 6.1 Selected Wedges: Strategies using CCS to reduce the carbon emission rate in 2054 by 1GtC/y, or to reduce 2004–2054 carbon emissions by 25GtC, based on Pacala and Socolow[286]

CO_2 Capture and Storage	Option	Effort by 2054 for one wedge	Comments, issues
	Capture CO_2 at baseload power plant	CCS at 800 GW coal or 1600 GW natural gas (1060 GW coal in 1999)	Technology is already used for H_2 production, with venting of 0.1 GtC/y
	Capture CO_2 at H_2 plant	CCS at plants producing 250 MtH_2/y from coal or 500 MtH_2/y from natural gas (40 MtH_2/y today from all sources)	Large plant size matches fuels used in industrial facilities
	Capture CO_2 at coal-to-synfuels plant	CCS at synfuels plants producing 30 mbd from coal (180x Sasol), if half of feedstock carbon is available for capture	Synfuels production *without* CCS raises carbon emissions
	Geological storage	3500 Sleipners	Global, local CO_2 leaks

In the short term, cost may be a limiting factor for the large-scale adoption of CCS, except where there is compensating revenue from enhanced oil or gas recovery or sufficient financial incentive to avoid emissions.[287] In Canada, revenue from enhanced recovery may exist, but over the long term, only a small proportion of the available CO_2 will be used for EOR. Furthermore, costs to industry for GHG mitigation have been limited by the Canadian government to $15/tonne in the first Kyoto commitment period, so at present there is little other financial incentive for CCS.

A discussion paper released by the Australia Institute examined the future of CCS in that country and suggested that CCS is unlikely to be an economic way of reducing GHGs from coal-fired power generating plants in the near future:

> When account is taken of the costs of abatement (measured by $/tonne CO_2-e of abatement), energy efficiency, natural gas, wind and biomass are more economically attractive than CCS as abatement options. . . . This conclusion applies not only to the period between now and when CCS technology is ready for commercial use, which will be 2020 at the earliest, but also for a considerable time after CCS could begin to be widely used.[288]

The authors of the Australian paper concluded that a combination of improvements in energy efficiency, gas-fired electricity generation and increased use of renewable energy could reduce GHGs in Australia by more than five times as much as CCS alone by 2030, and that the cumulative emissions could be reduced by a factor of ten since the alternatives are already commercially available. These findings may not apply to Canada, if CCS is first applied to industrial CO_2 sources (chemical, fertilizer, refinery and oilsands upgrader hydrogen plants), rather than to coal-fired power plants. The emissions from these plants have a higher

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[286] Socolow, Robert. Stephen Pacala and Jeffrey Greenblatt. 2004. "Wedges: Early Mitigation with Familiar Technology" in *Proceedings of GHGT-7, the 7ths International Conference on Greenhouse Gas Control Technology,* Vancouver, Canada, http://uregina.ca/ghgt7/PDF/papers/poster/233.pdf.

[287] Incentive options such as carbon taxes, or carbon constraints within a cap-and-trade system.

[288] Saddler, H., C. Riedy and R. Passey. 2004. *Geosequestration: What is it and how much can it contribute to a sustainable energy policy for Australia?* The Australia Institute. Discussion Paper 72, September, p.xi, http://www.tai.org.au/.

concentration of CO_2, and the costs of capture could be about half the cost of retrofitting a coal-fired plant. The Australian paper recognizes that over the longer term, CCS may be needed if emissions in 2050 are to be reduced to 50% below 1990 levels.

Natural gas power generation with carbon capture may be more expensive than wind power, using current technology. One study found that for it to be less expensive than wind power, the natural gas costs would have to be less than $3/GJ; above this point, wind power at *good* sites can produce electricity at lower per kWh cost.[289] As of May 2005, natural gas commodity prices were $7.37/GJ,[290] indicating that wind power at *average* sites could produce electricity with lower costs per kWh than natural gas with carbon capture. Coal power generation with capture was found to be more expensive than natural gas with capture.[291]

As Section 2.7 showed, the costs of capturing CO_2 varies, depending on the process and type of plant. While the capture cost could be US$10–$15 per tonne of CO_2 avoided for an IGCC plant, it would be closer to US$35 for the retrofit of a coal-burning power plant or even higher in some cases. The IEA estimates that the current costs of large-scale capture (including CO_2 pressurization, excluding transport and storage) range from US$25 to $50 per tonne, but that these costs are expected to decline with improving technology.[292] They could decline to about US$10–$25 for coal-fired power plants and $25–$30 for gas-fired plants over the next 25 years. Overall, the IEA found that the total cost of CCS (capture, transportation and storage) could range from US$50 to $100 per tonne of CO_2 at the present time.

