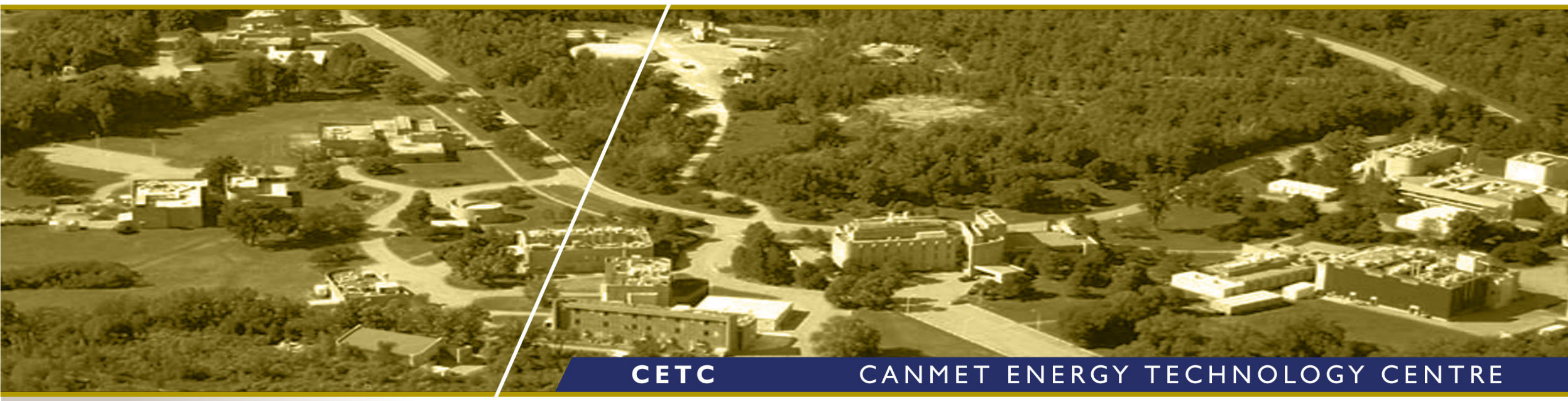


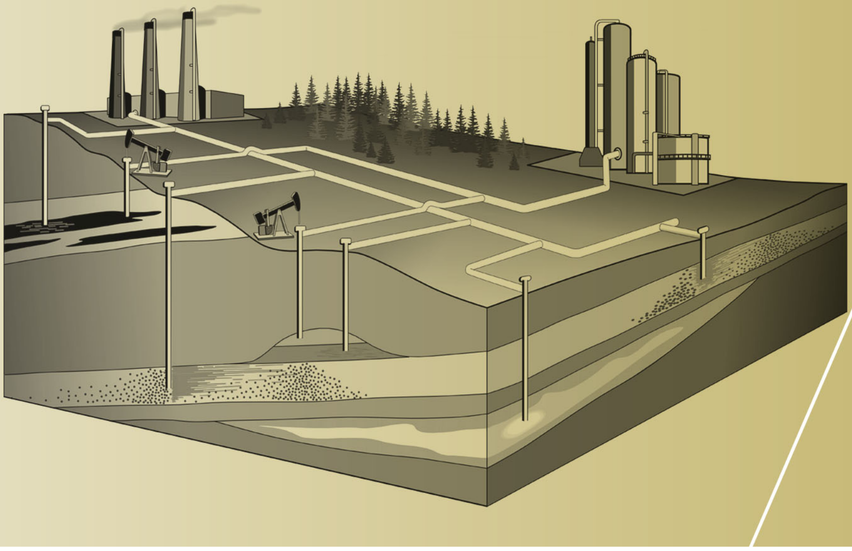
CETC CANMET ENERGY TECHNOLOGY CENTRE

CCSTRM

CANADA'S CO_2 CAPTURE & STORAGE TECHNOLOGY ROADMAP

www.co2trm.gc.ca

"technology for today's energy economy providing the basis for transformative change tomorrow"



CLEAN ENERGY TECHNOLOGIES
March 2006

Natural Resources Canada
Ressources naturelle Canada

Canada

Foreword

Climate change, caused by anthropogenic greenhouse gas emissions, is a century-scale and global issue. It represents clear risks characterized by significant uncertainties about both the costs and benefits of mitigation. It also, however, represents significant opportunities to develop new energy technologies and to secure additional value from Canada's resources by capturing, transporting and using carbon dioxide for enhanced oil and gas recovery as an initial phase of carbon dioxide capture and geological storage. Capture and storage holds an important position in the portfolio of options to reduce emissions, which include energy conservation, energy efficiency, and fuel switching, because it directly deals with emissions from fossil fuels and can deliver large greenhouse gas reductions starting in the near-term.

The magnitude of the problem cannot be underestimated, considering historic trends - while the efficiency in electrical appliances, light bulbs, turbines and other industrial instruments has increased by 30 to 50% in the past three decades, the use of energy has more than doubled. This is due to the dramatic increase in the use of electrical power which fuels our electronic age. We also need to consider the increase in world population (which is estimated to grow to 9.8 billion by the middle of this century), the gap between industrial and developing economies, and the fact that some 40% of the world's people currently have no access to modern energy. This added to the world's average real economic growth, estimated to be 2 to 3% per year for the next 50 years, suggests that conservation and efficiency gains will be overwhelmed by growth in energy use.

The above suggests that the world will need all the supply of energy it can access and indeed all projected trends indicate increased usage of fossil fuels in the 21st century. The hope for a low emissions hydrogen economy to replace today's fossil fuel based economy, remains far down the road. As a result, any efforts to stabilize greenhouse gas concentrations in the atmosphere should be seen as a long-term effort to slow the current emissions trend before ultimately reversing it.

An option to reduce the carbon intensity of the fossil fuel energy supply today is to capture the carbon dioxide, transport it, and store it in geological formations. This Carbon Dioxide Capture and Storage Technology Roadmap (CCSTRM) seeks to establish a robust architecture for addressing the technical risks and economic costs, with scientific understanding of geological, geotechnical, reservoir management and engineering aspects of capture and storage. In this way, a range of possible solutions is being developed to guide policy decisions and the domestic approach to be taken as part of international collaborative efforts. This roadmap must be seen as a critical first step to make Canada more competitive, as Canada is a major and growing exporter of energy resources.

The success of this roadmap, in helping frame the discussion of capture and storage to help achieve greenhouse gas reductions in Canada, requires industry-government collaboration to address the innovation gap and develop risk sharing mechanisms to reduce the risks inherent to the costly deployment of infrastructure and systems. In this regard, implementing the objectives of this CCSTRM would help accelerate collaboration, and align funders, researchers, industry, and governments, to ultimately achieve the vision embodied in this roadmap.

Dr. Eddy Isaacs, Managing Director

Alberta Energy Research Institute

Acknowledgements

Natural Resources Canada, Alberta Energy Research Institute and the Alberta Research Council, the co-leads of *Canada's Carbon Dioxide Capture and Storage Technology Roadmap* (CCSTRM), wish to acknowledge the vision, energy, financial support, and in-kind assistance of all contributors to the roadmap.

Financial Support and In-kind Assistance

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- Fluor Canada Ltd.
- Natural Resources Canada
- Natural Resources Defense Council
- Statoil
- United States Department of Energy
- University of Regina

Individual Efforts

The following individuals are acknowledged for their direct contributions to the CCSTRM. These individuals assisted on numerous occasions, both during and in between the workshops, and carried out much of the background research and the technical assessments that support the document (again in alphabetical order).

- Bill Gunter, Alberta Research Council
- Bill Pearson, Natural Resources Canada
- Bill Reynen, Natural Resources Canada
- Doug Macdonald, SNC-Lavalin (Downstream Oil and Gas Committee Leader)
- John Barrie, Fluor Daniel (Industrial Committee Leader)
- Kelly Thambimuthu, Natural Resources Canada
- Ken Brown, Alberta Research Council (Upstream Oil and Gas Committee Leader)
- Murlidhar Gupta, Natural Resources Canada

Appendix A provides a list of all the workshop participants (with special acknowledgments indicated for those who worked with one of the three committees), whose involvement and advice was greatly appreciated.

CCSTRM – Roadmap Advisory Committee

A special acknowledgement is given to Roadmap Advisory Committee members for their effort in providing feedback on drafts, attending meetings and putting the finishing touches on the final CCSTRM document.

- Bill Gunter, Alberta Research Council
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- Stefan Bachu, Alberta Energy and Utilities Board
- Stephen Kaufman, Suncor Energy Inc.

Authors of Roadmap Documents

The following are the pre-draft and final authors of the CCSTRM.

- Bob Mitchell, Inspired Value Inc. (author of preliminary draft roadmap)
- John Van Ham, Van Ham Resources Inc. (author of the final roadmap)

Everyone involved in the roadmap exercise wishes to acknowledge the work of Donna Baskin, whose dedication in organizing the three roadmap workshops, developing and maintaining the CCSTRM website, and support in writing and publishing the CCSTRM is greatly appreciated. Irene Coyle was an invaluable resource early on in the roadmap process and her assistance is also acknowledged.

Other Information Sources

The roadmap process benefited greatly from existing initiatives in Canada. The *Canadian Carbon Dioxide Capture and Storage Technology Network* (CCCSTN), which was established to promote the development and deployment of zero emissions technology in Canada, provided valuable information and resources.

The Alberta Research Council recently completed two reports on carbon dioxide capture and storage: *The CANiCAP Program*, and *The CANiSTORE Program* (Gunter *et al*, 2005; Gunter *et al*, 2004). These reports lay out planning options for the research, development and deployment of technology and knowledge related to CO_2 capture, transportation and geological storage in Canada.

The *Clean Coal Technology Roadmap* (CCTRM), recently released by Natural Resources Canada, is a sister document to the CCSTRM because of the strong relationship in subject matter (CCTRM, 2005). The development of clean coal technology is extremely dependent on CCS technology, and because coal-fired power plants represent a large opportunity for CCS, the latter is impacted by the success of clean coal. The CCTRM and CCSTRM together provide a consistent message on the value of low-emissions fossil fuels.

Other Canadian roadmap documents, including the *Oil Sands Technology Roadmap* and the *Hydrogen Roadmap*, also provide information and analysis used in the CCSTRM (ACR, 2004; H_2FCC, 2004).

As with any document of this type the CCSTRM is a snapshot in time. The situation is constantly changing and this document should be considered a work in progress to be augmented and added to as progress is made.

Table of Contents

Executive Summary

Industry, governments and research institutions around the world recognize that carbon dioxide capture and storage (CCS) is a technically viable option for significantly reducing the release of greenhouse gas (GHG) emissions to the atmosphere. By definition, CCS involves the capture and transport of carbon dioxide (CO_2) from industrial sources to an appropriate site for secure and long-term storage (see the Glossary for a detailed definition of CCS and other terms used in the roadmap). Storage options include injecting CO_2 into geological formations or oceans, or converting it to solid carbonates using mineral fixation, but the most promising option today is geological storage. Recognition of the role CCS can play in moving Canada closer to a low-emissions energy future has led to the writing of this guidance document on CCS technology in Canada: *Canada's Carbon Dioxide Capture and Storage Technology Roadmap*.

Embodied in this roadmap is the vision of *"technology for today's energy economy providing the basis for transformative change tomorrow."* CCS is seen as a technological solution that allows Canada to continue to increase its energy production while reducing emissions from these activities. This technology is one of many in a portfolio of options for reducing GHG emissions. Canada needs to consider as many economic options as possible, in light of the need to significantly reduce GHG emissions as part of the country's international commitments. However, the success of CCS depends on a number of important outcomes, including the research and development (R&D) of useful technology, the deployment of cost-effective CCS infrastructure, systems and human capacity and the engagement of Canadians in the debate on effective CCS policies and regulations.

CCS is strategically important to Canada for several reasons. First and foremost, Canada is endowed with an abundance of fossil fuels (including an unparalleled oil sands resource), around which a very strong set of industry sectors already exist. Second, CCS is not simply about enabling the use of existing energy reserves. It is also about increasing reserves through enhanced oil, natural gas and coalbed methane recovery. Third, reducing CO_2 emissions is a critical federal government policy priority as noted in Canada's climate change plan, which concludes that CCS technology could play a prominent role in domestic GHG reductions. Finally, Canadian researchers and energy industries are already recognized internationally in certain areas of CCS, and if Canada maintains its competitiveness, it could reap large economic advantages.

This roadmap is a snapshot of key information government policymakers and industry decision-makers need to know regarding Canadian opportunities in developing and deploying CCS infrastructure and systems, such as:

- ❑ The role of CCS in the emerging global and national energy contexts (Section 2)
- ❑ Global and national opportunities for CCS technologies (Section 3)
- ❑ The current state of CCS technology in the Canadian context (Section 4)
- ❑ Specific technology needs and pathways for developing them (Sections 4 and 5)
- ❑ The critical next steps and champions to facilitate the success of CCS (Section 5)

This roadmap concludes with a set of objectives for Canada, including: policy and regulatory frameworks, public outreach and education, technology watch and international collaboration, science and technology R&D, demonstrations, and national coordination. To fulfill these objectives requires championing efforts by industry and governments because investments in R&D and demonstrations of this magnitude are beyond the reach of any one company or government, and collaboration is essential. If meaningful collaboration takes place, achieving the goal of a low-emissions energy future is possible, and the ultimate result could be economic, environmental and social benefits for all Canadians.

The Challenges (Section 2)

As with any complex issue, a number of dynamics affect what will ultimately become of CCS. The changing international and national energy scenes both play into energy R&D decisions. The International Energy Agency indicates that by 2030 the world will be more fossil fuel dependent than today, both in absolute terms and in market share (at 82%). Canada's National Energy Board (NEB) also states that fossil fuels will continue to dominate domestic energy supply. The NEB indicates that, although conventional oil and natural gas resources are dwindling, unconventional sources like the oil sands and coalbed methane are making up for lost producible reserves. Current wisdom indicates that fossil fuels will continue to dominate energy supply in Canada and abroad.

Meanwhile, considerable pressure is mounting to mitigate climate change, and many believe that alternative or renewable energy sources are the solution. While alternatives like nuclear, hydro and renewable sources provide part of the solution, they are not the complete answer, particularly during the next few decades when some of the enabling technologies of these energy sources continue to mature. Technology is needed to satisfy climate change objectives today while at the same time allowing the Canadian economy to grow. CCS is one currently available option.

At the same time, much can be done to improve the efficient use of existing energy resources. Current oil and gas recovery factors range from quite low (below 10%) to very high (greater than 90%). It seems that many applications within that range might benefit from enhanced recovery using CO_2, either by increasing the recovery factor, or by producing the product more expeditiously.

Most work on CCS to date has been technical in nature, yet it is clear that addressing non-technical issues is equally important for the technology to develop. For example, clear and concise direction is needed for CCS development and deployment including policy and regulatory frameworks, capacity building and public awareness. Effective policy is important for the development and deployment of CCS on a large-scale in Canada and elsewhere.

The Opportunities (Section 3)

The opportunities offered by CCS are both local and global, with value-added benefits for traditional industries like fossil fuels, and with the potential for entirely new industry sectors to emerge over time. CCS may provide an economic option for reducing GHG emissions, and at the same time allow for the development of available and affordable energy sources to supply both local and global economies.

An enormous capture opportunity exists at the more than 8,000 facilities worldwide that each emit more than 100,000 tonnes of CO_2 equivalent per year. More than 16 giga tonnes (Gt) of CO_2 are available to be captured worldwide annually. Between 1,700 and 11,000 Gt of storage capacity is available in the world's sedimentary basins.

Canadian Large Final Emitters (LFEs) will produce more than half of the country's total GHG emissions by 2010, and LFE industrial sites provide the main domestic capture opportunities. Some of Canada's 68 sedimentary basins provide excellent storage opportunities, and the Western Canadian Sedimentary Basin (WCSB) in particular is considered to be world-class. Detailed analysis indicates that more than 3,700 mega tonnes (Mt) of storage capacity exists in the oil and gas reservoirs of the WCSB, with up to 450 Mt of economic capacity in enhanced oil recovery operations alone. The first Canadian CCS infrastructure and systems will be deployed in the WCSB to connect the emitting industrial facilities to storage sites via a CO_2 pipeline, gathering and distribution system.

Developing world-class, low-emissions energy sectors is the primary benefit of deploying domestic CCS infrastructure and systems. Achieving such an outcome would result in Canada becoming a leader in CCS technology deployment. However, this opportunity can only be realized if industry and government collaborate to address the technical, cost and policy barriers of CCS (noted previously), through targeted R&D and deployment activities.

Technology Pathways (Section 4)

The overarching technology pathway of developing CCS is actually a combination of passageways that converge around the common goal of CO_2 capture and long-term storage. These pathways each relate to one of the three CCS components: capture, transport and storage. Each component has its own research focus, goals and objectives, but the three must also be studied as an integrated system because each component is an essential element of operational CCS infrastructure and systems.

A number of technologies are being studied for capture (and compression) for a variety of industrial configurations, including post-combustion, pre-combustion and oxy-fuel combustion systems, as well as other industrial processes (details on each system are provided in Section 4). Specific technologies are being researched with these systems in mind.

Capture is the most costly of the three CCS components today, with cost ranges from (CDN) \$50 to \$70 per tonne of CO_2 (tCO_2) captured for post-combustion systems, (CDN) \$20 to \$50/tCO_2 captured for pre-combustion, and (CDN) \$13 to \$80/tCO_2 captured for oxy-fuel combustion (although, the actual cost of each option is likely to be nearer the bottom end of these ranges).

Capture has the greatest potential for future cost reductions at somewhere between 25 to 30% by 2025 (some specific components may experience 50% cost reductions).

CO_2 is easiest to transport in its dense phase whether by pipeline or tanker. Pipelines already transport CO_2 in North America today using existing technology and expertise from the energy pipeline industries. Tankers could also be used for land or ocean transport, with the latter potentially enabling the global movement of CO_2 from large source opportunities in places like China and the EU, to storage sites in Russia and the Middle East. However, tanker transport will be prohibitively expensive for some time.

Transport in Canada is estimated to cost (CDN) \$6/tCO_2 for every 650 km's transported in a common carrier pipeline network with a capacity of 14.5 MtCO_2/yr. Transportation involves relatively mature technology, so cost reductions will likely only come from the economies of scale of large infrastructure development.

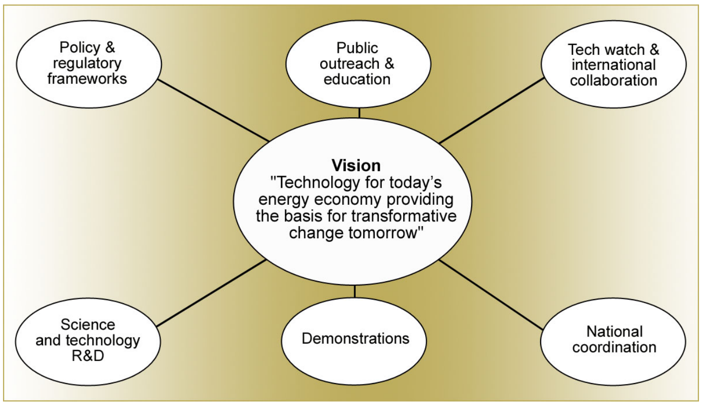
Although storage is the last step in the CCS process, it should be treated as a front-end consideration because the amount of CO_2 to be captured is limited by what can feasibly be stored. A number of natural mechanisms are proposed for storing CO_2 geologically in either value-added or non-value-added opportunities. Value-added opportunities include options like CO_2 enhanced oil recovery, CO_2 enhanced natural gas recovery, and CO_2 enhanced coalbed methane recovery and temporary storage. Non-value-added options include storage in depleted oil and gas fields and in deep saline aquifers. Although storage space is a limiting factor, it is not necessarily a constraint considering its availability around the world.

Injection and storage is often the least costly component of the CCS system, and in Canada costs range from (CDN) \$3 to \$9/tCO_2. The potential for future cost reductions in storage are low; however, the economic benefits of storage can sometimes eliminate any storage cost, and, in fact, offset part of the capture and transport costs.

Wide ranging costs are associated with each activity and the site specific characteristics of each capture facility, transport route or storage site will ultimately determine the full cost of any project. All costs will reduce over time as experience and learning is gained with the technology, or as economies of scale materialize. However, the deployment of cost-effective infrastructure and systems requires large upfront capital investments, which is not necessarily reflected in the previous cost estimates. An emerging concept in the WCSB is the notion of taking a more strategic approach to large-scale infrastructure development by developing a series of pre-selected emissions hubs. These would be connected (through a gathering system) to a CO_2 pipeline backbone that ultimately delivers the CO_2 (through a distribution network) to any one of a number of secure and long-term storage sites. However, to turn this concept into reality requires substantial investment.

The Way Forward (Section 5)

As previously noted, the vision that emerges from this roadmap is of *"technology for today's energy economy providing the basis for transformative change tomorrow."* To bring action to the roadmap and fulfill the vision, a number of critical objectives are identified, along with implementation champions whose responsibility will be to bring action to these objectives. As illustrated below, the six objectives include: policy and regulatory frameworks, public outreach and education, technology watch and international collaboration, science and technology R&D, demonstration, and national coordination. As indicated in the figure, each objective contributes to the overarching vision. The first three are policy oriented and achieving them would help develop enabling conditions for the deployment of CCS infrastructure and systems. The next two are technology oriented and are more closely linked with the technical content of the roadmap, the actual R&D and demonstration of technology. The final objective relates to the national coordination of any efforts related to the previous five objectives.



Policy and Regulatory Frameworks are necessary components of deploying CCS infrastructure and systems, which will ensure that the industry grows in an appropriate, safe and responsible manner. An effective policy framework is needed first because good policy acts as a guide for good regulation which will in turn ensure public health and safety, and environmental integrity.

Public Outreach and Education are needed to provide public information on the benefits and challenges associated with CCS. This objective could be implemented through a national CCS information program dedicated to the open and transparent gathering and dissemination of credible information on CCS technology and projects. The anticipated effect of such an effort would be the public's recognition of CCS as one of a number of options to reduce GHG emissions.

Technology Watch and International Collaboration are both needed to stay connected to international activities, and to keep watch on technology development around the world. Information from the technology could be made available through a virtual web-based national CCS intelligence centre which focuses on the gathering and exchange of competitive information. While competitive technology development will inevitably occur, international collaboration is important because of the magnitude of the effort required in developing and deploying CCS on a large enough scale to enable significant GHG emissions reductions. Such efforts will result in the provision of timely and relevant information which will accelerate CCS development in Canada.

Science and Technology R&D is of critical importance because of the role it plays in tackling specific challenges faced by domestic energy industries. Individual organizations or consortia can work to advance technology for all three CCS components (capture, transport and storage) in the context of Canada-specific science and technology needs. Conducting research and developing solutions to key technological gaps will enhance the prospect of successful CCS deployment in Canada, based on Canadian knowledge, expertise and technology.

Demonstration of new science and technology is one of the most important steps in installing new infrastructure and systems because it is the stage at which new technology and concepts are tested and proven (or unproven) to be technically and economically feasible. Joint industry-government consortia are an appropriate vehicle for carrying out demonstrations. Ultimately, successful demonstrations lead to minimized commercial and technical risks, and the development of Canadian infrastructure and systems.

National Coordination of R&D and demonstration activities in Canada can link all the work being done on CCS and provide synergistic benefits to all stakeholders. However, this objective goes beyond just technology coordination and includes the harmonization of policy and regulatory frameworks, public outreach and education, and technology watch. A robust and coordinated process for planning and undertaking CCS activities will result in the successful use of new science and technology in the commercial application of products and services for industry.

To implement the roadmap and successfully achieve the previous six objectives requires the support of a variety of industry, government and other stakeholder champions. As an initial step, the Roadmap Advisory Committee suggests the need for an implementation committee to meet and function as the implementer of the objectives of the roadmap over the coming year.

The time to invest is now, as a clear window of opportunity for developing CCS infrastructure and systems opens up over the next 25 years. If successful, Canada could see significant GHG emissions reductions by 2030, with estimates ranging from 10 to 100 $MtCO_2$ captured and stored annually in Canada within that timeframe. Successful demonstrations and the subsequent roll-out of technological components, expertise and know-how is the prize to be won. To achieve this, Canada needs a strategy and a plan that ensures that any new infrastructure and systems meet both current needs, and those of tomorrow. Significant funding will be needed to implement a strategy of this scale, but the returns will be equally large in terms of enhanced hydrocarbon recovery and tonnes of GHG emissions reductions delivered. A strategic plan with a made-in-Canada approach to technology and innovation will help meet our national objectives, and those of other nations around the world.

Ultimately, the message emerging from the roadmap initiative is the need for action today, to enable the vision of "technology for today's energy economy providing the basis for transformative change tomorrow"

List of Abbreviations and Units

ACR	Alberta Chamber of Resources
BAU	business as usual
BP	British Petroleum
Bt	billion tonnes
CANDU	Canada deuterium uranium
CBM	coalbed methane
CCCSTN	Canadian CO_2 Capture & Storage Technology Network
CCP	CO_2 Capture Program
CCPC	Canadian Clean Power Coalition
CCS	carbon dioxide capture and storage
CCSTRM	Carbon Dioxide Capture and Storage Technology Roadmap
CCTRM	Clean Coal Technology Roadmap
CDN	Canadian dollars
CETC	CANMET Energy Technology Centre
CH_4	methane
CO	carbon monoxide
CO_2	carbon dioxide
CO_2e	carbon dioxide equivalent
CO2CRC	Carbon Dioxide Cooperative Research Centre
CO_2-ECBM	CO_2 enhanced coal bed methane
CO_2-ENGR	CO_2 enhanced natural gas recovery
CO_2-EOR	CO_2 enhanced oil recovery
COS	carbonyl sulphides
CSEMP	CO_2 Sequestration and Methane Production
CSLF	Carbon Sequestration Leadership Forum
CSUG	Canadian Society for Unconventional Gas
DIP	direct iron production
ESA	electric swing adsorption
ECBM	enhanced coal bed methane
ENGR	enhanced natural gas recovery
EOR	enhanced oil recovery
EU	European Union
EUB	Alberta Energy and Utilities Board
GHG	greenhouse gas
Gt	giga tonne
H_2FCC	Hydrogen and Fuel Cell Committee

H_2S	hydrogen sulphide
HCN	hydrogen cyanide
HFP	Fuel Cell and Hydrogen Technology Program
IEA	International Energy Agency
IGCC	integrated gasification combined cycle
IPCC	Intergovernmental Panel on Climate Change
IPHE	International Partnership for the Hydrogen Economy
ITC	International Test Centre (for carbon dioxide capture)
ITM	ion transport membrane
km	kilo metre
kWh	kilo watt hour
LFE	Large Final Emitters
LNG	liquefied natural gas
Mb/d	million barrels per day
Mpa	mega Pascal
Mt	mega tonne (million tonnes)
MW	mega watt
MMV	monitoring, measurement and verification
N_2O	nitrous oxide
NEB	National Energy Board
NGO	non-government organization
NH_3	ammonia
NOx	nitrogen oxide
NRCan	Natural Resources Canada
OECD	Organisation for Economic Co-operation and Development
OPEC	Organization for Petroleum Exporting Countries
PJ	peta joule
ppm	parts per million
PSA	pressure swing adsorption
PTRC	Petroleum Technology Research Centre
R&D	research and development
SOx	sulphur oxide
SP	supply push
t/d	tonnes per day
t/yr	tonnes per year
tcf	trillion cubic feet
TSA	temperature swing adsorption

TV	techno-vert
UNFCCC	United Nations Framework Convention on Climate Change
US	United States
USD	US Dollars
USDOE	US Department of Energy
VSA	vacuum swing adsorption
WCI	World Coal Institute
WCSB	Western Canadian Sedimentary Basin

1. An Opportunity for Canada – Carbon Dioxide Capture and Storage

Around the world governments are becoming increasingly interested in capturing and storing carbon dioxide (CO_2) emissions as a way of mitigating greenhouse gas (GHG) emissions. A number of programs and initiatives have been undertaken as a result, under such forums as the Intergovernmental Panel on Climate Change (IPCC), the International Energy Agency (IEA) Greenhouse Gas R&D Programme and the Carbon Sequestration Leadership Forum (CSLF). Each of these organizations has produced reports and special papers on CO_2 capture and storage.