The costs of transport and storage of high pressure (liquefied) CO_2 are relatively low, compared with the cost of capture but will vary, depending on various factors, such as the length of pipeline. Large-scale pipeline transportation costs are likely to range between US$1 and $5 per tonne per 100 km, but if CO_2 is shipped over long distances, the cost can be as low as US$15-$25/tonne for 5,000 km.[293]

What role might CCS play in reducing emissions in Canada? Under the Kyoto Protocol, Canada committed to reducing its GHG emissions to 6% below 1990 levels. In 1990 Canada's GHG emissions were about 596 Mt, which means that emissions should not exceed 560 Mt if the country is to meet its commitment. By 2002 the "emissions gap" was estimated to be 240 Mt, and the federal government thinks that, as a result of recent growth in the economy, "the emissions gap is more likely in the area of 270Mt, and could be greater."[294] This indicates the magnitude of the CO_2 reductions required in Canada.

Canada has a large physical potential for CCS, especially in the Western Sedimentary Basin (see Section 4.4). The capacity of depleted oil and gas reservoirs is sufficient to store 2.7Gt CO_2, so

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[289] Davison, J. 2003. *Costs of Renewable Energy and CO_2 Capture and Storage*. IEA Greenhouse Gas R&D Programme. Proceedings of the Sixth International Conference on Greenhouse Gas Control Technologies (GHGT-6), Pergamon Press, Vol. II, Editors J.Gale, Y. Kaya (eds), pp 1251 – 1256, August. This paper is listed, but not provided at http://www.ieagreen.org.uk/papers.html. Here, "good" sites imply 40% load factor, "average" is 30%.

[290] Natural Resources Canada. 2005. Canadian Natural Gas; Monthly Market Update. May. Natural Gas Division Petroleum Resources Branch. Energy Policy Sector, http://www2.nrcan.gc.ca/es/erb/CMFiles/Market_Update_May_2005206QOK-05072005-3986.pdf.

[291] Davison, J. 2003. *Costs of Renewable Energy and CO_2 Capture and Storage*. IEA Greenhouse Gas R&D Programme. Proceedings of the Sixth International Conference on Greenhouse Gas Control Technologies (GHGT-6), Pergamon Press, Vol. II, Editors J.Gale, Y. Kaya (eds), pp 1251 – 1256, August. This paper is listed, but not provided at http://www.ieagreen.org.uk/papers.html.

[292] IEA. 2004. *Prospects for CO_2 Capture and Storage,* p.17 and 39.

[293] IEA. 2004. *Prospects for CO_2 Capture and Storage,* p.18.

[294] Government of Canada. 2005. *Project Green – Moving Forward on Climate Change: A Plan for Honouring our Kyoto Commitment, http://www.climatechange.gc.ca/kyoto_commitments/default.asp.*

they could hypothetically hold a volume of CO_2 equivalent of ten times Canada's current annual "emissions gap." The ultimate potential of the deep saline aquifers in the basin (4,000 Gt CO_2) is estimated to be almost 1,500 times as great as the potential in depleted oil and gas reservoirs. Of course, only a portion of the emissions are from large point sources from which the CO_2 can be captured, and many of these sources will be distant from the geologically most suitable reservoirs that underlie Alberta and adjacent areas of British Columbia and Saskatchewan. However, in general, lack of storage space is not likely to be a major issue.