Canada's federal government, provincial governments and industry have a strong interest in this technology area. Under the leadership of the federal Climate Change Innovation and Technology Program, in 2001, these Canadian stakeholders began to develop a CO_2 capture and storage strategy for Canada as part of a larger low-emissions energy agenda. It was decided that a technology roadmap would be written on CO_2 capture and storage for publication and distribution to interested parties. Industry Canada and Natural Resources Canada (NRCan), through the CANMET Energy Technology Centre in Ottawa (CETC-O), provided initial support and facilitation for a process that has led to the creation of *Canada's Carbon Dioxide Capture and Storage Technology Roadmap* (CCSTRM).

Section Observations:

CCS is important on a global scale because of the potential to disconnect the relationship between economic growth and global GHG emissions rates

CCS matters domestically because Canada:

- *Depends on its vast fossil fuel resources*
- *Is a top industrial producer and exporter of fossil fuels*
- *Has enormous CO_2 storage potential in a variety of regions across the country*
- *Has the potential to be a global leader in CCS knowledge and expertise*

The vision embodied in this roadmap is one of "technology for today's energy economy providing the basis for transformative change tomorrow"

In 2001, NRCan and Industry Canada began a national process for the CCSTRM with a mission to identify the technology strategies and the process and integration system pathways needed to allow CO_2 to be captured and stored in Canada. As such, both organizations engaged in developing a technology roadmap to act as a guidance piece on potential technology pathways for the near and longer-term timeframes. The process consisted of four phases between 2003 and 2005, which included first a situation analysis, second the identification of technology pathways and research and development (R&D) strategies, third the setting of priority opportunities for R&D, demonstration and deployment, and finally the writing of the CCSTRM (Appendix B provides a detailed account of the process).

The following section provides a general introduction to CO_2 capture and storage by beginning with an overview of what CCS is, and why it is being discussed today. This includes a description of the vision and goals of the CCSTRM exercise, and a summary of each subsequent section herein.

It is important to note that the information throughout this roadmap deals with CO_2 capture and storage technology, even though the capture and storage of other GHGs may also be involved in the process. CO_2 capture and storage is the primary focus of the CCSTRM.

What is CCS?

Carbon dioxide capture and storage is a process for reducing GHG emissions into the atmosphere by first extracting CO_2 from gas streams typically emitted during electricity production, fuel processing and other industrial process. Once captured and compressed, the CO_2 is transported by pipeline or tanker to a storage site, often to be injected into an underground storage site (or geological formation), where it will be safely stored for the long-term.

Ideal locations for large-scale CO_2 capture include gas processing plants, fertilizer manufacturing facilities, thermal power plants and other sites that produce large amounts of CO_2, often in excess of one million tonnes of CO_2 equivalent ($MtCO_2e$) annually (IEA, 2004). These industrial facilities are often located near others, thus increasing the amount of available CO_2 for capture within the general vicinity.

The most suitable sites for cost-effective long-term emissions storage in Canada include geological formations such as active or depleted oil, gas and coalbed methane reservoirs, deep saline aquifers and salt caverns. Other potential storage options include mineral fixation or ocean storage (discussed in further detail in Section 4). However, mineral fixation would be prohibitively costly and have enormous environmental implications (related to the mining of serpentine for fixation). Meanwhile, ocean storage is the most controversial of the options, because of the immaturity of the technology, uncertainty over how CO_2 storage will impact ocean ecosystems, and questions regarding the permanence of ocean storage (IEA, 2004). Geological storage is the most promising for development and deployment in Canada, and therefore the opportunities related to CO_2 capture and geological storage (CCS) are discussed in detail in this document.

Why CCS Matters

Developing and deploying CCS technology on a global scale offers the opportunity to maintain a strong and vibrant global economy fuelled by affordable, convenient and available fossil fuels, while disconnecting the linkage between growth in economic activity and GHG emissions. The technology involved in CCS is both transitional and transformative in nature, as it allows for the continued movement along the current technological trajectory of developing and providing a means to low-emissions fossil fuels. Meanwhile, CCS is critical to future transformational change to a hydrogen/electricity-based energy economy. CCS will be a crucial technology in the first commercial operations that produce hydrogen on a large-scale for transportation and distributed generation.

Developing CCS is strategically important to Canada for several reasons. First and foremost, Canada (and its closest trading partner, the United States) is endowed with abundant fossil fuel deposits. Canada ranks second only to Saudi Arabia in remaining oil reserves (NEB, 2004). Canada is also blessed with large natural gas deposits, especially frontier and unconventional opportunities such as coalbed methane, tight gas, shale gas, and gas hydrates. Canada also has rich coal reserves, and in fact, North America has one of the largest global coal resources. Developing CCS technology is a means to extract the economic benefits of these resources while maintaining strong environmental objectives.

The International Energy Agency predicts large growth rates in global demand for all primary energy, mainly because of increased industrial activity in regions like Asia, India, Latin America and some parts of Africa. This presents market opportunities for energy exporting nations like Canada. Low-emissions fossil fuels from Canada would go a long way in meeting this demand without compromising the global environment. Therefore, CCS technology and expertise developed anywhere (including Canada) would be well received in international markets.

Fossil fuels are of strategic national importance to Canada as a number of essential sectors depend on these resources. This includes coal-fired power generation, oil and gas production, oil sands development, petrochemical manufacturing and transportation. Developing CCS will enhance the future value of these sectors while increasing the value of industries that use fossil fuels in their day to day activities (such as forestry, mining, cement, steel and manufacturing).

CCS is not simply about enabling the use of existing energy reserves; rather it is about increasing resource recovery factors and thereby increasing total Canadian energy reserves through efficiency gains in recovery operations. It is possible that CCS may be used to enhance the recovery of oil, natural gas and coalbed methane resources.

The continued production, processing and use of these fossil fuel resources contributes to the economy and to the quality of life of all Canadians. However, the continuation of current production, processing and utilization practices would result in large quantities of domestic CO_2 emissions over the coming years, a clear contradiction to today's international and domestic policy related to climate change mitigation. Therefore, disconnecting the historically congruent trends of economic growth and CO_2 emissions growth is a critical policy priority. As noted in Environment Canada's climate change plan (entitled *Project Green*) Canada intends for CCS technology to play prominently as a means to reduce GHG emissions (Government of Canada, 2005). This is an important technology for nations like Canada which face a particularly formidable challenge in reducing GHG emissions. The *Oil Sands Technology Roadmap* (ACR, 2004) and *Canada's Clean Coal Technology Roadmap* (CCTRM, 2005) also indicate the importance of CCS as a foundation technology to allow for the production of Canada's vast fossil fuel resources in an environmentally friendly manner.

To ensure the long-term outcome of economic growth and emissions reductions, many domestic stakeholders have worked hard in the past to become international leaders in CCS development. However, retaining this position will be difficult considering the international effort currently underway on CCS development. Although Canada was an early leader in CCS development, other jurisdictions (such as the United States, European Union, Australia and Japan) are coming to the forefront with technology and expertise of their own. Governments across Canada, industry leaders and other stakeholders need to work together through effective collaborative efforts (like those formed in the US and Australia) to develop targeted and specific policies and programs to rebuild and maintain Canada's position as a technology development and applications leader in this lucrative technology area.

It is imperative that Canada aggressively pursue CCS R&D to take advantage of current Canadian strengths and to capitalize on domestic and international opportunities. As already noted, inherent CCS opportunities exist in Canada, which, in combination, set Canada apart from many other parts of the world. These include the nation's current position as a country with:

- Vast fossil fuel resources, particularly oil sands and coal
- Internationally competitive industry producers and exporters of fossil fuels
- Enormous potential for geological storage of CO_2 in various regions across the country
- Existing, leading-edge knowledge and expertise in CCS applications

Vision and Goals of Roadmap Exercise

Embodied in this roadmap is a vision of "*technology for today's energy economy providing the basis for transformative change tomorrow.*" CCS is a technological solution that can provide immediate results to deal with today's energy and environmental needs while enabling Canada to move ever closer to a low-emissions energy future of tomorrow.

Guided by this vision, the ultimate goals of the CCSTRM process include:

- Accelerating the development of cost-effective CO_2 capture, transportation and storage technologies
- Building on the intellectual foundation that already exists in Canada to enable the development of a home-grown, world class CCS industry
- Forging alliances and partnerships to advance research, development and demonstration programs and projects

The CCSTRM was developed to engage Canadian experts, researchers, practitioners and policymakers in CCS and related fields to work to complete the following specific tasks:

- Determine whether the emerging global and national energy context necessitates a role for CCS
- Identify the opportunities for CCS technologies
- Define the current state of applicable CCS technologies in the Canadian context
- Provide a summary of specific technology needs for Canada and a pathway for developing them
- Identify the critical next steps and the champions to facilitate the vision in this roadmap

The CCSTRM lays out a set of strategic objectives intended to help develop a robust and successful domestic CCS industry. This roadmap is an information source and a planning tool to help industry, government and other stakeholders evaluate promising new CCS technologies, and to serve as a guide for R&D and demonstration decisions being made today. Achieving the objectives (which are outlined in Section 5) would result in the eventual development of low-emissions fossil fuel industries in Canada and thus economic, environmental and social benefits for all Canadians.

Roadmap Overview

The information and analysis in this roadmap is structured as follows:

The Challenges – an Issues Scan (Section 2) provides an in-depth explanation of why CCS is necessary. By understanding how the world energy scene is unfolding (demand is increasing), and the challenges that the energy sector faces (such as environmental issues, competition within the energy sector, and resource recovery issues), it becomes clear CCS technology is a critical area of opportunity.

The Opportunities – Low-Emissions Fossil Fuels (Section 3) covers the global prospects for CCS, by identifying the known potential of capture and storage opportunities both nationally and internationally. Significant CO_2 sources exist in close proximity to excellent storage sites in Canada and elsewhere, which means that reducing emissions from fossil fuels may be possible. For Canada this would translate into economic and societal benefits from the growth of its energy sectors, while achieving the goal of improving the nation's environmental performance.

Technology Pathways (Section 4) provides a review of Canadian technological needs and timeframes for developing the technology. The cost of each component of the CCS system (capture, transport and storage) is estimated, the potential for future cost reductions are indicated, and the known risks are identified. Research, development and deployment are needed for each component, and therefore strategic R&D needs are provided for all three. It is recognized that infrastructure and systems are more important than any specific technology, and from this idea the concept of emissions hubs and storage sites linked by a CO_2 pipeline (or backbone) emerges.

The Way Forward (Section 5) identifies a pathway for developing CCS in Canada, one that enables capitalizing on Canada's inherent opportunities for such technology. Six critical objectives are identified and detailed in terms of activities, reach, outputs and desired outcomes, with a final discussion on the implementation of the roadmap. The CCS roadway ahead involves a long and challenging process, but the CCSTRM provides a basis of information to help government, industry and other champions strive to tackle that journey, and to achieve the objectives identified herein.

2. The Challenges – an Issues Scan

Carbon dioxide (CO_2) is a naturally forming compound that is essential to life on the planet. The carbon cycle, a never ending movement and transformation of carbon (in various forms including CO_2) between the biosphere, atmosphere, oceans and geosphere, is an important natural phenomenon, which is only beginning to be understood by the scientific community. What is known is that a delicate balance exists, and significant changes in this balance can cause a serious response in terms of the earth's climate.

A problem arises in that human induced CO_2 and other GHG emissions are occurring today at an unprecedented rate. As the global economy grows, so do GHG emissions, because of the direct link between economic growth and growth in energy demand (which is primarily met by combusting coal, oil or other fuels). Therefore a serious challenge arises: the need to reduce, or even eliminate, GHG emissions while maintaining a strong economy which is dependent on fossil fuels.

This, and a number of other critical issues are driving change in energy industries, and this section provides a valuable overview of some challenges that are motivating the need for CCS technology today. It begins with a review of the emerging global and national energy scenes (in terms of energy supply and demand), and is followed by a review of key challenges that are changing the energy picture. These challenges include the growing urgency of certain environmental concerns, competition from alternative energy sources, current petroleum recovery factors (which can be improved), and the need for a policy framework regarding CCS development.

Section Observations:

Global energy demand is set to grow with conventional fossil fuels being the primary supply choice; the same is true for Canada

Solutions are needed to address the critical issues that may impact energy in the future:

- *Reducing emissions from fossil fuels to mitigate climate change*
- *Providing access to all economic energy sources to help meet future demand – conventional and unconventional*
- *Improving the recovery factors for conventional energy resources to increase existing reserves*
- *Creating effective CCS policy so the technology can play a meaningful role in a low-emissions energy future*

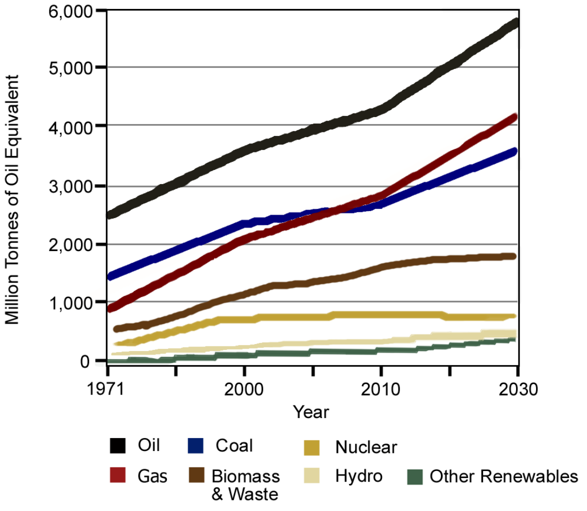
The Emerging Energy Scene

Throughout recent history the need for affordable, convenient and secure energy has led to a situation where fossil fuels accounted for 80% of the world's commercial energy supply in 2002 (IEA, 2004a). The IEA expects this number to rise to 82% by 2030. World primary energy demand is forecast to increase at a rate of 1.7%/yr between 2000 and 2030 (even with the looming prospect of higher energy prices); resulting in an increase equal to 60% of the current demand by 2030 (Figure 2.0).

Although increased demand for nuclear and renewable energy is anticipated, the IEA expects that fossil fuels will meet more than 85% of the global increase in energy demand over the coming 25 years (IEA, 2004a).

The IEA expects oil to remain the single largest fuel source in the global primary energy mix, as demand grows from 77 million barrels per day (Mb/d) in 2002 to 121 Mb/d in 2030 (IEA, 2004a). This growth will

Figure 2.0 World Primary Energy Demand



(Source: IEA, 2004)

primarily be driven by demand in the transportation and power generation sectors. However, oil's overall percentage market share will decrease slightly as its annual growth rate (at 1.6%/yr) is slightly less than the rate of increase in total energy demand.

The share of oil production from the Organization for Petroleum Exporting Countries (OPEC) will increase rapidly near the end of this timeframe, from a 2002 market share of 37% to a 2030 market share of 53%, as non-OPEC production begins to dwindle during this period due to decreasing reserves (IEA, 2004a). Large investments in supply infrastructure will need to be deployed to accommodate this shift in regional energy supply, which will likely result in increased security concerns regarding energy procurement, especially among energy importing nations like the United States (US), India, Japan, China and most European Union (EU) countries.

Oil will remain the most heavily traded fuel, and imports may account for 57% of North America's consumption (the US and Canada) by 2030. Demand will grow fastest in developing countries. However, escalating crude prices will force consumers to consider other options to meet their energy needs.

Part of oil's lost market share will be supplied by natural gas which has an expected growth rate of 2.3%/yr between now and 2030 (IEA, 2004a). Growth rates will be highest in Asia, Africa and Latin America, while actual growth will be highest in the mature European and North American markets.

Most gas markets are currently constrained by geographic boundaries, and market prices in each region depend on local supply and demand balances. The supply of liquefied natural gas (LNG) (which provides cross-boundary relief in gas markets) is expected to increase to 0.4 Mb/d in 2010 and 2.4 Mb/d in 2030. However, this will only serve a small amount of the global demand for energy (IEA, 2004a). The bottleneck is getting the gas to market which requires a large capital investment in exploration and infrastructure, estimated to be approximately (USD) $100 billion annually until 2030 (IEA, 2004a). Much of this expenditure will take place in Russia, the Middle East and Africa, which again raises security concerns over supply and capital investments.

Nevertheless, the IEA predicts that natural gas demand will double between now and 2030, mostly because of increased demand in Asia, Latin America and Africa. New power generation will account for more than 60% of the increase. LNG plants and new pipelines will be built in Russia and the Middle East, and account for over half of the gas traded by 2030.

Coal is the world's most abundant conventional energy source, accounting for 60% of remaining world hydrocarbon reserves, and 91% in the US and Canada combined (if oil sands or oil shale are not included) (NEB, 2003). The IEA states that proven world coal reserves of over 907 Billion tonnes (Bt) should last another 200 years with production at current rates (IEA, 2004a; BP, 2005). The EU, Australia, countries of the former Soviet Union (including Russia and Kazakhstan), China, and India all have extensive coal reserves. The latter two have large populations that rely heavily on coal for power generation – 75% of China's electricity is coal-fired.

Unlike oil and gas, many countries have domestic coal resources with 70 nations having recoverable reserves (WCI, 2005). Over 40% of these recoverable reserves are situated in Organisation for Economic Co-operation and Development (OECD) countries. Coal is a global commodity with relatively stable prices, which makes it an affordable and economically risk free source of energy.

Coal use will grow and continue to play a similar role in the world's energy mix in 2030, meeting 22% of global energy needs (IEA, 2004a). It will remain the primary energy source for power generation in 2030. Most of the growth will occur in developing Asian nations; China and India together will account for 68% of the total world growth (IEA, 2004a). The IEA emphasizes that the future of coal in OECD countries will rely to a great degree on climate change policy, and the development and deployment of advanced clean coal technology, which includes CCS.

The IEA (2004a) indicates that total nuclear capacity will grow by 2030, but by how much is uncertain. The cost of nuclear and environmental performance concerns may drive down demand. Meanwhile nuclear has enjoyed renewed interest in some countries because of it's near-zero emissions profile and the role it could play in energy security. As a result of these mixed driving forces there is little certainty over what role nuclear will play in future energy supply.

Nuclear energy's market share declined in recent years. The retirement of some existing plants led to a 2% decline in nuclear energy in 2003. In absolute terms, nuclear capacity may increase, but its overall share of the total primary energy market is predicted to decrease from 7% in 2002, to 6% in 2010, and 5% in 2030 (IEA, 2004a).

Biomass (and waste), hydro and other renewable energy sources all play a role in current markets and will continue to do so in the future. The sum contribution of these sources to total primary energy demand was 14% in 2002 – a number that will remain in 2030 (IEA, 2004a). Of the 14%, 7% is met using traditional biomass for energy (such as the burning of wood or dung) (IEA, 2004a). While contributions from traditional biomass will decrease, very high growth rates are expected for other renewable markets, thus resulting in the slight upward trend seen in Figure 2.0. The fastest growing markets, like wind and solar (which will grow six-fold by 2030), are starting from a very low penetration point so it will take time for their contributions to make a difference. Hydro is poised to grow, but will remain at 2% of primary energy supply because of resource limitations and the enormous amount of capital required to build new large hydro facilities (IEA, 2004a).

The National Scene

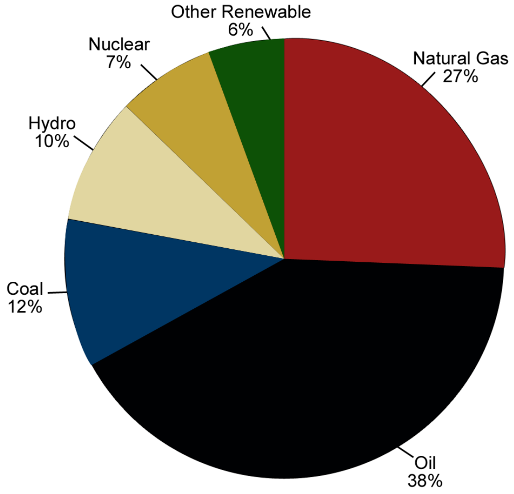
Canada is less reliant on fossil fuels than many nations; however, oil, natural gas and coal are still the top three sources for meeting primary energy demand even in Canada. Together they accounted for 77% of total primary energy demand in 2000 (see Figure 2.1). This reliance on fossil fuels increases in certain jurisdictions such as Saskatchewan where it is 93% and Alberta where it is 96% (NEB, 2003).

As indicated in the scenarios work done by Canada's National Energy Board (NEB) two years ago, it is expected that fossil fuels will continue to dominate energy demand in the future (Figure 2.2). Looking at either the Supply Push (SP) and Techno-Vert scenarios (TV) in Figure 2.2, fossil fuels are projected to dominate the picture in 2025.

In addition to relying on fossil fuels for domestic energy demand, Canada derives large revenue streams from their trade and export. In 2000, Canada produced 16,128 peta joules (PJ) of primary energy, of which 11,363 PJ was consumed domestically, leaving 4,765 PJ for export abroad. The majority of energy exports are fossil fuel based, such as oil, natural gas and coal.

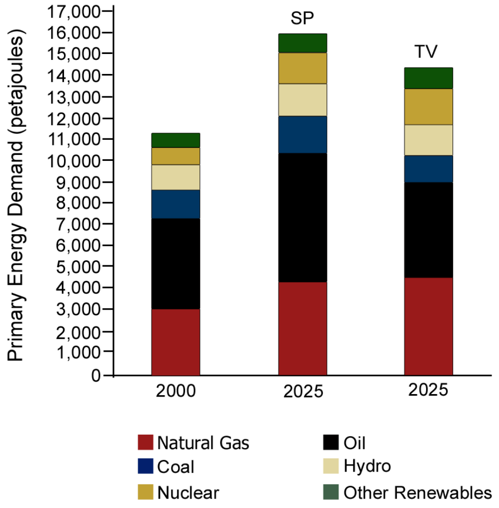
Fortunately, however, Canada is blessed with abundant energy resources, and its fossil fuels in particular are world-class in scale. With the recent addition of Alberta's vast oil sands deposits to conventional reserves, Canada quickly became the second largest nation in terms of established reserves in 2002, with 178 billion barrels in place (NEB, 2004). Canadian coal reserves are also large at 6.6 billion tonnes (with many hundreds of millions of tonnes more in resource) (WEC, 2004). With the scale and quality of hydrocarbon resources available in Canada, it's clear that careful consideration must be taken as to how to treat this economic

Figure 2.1 Primary Energy Demand by Fuel Type
(Total = 11,363 PJ in year 2000)



(Source: NEB, 2003)

Figure 2.2 Predicted Primary Energy Demand by Fuel Type



(Source: NEB, 2003)

opportunity. The future development of both conventional and unconventional hydrocarbon resources will greatly impact Canada's economic future.

Whether looking at the NEB scenarios or the previous IEA forecasts, a common theme is that energy demand will increasingly be met by fossil fuels. While conventional oil and gas reserves in the Western Canadian Sedimentary Basin (WCSB) are maturing, Canadian industry is moving to increase established reserves of its unconventional oil and gas resources (such as oil sands and coalbed methane) to meet demand long into the future. A vast coal resource can also easily be turned into reserves in Canada, and these too will supply energy long into the future. Meeting the demand projected by the NEB is possible, as there is no imminent shortage of fossil fuel energy resources in Canada.

The oil sands are a living example of how quickly Canada can add up reserves in a new world of relatively high energy prices. Official Canadian oil reserves jumped to 178 billion barrels in 2002, moving Canada from a very low standing (on the global scale) to its current position as the country with the second most reserves. A similar story emerges for coalbed methane. Canadian potential for coalbed methane is thought to be between 150 and 500 trillion cubic feet (tcf) in place, which compares to the estimated existing undiscovered conventional potential of 71 – 99 tcf in the WCSB (CSUG, 2003; NEB, 2003). It is also thought that the world's gas hydrate deposits contain more organic carbon than all other known fossil fuels combined, and some of the largest and best known deposits are in Canada. However, gas hydrates production is far from becoming economically feasible, and it will be some time before the world sees gas hydrate reserves added to the assets of any energy company (probably not until post-2025). However, the simple truth remains: while conventional petroleum resources are being exhausted, there is no shortage of other fossil fuels to make up the shortfall.

What all of this does highlight, however, is the growing need for CCS in Canada. To realize the future benefits of Canada's rich energy resource endowments (including conventional oil and gas, coal, oil sands and unconventional gas), while at the same time achieving reductions in domestic CO_2 emissions, requires new and innovative technologies, practices and processes that better enable efficient resource development and provide assurance of environmental integrity.

Challenges to Overcome

Energy systems, today and in the future, are extremely dependent on fossil fuels, and as global energy demand increases this may raise a number of critical challenges. The issues include: environmental concerns that arise from fossil fuel use, the potential need for alternative sources of energy to help meet demand, the need to enhance recovery of existing energy resources, and the need for effective policy to provide solutions to these issues.

Environmental Concerns

Today's fossil fuel industries already use many innovative technologies to reduce their environmental footprint on land, water and air resources. Examples include reduced land footprint from oil and gas activities and active land reclamation, reduced pipeline and offshore leaks and spills, tailings pond management for coal preparation plants and oil sands upgrading facilities, and reduced gas flaring and venting from oil and gas production sites. Continual improvement in practices and procedures, and higher industry standards also contribute to reduced environmental impacts.

Significant air emissions reductions have already been achieved at existing power plants, oil refineries and natural gas processing facilities. However, further reductions are needed to continue to reduce environmental impacts such as acid rain, smog, particulates and air toxics build-up, and climate change. Solutions to all of these problems are needed. CCS is one of many options suggested for dealing with climate change-causing GHG emissions, and therefore the issue of climate change is one of the primary drivers behind CCS development today.

Climate Change

A natural system called the 'greenhouse effect' regulates the earth's temperature by keeping a somewhat constant concentration of heat-trapping greenhouse gases (GHGs) in the atmosphere. Human induced or anthropogenic GHG emissions are a concern because they are increasing annually. Anthropogenic CO_2

emissions have increased atmospheric GHG concentrations by more than 31% in recent years, from pre-industrial levels of 280 parts per million (ppm) to 368 ppm in 1999 (IPCC, 2001). Most anthropogenic emissions are caused by fossil fuel energy production and consumption (mostly from combustion processes) with the remaining emissions (10 to 30%) coming from land use change and deforestation. Energy accounted for nearly 25 Gt of CO_2 emissions in 2003, with oil contributing 40.8% of these emissions, coal 38.4%, natural gas 20.4%, and only 0.4% coming from other fuel sources (IEA, 2005). As CO_2 and other GHG concentrations increase in the atmosphere, so does the planetary greenhouse or warming effect.

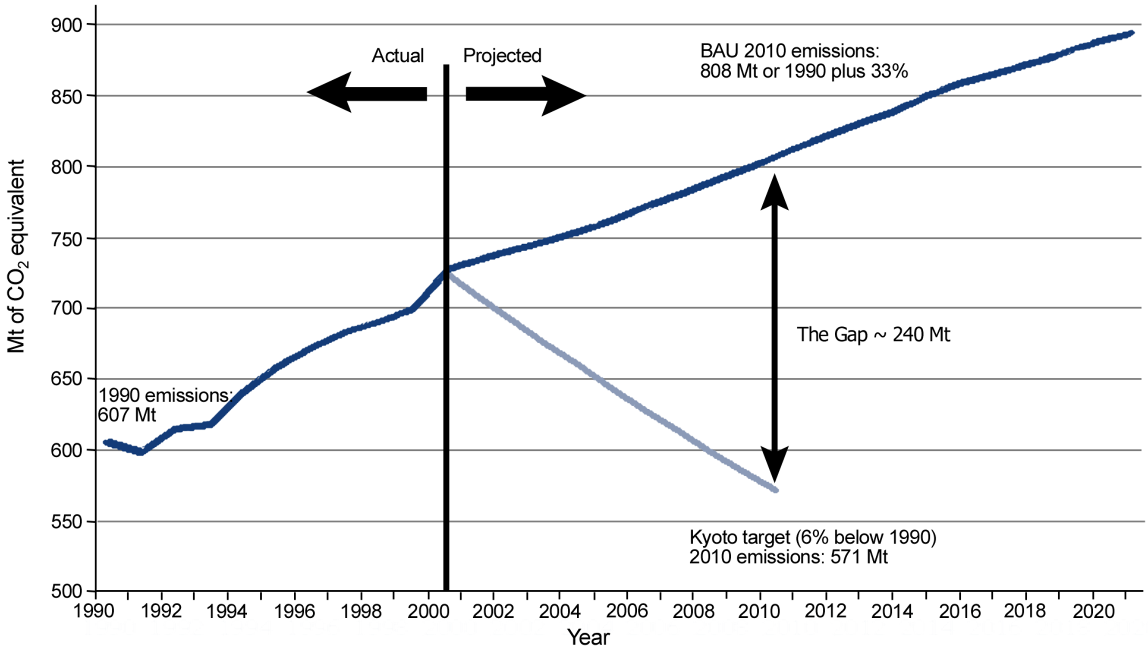
Carbon Dioxide (CO_2) is the GHG of most concern, being responsible for 62 to 64% of the enhanced greenhouse effect today. However, methane (CH_4) is another significant GHG, and one that escapes during coal mining and petroleum processing operations. Nitrous oxide (N_2O) is a GHG that results from many combustion processes, including those used in internal combustion engines which are used throughout the transportation industry (in trains, trucks and cars). Ozone and a number of trace gases also contribute to the greenhouse effect. Although CO_2 is the most problematic GHG of the group, other GHGs may become part of the capture and storage process as new technology is developed to accommodate other gas streams over time.

The United Nations Framework Convention on Climate Change (UNFCCC) was struck to address the climate change issue, and in fact has the ultimate objective of “achieving stabilization of GHG concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system” (UNFCCC, 1992). The Intergovernmental Panel on Climate Change (IPCC) was established to provide scientific, technical and socio-economic information relevant to the understanding of climate change, and provides much of the technical information used at UNFCCC meetings for discussion and decisions. The IPCC recently completed a report on CCS entitled *IPCC Special Report on Carbon Dioxide Capture and Storage*, which states the important role of CCS in a portfolio of global measures aimed at stabilizing GHG concentrations (IPCC, 2005). This role for CCS in a portfolio of options for reducing GHG emissions is also supported by the popular publication by Pacala and Socolow (2004) in Science magazine. The IPCC also identified the significant role that CCS will continue to play in developing transformational new energy systems and infrastructure based on hydrogen/electricity, and perhaps even bio-based energy carriers.

Canada ratified the Kyoto Protocol to the UNFCCC in 2002, thus agreeing to lower its GHG emissions to 6% below 1990 levels during the period from 2008 to 2012. However, the gap between Canada’s Kyoto target and the business as usual (BAU) scenario has increased since 1990 (see Figure 2.3). In 2002 it was estimated that the gap in the 2012 timeframe may reach 240 $MtCO_2e$ or more, if the appropriate reduction programs and initiatives are not in place (Government of Canada, 2005). The latest estimates indicate this gap may have grown to 270 Mt or more, due primarily to higher than expected growth in gross domestic product (Government of Canada, 2005). The challenge facing Canada is how to reduce these emissions while minimizing the negative economic impact of making the reductions. In an ideal (but perhaps somewhat unrealistic) situation, the negative impacts would be mitigated, and in fact turn out to be positive benefits resulting from the development of technology and knowledge that would result in a more innovative and competitive Canadian marketplace.

The Large Final Emitters (LFE) group, a compilation of over 700 large emitting companies in Canada, are responsible for the vast majority of Canadian industrial GHG emissions. Industry in general (which is largely represented by the LFE), is already responsible for more than half of Canada's total GHG emissions (as indicated in Figure 2.4) (Environment Canada, 2003), a share that is expected to increase by 2010. As a result, LFE companies are expected to collectively reduce their emissions by 39 Mt CO_2e/yr by 2008 to 2012 (using the original methodology for calculating the LFE target) in the Government of Canada climate change plan (Government of Canada, 2005).

Figure 2.3 Canada's Kyoto Protocol Challenge



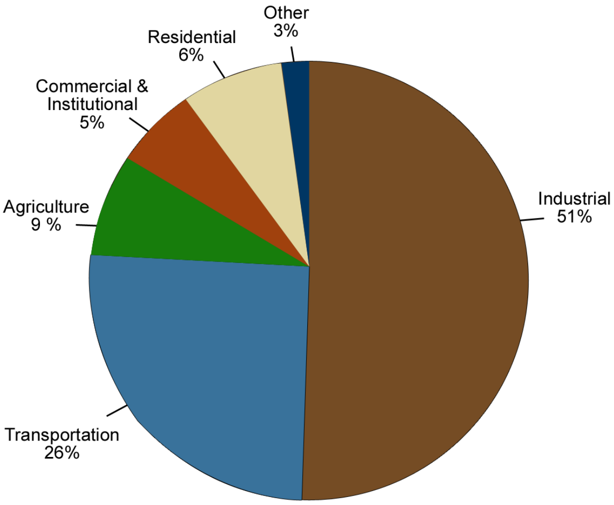
Note: actual and projected emissions numbers and the baseline are currently being revised
(Source: NCCP, 1999; Gov Can 2002)

This indicates that some sort of a carbon constraint is emerging in Canada, and it seems quite likely that industry could be expected to reduce emissions even more in subsequent years (post-Kyoto).

Within the LFE group, emissions are split as indicated in Figure 2.5. The fossil fuel sectors (thermal electricity and oil and gas combined) account for 78% of total LFE emissions, therefore reductions from these sectors are essential (Environment Canada, 2005). Thermal power generation is the largest single industry sector source, contributing nearly all of the 33% of emissions allocated for electricity in Figure 2.5, and the coal-fired facilities in Alberta, Saskatchewan, Ontario and Nova Scotia generate the majority of these emissions (Environment Canada, 2005).

Emissions from these thermal power plants and from other fossil fuel industries are some of the primary contributors to the asymmetrical distribution of GHG emissions by province across Canada (see Figure 2.6). Although Alberta only has the fourth largest population in Canada (its population of 3.3 million is far lower than the provinces of Ontario and Quebec which have 12.6 and 7.6 million inhabitants respectively), it emits the most GHGs of any province or territory (Statistics Canada, 2005). Saskatchewan has the highest GHG emissions on a per capita basis of all provinces in Canada.

Figure 2.4 GHG Emissions by Sector

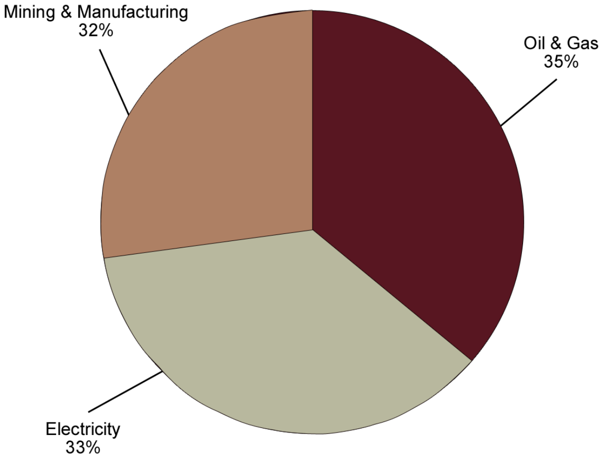


(Source: Environment Canada, 2005)

Currently Canada does not regulate GHGs emissions, but the situation is changing rapidly, and certain provincial jurisdictions plan to regulate regardless of federal direction. LFE companies will likely be able to use a number of flexible mechanisms under this legislation, including domestic emissions trading and the use of offsets and international mechanisms under the Kyoto Protocol (including International Carbon Markets, Clean Development Mechanism, and Joint Implementation). Canadian LFEs will also have the option to reduce emissions from their operations through energy efficiency, fuel switching, sequestering carbon in the biosphere, and capturing and storing CO_2 geologically.

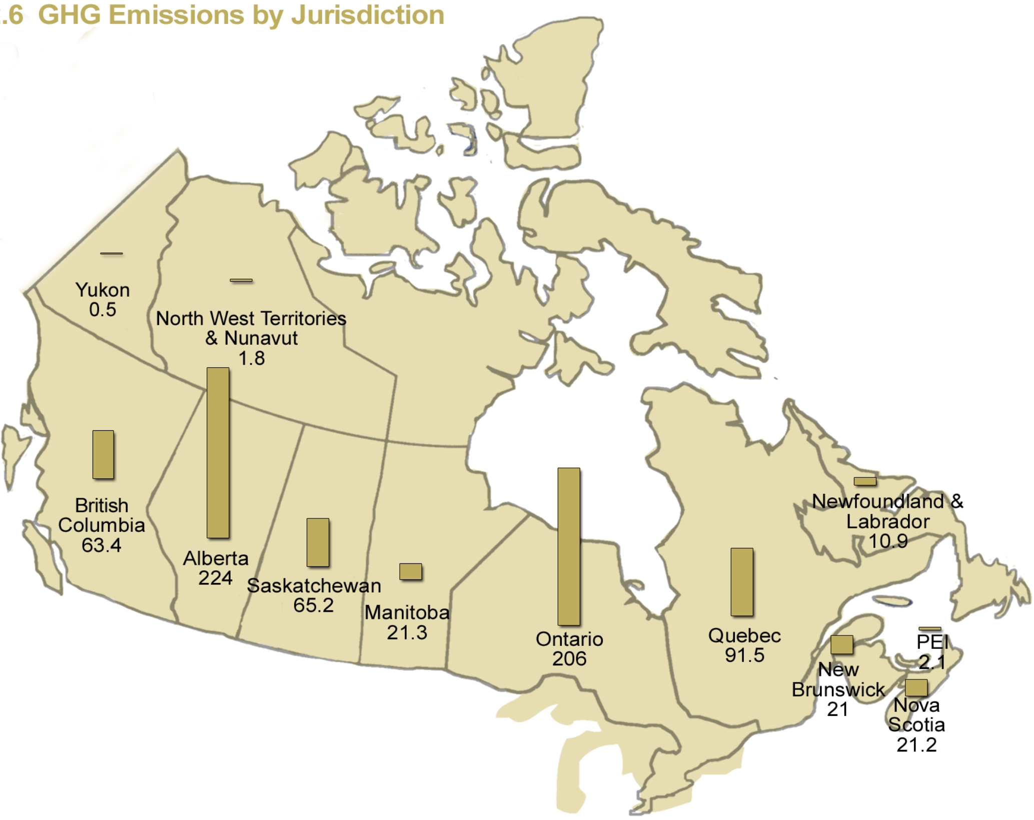
CCS offers an important opportunity to reduce Canada's net emissions, and the UNFCCC is expected to endorse CCS as a recognized and encouraged method of reducing CO_2 emissions into the atmosphere in the near future. Once accepted by the international community, CCS can begin contributing to Canada's emissions reduction efforts, but will likely not contribute in any significant way until sometime after 2012. How long until CCS contributes in a meaningful way depends on how aggressively Canada pursues the research, development, testing and deployment of CCS technology and practices.

Figure 2.5 Emissions from Large Industrial Emitters 2000 (Total 342 Mt)



(Source: Environment Canada, 2005)

Figure 2.6 GHG Emissions by Jurisdiction



(Source: Environment Canada, 2005)

Competing Alternative Energy Sources

As already noted, a number of other options exist to try to reduce CO_2 emissions from energy systems. This includes reducing emissions through energy efficiency and conservation, which has both economic and environmental benefits. However, energy efficiency and conservation can only go so far, beyond which a significant change to energy production and use is needed. Another option is to reduce emissions through fuel switching to less CO_2-intensive fuels like natural gas. However, using natural gas still results in significant GHG emissions, and therefore capturing these emissions for storage would still be necessary. While the fossil fuel sectors continue to be the most dominant providers of energy on the global scene, a number of alternative energy sources continue to compete, and over time, are making inroads into conventional markets. Therefore, these other sources (which have been briefly discussed) should be considered in the Canadian context to determine what impacts, if any, they might have on fossil fuel sectors, because any such impacts would also affect CCS.

Nuclear

The centrepiece of Canada's nuclear industry is the Canada Deuterium Uranium (CANDU) pressurized heavy water reactor. There are 22 CANDU reactors in Canada, 20 in Ontario, one in Quebec and one in New Brunswick. The Ontario plants were originally planned for decommissioning by 2010, but are being, or have been, refurbished to extend their lifetimes to at least 2020.

Today's appetite for new advanced reactor construction in Canada is uncertain. The industry still needs to improve the economics of nuclear power and prove that the handling of radioactive waste can be managed successfully. As well, to plan and commission a new nuclear facility takes a decade to complete, which is far too long for most private investors. In fact, only public institutions seem capable of bringing nuclear projects to fruition. Therefore public policy plays heavily into the future of nuclear, and as a result public acceptance becomes critical.

While nuclear may one day play a significant role in Canada's energy future it is not a clear-cut option at this point. As a result, another choice must be available to supply Canada's energy needs.

Hydro

Hydroelectricity provides 60% of Canada's electricity generation, with 62,500 MW of the 64,000 MW of hydroelectricity coming from large-scale hydro (NRCan, 2000). Large hydro is the least expensive source of base-load electricity because of its low associated fuel and operating costs. Hydro is also considered to be near-zero emissions which has served to increase its attraction. Canada's large hydro capacity is expected to increase by 20% by 2025 (NEB, 2003), with most of the new generation coming from British Columbia, Manitoba, Quebec and Newfoundland and Labrador.

This capacity is not enough to meet future growth in electricity demand, let alone to make up for the replacement of existing generation capacity that has served its plant life. New large-scale hydro projects are expensive and difficult to build. Building hydroelectric capacity entails long-term projects that are extremely capital intensive. These projects have significant impacts on land and water resources. As a result, hydro is no longer considered to be 'the' green option in power generation, despite its renewable stature. As with nuclear, hydro is not a clear-cut option for providing all the future electricity capacity Canada needs, therefore an alternative must be made available.

Wind

The cost of wind power has decreased dramatically due to technology improvements and economies of scale in turbine production over the past two decades. Canada has a large wind resource, but its development is limited because of competition from other low-cost electricity supplies. In addition, wind power is intermittent and therefore can only supply a portion of the total installed generation capacity. Although wind is the fastest growing source of new electricity generation in Canada (and in the world) in terms of the rate of installed new capacity, its overall presence in the energy mix will continue to be small in the near future.

Biomass

Biomass is the second most abundant source of renewable electricity in Canada, with the two main industrial sources of biomass being sawmill residues and black liquor from pulp and paper mills. The pulp and paper industry has more than 1,200 MW of installed capacity (often co-fired with fossil fuels). Independent power producers use wood waste from sawmills for an additional 200 MW in 10 plants across Canada. Small amounts of electricity are generated from landfill methane by incinerating municipal solid waste or using the biogas from anaerobic digesters.

Biomass on its own is not an economically feasible option in most cases, but it can be co-fed into advanced fossil fuel-fired facilities to generate significant emissions reductions over a regular plant. Energy efficiency improvements and biomass co-feeding can dramatically improve the emissions intensity of either coal or natural gas-fired generating stations. In addition, the same CCS processes being developed for fossil fuels may also be applied (with incremental changes) to co-fed facilities. By using CCS in conjunction with a biomass energy source, the result is not only the elimination of GHG emissions, but also the extraction of GHGs from the atmosphere and subsequent storage of them underground, thereby contributing net negative emissions (or 'neg-emissions'). This process would begin by promoting the growth of biomass to increase the sequestration of CO_2, followed by the capture of that CO_2 when the biomass is either combusted, liquefied or gasified, and finally storing the CO_2 in geological formations.

Hydrogen

A hope exists today for hydrogen to one day substitute for fossil-based energy. However, it should be noted that hydrogen is an extremely reactive substance not found in its pure form in the natural environment, and it must be derived from other substances such as water, hydrogen sulphide or hydrocarbons. This distinguishes hydrogen from the sources noted earlier in that it is a produced energy carrier much like electricity.

Today, hydrogen production in commercial quantities comes from hydrocarbons. Using today's hydrogen production technology results in more CO_2 being generated (on a per-unit-of-heat basis) by producing hydrogen from fossil fuels and then converting it to energy (via a fuel cell or a turbine), than by generating an equivalent amount of energy through directly combusting the fossil fuel.

Electrolysing water using a renewable energy source such as hydro or nuclear, is a possibility for producing emissions-free hydrogen. However, this process is nowhere near cost-effective on a commercial scale, and until it is, the best use for these energy sources is to directly feed the electricity into the grid.

Nevertheless, the notion of a 'hydrogen economy' receives a lot of attention and significant global efforts are underway to enable such a future. This includes the US-led *International Partnership for the Hydrogen Economy* and the *European Hydrogen and Fuel Cell Technology Platform* project. Canada's first hydrogen technology roadmap entitled *Charting the Course: A Program Roadmap for Canada's Transition to a Hydrogen Economy* (H_2FCCC, 2004), speaks to Canadian efforts to develop and commercialize hydrogen based technologies like fuel cells. All of these initiatives indicate that mass hydrogen will likely be produced from fossil fuels (for quite some time) in whatever hydrogen economy emerges (IPHE, 2005; HFP, 2005; H_2FCC, 2004). Therefore, like the fossil fuel based economy of today, a hydrogen economy of the future will likely rely on CCS technology to reduce CO_2 emissions arising from energy production.

Resource Recovery Factors

A challenge that has always faced the global energy industry is current recovery factors of certain hydrocarbon resources. Although both coal and natural gas have high recovery factors (~100% and 90% respectively), oil and coalbed methane are harder to extract from geological formations. With today's high energy prices, producers are looking for ways to increase these factors and thereby boost recoverable reserves and ultimately profits.

The situation is no different in Canada's WCSB, which is a maturing oil and gas region that has been extensively explored for any and all sources of conventional hydrocarbons. The focus of large energy companies investing in the WCSB today are the large unconventional oil and gas deposits (such as the oil sands and coalbed methane), and enhanced recovery opportunities such as enhanced oil recovery (EOR), and to a much lesser extent, enhanced coalbed methane recovery (ECBM) and enhanced natural gas recovery (ENGR).

Oil recovery factors are site specific and depend on the characteristics of the hydrocarbon product and host reservoir. Average recovery factors for Alberta light-medium versus heavy crude oil (using primary recovery techniques) is 23% and 13% respectively, which averages to 19% overall (EUB, 2005). The oil and gas industry has developed a number of secondary techniques to enhance recovery factors, and the use of water flooding and solvent flooding has brought the total average recovery factor to 27% (EUB, 2005).

A technique being used in some applications is CO_2 enhanced oil recovery (CO_2-EOR). It is anticipated that CO_2-EOR can recover anywhere between 8 to 15% of the total original oil in place, (IEA, 2004), and therefore this constitutes a significant boost in production in many cases. However, other secondary recovery techniques such as water flooding may have better results in certain locations, and a decision must be made on a reservoir by reservoir basis as to which EOR technique would be best.

CO_2 enhanced coalbed methane recovery (CO_2-ECBM) is still a speculative technology (in the infancy of its technological development), but, if successful, it is expected to improve CBM recovery factors to 90% from the current range of 40 to 50% (IEA, 2004). Even conventional natural gas, which has a recovery factor of 90%, may benefit from CO_2 enhanced natural gas recovery (CO_2-ENGR) in the form of a slight recovery boost, but more importantly, through a faster recovery process which would also prove economically beneficial. Much more detail is provided on all of the enhanced recovery techniques in Section 4.

Enhanced recovery techniques using CO_2 injection would increase the recoverable reserves of many North American hydrocarbon resources (with the exception of mined coal). Increased reserves, through the use of enhanced recovery techniques, have both economic and energy security implications, and are an indication of the benefits that CCS can provide on many fronts.

Effective Policy

A non-technical challenge facing today's energy industries is the lack of a clear and concise policy on the role of CCS, and the subsequent incentives and regulations that would result from such a policy agenda. Most of the work to date on CCS has focused on technical issues, but social, political and administrative issues related to CCS are very complex, and, unless properly addressed, could delay commercial deployment of the technology. It is completely understandable that some policy gaps exist today as this is a new technology area, and some of the uncertainties related to CCS are still being worked through. However, policymakers must begin to tackle the issues facing CCS today and start to develop a framework under which a robust and vibrant industry can develop.

Work is being done to address many of the policy gaps and the recent *IPCC Special Report on Carbon Dioxide Capture and Storage* communicates an enormous amount of important technical information to help policymakers make their decisions. Another useful document for policymakers is the IEA's *Prospects for CO_2 Capture and Storage*. Part of the role of the CCSTRM is to provide relevant information to the same senior policymakers. With the correct technical information in mind, appropriate actions and strategies can be taken to develop policy and regulatory frameworks, capacity building and public awareness in Canada.

Policy Framework

The building of a robust CCS policy framework needs to start now. An effective policy framework can start with a vision and strategy for the role that CCS can play both internationally and in Canada, in the portfolio of options for dealing with GHG reductions. This includes a clear indication of how CCS can operate within and along side other policies and measures related to climate change, energy and sustainable development, which was the overarching theme that emerged from the 2005 G8 Summit outcome in Gleneagles Scotland. At the centre of this theme is the idea that energy and energy technology are essential elements in achieving the necessary GHG reductions to stem climate change while also managing to sustain the global economy.

As outlined in a recent position paper by the Pembina Institute (Marr-Laing *et al*, 2005), the government needs to address some critical policy decisions related to climate change and CCS including: what amount of reductions are to be expected from CCS in Canada, and in what timeframe; who will pay for the development of CCS infrastructure and systems (government or industry); and, which specific CCS activities are most desirable from a societal point of view? Other overarching decisions related to climate change are also needed to guide CCS policy in Canada.

An important policy direction under this framework may be to assist in the safe and responsible development of both global and domestic CCS industries. This would require the use of appropriate policy incentives or penalties to either directly or indirectly drive the development and deployment of CCS infrastructure and systems. The policy framework and mix of incentives/penalties would be discussed openly and transparently, to engage Canadians in the debate, and include relevant opinions on how to develop a strong domestic CCS industry.

A joint effort between federal, provincial and territorial jurisdictions may be necessary for a Canadian policy framework, because there would be aspects of the framework that have international, federal, provincial and territorial implications.

It seems most appropriate for the policy work to precede the development of a regulatory framework, because once effective policy is in place it can guide the development of regulation. A policy framework would also include strategic planning for other essential elements such as capacity building and public awareness.

Regulatory Framework

A suitable regulatory framework must respond to the needs of different parties. Industry needs to be confident that regulation is workable and feasible. Planners of individual projects need to know the rules and regulations that govern their operations. Financial institutions need assurance that the projects they invest in meet regulatory requirements. The public needs to understand and accept that appropriate regulations are in place to ensure public safety and environmental protection. Finally, the regulator itself needs to have confidence that the framework is sufficient to meet its reporting, compliance and other regulatory needs.

One specific issue that needs resolution through regulation is the handling of “avoided” versus “captured” emissions. The use of CCS increases the amount of energy used by an energy system due to the additional energy that is required to capture, compress, transport and inject the CO_2. If this additional energy is supplied by using fossil fuels, more CO_2 is emitted from the system. Therefore, there is a difference between the actual amount of CO_2 captured and stored in a system (gross emissions), and the amount of CO_2 avoided (net emissions) by using CCS to reduce emissions from the original plant designed without CCS. As an example, if the CCS facility actually captures 90% of the emissions, the avoided emissions may only be 75 to 80% of the original emissions due to the excess emissions. Whatever regulatory framework is in place, it needs to distinguish between the two so that accurate tracking of both numbers can be undertaken.

Another issue that arises is the permanence of CO_2 stored in a geological formation. One interesting approach to the issue of slow, but persistent leakage of CO_2 through the lithosphere and potential seepage to the atmosphere is to determine the total quantity of fossil fuels in place to set an upper limit on the required storage time (IEA, 2004). For example, if fossil fuels are used to their full potential, and if a CO_2 concentration of 450 ppm is the acceptable limit in the atmosphere, then a retention time of at least 7000 years is needed for geological storage (IEA, 2004). Regardless of such a limit, geological repositories should be designed for zero leakage, with clear regulations on acceptable levels of leakage and seepage (based on the limit) in case such an event takes place.

Other issues important to a CCS regulatory framework include the monitoring, measurement and verification (MMV) of the stored emissions. MMV will be important in determining the performance of storage systems by verifying whether massive amounts of CO_2 can be stored over the long-term. MMV is an important area of regulation because it entails an essential set of procedures and protocols for addressing any health, safety and environmental concerns regarding storage operations.

Capacity Building

A CCS industry is poised to begin in Canada and internationally. However, the cost of developing and deploying new CCS technologies and approaches is high. Therefore, the industry needs to be focused and strategic in its activities and investments. An approach to investing in capacity building, both human and infrastructure, is an important step that needs to be guided by policy.

Canada and other nations will benefit most by supporting an approach of cost-sharing, pooling of expertise, collaborating and disseminating knowledge to build global capacities in CCS. CCS needs to be piloted, field tested, adapted and commercially demonstrated, and far too many promising technologies exist for any one nation to undertake the necessary steps in solitude. In addition, large-scale projects are expensive. For example, the *IEA Weyburn CO_2 Monitoring and Storage Project* – a Canadian CO_2-EOR project in Saskatchewan – has cost (CDN) $28 million to date, but this is on top of an initial commercial project investment of (CDN) $1.5 billion. The Norwegian *Saline Aquifer CO_2 Storage Project* (or the Sleipner Project) cost a similar amount. It will take at least five or six more of these demonstration projects, followed by testing the most promising concepts in different locations, to ultimately determine best approaches for CCS. Because of the size of these investments and the long lead times in project development and proofing, international collaboration is important, and strategic policy aimed at building this global capacity is critical.

Another essential form of formal capacity building is investment in human capital through education, research, mentorship and succession planning. Governments, companies and research organizations engaged in CCS activities have a vested interest in funding the development of formal education programs in CCS to help train the next generation of engineers, technicians, policymakers and business leaders that work in CCS. A big part of this training and education includes the transfer of existing skills, knowledge and expertise to the next generation of researchers and practitioners, and therefore formal efforts for succession planning and mentoring is needed.

Public Awareness

Public awareness and eventually acceptance of CCS is needed for capture and storage projects to be widely implemented across Canada and around the globe. However, the notion of capturing and storing CO_2 in geological structures is relatively new, and the general public is quite unaware of the topic in many countries. While surveys in Japan suggest that 31% of respondents know what CCS is, the US number is only 4% (IPCC, 2005). Further, some responses indicate that CCS risks are being seen as an 'end-of-pipe' solution, a technology that simply treats the symptoms and not the root cause of climate change. Others may view CCS as a delay tactic that enables the continued use of fossil fuels instead of other renewable energy sources. Most surveys conducted to date suggest that even where there is support for CCS, it is described as 'reluctant' rather than 'enthusiastic' (IPCC, 2005).

Effective outreach and awareness building will help balance any incomplete information or unsubstantiated views, and help contribute to the widespread understanding of this important option for meeting Canada's climate change goals, and the pivotal role the technology can play in transitioning today's economy to a new low-emissions energy future. However, raising public awareness is not a Canadian issue alone; it is a global problem that must be addressed internationally. Even if Canada or another society were to endorse the technology, global acceptance of the technology is required for the industry to be developed, simply because of the global nature of the climate change issue and the required solutions. Thus outreach and awareness building is needed for the general public, policymakers and regulators, both domestically and internationally.

A special case of awareness building is needed for financiers and insurers, because companies that develop and deploy CCS will depend on these stakeholders for investment dollars and for risk management approaches for the projects.

Section Summary

According to the IEA, fossil fuels supplied 80% of global energy demand in 2002 and will supply 82% in 2030. While efficiency gains are being made in energy use, it will take a 60% increase in energy supply to meet total demand in this timeframe. Essentially, world energy demand continues to grow and fossil fuel sources will continue to be the supply choice. Energy demand is also growing in Canada, a country that is richly endowed with world-class conventional and unconventional fossil fuel resources.