As indicated above, in the short term under present policy, the high cost of CCS compared to other mitigation options will be a limitation on development. Recall that since the Canadian government has chosen to limit the cost of industry's compliance with mandatory GHG targets during 2008–2012 to $15/tonne, companies do not have a substantial financial incentive to undertake CCS in the immediate future. The IEA has indicated that policy action equivalent to a penalty (or incentive) of about US$50 per tonne is needed if global CO_2 emissions are to be stabilized at 2000 levels by 2050, while fossil fuels are still being used.[295] In this scenario, about half the reduction would be achieved through CCS. If CCS were not used, emission levels in 2050 would increase by over one quarter, compared to the CCS scenario, even with the $50 penalty.

What issues must be addressed if CCS is to proceed?

A report published by the Pew Center on Global Climate Change identifies the most significant barriers to the implementation of CCS as[296]

- high costs and energy penalties of post-combustion capture and separation;
- high capital costs of converting coal-fired power plants to use the gasification process (which enables easy capture of CO_2) and the electrical sector's lack of experience with gasification;
- limited experience with large-scale geological storage, including "proving" the estimates of storage capacity in salt-water formations;
- uncertainty about public acceptance for CO_2 storage in geological formations, including resistance to CCS based on preference for energy efficiency and renewables;
- lack of appropriate legal and regulatory frameworks to support widespread application of CCS; and
- lack of financial resources to support projects of sufficiently large scale to evaluate the viability of CCS.

The environmental community is likely to insist that CCS, if adopted, must be part of an overall strategy to reduce GHG emissions that reflects a reasoned balance between the various GHG reduction approaches, with justification provided for the resources devoted to each approach. ENGOs will argue that energy conservation, energy efficiency and low-impact renewable energy should be at the top of the list of measures for reducing GHG emissions because they are truly sustainable, low-risk solutions that can be implemented rapidly and relatively inexpensively on a

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[295] IEA. 2004. *Prospects for CO_2 Capture and Storage*, p. 18 and 19.

[296] Benson, Sally. 2004. "Carbon Dioxide Sequestration/Coal Gasification", p.16 in *The 10-50 Solution: Technologies and Policies for Low Carbon Future.* Pew Center for Global Climate Change Workshop Proceedings, March 25-26, http://www.pewclimate.org.

large scale. With CCS the fuel source is not usually renewable[297] and the *production* of CO_2 is not reduced. Indeed, CO_2 production is increased because additional energy is required to capture and store the CO_2.

From a "polluter-pays" perspective, the environmental community will also want to focus on the question of who will end up paying for CCS if it is adopted on a large scale. The key argument will be that it is an industry's investors and shareholders who receive the primary benefit from the commercial activity. The viability of their investment faces significant future risk because of climate change and the potential for GHG emission restrictions. Accordingly, these players should pay for the majority of CCS costs. Imposing meaningful mandatory GHG emission limits would be the most important signal government could provide to create a market price for CO_2 and drive the economics of CCS or alternative management options. If government is to contribute towards the cost of implementing CCS, ENGOs are likely to look unfavourably on the use of scarce public funds to develop CCS if it occurs at the expense of significant investments in energy conservation, efficiency and low-impact renewable energy.

However, if the risks and the "who pays?" question can be satisfactorily addressed, CCS might play an important role in reducing industrial emissions while the overall economy restructures to a de-carbonized energy system, especially as renewable energy and energy conservation may be insufficient to achieve the deep reductions (in the range of 50%–60%) required in the mid-term. CCS may help the transition to a hydrogen-based economy for transportation (with hydrogen generated through renewable energy sources or hydrocarbons that incorporate CCS). Unless there is a major shift in government policy, oil production, especially from Alberta's oil sands, will continue to produce large quantities of GHGs. During this period, CCS may help reduce GHG oil sands emissions by, for example, capturing the CO_2 from the generation of hydrogen used in upgrading the bitumen, as well as from power plants associated with oil sands developments.

For public acceptance of CCS, the health and safety issues must be addressed, both in the short and long term. This requires a good regulatory framework, sound monitoring and verification of all CCS projects, and clear provisions about liability if there is a leak.

The technology already exists to measure and monitor emissions from the capture and surface facilities, injection rates and the condition of wells. More work will be needed to improve the monitoring of the CO_2 plume when CO_2 is injected into a geological formation.[298] Although seismic imaging has been successful at monitoring the Sleipner and Weyburn projects, seismic surveys will need to be supplemented by other techniques. There must also be an efficient government inspection system and public reporting process.