At the same time, a number of critical issues challenge the choices being made regarding energy supply. Environmental issues like climate change are creating pressure to reduce global dependence on fossil fuels. CCS technology offers an alternative approach by enabling the development of low-emissions fossil fuel industry sectors. This technology would be an enormous benefit to Canada and like nations that are endowed with vast fossil fuel resources, both conventional (like oil, gas and coal) and unconventional (like oil sands and coalbed methane). A robust and thriving CCS sector would assist countries like Canada in their struggle to meet global GHG reduction commitments, while continuing to grow the domestic economy.

A number of energy alternatives show promise for meeting future energy demand; however, each faces a number of its own issues. Hydroelectricity is limited in its growth potential by resource availability. Nuclear faces a complex set of economic, environmental, and societal challenges that keep the industry from growing in western countries. Other renewable energy technologies are at a very early stage of development. An alternative is needed for the interim period, such as a technology like CCS which allows for the use of low-emissions fossil fuels until alternative energy can be deployed at a later date. However, CCS should not only be viewed as a transitional remedy, rather it should be seen as a way to transform to a low-emissions future energy industry, such as a hydrogen/electricity, or perhaps even a bio-based, energy future.

Until then a much better job can be done on the use of existing resources. CCS can be used for CO_2-EOR, CO_2-ENGR or CO_2-ECBM to both increase recoverable reserves and enable their expeditious recovery. Either way the result is an economic benefit with environmental and social advantages for all Canadians.

A final challenge is the development of effective CCS policy for addressing the role of CCS in the energy system today and in the future. Much of the CCS work being done so far is of a technical nature, mostly on technology research, development and deployment. Much more work is required on a CCS policy framework, a regulatory framework, capacity building and public awareness. In part, the technical information provided in the CCSTRM is meant to help inform policymakers during their endeavours in these relatively new policy areas.

3. The Opportunities – Low-Emissions Fossil Fuels

Canada is well suited to benefit from the development and subsequent roll-out of CCS technology at home and abroad. CCS is an opportunity that will contribute to mitigating climate change effects. It is an economic opportunity in that the technology would be used in both Canadian and global applications, thus opening a large market to whoever develops the technology. Adding value to already innovative and advanced fossil fuel sectors and enhancing their resource base, through the development of new technology and knowledge, would provide further benefits to all Canadians.

As illustrated in Figure 3.0, CCS involves a suite of opportunities (and therefore technologies) along the entire value chain, from the capture of CO_2 from large point sources, to its subsequent compression and transportation from one site to another, and finally through its injection and storage into underground geological formations. As an example, the process may involve capture from industrial sources, like a power plant, transportation via a CO_2 pipeline, and injection into either value-added or non-value-added storage sites (such as producing oil and gas reservoirs, coal beds or deep saline aquifers).

Section Observations:

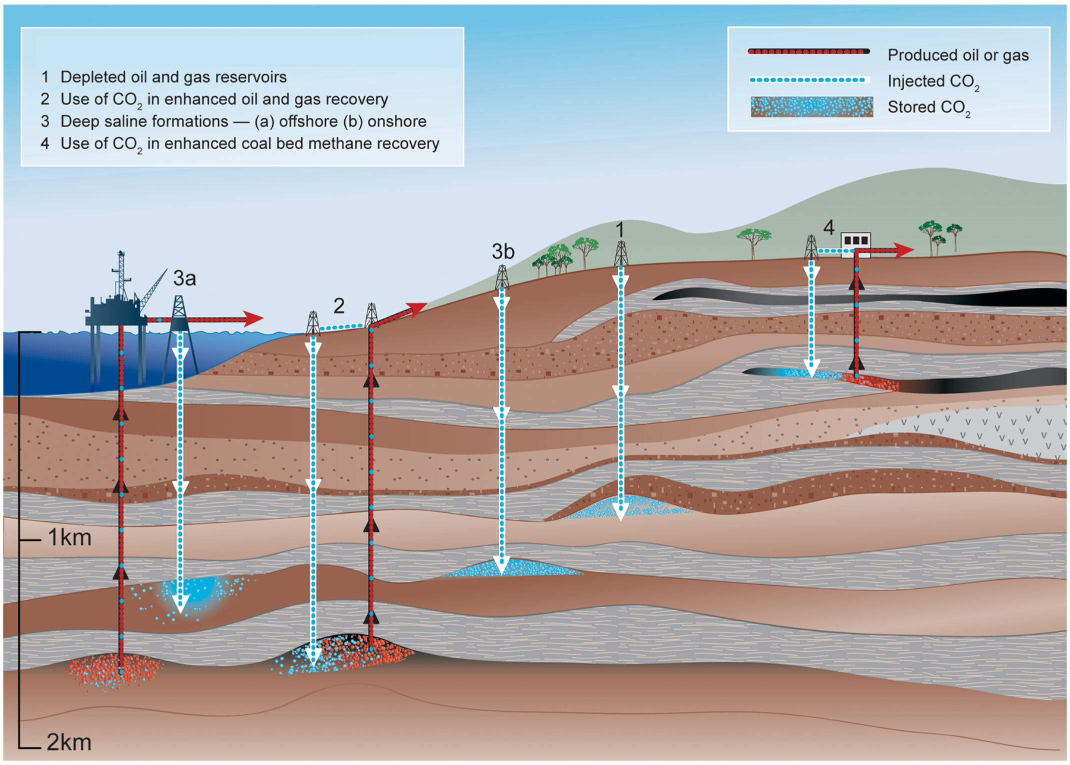
Developing CCS technology for domestic use will provide economic, environmental and societal benefits to all Canadians

Globally, over 8,000 capture sites have been identified today and between 1,700 and 11,000 $GtCO_2e$ of storage potential exists

Three local regions could be capturing nearly 3.4 $MtCO_2$/yr today for storage somewhere in the WCSB's 3,762 $MtCO_2$ of storage potential (in oil and gas reservoirs alone)

A low-emissions Canadian fossil fuel industry is the ultimate goal, and gaining ground in CCS R&D and deployment would be inherently advantageous for the nation

Figure 3.0 Geological Storage Options for CO_2



(Source: IPCC, 2005)

It is serendipitous that fossil fuel combustion contributes the majority of global anthropogenic CO_2 emissions, and yet one of the greatest opportunities for storage is the available pore space in former fossil fuel reservoirs. In addition, many of the capture opportunities are in the fossil fuel installations and facilities. Added to this, CO_2 can be used to enhance the recovery of fossil fuels by using it to sweep the resource out of pore space thereby storing the CO_2 in the vacated reservoir space (as illustrated in option 2 of Figure 3.0*)*. The side benefit of enhancing recovery (whether using CO_2-EOR, CO_2-ENGR, or CO_2-ECBM) means that these storage opportunities will likely be pursued first, followed by storage in depleted hydrocarbon reservoirs and in deep saline aquifers.

This section begins with a look at the opportunities for CCS in a global setting, by looking at global storage potential and source opportunities. Following this is an account of the opportunity in Canada, again looking at both storage and source potentials. The approach of discussing storage prior to sources is intentional as it is important to know something about ultimate storage capacity before discussing how much CO_2 to capture.

International Opportunities for CCS

Table 3.0 CCS Programs and Initiatives

Program/Initiative	Organizational Facts	Mission
CO_2 Capture Project (CCP)	Industry led initiative of 8 oil and gas companies which includes some government involvement; initiated in 2000.	Develop new breakthrough technologies which reduce the cost of CCS.
Carbon Sequestration Leadership Forum (CSLF)	International initiative established in 2003; consists of 20 members, including China, the US, Japan, Canada and several EU members. The CSLF consists of major energy producing countries and users under one organization.	Facilitate the development of CCS technologies; make CCS technologies broadly available internationally; and identify and address wider issues relating to CCS (such as policy or regulatory issues).
International Energy Agency Greenhouse Gas Programme (IEA GHG Programme)	International collaborative research program (includes 16 member countries and 10 industry sponsors) established in 1991. A major focus under the IEA GHG Programme is CCS.	Evaluation of technologies aimed at reducing GHG emissions; promote and disseminate results and data from evaluation studies; facilitate practical research, development and demonstrtion (RD&D) activities.
United States Department of Energy (USDOE) Carbon Sequestration Technology Roadmap and Program Plan	US government R&D program focused on CCS; annually updates its Carbon Sequestration Technology Roadmap and Program Plan.	R&D on affordable and safe sequestration approaches to reduce GHG emissions using CCS, and thereby helping stabilize atmospheric GHG concentrations.
Cooperative Research Centre for Greenhouse Gas Technologies (CO_2CRC)	Australian government program to support collaboration between government, industry and research centres in Australia and like entities around the world.	Research the logistic, technicial, financial and environmental issues of capturing inudstrial sources of CO_2 emissions and storing them in deep geological formations.
Canadian CO_2 Capture and Storage Technology Network (CCCSTN)	Collaborative multi-stakeholder effort to draw on synergies among Canadian CCS research efforts underway; initiated CCSTRM process in Canada.	Promote the development and deployment of zero emissions technology in Canada, with a focus on CCS technology.

(Source: CCP, 2005; CSLF, 2005; IEA GHG Programme, 2005; USDOE, 2005; CO2CRC, 2005; and CCCSTN, 2005)

To date, most CCS activities have been or are taking place in North America, Europe (in and around the North Sea), Australia and Japan, and these countries/regions are considered the past and present leaders in developing CCS. Many years ago the International Energy Agency (under its *Greenhouse Gas R&D Programme*) foresaw that CCS technology would play a significant role in future efforts to mitigate climate change. The IEA still sees CCS as a "promising storage option capable of achieving deep reductions in the foreseeable future" (IEA GHG R&D Programme, 2005). A number of international initiatives, programs and partnerships have the specific intent of developing and deploying CCS technology (see Table 3.0), which indicates the degree of international support this technology area is receiving today.

The IPCC has recently provided the UNFCCC with advice on CCS technologies (for both geological and ocean storage). The recent report, entitled *IPCC Special Report on Carbon Dioxide Capture and Storage*, will be used in future UNFCCC deliberations to discuss and make policy decisions on the future role for geological and/or ocean storage in mitigating climate change. The IPCC report states that, in the portfolio of measures for stabilizing GHG concentrations, capture and geological storage is important because it offers the potential to make GHG reductions during the next decades while fossil fuels continue to dominate energy markets (IPCC, 2005). CCS (using geological storage) is one of few options available today that can offer the deep GHG reductions needed beyond those achieved through energy efficiency and fuel switching. Even during a new energy future, where hydrogen and electricity are the energy carriers, CCS would have a role.

Storage Potential

Based on the study of natural and engineered analogues, it seems likely that CO_2 can safely be stored in geological formations around the world. CO_2 already occurs naturally in large volumes in many different geological formations around the world, where it has been safely trapped for millions of years. Often CO_2 occurs in sedimentary basins that also hold oil, natural gas and other liquids or gases for geological timeframes. At depths below 800 m, CO_2 is in a supercritical (liquid-like) phase, and has a density that efficiently allows it to be stored in pore space (IPCC, 2005).

The geological structures and physical properties of oil and gas fields have been extensively studied and are very well understood worldwide. In addition, infrastructure and wells are already in place in these regions and could be adapted or augmented for the handling and storing of CO_2. This significantly increases ultimate storage potential because it increases the economics of actually injecting and storing CO_2 underground.

The world houses hundreds of sedimentary basins which are variously suited for CO_2 storage; some provide excellent opportunities, others require further study, and some are not at all suitable. Estimates of the global technical potential for geological storage are shown in Table 3.1. Clearly the greatest volumetric potential exists in deep saline aquifers, but enormous potential also exists in depleted oil and gas fields and coal seams (that cannot be mined). Because of existing expertise and knowledge related to the oil and gas reservoirs, and because of the economic benefit of using CO_2 for EOR, ENGR and ECBM, it is likely that these opportunities will be the focus for initiating CCS infrastructure and systems development. At today's rate of GHG emissions, this economic capacity may represent hundreds of years of storage potential (IPCC, 2005).

Table 3.1 Global Geologic Storage Capacity

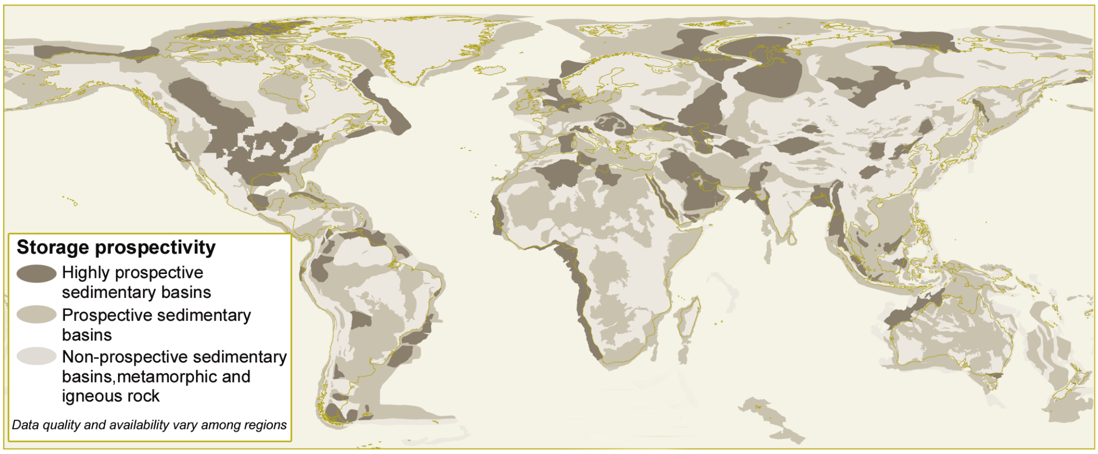
Storage Opportunity	Storage Potential *(in $GtCO_2$)*
Depleted oil and gas fields (including EOR and EGR)	675 - 900
Unminable coal seams (including ECBM)	3-15 - 200
Deep Saline Aquifers	1,000 - 10,000
Total Geological Storage	1,678 - 11,100

(Source: IPCC, 2005)

Figure 3.1 depicts the geographic location of storage sites around the world, indicating the locations where storage potential is highly prospective versus improbable. The information in this figure is relatively cursory and will likely change as further research is conducted, however it serves well for illustrative purposes. While storage capacity exists around the world, certain regions have greater potential than others.

fig2-4_storage

Figure 3.1 Global Storage Opportunities



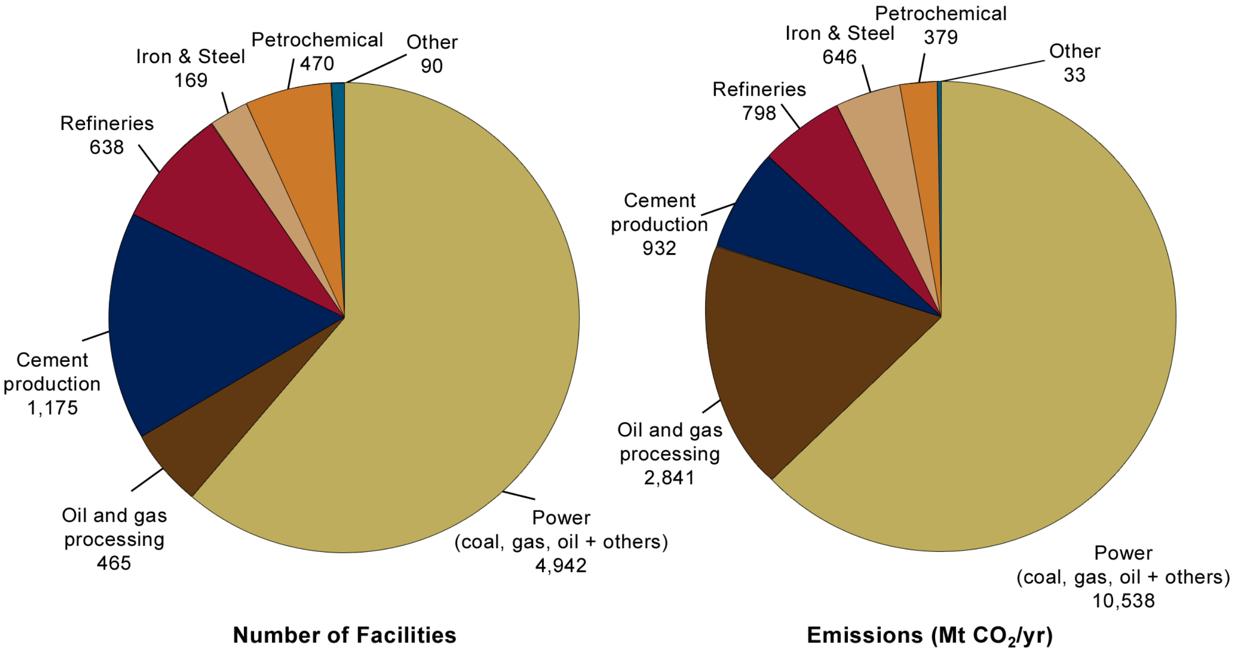
(Source: IPCC, 2005)

Sources

A number of factors are used to determine the practicality of CO_2 source opportunities. The volume of CO_2 emissions available is important because high volumes are needed to justify the cost of developing infrastructure. CO_2 concentration, and its partial pressure in the gas stream, is also important as both play into the efficiency of capturing and compressing the CO_2. Only stationary sources are being considered at this time because even the largest non-stationary sources (ocean liners or aircraft) are too small to justify CO_2 capture in these applications today.

A database of 8,049 industrial facilities around the world has been compiled, each of which emits more than 100 $ktCO_2e$ annually. Together, these facilities account for 70% of global CO_2 emissions (IPCC, 2005). Of these sources 4,942 generate power and collectively account for 10,538 $MtCO_2e/yr$. Figure 3.2 illustrates these sources by depicting the total number of large point sources by category and the total allocated emissions globally by facility type.

Figure 3.2 Global Sources of CO_2 by Number of Facilities and Total Emissions



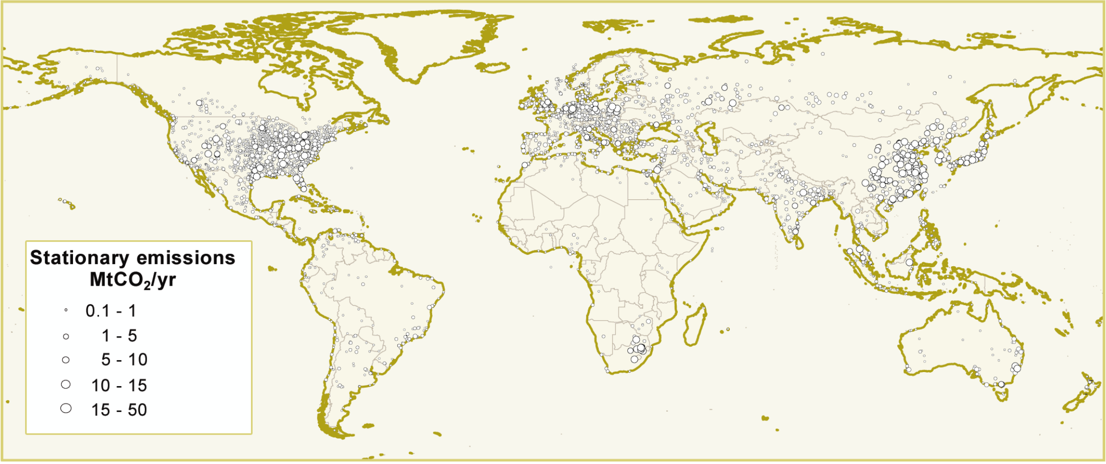
(Source: IPCC, 2005)

A wide variety of sources exist, including thermal power plants, oil and gas processing plants and other industrial facilities. Power generation, especially coal-fired, is considered the greatest opportunity for CCS in the long-term because of the abundance of global coal reserves and because of the CO_2 emissions profile from this industry. CCS will likely have its greatest impact in this segment of the energy sector. The next priority industries become oil and gas processing and refining, and manufacturing (such as cement, iron and steel and petrochemicals). A third category would likely be transporation emissions (not included in the figure), with the intent being to de-carbonize transporation fuels prior to using them, which of course will not happen until significant changes occur to the transporation infrastructure and systems.

From all these potential source options, a number of niche opportunities rise to the top. These include the high concentrated sources such as hydrogen production and fertilizer manufacturing facilities. Fertilizer plants are often considered the earliest opportunities for deploying CO_2 capture in commercial applications. Approximately 13 $MtCO_2$ could be captured from these facilities today (IPCC, 2005).

The geographic distribution of industrial sources is important when identifying the top opportunities. Remote sources are not ideal because of the cost of transportation. Figure 3.3 illustrates the global source opportunities (by size) overlaid on the same map as was used in Figure 3.1. First examination of the two maps reveals some good potential correlations between sources and storage basins, with many sources either situated on top of or within 300 km of a storage site (IPCC, 2005). In some cases, the sources are close to producing oil or gas fields (as in the Western Canadian Sedimentary Basin), thus offering both the environmental opportunity for storage and the economic opportunity for enhanced hydrocarbon production. However, the IEA notes that many of the largest sources in Europe, China and India are far from the best storage opportunities in Russia, the Middle East and Africa (IEA, 2004). Therefore, while there is some geographic correlation, many of the largest opportunities to reduce emissions would require large-scale transportation networks (either pipelines or ocean tankers) to move CO_2 to adequate storage sites. The relative location of sources and storage opportunities is one of the limiting factors on the development of CCS infrastructure and systems.

Figure 3.3 Global Source Opportunities



(Source: IPCC, 2005)

By matching local point sources with commercially CO_2-EOR, CO_2-ENGR or CO_2-ECBM opportunities, the IPCC has identified over 500 international projects with potentially low net CCS costs. This constitutes quite a lot of potential to initiate the development of a global CCS industry just by focusing on these 500 sites alone.

National Opportunities for CCS

The development and commercialization of CCS technology would have positive impacts in certain regions of Canada. Many domestic industries utilize CO_2-intensive processes in their activities and many regions throughout the country have excellent storage potential in close proximity to the sources. The greatest opportunities, on both the capture and storage sides of the equation, are in the Western Canadian Sedimentary Basin (WCSB), an area spanning the Canadian jurisdictions of British Columbia, Alberta, Saskatchewan, Manitoba and the Northwest Territories, and stretching into the US. Several cross-border CCS opportunities exist, not unlike the current project underway in Weyburn, Saskatchewan – a Canadian CO_2-EOR project being supplied with CO_2 from a US coal gasification facility.

Storage Potential

Canadian territory includes 68 individual sedimentary basins, many of which are offshore and along the Pacific, Atlantic and Arctic coasts. The sedimentary basins with the highest CO_2 storage potential are illustrated in Figure 3.4, which depicts the individual, smaller basins under 11 regional basins such as the Western Canadian Sedimentary Basin, the Beaufort-Mackenzie Basin and the South West Ontario Basin.

Figure 3.4 Canada's Sedimentary Basins

(Source: Bachu, 2003)

Two continental basins (the Alberta and Williston Basins) comprise the WCSB, which contains most of oil and natural gas production in Canada. The WCSB is world class in terms of hydrocarbon resources and geological storage potential. The offshore basins along the east coast (such as the Atlantic and Labrador Basins), and northern basins (like the Beaufort-Mackenzie, Canadian Arctic Island and Baffin Basins) may also become important storage sites in the future as the hydrocarbon resources are extracted and produced from these regions.

The sedimentary basins in Figure 3.4 are examined and ranked in terms of suitability for long-term CO_2 storage in Table 3.2, using the following criteria for the ranking:

- Appropriate depth and pressure to allow CO_2 storage in its dense phase (800 to 1,000 m in warm basins and 1,000 to 1,500 m in cold basins); or, if the storage mechanism is coal adsorption, 300 to 1,500 m.
- Tectonically stable areas not subject to folding and faulting, which increase the chance of leakage and seepage (thus the Pacific and Intramontane Basins are generally not considered appropriate).
- Under-pressured formations, which generally have fewer technical and safety issues and are therefore more suitable (deep formations in the Beaufort-Mackenzie and Atlantic Basin are often over-pressured).
- Deep saline aquifers, for which there is an understanding of long range regional-scale flows which ensure extremely long residence times for the CO_2.
- Extensive cap-rock to ensure that the CO_2 has little chance to migrate to shallower horizons and eventually seep to the surface.
- Mature and developed hydrocarbon fields where reservoir characteristics at the injection site are well known; knowledge and experience helps ensure the viability of effective injection into depleted pools.
- Close proximity to substantial CO_2 emissions sources and where the local conditions and infrastructure may enable CO_2 transport to the injection sites.

Table 3.2 Suitable Canadian CO_2 Storage Basins

Basin Name	Suitability Ranking	Suitability Rationale
WCSB (includes Alberta and Williston)	1 (top score)	Mature, thick sedimentary basin with well understood geological characteristics; most hydrocarbon pools have been discovered and are being produced and many pools are either depleted or nearing depletion. Many locations have infrastructure in place that could be leveraged and utilized for CO_2 transportation and injection.
Beaufort-Mackenzie	2	Immature sedimentary basin still being explored. Hydrocarbon pools not yet producing and infrastructure not in place. Remote from large CO_2 sources.
South West Ontario	3	Thin sedimentary cover over the arch that separates the Michigan and Algonquin Basins; has undergone substantial diagenesis (i.e., subjected to large changes). Close proximity to large CO_2 sources.
St. Lawrence River	4	Thin sedimentary basin that has undergone substantial diagenesis. Close proximity to large CO_2 sources.
Atlantic Shelf	5	Immature sedimentary basin that is still being explored. Production of developed pools is still in early stages. Expensive offshore transportation and injection infrastructure.
Canadian Arctic Island	6	Immature sedimentary basin that is still being explored. Remote from large CO_2 sources, plus offshore transportation and injection infrastructure will be costly.
Gulf of St. Lawrence	7	Good potential in eastern parts of basin that underlies western Nova Scotia, particularly in deep coal beds. Rest of basin is generally unexplored. Offshore location makes it expensive to build transportation and injection infrastructure.
Hudson Bay	8	Immature sedimentary basin, largely unexplored. No commercial hydrocarbon discoveries, thus no infrastructure in place. Remote and far from large CO_2 sources.
Intramontane	9	Significant potential for storage in coal beds. Considerable faulting and folding and significant potential for leakage. Distant from large CO_2 sources.
Baffin & Labrador	10	Immature sedimentary basin still being explored, production of developed pools still in early stages. Remote and far from CO_2 sources, very costly to build transportation and injection infrastructure in region.
Pacific	11	Located in tectonically active area along subduction zone. Significant potential for slow or catastrophic leakage.

Note: The ranking of offshore sedimentary basins also reflects the legal uncertainty of the permissibility of geological CO_2 storage under the London Convention and/or the United Nations Convention on the Law of the Sea.

(Source: Bachu, 2003; Gunter and Chalaturnyk, 2004)

As already noted, the WCSB is considered a world class site for geological storage, and as a result a considerable effort is underway to conduct detailed regional characterizations and assessments of the basin. Overall, the estimated storage capacity within the 25,777 gas reservoirs and 9,149 oil reservoirs producing in the WCSB is 8,557 $MtCO_2$ and 853 $MtCO_2$ respectively, with 639 $MtCO_2$ of capacity in CO_2-EOR opportunities alone (Bachu and Shaw, 2005). If only projects with a capacity for 1 $MtCO_2$ or more at a depth of between 900 and 3500 m are considered (which narrows the list to the most economic prospects and those likely to be pursued over the next three decades), then the practical storage capacity drops to 3,200 $MtCO_2$ and 562 $MtCO_2$ respectively, of which 450 $MtCO_2$ of capacity would be EOR related (Bachu and Shaw, 2005). Of the eligible storage capacity in oil and gas reservoirs in the WCSB, 2822 Mt are located in Alberta, 800 $MtCO_2$ in north eastern British Columbia, 118 $MtCO_2$ in Saskatchewan, and 1 $MtCO_2$ in Manitoba (Bachu and Shaw, 2005). Note that all of these numbers (and the numbers below) are currently under revision, but the orders of magnitude are representative.

Other sites also hold promise for storage in Canada. One estimate for coal bed storage capacity is 2,000 $MtCO_2$. Aquifer capacity in Canada is considered to be some 100 times greater than the previous estimates for oil and gas reservoirs in the WCSB. In other words, storage capacity is not a limiting factor on CCS development in Canada. What does limit overall storage opportunities in Canada is the location of many storage sites. Although the WCSB is well situated for industrial emissions sources in Alberta, Saskatchewan and parts of British Columbia, Ontario has fewer storage options for its large industrial emitters.

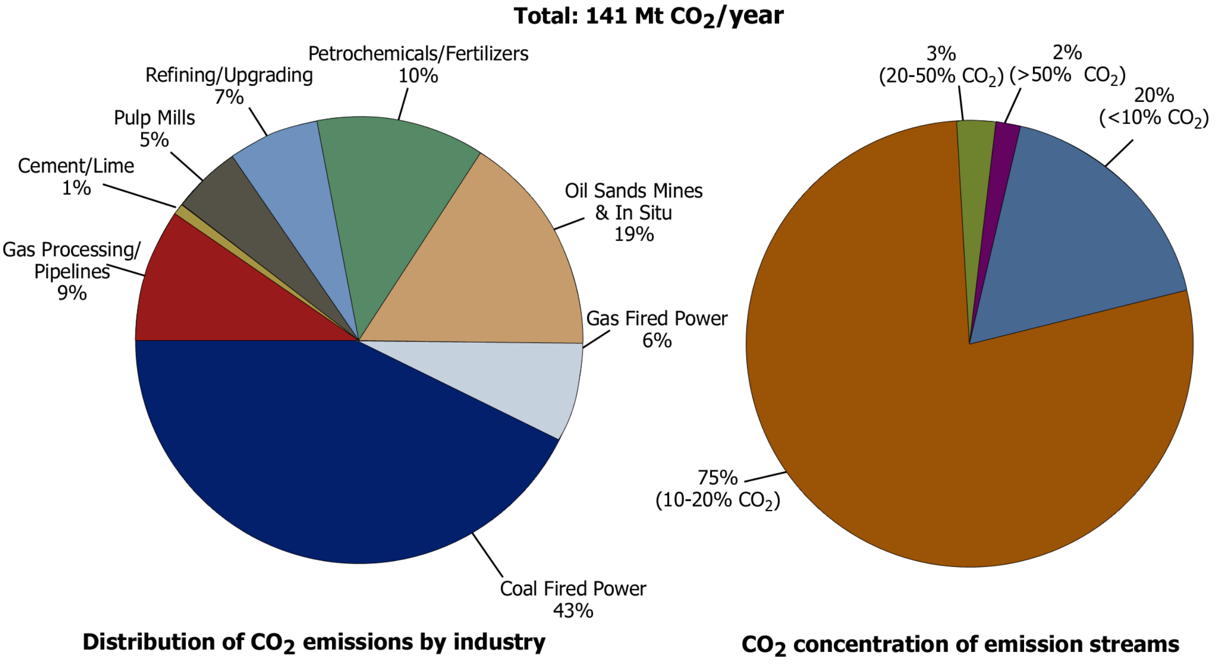
The first applications for CO_2 storage will likely be value-added opportunities such as CO_2-EOR or CO_2-ECBM. In fact, approximately 2 $MtCO_2$ is already being stored annually in the WCSB in CO_2-EOR projects (IEA, 2004). Another 1 Mt annually is being stored as a co-benefit of acid gas injection processes in the WCSB (IEA, 2004). Several other CO_2-EOR projects could reasonably begin injecting CO_2 prior to 2015 with great potential for large-scale CO_2 storage (perhaps up to 40 Mt) by 2030. If CO_2-ECBM recovery is proven commercial in the WCSB, coal beds may also be used to store CO_2 in the period from 2015 to 2030.

If the estimated potential capacity in the WCSB (the 3,762 $MtCO_2$ noted previously) were to be realized, it would represent nearly 100 years of compliance for LFE companies assuming their 39Mt annual emissions reduction target in *Project Green* (Government of Canada, 2005). For fossil fuel companies in the WCSB, CCS may provide major economic benefits while reducing CO_2 emissions on a large scale.

Sources

The main CO_2 capture opportunities in Canada are large industrial facilities that use fossil fuels (and to a much lesser extent, biomass) as part of their manufacturing or industrial processes. Although these operations exist across Canada, the concentrated clusters in the WCSB are the first to consider because capture only makes economic sense if commercial storage is available. As indicated in Figure 3.5, these WCSB facilities include power plants, oil sands facilities, refineries and upgraders, petrochemical and fertilizer plants, gas processing plants and pipelines, cement or lime facilities, and pulp mills. The first pie chart indicates the percentage share of each sector in terms of total LFE emissions in the WCSB. Thermal electricity (including coal and gas-fired generation) accounts for 49% of these emissions. Upstream and downstream oil and gas together account for another 35%. Many of the other facilities illustrated in the figure are located in the WCSB because of the availability of affordable fossil fuels for energy and/or feedstock.

Figure 3.5 WCSB Sources of CO_2 and Concentrations

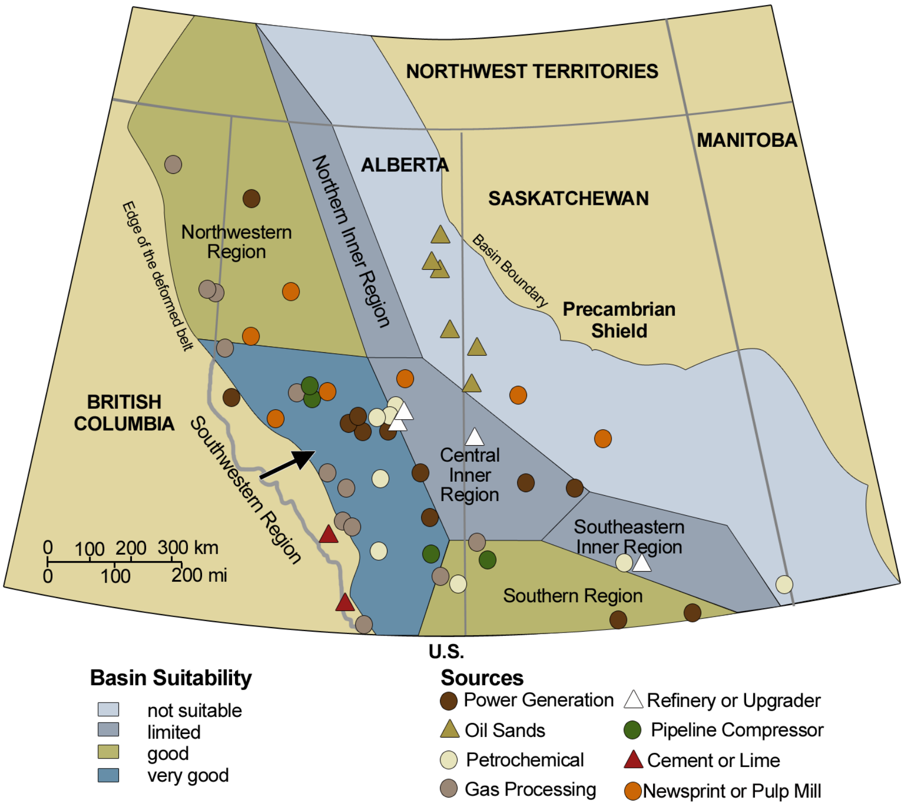


(Source: Barrie and Gupta, 2005)

Along with the total volume of available CO_2 emissions for capture, the purity of the source also influences capture cost. Many industrial flue gas streams have CO_2 concentrations below 20% (see the brown and blue segments of the second pie chart in Figure 3.5), and the cost of capturing these relatively dilute streams is very high. The lowest cost sources to capture are the high purity industrial sites which include hydrogen production facilities, ammonia plants, natural gas separation facilities, and ethane and ethylene oxide facilities. CO_2 concentrations of the exit gases in these sites can run over 90% which makes for very low capture costs, because there is often no need for separation processes. Industrial sources with these highly concentrated emissions include the oil sands facilities, natural gas plants and ammonia plants.

Figure 3.6 illustrates the location of the major CO_2 emissions sources within the WCSB, along with the general geological suitability for CO_2 storage in a number of basin sub-regions. Many CO_2 source opportunities are reasonably close to good storage sites in the WCSB, which reduces the cost of transportation. It is this combination of good source opportunities located alongside good storage sites which makes the WCSB the best opportunity for beginning to develop a CCS industry in Canada today. In many ways, this combination sets Canada apart from other nations and therefore describes the Canadian advantage in developing a domestic CCS infrastructure and systems.

Figure 3.6 Major CO_2 Sources in the Western Canada Sedimentary Basin



(Source: Bachu and Stewart, 2002)

One study has estimated the potential volume of CO_2 supply from high concentration sources in three WCSB locations to be 9,300 t/d (or nearly 3.4 Mt annually) (see Table 3.3). The *Pragmatic Business Solutions Initiative*, co-sponsored by the Alberta Department of Energy and the Alberta Chamber of Resources (ACR), identified these same three locations in an assessment of potential emissions hubs – places where significant emissions sources are clustered together and could be economically captured using a CO_2 gathering system. The concept of emissions hubs originates from the need to aggregate emissions from a number of sources in a given region; much like natural gas hubs operate today (the concept of emissions hubs is discussed in detail in Section 4).

Many more emissions could be captured if cost-effective clean coal and CCS technologies were developed and deployed in Canada. In the meantime, the top prospects for capturing CO_2 in Canada today are the niche opportunities noted previously, the oil sands, fertilizer, ethanol and ethylene oxide plants. As well, any new infrastructure developed in these and other

Table 3.3 CO_2 Supply Estimates from Three Locations

Location	CO_2 Supply (t/day)	Industrial Source
Fort McMurray	5,500	Hydrogen plants
Fort Saskatchewan	2,500	Ethylene oxide and urea plants
Red Deer-Joffre	1,300	Ethane, ethylene oxide and ethanol plants

(Source: Luhning *et al*, 2005)

regions could be built to be CO_2 capture-ready for a future day when a fully commercial CCS industry is thriving. A range of estimates indicate that between 10 and 100 $MtCO_2$ could be captured from a variety of industrial sources and stored annually in the WCSB (over the coming decades) if Canada aggressively pursues this important technology opportunity.

Value of Low-Emissions Fossil Fuels

The most valuable outcome of developing CCS technology and knowledge in Canada is that it will enable the development of low-emissions fossil fuel industries in Canada that will lead the world. Canada could become an example of how to tackle the issue of climate change while continuing to increase the value of its fossil fuel resource base, all the while developing and commercializing technology for the world to use.

The wide-scale use of CCS would contribute enormously to climate change mitigation while maintaining energy self-sufficiency (and therefore energy security), and allowing for the continued export of fossil fuels. By aggressively pursuing CCS technology development, Canada will ensure a continued role for its energy and petrochemical sectors. Using CO_2 for EOR, ENGR and ECBM would increase recoverable hydrocarbon reserves and help generate more energy-related revenue for Canada.

Using CO_2 capture technologies in a number of emissions hubs, which would then be linked via a CO_2 pipeline to storage sites, could form the base infrastructure for de-carbonising Canadian industry. Additional investments in CCS could result in a step-wise transformation to a new energy future based on hydrogen or clean electricity as the energy carriers. In this light, CCS can be seen as a foundation-building technology that allows for the production and use of Canada's world class fossil fuel resources in an environmentally responsible manner, while also enabling transformational change for tomorrow's energy economy.

To ensure the long-term outcome of economic growth along with emissions reductions, many Canadian organizations have emerged as CCS technology leaders. In addition to the programs already noted, several studies are being led by the Alberta Energy and Utilities Board and the British Columbia Ministry of Energy Mines and Petroleum Resources (BC MEMPR) to better understand the suitability of Canada's sedimentary basins for CO_2 storage. The *CANMET CO_2 Consortium* is working on several technologies including oxygen/CO_2 recycle combustion, integrated CO_2 purification and multi-pollutant capture systems at CETC-O. The *International Test Centre for Carbon Dioxide Capture* (ITC) in Saskatchewan is working on capture techniques at its demonstration plant, which is attached to a commercial coal-fired generation plant. The *Canadian Clean Power Coalition* (CCPC) is an association of coal-fired electricity producers working to build the first full-scale clean coal facility (likely using gasification technology) in Canada. These efforts can and should be maintained by making the appropriate investments to make it happen. Industry, government and other stakeholders can work collaboratively to address the technical, economic and policy barriers facing CCS technology today, through targeted research and development (R&D) and technology deployment, and by developing supportive and appropriate policy and regulatory frameworks to enable a viable and robust CCS industry at home.

Section Summary

Developing new CCS knowledge and technology is a value-added opportunity worth pursuing. CCS offers the option of mitigating GHG emissions from the use of fossil fuels, thus tackling climate change from a progressively new angle. Much of the technology and expertise can be developed at home with the opportunity of transferring it to international markets. The technology will help increase domestic energy reserves by improving the recovery of what is already known to be in place. In the end, the development of CCS technology will provide economic, environmental and societal benefits to all Canadians.

A number of international activities are underway to develop CCS technology and knowhow, including those under the IPCC, IEA and CSLF. Their research to date indicates that the total global capacity for CO_2 storage is somewhere between 1,700 and 11,000 $GtCO_2e$. Often these storage sites coincide with excellent CO_2 source opportunities. Of the 8,049 facilities worldwide that each emit greater than 100 $ktCO_2e$/yr, 500 projects have been identified as having good potential for both capture and storage. Initial infrastructure and systems will be built around these first projects, and will be added to as subsequent stages of development are undertaken.

Domestically, CCS opportunities exist in many regions with concentrations of CO_2 sources in the Prairies, Ontario and the Maritimes, with opportunities for storage also in some of these regions. It is estimated that 3,762 $MtCO_2$ of practical capacity exists in the oil and gas reservoirs of WCSB today. This basin is the focal point for initializing a Canadian CCS industry because of opportunities to enhance hydrocarbon recovery (with approximately 450 Mt of CO_2-EOR capacity available today), and the number of large CO_2 sources that exist (including coal-fired facilities, oil sands plants and other fossil fuel industries). Almost 3.4 $MtCO_2$/yr could be economically captured in the WCSB today, with many more megatonnes available if appropriate policies emerge for dealing with CO_2 emissions. Building CCS infrastructure in existing niche opportunities and in new industrial facilities, could be the start of rolling out CCS infrastructure and systems in Canada.

Agressively pursuing the development of CCS technology would provide a variety of benefits to Canada. The biggest opportunity is the enabling of low-emissions Canadian fossil fuel industries, which would ensure a future role for the energy and petrochemical sectors in Canada. Enhanced hydrocarbon recovery would increase the value of known reserves. Capturing CO_2 emissions and storing them underground would provide a global environmental benefit. New technology and infrastructure would help diversify the economy and help transform Canadian society into one that is highly advanced and leading edge.

4. Technology Pathways

The overarching technology pathway often discussed regarding CCS is in actual fact a combination of many pathways that converge around the common goal of CO_2 capture and long-term storage. These pathways each relate to one of the three necessary components: capture and compression, transport and storage. Each component is essential for the development and deployment of fully commercial CCS infrastructure and systems in Canada.

Although each component has its own technical focus and set of goals and objectives, it is important to study the integrated system because all three components are essential to it. After all, the technological success of capture and transport will not matter if storage cannot be proven technically feasible.

Therefore, this section provides a description of each component or technology area in terms of specific technologies and potential applications. The current costs of these components are estimated for the Canadian context. R&D needs are proposed for each technology area, which identifies critical areas where further research may make the difference in terms of commercial success. A final section is devoted to the strategic development and deployment of CCS infrastructure and systems.

Section Observations:

Specific R&D needs exist for each CCS component (capture, transport and storage), with the ultimate goal being technically and economically feasible CCS infrastructure and systems

Current CO_2 capture costs range from (CDN) $13 to 80/t$CO_2$ captured; capture offers the greatest potential for cost reductions in the CCS system

Transportation costs are (CDN) $6/t$CO_2$ per 650 km's transported; transport technology is largely available today

Geological storage costs range from (CDN) $3 to 9/t$CO_2$; long-term storage is one of many promising ways to reduce GHG emissions from the portfolio of options available today

The development of emissions hubs, a pipeline backbone and long-term storage will require upfront capital, but using this systems view will result in technologically and economically sound infrastructure development for the long term

It is important to note that referring to any specific CCS technology as the ultimate solution, or silver bullet for a technology area, would be premature. At this early stage of CCS development, it is difficult to predict how the technological pathway might progress. However, a forward-looking description of potential pathways based on what is known today, and some generally accepted assumptions, can provide valuable insight into what the future might hold.

Capture Technology

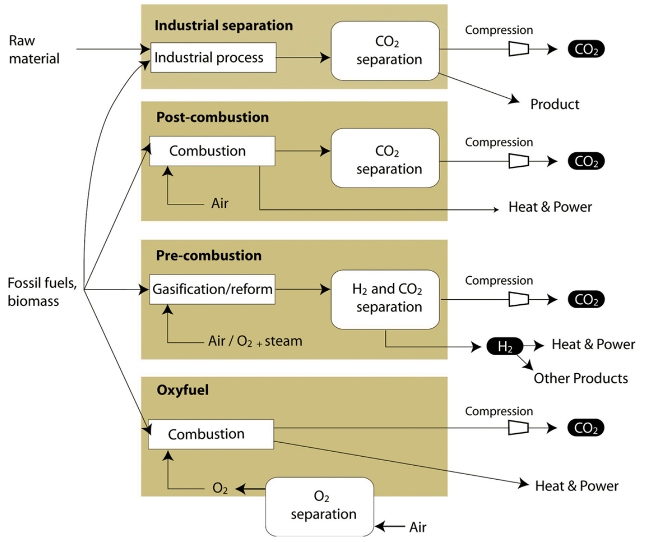
Capture Systems

In any discussion on technology the subject can be divided along a number of lines. In this section the discussion starts with the larger integrated systems in which specific technologies are applied, followed by a deeper discussion of each technology. This split discussion is most prominent for the capture component, because of the variety of technological options for separating and capturing CO_2.

The most promising CO_2 capture systems are often classified under four types: post-combustion systems, pre-combustion systems, oxy-fuel combustion systems and industrial processes (see Figure 4.0). Post-combustion refers to a system that captures CO_2 from a flue gas after the fuel (whether fossil or biomass) has been combusted in air. Pre-combustion is a process where the fuel source is gasified to create syngas, a mixture of hydrogen and carbon monoxide. The carbon monoxide then undergoes a shift reaction to generate hydrogen and CO_2 which can then be captured prior to combusting the gas mixture. In oxy-fuel systems the fuel is combusted in an oxygen enriched environment rather than simply air. The exhaust mixture of CO_2 and water in an oxy-fuel system can be easily separated to produce high purity CO_2 streams. Certain industrial processes, such as cement manufacturing and hydrogen production, utilize chemical reactions that generate

CO_2 emissions. Natural gas processing involves the separation and capture of naturally occurring CO_2 that flows to the surface during gas production. Each of the four capture systems has its own merits and challenges, and each has a number of technology needs which are discussed in a subsequent section.

Figure 4.0



(Source: IPCC, 2005)

Post-combustion Systems

When capturing CO_2 from a typical air-fired combustion unit after the burning process has taken place, it is referred to as post-combustion capture. Any industry that generates thermal electricity as part of its process (either by using fossil fuels or biomass) is a primary opportunity for post-combustion. More than 90% of industrial facilities today use conventional process heaters and industrial utility boilers in which post-combustion systems could be tagged-on to existing facilities. The disadvantage of these systems is that typical flue gas streams have CO_2 concentrations of 20% or less. Although the CO_2 can be separated using membranes or cryogenics, these are costly endeavours, and only absorption (using chemical solvents like amines) is commercially viable today.

The challenge for post-combustion capture systems is to develop new designs for commercial-scale applications in large industrial facilities. Specifically, there is a need for improved solvents which could significantly reduce both the high energy penalty and capital cost of post-combustion capture. Amine scrubbing capture processes require lots of heat for solvent regeneration which contributes to the energy penalty. Because the process operates at atmospheric pressure, a lot of energy is needed to compress the CO_2 for transportation. Parasitic losses for thermal power plants that use amine scrubbing ranges between 10 and 30% of the total power the plant would generate if CO_2 capture were not included (IEA, 2004b). This energy penalty translates into a noticeable impact on electricity prices.

Other needed technologies for post-combustion systems are energy efficiency and integrated pollutant controls, waste management processes and CO_2 separation technologies (both for retrofits and for new facilities). The control technologies include combined CO_2/sulphur oxide (SO_x) removal systems for multi-pollutant capture. Additional work is needed to improve instrumentation and controls, new process integration methods and tools to conserve in-plant energy use. A final area of focus is on the co-production of other useful industrial by-products, such as fertilizer, ash and gypsum.

Pre-combustion Systems

Pre-combustion capture systems basically involve de-carbonizing the fuel source prior to combustion, a process that is widely used in the manufacture of hydrogen and fertilizer (IPCC, 2005). The fuel source can be converted to a syngas, which consists mostly of a mixture of carbon monoxide (CO) and hydrogen. This conversion can be done using gasification, partial oxidation or steam reforming technology. Gasification is most often used for solid fuels, partial oxidation for liquids, and steam reforming for gases. Then the CO is converted into CO_2 through a shift conversion process which also produces a stream of hydrogen. The most valuable by-product of pre-combustion is the hydrogen, and as the world shifts towards a hydrogen-based economy it will become even more valuable as a fuel source for transportation or distributed generation.

Compared to other combustion processes, the incremental energy penalty of pre-combustion capture is low at 6% (IEA, 2003); because of the relatively favourable CO_2 concentrations in the process (which range from 15 to 80%) and the high pressure involved (IPCC, 2005). Both factors make the separation and compression of CO_2 in pre-combustion systems relatively efficient.

Pre-combustion systems are costly and questions exist regarding the reliability of using gasification technology on low-rank Canadian coals such as the sub-bituminous and lignite coals in western Canada.

Shift converters weren't made for fuels like coal, and process-related ash particles will result in system damage. Other problems include hot gas clean-up and the issues related to pure hydrogen-fired turbines. While integrated gasification combined cycle (IGCC) technology (gasification technology) has been commercially demonstrated in other settings around the world, it has yet to be proven technically feasible using Canada's variety of low rank coals.

Therefore, second generation IGCC concepts are needed; ones that incorporate improved membrane processes for the water gas shift reaction and for hydrogen/CO_2 separation. These concepts will need to include more energy efficient CO_2 and multi-pollutant capture processes that apply to low rank coals. Ultimately, a pilot-scale gasification facility is needed so that industrial operators conducting research on new configurations (specifically designed for heat, power and hydrogen production) can test their new designs in an economic setting. IGCC technology, optimized for generating power in Canada, would enable the roll-out of a whole new fleet of power generation facilities across the country (CCTRM, 2005).

Oxy-fuel Combustion Systems

Oxy-fuel is an emerging approach to post-combustion capture, whereby the combustion process takes place in an oxygen enriched setting which results in low-emissions fossil fuel combustion. Removing nitrogen from the air, and then combusting the input fuel in an oxygen-rich environment, results in a highly concentrated flue gas stream (with greater than 80% CO_2) which can be further concentrated using physical gas purification techniques such as cryogenic separation.

This concentrated flue gas stream is one of the primary benefits of oxy-fuel combustion. A second advantage stems from the absence of nitrogen which results in the virtual elimination of nitrogen oxide (NO_x) emissions. An overall systemic advantage is the reduced size of the entire process, due to the reduced volumes of both the input and exit gases, both of which translate into reduced capital and operating costs.

A variant of oxy-fuel technology, oxy-fuel recycling, can be used to control flame temperatures by recycling a portion of the exit flue gas into the oxygen input gas prior to combustion. By diluting the oxygen in the input gas it is possible to achieve conventional flame and heat transfer characteristics, thus potentially allowing the technology to be retrofit into current power plants. Another emerging variant is hydroxy-fuel combustion, which again provides an opportunity to moderate process temperatures by facilitating the combustion process in an oxygen and steam environment.

The greatest challenge facing oxy-fuel today is to lower the energy penalty (and therefore the cost penalty) involved in producing oxygen, which ranges from 8 to 30% (or perhaps even higher) of the total fuel cost depending on the fuel source and process used (Dillon, 2004). The US Department of Energy is working on improved ion transport membrane (ITM) systems, which are meant for low-cost, large-scale oxygen production. Success would result in a key enabling technology that significantly reduces the energy penalty involved in producing oxygen.

Another important challenge is that current design configurations and materials are unable to operate at the high temperature ranges for oxy-fuel combustion; however, CO_2 or steam recycling may mitigate this issue. A final issue is the need to reduce the total energy consumption for CO_2 separation and compression. However, this issue is not unique to oxy-fuel, as all four capture systems face this problem.

While oxy-fuel will assist in reducing the size, number and cost of the units required to produce energy, and will make emissions capture easier, its full potential is unlikely to be realized until new high-temperature materials become available for combustors and boilers. CETC-O is working on oxy-fuel combustion systems, and is collaborating with partners who are developing super alloys and other advanced materials. The EU's *Thermie Program* on advanced materials is working on materials that will be used in future applications of oxy-fuel combustion, as well as in ultra-supercritical pulverized coal and natural gas systems.

Early-stage commercial demonstrations are needed for oxy-fuel and/or hydroxy-fuel recycle systems, through which researchers could conduct the work needed to better define the science around oxy-fuel combustion, and develop new equipment, design principles and energy system process configurations.

Industrial Processes

The separation of CO_2 from flue gases has been a common practice in certain industries, such as natural gas processing, and hydrogen and fertilizer production, for over 60 years. The current practice is most often to separate the CO_2 and simply vent any unused portion to the atmosphere. Therefore, the concept of CO_2 separation using industrial processes is not new, unlike the concept of capturing those emissions for environmental reasons.

For industries like upstream natural gas processing, and hydrogen and fertilizers manufacturing, flue gas streams often contain greater than 90% CO_2. Consequently, many of these opportunities only require compression technology to pressurize the flue gas for transportation. This advantage makes these capture opportunities some of the most economic today. As noted previously, fertilizer manufacturing (of products such as ammonia and urea) is considered one of the best early opportunities for commercial CO_2 capture today, and approximately 13 $MtCO_2$/yr could be captured from this industry now (IPCC, 2005).

CO_2 concentrations in natural gas varies by region, with almost no CO_2 in Siberian gas and up to 70% in some Indonesian fields; the global average for natural gas is 1 - 2% CO_2 (IEA, 2004). Natural gas in Canada can contain anywhere from no CO_2 up to 36%. Therefore, the opportunity of capturing CO_2 from natural gas processing facilities varies by location.

Other opportunities in the fuel supply industries include oil refineries, hydrogen production and gasification facilities. However, because of the variety of oil refining processes used worldwide, it is impossible to characterize the industry and to indicate the total potential for CCS. That being said, oil refining is one of the largest emitting industries worldwide, thus opportunities do exist. Hydrogen is considered by many to be the transportation fuel of the future, and hydrogen production (using other fossil fuels as the feedstock) offers the potential to capture CO_2 emissions from the transportation industry by capturing it where the fuel is produced. As already discussed, gasification is another option for producing hydrogen in a synfuel mix which also contains CO which could be converted to CO_2 for transport to a suitable storage site.

Other high quality industrial sources of CO_2 include cement, steel and pulp and paper, where average CO_2 concentrations of the flue gases generally exceed 20%. CO_2 concentrations from cement production are higher than those from conventional furnaces because more than half of the CO_2 comes from an essential chemical reaction used in cement production (IEA, 2004). Substantial amounts of CO_2 could be captured during direct iron production (DIP), a process used in regions with a lot of stranded gas (such as the Middle East). Paper mills and ethanol plants both recover ‘black liquor’ (the remaining lignin fraction) from industrial processes and use it to generate energy. These facilities are a source of CO_2 emissions that, if captured and stored, may result in the neg-emissions noted earlier, depending on the sustainability of the fuel source.

Some new technologies are needed for applications in existing facilities, to better enable the capture of high concentration streams in the existing capital stock. As well, better process integration is needed for CO_2 capture technologies which in many cases could make a big difference in the capture economics. A lack of information on the application of solvent scrubbing or oxy-fuel combustion in industries like cement, glass and metals is a critical gap. If implemented appropriately, industrial processes could be some of the first areas to produce low-cost and very pure CO_2 streams for CCS.