When specific projects are proposed, members of the public will probably be concerned about the risk of leaks and potential impacts on water quality and on property values, as with any form of fossil fuel development. Companies must be transparent in providing information on projects and in addressing all local concerns.

[297] Although if CCS is used with energy generated from biomass, it can provide negative CO_2 emissions.

[298] Benson, Sally. 2004. "Carbon Dioxide Sequestration/Coal Gasification", p.11 in *The 10-50 Solution: Technologies and Policies for Low Carbon Future.* Pew Center for Global Climate Change Workshop Proceedings, March 25-26, http://www.pewclimate.org.

The Pew Center report states: "Laws and regulations that protect the public and the environment are critical to the success of CCS."[299] It is important for the public to be involved in determining what laws and regulations are needed and whether these will sufficiently address their concerns. Considering that industry and government are already moving ahead with CCS projects, it is important that they engage the public in this debate in the near future.

[299] Benson, Sally. 2004. "Carbon Dioxide Sequestration/Coal Gasification", p.15 in *The 10-50 Solution: Technologies and Policies for Low Carbon Future.* Pew Center for Global Climate Change Workshop Proceedings, March 25-26, http://www.pewclimate.org.

7 Glossary

Acid gas	A mixture of CO_2 and hydrogen sulphide, which is a waste product from treating sour natural gas (i.e., natural gas that contains hydrogen sulphide).
Aquifer	An underground water-bearing formation that is capable of yielding water.
Bitumen	Hydrocarbons that are in a thick or solid form in natural deposits, often referred to as oil sands. The term also describes a thick form of crude oil that must be heated or diluted before it will flow into a well or through a pipeline.
Carbon dioxide (CO_2)	A gas produced by the decay of organic matter and the burning of fossil fuels, as well as by the respiration of plant and animal life. It is the most common greenhouse gas produced by human activities.
CO_2 equivalent	The quantity of a given greenhouse gas multiplied by its global warming potential. This is the standard unit for comparing the degree of harm that can be caused by emissions of different greenhouse gases.
Carbon sequestration	This term is defined in various ways. It traditionally refers to the process by which atmospheric carbon is absorbed in carbon sinks such as the oceans, forests and soil. The Carbon Sequestration Leadership Forum gives a wider definition: "The capture and storage of carbon dioxide and other greenhouse gases that would otherwise be emitted to the atmosphere . . . The captured gases can be stored in underground reservoirs, dissolved in deep oceans, converted to rock-like solid materials, or contained in trees, grasses, soils, or algae."[300] Others have a narrower definition and distinguish between carbon storage (not necessarily permanent, may have some leakage risk, could be produced back if deemed necessary later) and carbon sequestration ("permanent" with very little chance of leaks).[301] In the current paper we use the narrow definition, using the term if the carbon is retained in a permanent form (e.g., dissolution in

[300] Part of this definition and some other definitions in this glossary have been taken from the Carbon Sequestration Leadership Forum Glossary online at http://www.cslforum.org/glossary.htm.

[301] Hill, Gardiner, BP and Craig Lewis, Chevron. 2001. *An Industry Perspective on Geologic Storage and Sequestration.* NETLs First Conference on Carbon Sequestration. May 15, http://www.netl.doe.gov/publications/ proceedings/01/carbon_seq/pan1c.pdf.