Final Systems Discussion

A critical question that arises when discussing any of the previous capture systems: what is the role of developing technology for new plant designs versus retrofits to existing applications? For North America, this question is less important because of the age of existing capital stock. Many North American thermal power plants are reaching their economic lifetime and new plants need to be built. Therefore, an opportunity arises in that any new facilities could be designed to accommodate the addition of CCS technology when it becomes available in the future (to be capture-ready).

Oxy-fuel is often discussed as a future retrofit option for coal-fired facilities in Canada and elsewhere. However, the Canadian Clean Power Coalition (CCPC) recently conducted an extensive study which indicated that retrofitting Canada’s existing facilities today would result in an incremental cost increase of (CDN) ¢1.5 – 2.7/kWh of electricity produced (CCPC, 2004). As a result, the CCPC has decided that retrofits using oxy-fuel are not an economically viable option for coal-fired facilities in Canada, and that Canada may instead wish to deal with CO_2 emissions from power generation by making sure that any new facilities or brown-field installations use new clean coal technology (CCTRM, 2005).

The same situation may be true in other Canadian industries. While the thought of applying new technology to existing facilities may appear to be a good option, it is often easier and more economic to focus on any new facilities being built to be CO_2 capture-ready, especially in cases like the oil sands where new infrastructure is being built at an unprecedented rate. This does not imply ignoring the niche opportunities that exist in industry today (such as the hydrogen and fertilizer manufacturing facilities), rather it implies setting some criteria to help prioritize and decide on what opportunities to pursue first.

When prioritizing, it is important to understand the counter-intuitive situation that exists today – the best candidates for CO_2 capture are generally the most efficient plants in operation. Older and inefficient facilities generally emit low CO_2-concentration flue gas streams, thus making capture very difficult. While CCS is seen by some as a means of reducing emissions from the most polluting old fossil fuel plants, a better environmental and economic outcome would result from using CCS in the most up-to-date and modern facilities being built today. Despite the fact that so many emissions come from low concentration sources, these should not be the top priority. Rather, the top priority should be to capture emissions from existing high concentration sources and from any new facilities that are built as the capital stock turns over.

Capture Technologies

The capture technologies discussed below are broadly classified under the four categories: absorption, adsorption, membranes and cryogenic separation. Table 4.0 illustrates these and some specific technologies under each category. Many of these technologies have been in use in industrial processes for years. Chemical absorption was developed more than 60 years ago to remove CO_2 from impure natural gas streams. Solvent scrubbing processes are widely used to separate CO_2 in hydrogen and fertilizer plants. Many facilities use solvents to recover pure CO_2 for food processing and chemical manufacturing.

Table 4.0 The Spectrum of Capture Technologies

Category of Capture	Specific Technologies
Absorption	Physical Absorption
	Chemical Absorption (amine, hindered amine and inorganic)
Adsorption	Pressure Swing Adsorption
	Temperature Swing Adsorption
	Electric Swing Adsorption
	Vacuum Swing Adsorption
Membranes	Gas Absorption
	Gas Separation
	Water Gas Shift Membrane Reactor
Cryogenics Separation	Compression and Refrigeration

The technology selected for any given capture system depends on many factors which include the partial pressure of the CO_2 in the gas stream, the extent of CO_2 recovery required, the purity of the desired CO_2 product, sensitivities to impurities in the system (such as acid gases and particulates), the cost of additives needed to prevent corrosion (where applicable), capital and operating costs of the process and potential environmental impacts. Because these factors determine the choice of technology used, they are also considered important design principles that must be considered when developing new technology.

Absorption

Both chemical and physical absorption are widely used to separate CO_2 from flue gases in the oil and gas and chemical industries. The process generally involves a repetitive cycle of absorbing CO_2 followed by regenerating it upon removal.

Chemical absorption uses organic or inorganic aqueous solutions to attract the CO_2 and form weakly bonded intermediate compounds. Organic amines are the most commonly used chemical solvents, and different ones are selected based on their reaction rates, equilibrium absorption characteristics, and sensitivities with respect to solvent stability and corrosion factors. The target gas stream also affects appropriate amine selection. The three most commonly used amine groups include primary amines like monoethanol-amine and diglycol-amine, secondary amines like diethanol-amine, di-isopropyl-amine, and tertiary amines like triethanol-amine and methyl-diethanol-amine. Hindered amines are another class of organic amines that typically have an amino group attached to an alkyl group. Inorganic chemical solvents include potassium carbonate, sodium carbonate and aqueous ammonia, with potassium carbonate being the most commonly used. The Benfield process is a solvent scrubbing process that uses hot potassium carbonate as the solvent. The CO_2 is regenerated using a stripping process in which the CO_2-rich chemical solvent is heated to desorb the CO_2 from the chemical solvent.

Physical solvents have been used in ammonia production for years and are ideally suited for CO_2 removal under high vapour pressures. They are considered suitable for pre-combustion systems like IGCC, where the CO_2 partial pressure is quite high as a result of the shift conversion. Physical solvents form a weaker bond to CO_2 than chemical solvent. This is their inherent advantage in that all that is needed to regenerate the CO_2 is a reduction in system pressure or an increase in temperature. Specific physical solvent technologies include cold methanol which is used in the Rectisol process, dimethylether or polyethylene glycol which is used in the Selexol process, propylene carbonate used in the Fluor process, and n-methyl-2pyrollidone. The Rectisol process has been used in the past to treat syngas, hydrogen and town gas streams. A coal gasification plant in North Dakota uses this process to capture 5,000 t/d of CO_2, which is then shipped to Weyburn Saskatchewan via pipeline for use in EnCana's CO_2-EOR project.

Adsorption

Adsorption is a process of selective separation of gases in a flue stream, which takes advantage of the intermolecular forces that exist between certain gases and the surfaces of solid materials. Adsorption rates depend on factors like temperature, partial pressure, surface forces and adsorbent pore size. The process employed when using adsorption technology is similar to absorption in that a repeat cycle of adsorption is followed by the regeneration of the adsorbed gas.

When using adsorption for CO_2 capture, a flue gas stream is fed onto a bed of solids (often sieves arranged as packed beds or spherical particles) which selectively adsorb the CO_2 while allowing other gases to pass through. When a bed is CO_2-saturated, the feed gas is switched to another clean adsorption bed and the saturated bed undergoes the regeneration process. The switch from adsorption to regeneration is induced by changing the physical parameters in the environment. In pressure swing adsorption (PSA) the CO_2 is regenerated by reducing the system pressure. In temperature swing adsorption (TSA) it is regenerated using a temperature increase. Two variants of adsorption technology under development today include electric swing adsorption (ESA) and vacuum swing adsorption (VSA).

The simplicity of the technology is driving considerable research in this area, and ESA in particular holds the most promise for future compact solid state CO_2 capture technology. In the future, adsorption may play another important role in CCS. Coal's preference to bond with CO_2 instead of methane is the dynamic driving much of the research around CO_2-ECBM recovery.

Membranes

Membranes are basically barrier films that allow for the selective and specific permeation of different gases. Selectivity depends on system parameters and on gas conditions and therefore different membranes are being designed for the variety of roles in capture systems. For example, membranes are being developed to capture CO_2 during the downstream shift conversion in gasification systems. In post-combustion systems, membranes are used to capture CO_2 from low concentration flue gases. Other membranes are being developed for oxygen separation in oxy-fuel systems, such as the ITM technology being developed in the US.

Two basic membrane types are being considered for CO_2 capture: gas separation and gas absorption membranes. The first group rely on the variations in physical and/or chemical interactions between different gases and the membrane material, with the intent being one component passing through the membrane faster than another (thus driving the separation process). This technique relies on the diffusivity of gas molecules, and taking advantage of different pressures on either side of the membrane. Various versions of gas separation membranes are available today including ceramic, polymeric and ceramic/polymeric hybrids. The second group, gas absorption membranes, are micro-porous solid membranes which act as contacting devices between gas flow and liquid flow. While flue gases flow on one side of a membrane, an absorptive liquid is used on the other side to selectively attract certain components. In this case, it is the absorption liquid (not the membrane) that drives the selectivity.

Cryogenic Separation

Cryogenics is a science that takes advantage of the critical pressures and temperatures of specific elements and compounds in a mixture. Through careful manipulation of the pressure and temperature (using compression and refrigeration) it is possible to separate specific gases from a mixed gas stream either through liquefaction or distillation.

Cryogenics is commonly used today for the purification of CO_2 in gas streams that already have high CO_2 concentrations (greater than 70% CO_2) (Gupta and Pearson, 2005). Cryogenics is advantageous in that it enables the direct production of liquid CO_2, which makes transportation more cost-effective. However, cryogenics is unsuitable for dilute CO_2 streams because of the amount of energy needed, whether for compression or refrigeration. The most promising applications for cryogenics in CCS are in the separation of CO_2 in high partial pressure gases (such as pre-combustion systems), or in oxy-fuel recycle systems where the input gas has a high CO_2 concentration.

Cost of Capture

The cost to capture CO_2 in Canada depends very much on the industrial application being discussed, and in fact, is generally a function of the CO_2 concentration of the flue gas stream being processed. Benfield (or amine) processes, oxy-fuel capture or pre-combustion capture options (in an IGCC facility) can be the least costly means of CO_2 capture today. Generally speaking, capturing CO_2 from low concentration flue gas streams, such as natural gas combined cycle or pulverized coal combustion facilities is most costly.

It is estimated that most post-combustion capture systems would cost between (CDN) \$50 and \$70/tCO_2 captured (this includes compression costs) (Thambimuthu, 2004). The cost for pre-combustion ranges anywhere from (CDN) \$20 to \$50/tCO_2 captured, and the cost for oxy-fuel is anywhere from (CDN) \$13 to \$80/tCO_2 captured (Thambimuthu, 2004). The current cost of each of these technologies, in actual fact, is probably near the bottom end of these ranges, as the upper ends are somewhat of an artefact of historical cost estimates. The lowest cost opportunities are in the niche applications discussed earlier, the hydrogen and fertilizer facilities where Benfield processes or other technologies are used today. While these cost ranges give an indication as to the best technologies to pursue in terms of capture cost-effectiveness, it is important to remember that it is the overall economics of a project that will ultimately determine the technological choice. In addition, the deployment of cost-effective infrastructure and systems requires large upfront capital investments, which are not necessarily reflected in the previous cost estimates.

The cost of adding capture, transportation and storage to a typical coal-fired power plant in Canada (of which capture would account for the majority of the cost) would result in almost a 50% increase in power production costs. If the original cost to produce power were (CDN) ¢4.5/kWh then the cost to produce the same power and capture the emissions would be nearly ¢7/kWh.

In most cases, building a facility to be capture-ready (as described earlier) is a costly endeavour and it would require a significant price signal (for CO_2 emissions) to cause industry to begin building these plants. The prospect of such a price signal plays heavily on the technological choice for new power plants today because with no incentive to reduce GHG emissions, pulverized coal technology is the economic choice. However, in a carbon-constrained world the choice changes, and the IPCC indicates that a price signal of (USD) \$25 to 30/tCO_2 may be enough to induce the development and deployment of CCS technology (IPCC, 2005) (note that some cost figures are in US dollars because the source documents report costs in US dollars).

A very important factor to keep in mind is that capture is generally the most costly of the three CCS components but that it also has the most room for cost reductions. Reductions in the order of 25 to 30% (with the potential for 50% reductions for certain applications) are expected over the next two decades (IPCC, 2005). These reductions can be attributed to the learning effect of working with the capture technology – a phenomenon whereby the unit cost of a technology reduces over time, driven by R&D resulting in new processes, learning-by-doing, efficiency gains in equipment manufacturing, standardization of equipment and economies of scale (IEA, 2004). In immature technology areas, such as CO_2 capture, the learning effect can be very high.

Capture Risks

Technical risk is an important consideration in the cost of any endeavour. Risks associated with CCS are generally characterized as global (those that impact the ultimate objective of global emissions reductions) and local (those that are site specific and often more immediately impact human health, ecosystems or water quality) (IPCC, 2005).

The risks associated with capture tend to be more local in nature, such as catastrophic equipment failure with the release of CO_2 into the local environment. While large concentrations of CO_2 may be damaging, it would require exposure concentrations of CO_2 greater than 7 to 10% (by volume of air) to constitute a dangerous level, and the risk posed by such a release is comparable or less than that of other industrial activities, and is considered to be manageable (IPCC, 2005). A CO_2 release is less risky than the release of other flammable or toxic fluids used in other industrial processes. Most CO_2 capture risks can be dealt with using current approaches, and the cost associated with managing such risks are relatively small compared to the cost of capture.

Capture R&D Needs

A number R&D gaps have been identified for CO_2 capture technology, which lead to a number of critical R&D needs. The following sections summarize these needs for Canadian industry by type of capture system.

Post-combustion

Research and development related to post-combustion systems would include system integration of heat and power requirements for the inclusion of capture in the process cycle. Integrated secondary air pollutant and waste management control technologies for such things as NOx, SOx, mercury and fine particulates are needed. Low-cost solvents are required, with improved stability, and which are corrosion and degradation resistant. Improved contactors and mass transfer systems (such as membranes or membrane/solvent technologies) for large-scale applications of CO_2 capture are needed. Improved solid sorbent technologies are also needed. Moderate temperature and pressure hybrid technologies should also be considered for CO_2 separation.

Pre-combustion

There is a need for modular test facilities for assessing advanced gasification, reformation, carbonation and hydrogen separation processes for Canadian circumstances. The scale of these tests need to be large enough to evaluate advanced capture concepts such that the results can be scaled up to applications at a commercial scale Such test equipment could help study the optimization of gasification systems integrated with CO_2 capture. Such systems will enable the conversion of Canada's abundant bitumen, low rank coals and other solid fuel sources into useful energy.

Specific technological needs include advanced physical solvent contactors that can be scaled-up for commercial capture applications. High-temperature membrane reactors are needed for combined steam reforming (or water-gas shift reactions) and hydrogen separation. Solid sorbent enhanced reaction systems are needed for CO_2 separation and steam reforming. Hybrid systems for CO_2 separation from hydrogen are needed, as are new hydrogen-fired boilers and process heaters. Integrated hot gas clean-up systems are needed for removing impurities such as hydrogen sulphide (H_2S), carbonyl sulphides (COS), hydrogen cyanide (HCN), ammonia (NH_3), particulates, heavy metals and alkali.

A final need is systems integration of capture technologies to pre-combustion facilities with overall process efficiencies in mind, whether it be for steam reforming or partial oxidation of natural gas.

Oxy-fuel

System integration and cycle development is needed for oxy-fuel based combustion of fossil fuels, whether it is in Rankine, Brayton or combined cycles, or whether it is used in fuel cells. This entails a better understanding of the combustion, heat transfer and pollution forming behaviours of pure oxygen, oxy-fuel recycle or hydroxy-fuel recycle combustion.

Specific technological needs include optimized recycle flows in combustors, process heaters and boilers. High-temperature tolerant combustors, process heaters, boilers, compressors and turbo-machinery are needed for oxy-fuel recycle and hydroxyl-fuel recycle, but more importantly for oxygen-rich combustion. There is also a need for oxy-fuel fired process heaters with a common header for CO_2 capture in integrated chemical complexes. Improved cycles and methods are needed for CO_2 compression cooling and separation in the presence of trace concentrations of other impurities. Novel integrated multi-emissions control technology is needed for CO_2, NOx, SOx, mercury and fine particulates.

Improved and lower energy penalty cryogenic air separation processes are needed to supply oxygen for oxy-fuel combustion. Another option is low energy penalty adsorption or low temperature membrane technology for oxygen production. Finally, novel ion (or oxygen) transport membrane technology would be useful for oxygen separation.

Industrial Processes

The understanding of process chemistry for a variety of industrial processes could be improved and provide insight into increasing CO_2 concentrations in industrial flue gases. Further, process modelling and systems integration for CO_2 capture would be useful. In particular, such modelling and integration in oil refineries, oil sands operations and petrochemical manufacturing would be beneficial for Canadian industry.

Transport Technology

Transport Systems

After the CO_2 is captured and compressed, it is transported to a storage site in either its gas or liquid phase. Like other gases, it is most convenient and economic to transport CO_2 in its dense phase which could be either a supercritical phase or a liquid phase. The two primary means of moving CO_2 in either phase are by pipeline or tanker transportation.

Pipeline Transportation

Pipelines are a commercially established technology today. They are used around the world for moving large quantities of fluids over great distances. Energy pipelines are in operation in desert regions, in the Arctic, over mountain ranges, under seas and lakes and through densely populated areas. Pipelines crisscross North America carrying natural gas, oil, condensate and water over distances of thousands of kilometres.

CO_2 pipelines are also in commercial use today, most using the technology applied in energy pipelines. Large-diameter lines currently safely move up to 20 to 30 $MtCO_2$ annually, most of which (22 $MtCO_2$/yr) is in the US. Both natural sources of CO_2 from New Mexico and Colorado, and industrial emissions (captured using amine scrubbing) are shipped to CO_2-EOR projects in West Texas. Some projects have operated since the 1970's. A separate 330 km pipeline carries 2 $MtCO_2$/yr from the Great Plains Synfuels Plant in North Dakota to the *Weyburn CO_2 Flood Project* in Saskatchewan, the largest operating CO_2-EOR project in Canada. Another short, small-diameter pipeline has been operating in the Joffre-Red Deer area since 1986.

Important components of any pipeline transportation system are local storage facilities (such as depleted oil or gas reservoirs or salt caverns) which are used as surge tanks in gathering and distribution networks. These facilities can be used for temporary storage to help with pipeline system optimization and with delivery balancing. Similar temporary storage facilities would also likely be needed for a CO_2 pipeline system.

Pipelines can be used for multi-product transportation, which often help with the economics of a project. Slurries can be used to transport two phases of product simultaneously, and it is possible that CO_2 could be useful as a diluent when transporting bitumen (however, some technical questions still need answering). Alternatively, slugging or batching the bitumen and liquid CO_2 is another consideration.

Despite the current maturity of the technology available for CO_2 pipeline transportation, some issues persist. For example, the product needs to be free of hydrates or corrosive compounds, which highlights the need for more advanced capture technologies. This issue also indicates the need for industry standards on factors like the temperature and composition of the CO_2 streams, to ensure pipeline quality and integrity. Special attention is required when designing new pipelines through populated areas, such as overpressure protection and leak detection technologies. However, moving CO_2 by pipeline is even safer than the current practice of moving hydrocarbon liquids and petrochemicals by pipeline (because CO_2 is neither flammable nor explosive and it is not considered toxic unless it is present in very high concentrations), and therefore many safety concerns can be dealt with using existing knowledge and experience.

Tanker Transportation

Moving CO_2 overland by tanker is economic if the distance is short, if the volume being transported and frequency of trips are low, and if the customer is willing to pay a high price for CO_2. In most cases tanks would be loaded onto trains or trucks, with rail being more competitive than road transportation, provided the logistics fit the parameters of existing rail systems.

An alternative is to use rail or ships for large-scale transportation, which would mean using liquefied natural gas (LNG) technology in marine tankers today. This option would improve the chances of developing an international market for CO_2. Such a system would provide buffer capacity to handle any local shut downs in CO_2 supply that might occur (for example, the shut down at a power plant or large injection site). However, such a global system would require massive infrastructure investment. This means the option might develop over time (if a sufficiently high enough carbon constraint emerges), but it certainly will not be a starting point for CCS deployment. Transportation of this scale will only occur after CCS proves to be a commercially viable way of reducing GHG emissions on a local scale.

A global market for CO_2 with all the necessary infrastructure is an important long-term concept to consider, no matter how far away from commercialization it might be, because of the potential to capture CO_2 from large source countries or regions like China, India and the EU, and transport it to large storage and CO_2-EOR opportunities in the Middle East, Russia and elsewhere.

Cost of Transport

Many factors play into the economics of the transportation options. The cost of pipeline transport depends on the physical geography of the route taken (for example, onshore versus offshore or arctic versus temperate climates) and whether or not the route is heavily populated. Factors that impact the cost of ocean transport include the volumetric capacity of marine tankers and the availability of loading and unloading infrastructure. Both transport options are obviously affected by the distance of the route taken and the volume of product moved.

Pipeline transportation is estimated to cost (CDN) \$6/tCO_2 for 650 km's transported in a common carrier network with a capacity of 14.5 MtCO_2/yr (Thambimuthu, 2004). To construct such a pipeline would also entail an additional upfront capital investment. There are no solid estimates of how much overland tanker transportation would cost within Canada (either by truck or train), but it would certainly cost more than pipeline transport considering the volume of CO_2 that needs to be moved. Further, the cost to ship CO_2 from other countries to Canada (for storage in the WCSB for example) would be prohibitively high at this stage and will likely remain that way for some time. Although oceanic tanker transport may be the only option in countries without easy access to geological storage, an investment in this type of infrastructure development is a costly endeavour and would only occur in a world that places a very high value on CO_2 emissions reductions.

Pipeline transportation is not a terribly costly component of a CCS system, especially when compared to the cost of capture and compression. Economies of scale are a big factor in transportation cost, but learning effects are generally quite small because transportation technology is already mature and in commercial use.

Transportation Risks

The risks associated with CO_2 transportation tend to be local (like the capture risks noted previously), such as pipeline ruptures or leaks to the nearby environment. As already noted the risks posed by such events are comparable or even lesser in severity than those of other industrial activities, and these risks are considered manageable using current approaches (IPCC, 2005). The cost of risk management approaches for CCS movement is generally quite small compared to the overall cost of transportation.

Transport R&D Needs

Practical experience shows that CO_2 transportation by pipeline is an established and commercial technology in most applications, and only incremental improvements are expected in most areas. However, new technology and knowledge is needed in two priority R&D areas.

Gas Characterization

A comprehensive database of CO_2 emissions streams in Canada, which would include CO_2-purity levels and other important information (related to other gases [and trace gases] in the emissions stream), would be a valuable undertaking. A list of end uses for each CO_2 source would help identify whether certain gas streams are best suited for CO_2-EOR, CO_2-ENGR, CO_2-ECBM or other opportunities.

Gas characterization can include developing an understanding of the effects of impurities on the physical state of the CO_2-rich gas streams, and on the physical state of CCS infrastructure like pipelines, compressors and storage tanks. Understanding the reactivity of trace elements like H_2S, SO_X, NO_X, oxygen, nitrogen and argon would be extremely valuable.

Pipeline Parameters

A second priority is to better understand optimal pipeline parameters for CO_2 transportation, which includes the study of using existing pipelines, or the co-transportation of CO_2 with other products in a dedicated pipeline. The study would include addressing any environmental and safety issues associated with large-scale CO_2 transport, as this would help in setting optimal pipeline parameters, and perhaps even specific codes and standards for building and operating CO_2 pipelines in Canada. As the important technology that links the capture and storage components of CCS, transportation plays an integrating role. Process modelling and process optimization studies on integrated approaches to CCS are an important part of better understanding pipeline parameters.

Storage Technology

Storage Systems

Although storage is one of the last steps in the CCS process it is one of the first to be considered when developing a strategy to roll-out CCS infrastructure and systems. There is no benefit to capturing CO_2 unless it can be stored and thus the total storage capacity and its location is an important constraint on how much CO_2 can actually be managed.

An important consideration becomes the type of storage media being used. CO_2 can be injected into porous geological formations such as sedimentary basins, but igneous and metamorphic rocks are ill-suited because of their fractured nature and lack of the needed porosity and permeability.

Other options for storage include terrestrial mineralization and ocean storage. Mineralization is prohibitively costly because of the large (and visible) environmental footprint it would leave due to mining operations. Further, most regions that have the serpentinite or other reactive deposits are far from CO_2 sources. Therefore, this would entail transporting CO_2 from places like the WCSB and Ontario to locations in British Columbia or Quebec.

Ocean storage refers to two options being discussed today. The first is dissolution in sea water, which simply means putting the CO_2 into solution in the ocean water column (IEA, 2004). The second choice is to store liquid CO_2 at depths of greater than 4000 m (IEA, 2004). Ocean storage is the most controversial of the options being considered primarily because of the relative immaturity of the technology and the resulting uncertainty and lack of knowledge of the potential environmental impacts of CO_2 in ocean ecosystems. Pilot projects in both Hawaii and Norway have been cancelled because of public opposition (IEA, 2004).

As a result, geological storage is the primary option being discussed in Canada today. The primary mechanisms for geological CO_2 storage include:

- Volumetric traps – sites where free-phase and un-dissolved CO_2 is trapped in pore spaces and is prevented from seeping to the surface by physical or hydrodynamic barriers (in oil and gas reservoirs and deep saline aquifers). Volumetric traps also include man-made cavities such as salt caverns and mine shafts.
- Residual traps – in places where CO_2 has migrated through a formation, a portion of the gas is retained in the pore space as a result of capillary forces. Thus, a portion of the gas is trapped by forces other than a simple physical cap rock.
- Solution traps – where CO_2 is either in solution in the formation fluids, or forms ionic bonds with the fluids, such as in the water or oil that saturates the pore space within a rock formation.
- Adsorption – options where the CO_2 bonds with formation rocks that contain organic material, such as coal or shale.

- Mineral traps – sites where the CO_2 precipitates out as a carbonate mineral. Such reactions can occur when CO_2-charged formation fluids react with other formation minerals.

The first two of these geological storage options traps the CO_2 in its free phase, the next two entail a geochemical trapping mechanism, and the final option relies on a chemical process to govern the fixation. Most geological storage options (with the exception of adsorption) are most efficient at a depth of 800 m or more, where the CO_2 stays in its dense phase because of formation pressure. Compressed fluids are pumped (or injected) down a borehole, which raises the formation pressure and results in the CO_2 entering the pore space that was formerly occupied by formation fluids. The spread or migration of CO_2 within a formation is controlled by factors like buoyancy, diffusion, dissolution and mineralization (IPCC, 2005).

Much of the current discussion of geological storage in Canada is on the selection of appropriate storage sites, which comes down to one of two options: value-added or non-value-added opportunities.

Value-added storage

Value-added storage is often considered to be the best use for captured CO_2 because of the added benefits beyond simply storing the CO_2. The first and most obvious benefit is using CO_2 for enhanced hydrocarbon recovery. The timing for using CCS in the WCSB is good because the maturity of the basin dictates a need for enhanced recovery methods. In addition, the geological trapping mechanisms in these reservoirs are known to have held gases and liquids (which include CO_2) in formation for millions of years. Production of these hydrocarbons has created substantial capacity to store CO_2 in what have already proven to be permanent storage sites.

Enhanced Oil Recovery

Only a portion of an oil reserve can be recovered using conventional methods, and as a result a variety of enhanced recovery techniques have been developed such as water flooding (waterflood), solvent flooding and gas flooding (which uses stranded gas or CO_2). When CO_2 is injected into a pool, it mixes with, and dissolves into, the crude oil which causes the hydrocarbon to swell thus reducing its viscosity, which results in more oil flowing to the well. Even when CO_2 doesn't go into solution, the result is still increased reservoir pressure which helps sweep oil towards the production well. CO_2 enhanced oil recovery (CO_2-EOR) can result in additional recoveries of 8 to 15% of the total resource in place, which translates to an average reservoir experiencing a 50% increase in recoverable reserves (IEA, 2004).

Up to half of the injected CO_2 flows back to the surface with the produced oil; the rest remains trapped in the reservoir. Any produced CO_2 is typically re-captured and re-injected. This production, capture and re-injection cycle has been considered an economic benefit in the past, because it reduces the volume of CO_2 required for a project. However, if one of the goals is to store GHG emissions long-term it may become more cost-effective to leave as much CO_2 in the ground as possible on the first pass. Because this was never the original intent of using CO_2-EOR, the technology will need re-engineering to co-optimize oil production and CO_2 storage.

CO_2-EOR is already a common practice and is in use in seventy-four operating projects in the US. Combined, these projects inject up to 30 $MtCO_2$ annually, with only 3 Mt coming from industrial sources, and the remainder coming from natural underground sources. The main reason for this use of natural CO_2 over industrial CO_2 is the low cost of natural sources, which highlights the need for more cost-effective capture technology to separate CO_2 streams at industrial facilities. An important change to current practice is the increasing attractiveness of these industrial sources, driven by the global desire to reduce CO_2 emissions.

Both commercial CO_2-EOR projects operating in Canada today (EnCana's Weyburn Project and Penn West's Joffre Project) derive CO_2 from industrial sources. The Joffre project is nearing its end of life, but the Weyburn project is still relatively new. Weyburn injects 2 $MtCO_2$/yr, with half of the CO_2 being recycled resulting in a net long-term storage of 1$MtCO_2$/yr. If Weyburn produces for the next twenty years it will store 30 $MtCO_2$ in total (20 $MtCO_2$ net – when project-related emissions are accounted for). When fully depleted, the reservoir will have much more available storage capacity, but filling this will require the injection of CO_2 for storage purposes only.

At least five new pilot CO_2-EOR projects are at various stages of development in Canada. However, the current cost of CO_2 is high, and until it becomes more available (like a commodity) this innovative practice will only grow incrementally. If the cost of CO_2 were sufficiently low, CO_2-EOR could potentially be applied to many major oil fields worldwide making the potential market for CO_2-EOR technology enormous.

Enhanced Gas Recovery

As natural gas pools near the end of their productive lives, gas recovery factors decline and compressors, pumps and other equipment must work just as hard to produce less gas. It's possible that there are significant economic advantages to injecting CO_2 into gas reservoirs during these last productive years to produce the remaining recoverable reserves in less time and without significantly contaminating the resource. CO_2 is denser than natural gas in any of the phases (solid, liquid, supercritical or gas), and thus it would be expected to flow down a reservoir thereby pushing the gas up (IEA, 2004). However, this option for enhanced recovery is still highly speculative, and it still needs to be tested and proven in actual applications. Low permeability reservoirs may provide some of the first applications because the anticipated benefits of CO_2 enhanced natural gas recovery (CO_2-ENGR) may be most prominent in these settings.

An opportunity often discussed for CO_2-ENGR is using it in past conventional EOR projects where stranded natural gas liquids were often injected into oil pools to enhance recovery. Significant amounts of this injected gas remain in formation throughout the WCSB, which in theory could be recovered using CO_2-EOR today. At a future time, with the right combination of high natural gas prices and low CO_2 prices, it may be economic to re-open these projects and produce the injected natural gas liquids using CO_2-ENGR.

At present, a number of barriers stand in the way of CO_2-ENGR in Canada. First, CO_2 is far too expensive to run these projects economically today. Second, conventional production typically recovers up to 90% of the available gas in a reservoir, and CO_2-ENGR mainly helps in speeding up the recovery process with limited potential to increase overall recovery factors. While faster recovery is an economic advantage, it is not as valuable as increased recovery factors. Third, CO_2-ENGR has yet to be applied anywhere in the world and the technology is still in the conceptual stage (IEA, 2004). Other potential issues are the unknown effects of CO_2 mixing with hydrocarbon gases, and the potential for early CO_2 breakthrough to producing wells. More work is needed to develop, demonstrate and commercialize this technological opportunity.

Enhanced Coalbed Methane Recovery

Coal beds (or coal seams) naturally contain gases including methane, which can occur in varying amounts depending on depth (normally at 300 to 1500 m), and how much methane has already seeped to the surface. The methane sits adsorbed onto coal surfaces and occurs as a free gas in the fractures and cleats, with an undisturbed coal seam containing up to 25 m^3 of methane per tonne of coal (IEA, 2004). While this technology is only being developed, expectations for its success are very high.

The US has been producing coalbed methane (CBM) using primary production methods for more than two decades. Daily production levels in the US exceed 28 Mm^3, which comes from some 6000 wells. The Canadian CBM industry is in its infancy, but growing rapidly, and CO_2 enhanced CBM recovery (CO_2-ECBM) techniques may significantly improve conventional recovery factors, which often range between 40 and 50% depending on the resource and the recovery method used (IEA, 2004). These factors will increase to more than 90% using CO_2-ECBM, and to 100% in deep seams that have good permeability. This is because the methane has a lower affinity to coal than CO_2, and therefore, by injecting CO_2 into coal beds, it is naturally adsorbed onto coal surfaces, thus freeing up the methane for production (IPCC, 2005).

Laboratory analysis indicates that two to ten times as much CO_2 can be adsorbed by coal as methane, thus the storage potential is large. If the coal is deep enough and remains undisturbed, the CO_2 can be stored for thousands of years. However, much of the experience with CO_2-ECBM is at the R&D and applied R&D stages. In fact, this is still a very immature and unproven technology area.

Some specific issues that need to be addressed to prove the technical and economic feasibility of CO_2-ECBM include work on coal swelling caused by the adsorbed CO_2 which decreases the permeability of the formation. Another issue is the diffusion rates of gas to and from the coal and into the cleats. Brackish water production is another issue in some commercial CBM operations, notably in the US. The cost of drilling injection wells, and the environmental impacts and footprint, are issues because of the large number of wells needed for CBM production, which will only be exacerbated when using CO_2-ECBM.

One of the largest problems is in resource characterization and in identifying the specific coal seams that are best suited for CO_2-ECBM. For example, the reservoir needs to be both horizontally and vertically homogeneous (with minimal faulting and folding), permeability needs to be at least 1 to 5 millidarcies, methane content needs to be sufficiently high with the coal at a depth of between 300 and 1500 m.

Acid Gas Injection

As already noted, many natural gas fields around the world have high CO_2, H_2S and other associated gas concentrations. Deep sour gas pools in the WCSB have large quantities of both H_2S and CO_2. Traditionally these gases were separated from the produced natural gas, with the CO_2 being vented to the atmosphere and the H_2S being processed and stored as sulphur for eventual sale. In 1990, certain Canadian natural gas plants were granted regulatory approval to inject acid gas (the combination of H_2S and CO_2) back into the deep geological formations near where it originated. In many cases, this acid gas injection is the most cost-effective and environmentally sound way of dealing with the H_2S, as it eliminates the need for costly sulphur recovery facilities and is a less energy-intensive way of handling the acid gas.

Today, more than 40 of the 60+ global acid gas projects in operation are located in Alberta and British Columbia, and these projects currently store up to 1 Mt of CO_2 annually in Canada (IEA, 2004). A lot can be learned from acid gas projects because they are some of the only commercial scale analogues for geological CO_2 storage. Much can be learned about the fate of CO_2 and its interaction with formation substances. Regulation already exists for acid gas injection and storage, and many parallels and learning, can be drawn from this process when developing CO_2 storage regulation.

Gas over Bitumen

An issue currently being discussed is the potential adverse impact of producing natural gas in contact with bitumen (and vice versa) in the WCSB. It may be possible for CO_2 to play a role in re-pressuring formations where one resource has been removed, which might enable production of the remaining resource. This potential opportunity is still being explored in the laboratory and is only at the pre-field test stage today.

Temporary Storage

Underground caverns, especially from salt or potash mines, provide some capacity to temporarily store CO_2. In western Canada, depleted oil and gas reservoirs or other porous media are used for the temporary storage of natural gas. This storage will play an important role in balancing pipeline pressures in a CO_2 transportation system. Such storage can also help ensure a steady supply of CO_2, by acting as a strategic buffer or reserve. In many ways, this is the same role that natural gas hubs play today. Because of the experience and knowledge that already exists regarding temporary natural gas storage, little research seems necessary on temporary CO_2 storage.

Non-value-added Storage

The storage options that generally don't provide an economic benefit other than simply storing the CO_2 are referred to as non-value-added opportunities. Until a significant cost is associated with CO_2, emissions these non-value-added opportunities will remain uneconomic in Canada. Even in a carbon constrained world, value-added opportunities are most appealing. However, if certain constraints make value-added storage too costly (for example, if impure emissions sources require significant cleaning and conditioning prior to injection), the opposite may hold true, and simply storing the CO_2 may be most cost-effective. As a result, the timing to develop these opportunities depends heavily on future climate change policy and on emissions reduction crediting. Regardless, there is general recognition of the need to improve the understanding of non-value-added storage opportunities (IEA, 2004).

Depleted Oil and Gas Pools

Depleted oil and gas pools and (some day soon) coal seams, provide empty pore space that can be reoccupied by CO_2. A sliding scale is used to distinguish between operating and depleted oil and gas pools, and depending on a number of dynamics (such as fossil fuel prices and the physical nature of the reservoir), an abandoned pool may operate again at a future point in time.

Like many of the value-added options, depleted pools afford project operators the advantage of knowing the geological formations being used. In places like the WCSB, the geology is very well understood and the traps and formations are known to have held gases and other liquids for millions of years. In addition, a lot of depleted capacity already exists in mature basins like the WCSB. Depleted gas fields have more potential, simply because they are larger in size than oil fields, there are many more of them, and the recovery factor for gas is much higher than for oil. Spare capacity in undeveloped fields like the Atlantic and Beaufort-Mackenzie Basins will become available as oil and gas is produced.

Any technical issues related to these formations are similar to those noted earlier for CO_2-EOR or CO_2-ENGR.

Deep Saline Aquifers

A saline aquifer can refer to any one of a number of sedimentary rock types saturated with saline, non-potable water, from which the water can be drawn, and into which fluids can be injected (IEA, 2004). Aquitards are rock layers in which water can exist, but from which water cannot be produced, because the permeability is to low to allow water to flow at an acceptable rate. An aquiclude is a rock with almost zero permeability. All three of these formations play a role in deep CO_2 injection, with aquifers providing the pore space for storage, and aquitards and aquicludes providing the physical trapping mechanisms.

Deep saline aquifers provide the greatest volumetric potential for storage anywhere in the world (refer back to the 1,000 to 10,000 Gt noted previously). Saline aquifers run deep under all 68 Canadian sedimentary basins, and provide access to storage opportunities in many parts of the country.

Statoil's Sleipner Project, which is 250 km off the coast of Norway in the North Sea, is the first commercial-scale project dedicated to CO_2 storage in a deep saline aquifer. The Sleipner natural gas production field provides approximately 1 $MtCO_2$/yr for storage in the aquifer (IEA, 2004). Since 1996, the site has not experienced any CO_2 leakage, and the project is proving technically feasible (IEA, 2004). The entire project will store some 20 $MtCO_2$ in its lifetime, although the total storage capacity is hundreds of times larger (IPCC, 2005).

Cost of Storage

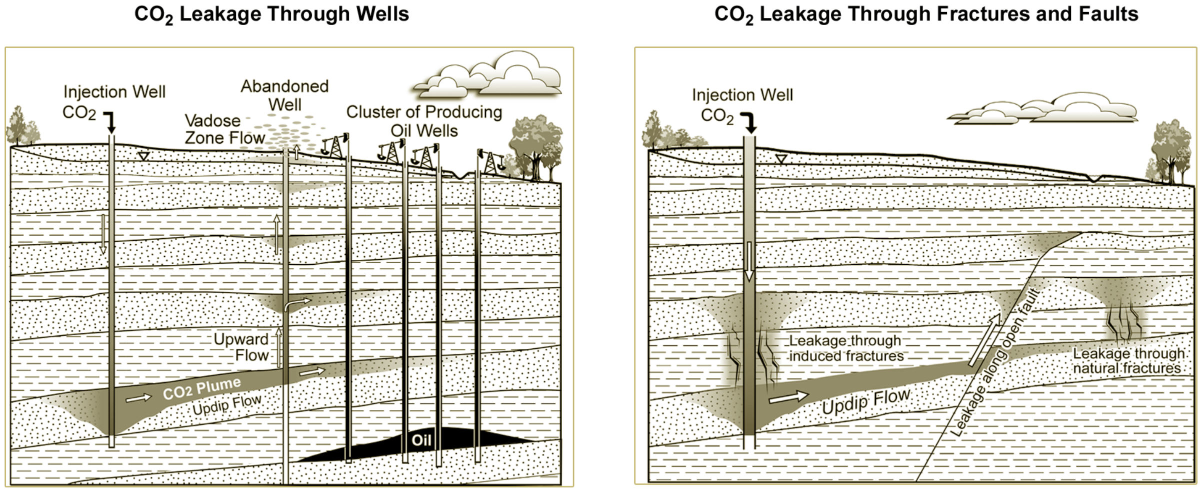
Storage is typically the least costly of the three CCS components. The main drivers of the cost of storage include geographic considerations (onshore versus offshore storage), reservoir depth and other reservoir characteristics (such as injection capacity). Storage costs can range between (CDN) \$3 and \$9/tCO_2 in Canada (Thambimuthu, 2004). The cost of monitoring (which is discussed below) is not known for Canada specifically, but is estimated by the IPCC (2005) to be (USD) \$0.1 to \$0.3/tCO_2. When CO_2 is used for enhanced hydrocarbon recovery, the economics can change significantly, and in many cases can provide a net benefit. As already noted, the deployment of cost-effective infrastructure and systems requires upfront capital investments which must also be accounted for in the economic analysis.

Storage Risks

The storage component of CCS poses a new set of risks that tend to be: global in the sense that any seepage would diminish the effect of storage by increasing the amount of CO_2 that escapes to the earth's atmosphere; and, local in that CO_2 may leak and contaminate other energy, mineral resources and groundwater (and may harm vegetation and life depending on leak rates and concentrations). While there is little experience with geological storage, closely related industrial experience and scientific knowledge can serve as the basis for risk management (IPCC, 2005). The identification of potential escape pathways for leakage and/or seepage (as illustrated in Figure 4.1) is an important step in this, and any other risk assessment.

Evidence from engineered and natural comparisons, and from models to date, indicate that up to 99% of CO_2 injected into a geological formation is "very likely" to be retained for over 100 years; that 99% is "likely" to be retained over 1000 years if the formation is appropriately selected and the project well managed (IPCC, 2005). In most of these sites, the majority of CO_2 will gradually be immobilized by the many trapping mechanisms noted previously.

Figure 4.1 Potential CO_2 Leakage Pathways



CO_2 Leakage Through Wells

CO_2 Leakage Through Fractures and Faults

(Source: Bachu and Celia, 2006 [in press])

However, it is important to recognize that a small amount of CO_2 will leak (and perhaps even seep to the surface) and strict requirements like zero leakage/seepage are unnecessarily restrictive. Studies to date indicate that an allowable rate of seepage of up to 0.1%/yr would still result in an effective outcome when dealing with GHG emissions reductions (IEA, 2004). This rate is not an indication of what the research community anticipates the actual rate to be; rather it is considered an upper bound (or tolerance level) for the earth to deal with slow and steady CO_2 seepage to the atmosphere, considering the need to maintain atmospheric GHG concentrations below a certain level. Regardless, a variety of storage monitoring programs and response plans are needed, and appropriate technologies are required to minimize the impacts of each kind of underground leak, or seep to the earth's surface.

Of course, it must also be recognized that there are places where geological CO_2 storage should probably not take place, such as places that experience high seismic activity. As was noted in Section 3, this is one of many criteria used to select sites for CCS activities.

Storage Monitoring Options

Short and long-term monitoring options are required to ensure that any gases injected into a geological formation do not return to the atmosphere, cause environmental damage or pose safety concerns. Monitoring is also needed to provide the data for calculating net emissions balances to which any emissions reduction credits will be tied. Because these credits will have a monetary value and environmental attributes associated with them, they will need to be substantiated and proven to be representative of actual storage taking place, using some sort of measurement and verification protocol based on accurate monitoring. Because of the different monitoring needs, a number of technologies are proposed for operation, verification and environmental requirements.

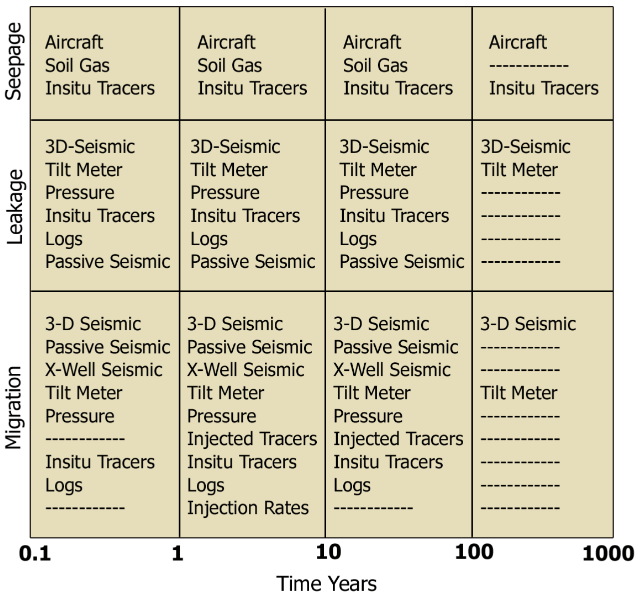
An operator will need to monitor any project for regulatory purposes (operational monitoring), which will likely include checking injection rates and CO_2 recycle and re-injection rates in the case of enhanced recovery processes. In addition, the project operator may have their own (and more specific) monitoring needs since good information leads to better project management and optimized performance. Operational monitoring is initiated during the injection phase of the project and is concerned primarily with the underground migration of the CO_2 injected, and the associated emissions when running the project.

Verification (or scientific) monitoring is done for research purposes, to improve the understanding of the complex processes that occur at injection sites. Verification monitoring is needed to learn how CO_2 migrates and either reacts or adsorbs in rock formations; it is a major focus in all research, pilot, demonstration and commercial projects today. Another element of research is minimizing leakage into other formations and seepage to the surface, and includes developing models that enhance the predictive power of science today.

Environmental monitoring is meant as a safeguard against health, safety and other environmental risks, and is generally focused on CO_2 seepage – the movement of injected CO_2 towards the earth's surface where it can interact with the biosphere. Depending on the risk level of the project, aspects of environmental monitoring may be similar to operational monitoring. Since leakage or seepage may occur anytime during a project, or long after the project has ceased, environmental monitoring doesn't end when the injection stops.

Researching, testing and continuously refining these monitoring, measurement and verification (MMV) technologies is essential to ensuring that the CO_2 is properly stored and neither leaks from the storage unit nor seeps to the earth's surface. Figure 4.2 lists some technologies being discussed for monitoring CO_2 movement over different timeframes. Many technologies are either costly or require further development to be used in commercial applications. Current field experience can help in determining which of these technologies can deliver the needed information for scientific learning, operational excellence and environmental integrity.

Figure 4.2 Monitoring Technologies for Different Timeframes



Seepage	Aircraft Soil Gas Insitu Tracers	Aircraft Soil Gas Insitu Tracers	Aircraft Soil Gas Insitu Tracers	Aircraft ------------ Insitu Tracers
Leakage	3D-Seismic Tilt Meter Pressure Insitu Tracers Logs Passive Seismic	3D-Seismic Tilt Meter Pressure Insitu Tracers Logs Passive Seismic	3D-Seismic Tilt Meter Pressure Insitu Tracers Logs Passive Seismic	3D-Seismic Tilt Meter ------------ ------------ ------------ ------------
Migration	3-D Seismic Passive Seismic X-Well Seismic Tilt Meter Pressure ------------ Insitu Tracers Logs ------------	3-D Seismic Passive Seismic X-Well Seismic Tilt Meter Pressure Injected Tracers Insitu Tracers Logs Injection Rates	3-D Seismic Passive Seismic X-Well Seismic Tilt Meter Pressure Injected Tracers Insitu Tracers Logs ------------	3-D Seismic ------------ ------------ Tilt Meter ------------ ------------ ------------ ------------ ------------

(Source: Chalaturnyk and Gunter, 2005)

Storage R&D Needs

A number of priorities have been identified for research spanning all aspects of geological storage (again based on identified gaps), and the following are suggestions for an overarching CO_2 storage R&D framework for Canada.

Storage Integrity

The top priority for storage research is the confirmation that CCS is a safe, reliable and environmentally beneficial practice for long-term CO_2 storage (the order of thousands of years). The issue here is the possibility of leakage from the containment unit (the geological formation) or seepage from underground to the earth's surface, and although it seems likely that well-engineered sites in optimal locations pose a very small risk of significant leakage or seepage, in actual fact, this assertion is very difficult to prove. Scientific evidence and field experience are both needed to improve technologies and practices for geological storage.

Site Identification and Characterization

Sites need to first be identified on a broad scale, using the basic information available. Selected sites should be evaluated using several basic criteria. First, in broad terms, there needs to be sufficient capacity to store the desired amount of captured CO_2. In fact, the amount of available storage capacity will be a factor in how much CO_2 can actually be captured. Second, the selected storage sites will collectively need to be capable of injecting the CO_2 at the supply rate. Third, the confining properties of the storage site (meaning, the ability of the storage sites to actually hold CO_2 long-term), such as its ability to avoid CO_2 leakage within the subsurface or seepage to the earth's surface, is an important criterion. Safety is another consideration, as any sites that are considered to be unsafe will be rejected. The economics of the various storage options are the ultimate deciding factor for which sites to pursue and in what relative order. The parameters for this last criterion (economics) change with time because of technological maturation, and because of changes to fiscal regimes, incentives and penalties.

After the top candidate sites are selected, they need to be characterized in detail regarding their geology, faults and fractures (if there are any present), internal architecture, mineralogy and geochemistry, fluids contained in the pore space, pressure and geothermal regimes, stresses and geomechanical properties, flow of contained fluids, and the number and type of wells penetrating the storage unit. Numerical models need to be run to evaluate the long-term fate of injected CO_2 in the candidate sites. Potential natural or man made leakage pathways (such as fracture systems, abandoned wells or mine shafts) should be better understood, and a review of historic well-drilling practices in Canada would help develop an understanding of the stability of well casings and cement, and the bonds between casing, cement and rock formations.

Canadian Storage Capacity

Further study is needed to improve existing knowledge of the potential source sites and storage basins in Canada because of the regional distribution of CO_2 emissions, and the asymmetry in storage opportunities across the county.

The largest CO_2 emitting provinces are Alberta and Ontario, each with more than 200 $MtCO_2$/yr. Two thirds of the Alberta emissions are from large, stationary sources (which are suitable for CCS), while most of Ontario's emissions are from transportation. Saskatchewan and northeast British Columbia represent two other candidate regions in terms of CO_2 sources, with the Atlantic Provinces providing smaller opportunities.

On the storage side, potential in the WCSB (which extends from northeast British Columbia to Manitoba) is in the order of hundreds of mega tonnes in the existing and depleted oil reservoirs, several thousand mega tonnes in existing and depleted gas reservoirs, 1,000 to 2,000 mega tonnes in coal beds, and tens to hundreds of giga tonnes in deep saline aquifers. In the Atlantic Provinces there is some potential for storage in onshore coal beds (once the technology is proven), offshore oil and gas reservoirs and deep saline aquifers, but all of these opportunities need to be evaluated. In addition, there are opportunities for smaller more local storage in parts of British Columbia, Ontario and Quebec; however, there is little current knowledge of any of these options. Only the depleted and existing oil and gas reservoirs in the WCSB, and recently the coal beds in Alberta, have been thoroughly studied.

An important research area may simply be to gain a better understanding of the economics of all storage options, value-added and non-value added. It is possible that some deep aquifer projects may be less costly overall if the systemic cost savings of straight storage are fully realized.

Tag-on Opportunities

To develop infrastructure is often more costly than tagging it on (or appending it) to existing infrastructure opportunities. Surface facilities and equipment for compression or liquefaction, and the subsequent injection and monitoring of CO_2 will be costly. As well, unless the source and storage sites are near each other, transportation is expensive. Therefore, a sensible approach for development of such infrastructure and systems is to reduce costs by having governments, research communities and industry work together to maximize synergies through collaborative efforts, and by tagging research and science projects onto existing commercial opportunities. This tag-on approach was used for the Weyburn CO_2-EOR project and will be used for the *CO_2 Sequestration and Methane Production Project* (CSEMP), as well as Penn West's new CO_2-EOR project.

The benefits of tag-on projects are many-fold. The sites (such as compressor stations, field production centres, and pipeline facilities) are often fully serviced and staffed, and may already have the necessary resources to undertake the actual storage and monitoring activities. In the case of oil and gas production sites, a lot of information and expertise exists on-site which would be helpful when developing reservoir and storage engineering approaches, and when identifying best practices to optimize the dual goals of petroleum recovery and long-term CO_2 storage. In addition, site specific reservoir expertise can be used to develop mitigation strategies for potential CO_2 leakage and seepage. Existing commercial sites also have practices and procedures, standards and protocols that can be used to address safety, environmental and other risks.

Assessment Approaches and Expertise

Experts around the world are working to develop better risk assessment tools and approaches for CCS, and many Canadians are leading the way. Resident expertise in the petroleum exploration and production sectors, including hands-on experience with acid gas injection and CO_2-EOR, has contributed to developing this expertise. Canada has been very involved in developing an international collaborative mechanism and in sharing its expertise with international research organizations. However, more work is needed, and therefore the effort should continue.

Making integrated evaluation tools on geological storage available would be useful for decision-makers. When assessing storage options from a business perspective, useful parameters for an integrated tool would include rate of return, project value and CO_2 credit value. From a policy perspective, parameters might include emissions reductions calculators, tax and royalty calculators. Such integrated evaluative models and tools are not currently available, but components of them do exist. These tools should be based on sound engineering design drawn from petroleum reservoir experience, be capable of generating credible results, and should include a wide range of options that are useful to both industry and government.

International Collaboration

The international community is already engaged in developing CCS technology, and Canada is very involved in both the IEA's *Greenhouse Gas R&D Programme* and the *Carbon Sequestration Leadership Forum*. Canada also houses the *International Test Centre for Carbon Dioxide Capture* (ITC) at the University of Regina and the *IEA Weyburn CO_2 Monitoring and Storage Project* in Weyburn. Canada has world research facilities at the *CANMET Energy Technology Centre in Ottawa* (CETC-O). The *CBM Technology/CO_2 Sequestration Project* (in China) is another example of Canada's efforts to work with international partners on CCS. Collaborative efforts like these have dual benefits of helping Canadians learn from the experience of other researchers, project operators and policymakers, while reinforcing Canada's own knowledge capacity and ability to contribute to international capacities. This international collaboration applies to all aspects of CCS technology development (not just to storage).

A great deal could also be learned through selective bilateral relationships with countries that are active in CCS research and demonstrations. Such arrangements could include international missions, joint participation in research and monitoring projects, or even the exchange or secondment of experts.

The Hub and Backbone Concept

An emerging research priority today is in gathering and aggregating CO_2 emissions from a number of high-quality and high-quantity sources, locations that are commonly referred to as emissions hubs, and the transportation of the captured emissions through a common carrier pipeline or backbone system.

Hubs are locations where large volumes of CO_2 can be collected by gathering it from a number of sources in close proximity. By aggregating the CO_2 in a central hub, end customers have greater assurance regarding the availability of a long-term supply. This means reduced supply risk, and therefore some reassurance to storage project developers.

A backbone pipeline could be built to connect all the major emissions hubs in western Canada to the variety of available WCSB storage sites, and the entire system could operate much like a pipeline gathering, transmission and distribution systems for oil and gas today. A number of existing and underutilized small diameter pipelines (2 to 4 inch lines) already criss-cross Alberta and Saskatchewan, and could be used to transport CO_2 from emissions sources to the backbone system. This existing infrastructure could potentially become the ribs that connect to the large-diameter backbone, which may one day run all the way from Ft. McMurray to Ft. Saskatchewan, Joffre-Red Deer, Medicine Hat and on to Regina-Belle Plaine.

Eligible sites for the first Canadian emissions hubs would include those that have a significant daily tonnage of CO_2, and would be in close proximity or connected by the backbone to large storage opportunities, preferably enhanced recovery opportunities. Potential hubs in the WCSB include the Ft. McMurray region, Ft. Saskatchewan, the Joffre-Red Deer area and Wabamun (and each is discussed in detail below). Additional work is needed to determine whether Regina-Belle Plaine may become another hub, especially considering the recent agreement between the Governments of Canada and Saskatchewan to co-fund projects that include elements of clean coal, industrial gasification and poly-generation. Other regions may fulfill the necessary source requirement, but local storage basins are either not as well known or not as economical for storage as the WCSB is today. A Halifax hub could potentially be connected to offshore CO_2-ECBM projects. A Sarnia emissions hub may one day connect to storage opportunities in the US. Until CO_2 emissions reductions become a pressing societal priority, these other hubs will remain as potential opportunities; however, the WCSB presents options for cost-effective CCS today.