	deep saline aquifers, or precipitated on rock), rather than stored.
Carbon storage	In the current paper, we use the term carbon storage to refer to the storage of captured CO_2, primarily in underground reservoirs, in any form that may not be permanent.
Deep saline aquifer	A saline aquifer contains water and common salt (sodium chloride), and usually some other salts. Deep saline aquifers may contain 20% salt or more (compared to ocean water, which contains 3% salt). Deep saline aquifers used for storing CO_2 would normally be at least 800 metres deep, and probably more.
Enhanced coalbed methane recovery	It is common for coal beds to have methane trapped in pore spaces and adsorbed onto the surface of the coal. In the case of seams that are too deep for economical mining, this coal bed methane (CBM) can be recovered and sold. CBM recovery can be enhanced by injecting CO_2 into the coal seam, as CO_2 preferentially adsorbs onto the coal surface and displaces the methane.
Enhanced oil recovery	A method that increases oil production by using methods that are not part of the normal pressure maintenance or water flooding. CO_2 EOR involves injecting CO_2 into depleting oil reservoirs to recover additional oil beyond that which would have been recovered by conventional drilling.
Fossil fuel	Any naturally occurring fuel of an organic nature formed by the decomposition of plants or animals; includes coal, natural gas, and petroleum.
Geosphere	The solid Earth that includes continental and oceanic crust.
Greenhouse gas (GHG)	A gas that does not absorb radiation of wavelengths in the visible light spectrum but does absorb infrared (heat) radiation. In the atmosphere these gases allow energy from the sun to reach the earth's surface, but limit infrared energy (heat) from escaping. CO_2 accounts for over 80% of the anthropogenic GHG effect. Other GHGs include methane, ozone, CFCs, HFCs, nitrous oxide and sulfur hexafluoride. Each gas has a different global warming potential and longevity in the atmosphere.
Hydrates	A hydrate is a naturally occurring, ice-like crystalline compound in which a crystal lattice of water molecules encloses a molecule of some other substance. The compounds are very dense and insoluble in water. CO_2 hydrates are being investigated for use in CO_2 capture and storage.
Kyoto Protocol	The result of negotiations at the third Conference of the Parties (COP-3) in Kyoto, Japan, in December of 1997. The Kyoto Protocol sets binding GHG emissions targets for countries that sign and ratify the agreement. The gases covered under the

	Protocol include carbon dioxide, methane, nitrous oxide, hydrofluorocarbons (HFCs), perfluorocarbons (PFCs) and sulfur hexafluoride (SF_6).
Mature fine tailings	A dense mixture of clay, silt and water that settles out of the tailings waste and forms a layer at the bottom of the tailings pond under a layer of water.
Methane	The main component in natural gas. It is also produced by the decay of organic matter.
Microseismic	Very small movements in the earth; earth tremor. Micro-seismic sensors detect sonic-bursts (sounds) generated by sudden small-scale slips/cracking, or changes in temperature, volume, pressure, or stress in rock mass formations and geomaterials. These sensors can be used to monitor oil and gas reservoirs for deformation, cracking, and other changes in condition.
Oil sands	Naturally occurring mixture of bitumen, water, sand and clay. Also referred to as "tar sands."
Pre-combustion capture	A system for CO_2 capture from a fossil fuel conversion where the fuel is combusted in air and resulting CO_2 is scrubbed, absorbed, or otherwise captured from the flue gas, which is primarily CO_2 and nitrogen.
Post-combustion capture	A system for CO_2 capture from a fossil fuel conversion where the fuel is decarbonized via gasification, pyrolysis, or reforming prior to combustion. The synthesis gas from decarbonization is primarily a mixture of CO_2 and hydrogen. The CO_2 is captured from the hydrogen before the hydrogen is combusted.
Seismic survey	A survey of geological layers under the ground, conducted by sending out shock waves and measuring the way in which the waves are reflected back from the different layers. The shock waves may be created by dynamite charges in holes or by mechanical vibrations at the surface (vibroseis). Geophones at the surface record the energy reflected back from different layers beneath the surface, making it possible to identify the geological structure.
Sequestration	See "Carbon sequestration."
Supercritical	Supercritical fluids are highly compressed gases, which combine properties of gases and liquids. This state occurs only when the temperature and pressure reach or exceed the critical point for a substance.
Unmineable coal seams	Coal seams which are inaccessible and/or uneconomical to mine due to the depth, coal quality, and technological or land use restrictions.

Abbreviations	
CO_2	carbon dioxide
CCS	carbon capture and storage
EOR	enhanced oil recovery
EUB	Alberta Energy and Utilities Board
GHG	greenhouse gas
H_2S	hydrogen sulphide
IEA	International Energy Agency
IPCC	International Panel on Climate Change
Mt	megatonne
Mtoe	Million tonne of oil equivalent
ppm	parts per million
TPES	total primary energy supply
UNFCCC	United Nations Framework Convention on Climate Change