There is considerable support for the concept of hub and backbone infrastructure and systems as the foundation for a growing and robust CCS sector in Canada. An industry-government task group could be commissioned with implementing detailed development plans for such an endeavour. The first task would be the creation of a long-term vision of a Canadian backbone interconnected with emissions hubs across the WCSB. The characteristics and parameters (including physical and operational) of the hubs and backbone would need to be developed. Draft business rules for operating this infrastructure, including tolling and operating standards, could be established for pipeline operators and for CO_2 buyers and sellers.

Oil Sands Hub

Today, the Ft. McMurray region of Alberta could supply 5,500 t/d of high quality CO_2 and an additional 4,000 t/d of medium quality CO_2. This supply will grow as new infrastructure is built. The future use of gasifier technology in the oil sands, which would provide medium-concentration CO_2 streams and CO2 storage sites, would add to the region's potential as a hub.

Although Ft. McMurray is far from any CO_2-EOR opportunities, the volume of CO_2 in the region may be sufficient to justify a gathering system and a pipeline to transport the CO_2 elsewhere in the WCSB. Such a pipeline could be designed for multi-product transport, to help deliver other co-benefits by moving under-utilized hydrocarbon products (like benzene or other petroleum fractions) to the petrochemical facilities near Edmonton. Construction of such a pipeline would greatly impact CCS opportunities in the WCSB over the medium to long-term from 2015 to 2030.

The steps toward developing such a hub would begin by gathering the CO_2 from high purity sources (greater than 90% CO_2) between now and 2010. This means capturing the 5,500 t/d from the Benfield hydrogen production units in existing plants. By 2015, operators could begin gathering the 4,000 t/d of medium concentration CO_2 from the PSA units in hydrogen separation facilities. Upon further R&D, it may be possible to use physical absorption or oxy-fuel combustion in such applications. As new oil sands facilities are built and existing plants expand (post-2015) it would be possible to integrate new units into the existing capture and transportation infrastructure. Between 2015 to 2030 it will be possible to capture emissions from new gasification plants (such as petroleum coke fuelled plants), but this will require new solid sorbent, physical solvent and membranes technology, or hybrid processes, to capture medium to high-quality CO_2 sources.

Multi-industry Hub

More than 40 different industrial activities take place in Ft. Saskatchewan and east Edmonton, in Alberta, ranging from power generation, to refining, to petrochemical and fertilizer production to cement manufacturing. Presently, 2,500 t/d of high quality CO_2 could be aggregated locally, enough to justify a gathering system and a pipeline to nearby CO_2-EOR opportunities in Swan Hills or Pembina. Another 3,000 t/d of medium quality CO_2 is available from the hydrogen production facilities in local refineries.

A multi-industry hub may start by first gathering the 2,500t/d that is available from feed gas processing, ethylene oxide production and hydrogen production in ammonia plants, by using available dehydration and compression technology. The next step is to capture medium to medium-quality CO_2 streams from local hydrogen production facilities, and from Shell's upgrader (the 3,000 t/d noted previously), perhaps using physical absorption or oxy-fuel combustion (both of which need to be demonstrated first). From 2012 to 2015, any new plants, such as coal or pet-coke gasification units, could be CO_2 capture-ready which might include physical solvent, solid sorbent, membrane or hybrid technologies. Post-2015 would continue with CO_2 capture from new or expanded hydrogen production facilities (in the refineries and upgraders), or from new commercial IGCC facilities (assuming the successful demonstration of this technology).

Petrochemical Hub

The petrochemical complex at Joffre, Alberta produces 1,300 t/d of high quality CO_2, in addition to a CO_2 stream that it already supplies to Penn West Energy Trust for its CO_2-EOR project. The area includes an ethylene oxide facility, an ethane processing facility and an ethanol plant. Emissions from the complex would grow if oil sands by-products became available as feedstock, or if ethane and other natural gas products from the north (Alaska or the Beaufort-Mackenzie areas) became accessible.

The beginning of a petrochemical hub in Joffre could start with expanding the current CO_2 gathering system to include the full 1,300 t/d. It is a very highly concentrated source in Joffre, at greater than 90% CO_2, which could be captured using existing dehydration and compression technology. This could follow with the capture of any new emissions from the increased processing of bitumen-derived or other feedstock after 2015. In addition, CO_2 emissions from on-site coal or bitumen gasification could be captured.

Electricity Hub

Since coal-fired power accounts for 35% of the CO_2 emissions from LFEs in Canada, it seems a natural activity around which to build an emissions hub, and perhaps Lake Wabamun in Alberta would be an ideal location. However, current coal-fired facilities use pulverized coal in sub-critical steam cycles and the resultant flue gas is only 13 to 15% CO_2. The cost of capturing CO_2 from such dilute streams makes it uneconomical today. Therefore, a number of dynamics need to play out, including technology breakthroughs, stringent CO_2 emissions regulations and the public's willingness to pay higher electricity prices.

The CCPC is currently looking to locate its first commercial-scale clean coal facility, which may be an IGCC plant that uses coal or pet-coke, a supercritical plant with amine scrubbing, or even a new oxy-fuel plant. Individual companies are considering small demonstration gasifiers in other applications. Until one of these opportunities comes through, it will be difficult to economically capture CO_2 from electricity until after 2015.

Some general steps towards building an electricity emissions hub would be to initiate CO_2 capture from an oxy-fuel combustion demonstration unit somewhere between 2008 and 2015. If the oxy-fuel demonstration is successful, a next phase might be to retrofit existing commercial plants for capture. Also post-2015, CO_2 might also be captured from the first demonstration IGCC gasifier noted previously. However, the real opportunity for capture from an electricity hub may not be realized until post-2020 when CO_2 streams from any new commercial gasifiers could be captured. The ultimate achievement would be the eventual roll-out of an entirely new fleet of clean coal-fired facilities, all of which are connected to CCS infrastructure.

Section Summary

Each component of CCS (capture, transport and storage) has specific R&D needs and requirements, but ultimately a complete and integrated system needs to be developed, and therefore, the larger systems view cannot be overlooked.

A number of technologies are being studied for capture and compression in post-combustion, pre-combustion, oxy-fuel combustion and industrial process systems. The specific technologies include absorption, adsorption, membranes and cryogenics. Each technology is being researched with specific systems applications in mind, and there is no single solution being proposed for all applications. Some technologies are at a more advanced state today and are commercially proven, but this doesn't necessarily guarantee their future role in CCS.

Capture and compression is the most costly component of CCS today, and ranges from (CDN) \$50 to \$70/tCO_2 captured for post-combustion systems, (CDN) \$20 to \$50/tCO_2 captured for pre-combustion, and (CDN) \$13 to \$80/tCO_2 captured for oxy-fuel combustion. Again, the actual cost of each option is likely to be nearer the bottom end of these ranges (as noted previously). However, capture also has the greatest potential for future cost reductions, which may range from 25 to 30% by 2025 (specific components may experience 50% cost reductions).

CO_2 is easiest to transport in its dense phase whether by pipeline or tanker. Pipelines already transport CO_2 today using technology and expertise from existing energy pipeline industries. Tankers can be used for land or ocean transport, with the latter enabling the movement of CO_2 from large source opportunities in China, India and the EU to storage sites in Russia, the Middle East and elsewhere.

Transportation is less costly than capture at (CDN) \$6/tCO_2 for every 650 km's transported in a common carrier network with a capacity of 14.5 MtCO_2/yr, with much of the cost going to upfront capital investment. The transportation component involves relatively mature technology and the potential for cost reductions are low. However, economies of scale are important, and if mass transportation is needed, a large-diameter CO_2 pipeline (or backbone) with many lateral lines would be most economic.

Although storage is the last step in the CCS process it is the first component to be considered, primarily because it is only necessary to capture as much CO_2 as can actually be stored. A number of natural mechanisms are used to store CO_2 in geological formations, including volumetric trapping, residual trapping, solution trapping, mineralization and adsorption. Spanning these possible mechanisms, two categories of geological storage have been identified: value-added and non-value-added opportunities. Value-added opportunities include CO_2-EOR, CO_2-ENGR, CO_2-ECBM and temporary storage, as well as smaller niche opportunities in Canada like acid gas injection and gas over bitumen. Non-value-added options include storage in depleted oil and gas fields and in deep saline aquifers.

Storage is often the least costly component of the CCS system and is estimated to range from (CDN) \$3 to \$9/tCO_2 captured in Canada. Monitoring costs associated with storage may constitute an additional (USD) \$0.1 to \$0.3/tCO_2 avoided (note, the distinction between captured and avoided cost was addressed in section 2). In many of the value-added situations there may even be an economic advantage to storage. The potential for future cost reductions in storage are quite low.

Wide ranging costs are associated with each activity, which is a result of the site specific characteristics in each capture facility, transportation route or storage site. All of these costs should reduce over time, as experience and learning is gained with the technology, and as economies of scale materialize. Economies of scale are a strong force in driving down the cost of large capital investments, especially investments in shared (or common) infrastructure, such as an emissions hub gathering system, a large-diameter backbone pipeline, or distribution systems for multiple storage sites in one local region. However, CCS infrastructure and systems require massive upfront capital investments and it may take a strong CO_2 price signal for such development to begin. The IPCC suggests a price of (USD) \$25 to 30/tCO_2 would be sufficient to initiate CCS development around the world (IPCC, 2005).

5. The Way Forward

The Vision Revisited

What emerges from the CCSTRM is a vision of *"technology for today's energy economy providing the basis for transformative change tomorrow."* This vision describes a world in which a robust and vibrant CCS industry is built upon the inherent opportunities for CCS in Canada, including the nation's current position as a country with:

- Vast fossil fuel resources
- Internationally competitive industry producers and exporters of fossil fuels
- Enormous potential for geological storage of CO_2 in various regions across the country
- Existing, leading-edge knowledge and expertise in CCS applications

The ability to pursue the development of environmentally sound and economically feasible technological approaches for CCS is an opportunity for Canada to address the issue of GHG reductions at home using local solutions. The timing is right considering Canada's need to meet its international climate change objectives, and in light of the recent federal and provincial plans and other announcements for dealing with climate change, which largely call for the use of domestic measures as much as possible. *Project Green* (as the federal plan is entitled) has scope for pursuing CCS in Canada, and in fact mentions the possibility of partnership funding for domestic CCS projects. As well, industry is ready and willing to participate in developing and deploying CCS technology. The level of engagement in developing this CCSTRM (see Appendix A) is a sign of the level of commitment that exists across Canada for bringing action to the current discussion on CCS by rolling-out the development of technology to make Canadian industry competitive.

Section Observations:

Achieving a number of critical objectives will help facilitate the vision embodied in this roadmap:

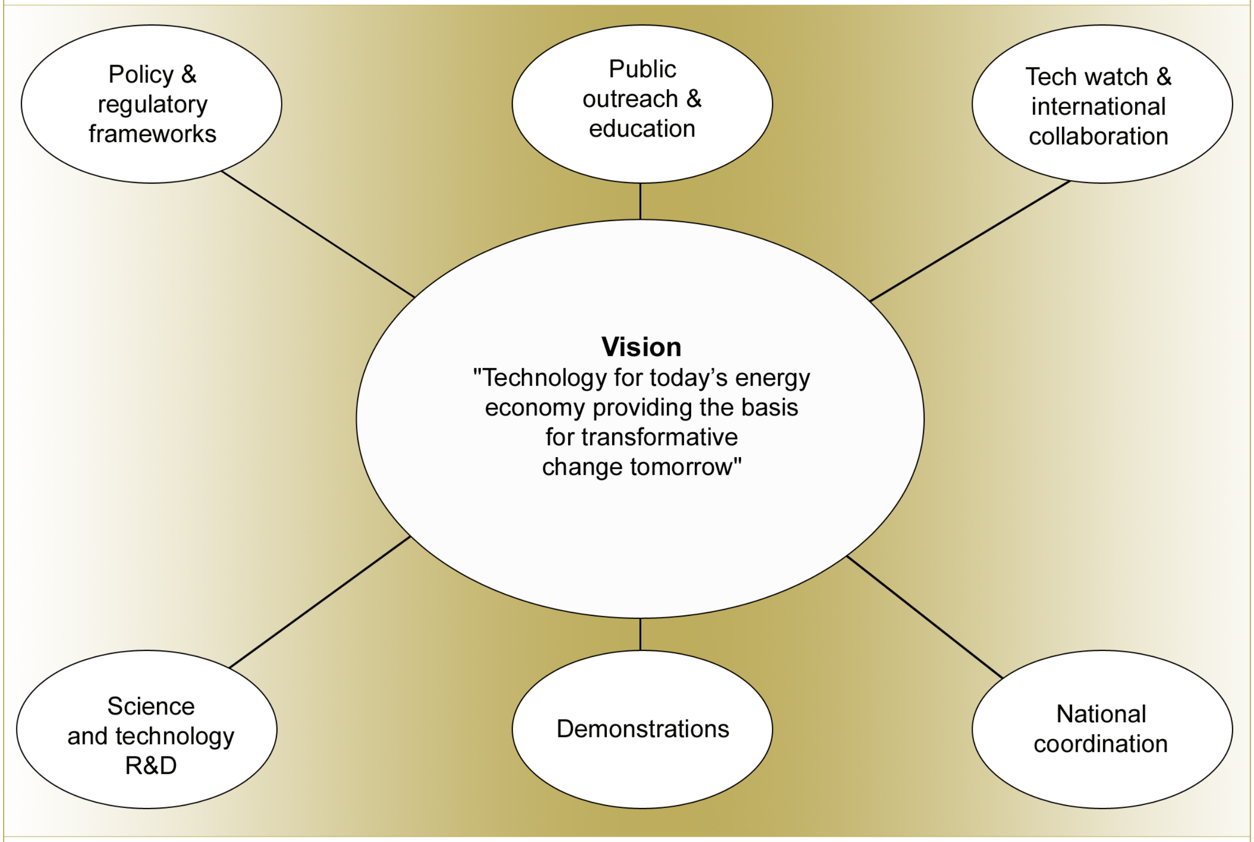
- *CCS policy and regulatory frameworks*
- *Public outreach and education*
- *Technology watch and international collaboration*
- *Science and technology R&D*
- *Demonstrations*
- *National coordination*

A variety of organizations are required to undertake the championing of these objectives, and the Roadmap Advisory Committee suggests the need for an implementation committee to begin the process and to identify long-term champions

The message emerging from the roadmap initiative is a need for action today, to enable the vision of "technology for today's energy economy providing the basis for transformative change tomorrow"

In order to bring action to the roadmap, a variety of next steps or critical objectives are identified, along with a group of implementation champions who will be responsible for bringing action to these words. This section provides the way forward, the pathway to be taken to realize the vision embodied in the roadmap. Six critical objectives are identified, including the need for policy and regulatory frameworks, public outreach and education, technology watch and international collaboration, science and technology R&D, demonstration of systems and applications, and national coordination. As indicated in Figure 5.0, each objective contributes to the overall vision described previously. Achieving the first three objectives would help lay the groundwork for developing CCS infrastructure and systems, as policy and regulation, outreach and education, and collaboration and intelligence gathering are each necessary components to guide technology development and deployment. The next two objectives are more closely linked to the technical content of the roadmap, the actual R&D and demonstration of technology. The final objective relates to the national coordination of any efforts related to the previous five. Some of the anticipated impacts of developing a CCS industry are indicated, and a final section on the CCS roadway ahead summarizes the pertinent information in the roadmap, while providing a call to continue to build domestic CCS expertise and knowledge.

Figure 5.0 Canadian CCS Vision and Objectives



Critical Objectives

The most immediate objective to help build a robust and flourishing Canadian CCS industry is to develop a timely and strategic approach for carrying Canada forward from the current state to a future desired state. This requires vision, commitment, and the continuous championing of strategic activities aimed at achieving the six critical objectives outlined below, each of which are described under the sub-categories of planned activities, reach, outputs and desired outcomes. One outcome of the roadmap exercise is the Roadmap Advisory Committee's commitment to continue to work to develop an implementation vehicle for the roadmap over the coming year (which is also discussed below).

1) Policy and Regulatory Frameworks

As a CCS industry emerges in Canada, both policy and regulatory frameworks will be required. A policy framework is the first of these two components, as it is expected that good policy will eventually guide appropriate regulations.

A policy framework is needed to help guide the appropriate development of a CCS industry sector in Canada and to guide regulators as they develop their own framework for the regulation of CCS activities. Important aspects of the policy framework include:

- A vision of the role of CCS in Canada (among the portfolio of policy options) and a strategy for how CCS will be used to reduce domestic GHG emissions
- Recognition of the important linkage between the structure of the energy economy and opportunities for achieving significant GHG reductions in Canada

  - Integration, so that any CCS policy can operate along side (and in unison with) other Canadian policies and measures related to the economy, energy and climate change (both federal and provincial policies and measures)
  - Joint efforts and coordination between federal, provincial and territorial jurisdictions because of the federal and regional implications CCS policy would have across the country, and because of the different jurisdictional boundaries that exist
  - Direction related to other outstanding policy questions such as:
    - What amount of reductions can be expected from CCS in Canada, and in what timeframe?
    - How will the costs of CCS infrastructure and systems be shared?
    - Which specific CCS activities are most desirable from a societal point of view?
- A way to address long-term liability, property rights, ownership and time related issues where the storage of CO_2 is being considered
- Direction on questions related to the use or ownership of pore space for storage, and any subsequent royalties
- A means to establish a fiscal framework for CCS deployment, whether it is one that includes incentives, penalties or a mix thereof

A regulatory framework is necessary to accomplish the following goals related to the capture, transport, injection and post-injection phases of storage:

- Provides sufficient transparency and stability concerning storage requirements
- Manages risks associated with geological storage of CO_2
- Incorporates monitoring, measurement and verification regimes for the purposes of:
    - Addressing health, safety and environmental issues arising from storage operations
    - Determining the performance of the storage system, over a pre-determined time period
    - Verifying the mass of CO_2 to be stored, for emissions trading and GHG inventorying purposes
    - Resolving any potential disputes arising from conflicts over the use of the subsurface and possible contamination of underground resources
    - Identifying monitoring plans and mitigation measures in the event of leaks, seepage or unexpected migration out of the storage reservoir
- Identifies required elements of a permit system, including operating, monitoring & remediation requirements and terms for abandonment
- Accounts for the site-specific nature of storage sites and the flexibility that may be required within a framework to monitor different sites
- Clearly states any specific regulations related to CO_2 pipeline operations
- Reflects jurisdictional cooperation on the development of regulations to ensure equivalent treatment of CO_2 storage within provinces and across provincial boundaries

Activities

- Assess relevant existing policies and regulations related to subsurface oil and gas operations to assess their applicability to CO_2 storage
- Identify any gaps within current policy and regulatory frameworks with reference to CO_2 storage
- Initiate discussions with major interest groups regarding the development of policy and regulations
- Prepare a set of draft policies and regulations for consideration and discussion

- Monitor and review developments in current projects such as the *IEA Weyburn CO_2 Monitoring and Storage Project*, the *CO_2 Sequestration and Enhanced Methane Production Project*, and future EOR and acid gas injection monitoring projects

Reach

Target audiences will be Canada's federal and provincial policymakers and regulators, industry groups (like the oil and gas industry and fossil-fuel energy users), environmental groups and non-government organizations (NGOs), the public and other interested stakeholders.

Outputs

The outputs include the development of science-based policies, regulations and protocols (through the work of the appropriate legislative and regulatory bodies) to facilitate the capture, transport and storage of CO_2 in geological formations. These policies, regulations and protocols would reflect health, safety and environmental considerations and allow for the verification of stored CO_2.

Desired Outcomes

The anticipated result is a well regulated industry for CO_2 storage, meaning it is guided by sound policy that ensures the health and safety of the public and the environment, and allows for the inventorying of GHG emissions reductions.

2) Public Outreach and Education

The public needs to be better informed of CCS and any benefits and challenges related to its application. Open and transparent public outreach and education needs to take place with verifiable information made available to the public so stakeholders can make their own decisions on CCS. Developing public support for CCS through such engagement would help Canada in achieving its international emissions reduction commitments while continuing to benefit economically from the country’s vast fossil fuel energy sources. A national information program devoted to CCS could be used to disseminate relevant information through websites, publications and public speaking forums.

- Activities Identify recognizable independent experts in the scientific, engineering and NGO communities and encourage their participation on task forces or advisory panels to whom the media will turn for information
- Inform education leaders and educational institutions of the importance of science in maintaining an informed public, and how to use science to make important decisions
- Develop a public outreach program to act as a forum for discussion on energy and energy system options available to Canada (both fossil fuel, and alternative, systems and infrastructure)
- Provide more public education about climate change and its implications for Canada
- Increase public outreach on the capture and geological storage of CO_2, focusing on:
    - How geological storage works
    - CCS’ climate change benefits
    - The low probability of negative effects based on the current understanding
    - Available preventative/remediation measures
    - The role that geological storage can play in EOR
    - The use of CCS historically and around the world
- Reach out to the media proactively to increase the public’s awareness and prevent misinformation
- Actively involve the federal and provincial governments in managing CCS

Reach

A national stakeholder CCS information program would target government officials, policymakers, the scientific community, the media and other stakeholders from the general public.

Outputs

The deliverables could be a public website, brochures, reports and presentations at public forums, with targeted communication mechanisms depending on the needs of the audience.

Desired Outcomes

The anticipated effect would be the public's recognition of CCS as one of a suite of options for GHG emissions reductions. This implies CCS will be seen as a strategically important technology to help Canada achieve its international emissions reduction commitments, while maintaining economically viable and environmentally sound fossil fuel sectors as a vibrant part of Canada's economy.

3) Technology Watch and International Collaboration

When conducting Canadian R&D on CCS it is imperative to stay connected to international activities and to keep a watch on technology development. Doing so results in avoided duplication of research efforts, and instead results in collaborative efforts with funds and resources that can lead to higher quality outcomes. International collaboration is a useful vehicle for finding knowledge gaps, thereby identifying opportunities for both technology development and transfer. As noted recently by the IPCC (2005), the development of CCS technology requires an international effort, and tackling the issues and challenges facing CCS is not a simple project for any one country or company to undertake – international collaboration is required for CCS to succeed.

An international technology watch could take place under a virtual web-based national CCS intelligence centre, which would focus on exchanging information on technology advancements. This would provide a forum for both technology watch and collaborative activities. The centre would enable CCS stakeholders to respond effectively to shifting energy market demands and environmental requirements, based on knowledge of what is happening abroad and at home. The centre could provide information for the coordination of CCS research, development and deployment efforts.

Activities

- Identify national and international CCS development and business opportunities
- Establish a network of experts among R&D organizations, technology suppliers and other stakeholders
- Establish a network of information related to technology pilots, demonstrations and deployment
- Promote partnerships and collaboration among industry, academia and government, to form the best alliances for developing and commercializing technology
- Promote network member products and services
- Foster public and private sharing of specialized CCS R&D facilities
- Prepare newsletters
- Promote membership growth, participation and interaction

Reach

A network of collaboration would target fossil fuel companies, industrial operators, equipment manufacturers, service providers, consultants, industry associations, regulatory agencies (federal, provincial and territorial), universities and other research organizations or NGOs.

Outputs

The output would be a comprehensive web-based national CCS stakeholder intelligence centre with information on R&D organizations, technology suppliers and manufacturers, specific CCS technologies and their components and all types of projects and initiatives (pilots, demonstrations and commercial applications).

Desired Outcomes

The result will be to build and enhance communication linkages to improve the quality of activities undertaken by individuals or consortia (of institutes, industry and government partners). The intent is to provide access to timely information to accelerate the development and deployment of CCS in Canada.

4) Science and Technology R&D

Identifying the relevant R&D areas to address Canadian circumstances is important, because of the role it will play in tackling the critical challenges the energy industries face at home. These issues include the environmental challenge of climate change, the limitations of alternative energy options and the current inability to maximize the recovery of existing energy resources. Technologies that address these issues are also of interest to the international community because the same issues are global in nature.

Because embarking on a new R&D pathway is both a costly and risky endeavour, and because of the global interest in the technological outcomes, it is logical to pursue international R&D with researchers from around the world. Both local and international consortia can be formed to advance technology for all three components of CCS systems, which would result in research efforts of a sufficient scale to address the size of the task at hand. However, while international efforts are a necessary component, so are local efforts to develop technology in Canada which will work in the Canadian context.

Activities

The following provides a summary of the specific R&D requirements that are needed to enable the successful commercial application of CCS in Canada. This brief summary is drawn from the information provided in Section 4 which provides more detail on the key R&D needs for each research stream (capture, transport and storage).

Capture R&D Needs

The major technological issues facing CO_2 capture include the high cost and relatively unproven performance of existing and emerging technologies.

Post-combustion or flue gas separation (solvent-scrubbing) – needs are focused on the development and scale-up of solvent technologies for the treatment of air-fired combustion flue gases (post-combustion capture). Existing approaches are costly and energy intensive. Technologies to address more stringent environmental regulations through post-combustion treatment are needed for Canadian coal-fired electricity generators.

Advanced integrated processes using oxy-fuel combustion – requires definition of the science, equipment design principles, systems integration of oxygen/CO_2 recycle or pure oxygen and other process configurations for the low-emissions combustion of fossil fuels with CO_2 capture. The objective is to achieve significantly lower capital and operating costs for oxy-fuel combustion with CO_2 and multi-pollutant controls. R&D will focus on the mechanics of combustion and heat transfer, burner development, furnace design, integrated flue gas cleaning, and CO_2 gas separation and compression.

Pre-combustion Capture of CO_2 (gasification) – involves integrated concepts for CO_2 and multi-pollutant capture, improved catalyst/membrane processes for water-gas shift reactions and hydrogen/CO_2 separation, and the investigation of novel CO_2 capture processes in natural gas reforming or coal, bitumen and pet-coke gasification.

Industrial processes – includes improving the understanding of process chemistry to increase CO_2 concentrations in flue gases from major industrial processes, and developing process modelling and systems integration tools for CO_2 capture from industrial processes, conventional oil and gas refineries and the oil sands upgrading operations.

Staging emissions hub development – requires the development of a long-term view of Canadian emissions hubs along with developing the characteristics and parameters (both physical and operating) of the infrastructure and systems involved in the hubs. Business rules for operations are also needed.

Transport R&D Needs

Transport – includes improving the understanding of the impact of transporting liquid or supercritical CO_2, with or without trace impurities, on the design and operation of pipelines and associated equipment, and on the physical state of CO_2-rich pipeline fluids. A process for developing the specifications for the variety of CO_2 streams to be shipped needs to involve capture, transport and storage site proponents. Another need is the development of a database of required purities of CO_2 streams for a variety of end uses, including EOR, ENGR, ECBM, depleted oil and gas fields, and deep saline aquifers.

Staging pipeline backbone development – requires the identification of a long-term view of the Canadian backbone along with developing the characteristics and parameters (both physical and operating) of the backbone and its interconnections with emissions hubs. Business rules for pipeline construction, operations and throughput are needed. Firm contractual commitments with CO_2 suppliers and purchasers, including details on site locations and anticipated volumes, will accelerate pipeline development.

Storage R&D Needs

Capacity assessment – includes the identification and assessment of the top sites for storage in consideration of the full context, which includes the location of other infrastructure and systems such as a backbone pipeline and industry hubs. There is a large need for geological site identification and characterization followed by the aggregation of data from all suitable sites to better understand the total economic capacity in Canada. Another need is the development of universal screening protocols for selecting geological storage sites and assessing risks.

Injection – needs include the assessment of CO_2 flow down wells, modelling and prediction of geomechanical and geochemical effects, potential near-well bore formation damage from injection, and an understanding of the impacts of the presence of other flue gases such as NOx, SOx, H_2S, particulates and others on CO_2 through the investigation of operating and decommissioned wells.

Long-term storage – requires understanding the ultimate fate of CO_2 in a variety of geological formations, through geomechanical and geochemical modelling, to determine the long-term integrity of CO_2 containment in natural and man-made structures. R&D needs also include assessing CO_2 properties and behaviours in geological formations, understanding the impact of including other gases and developing a suite of modelling techniques to predict the long-term fate of stored CO_2 in a variety of formations.

Monitoring, measurement and verification – requires investigation of a variety of monitoring technologies including remote sensing, subsurface chemical/biological tools and in-situ tools used to examine formation specific challenges. Stored CO_2 in depleted oil and gas fields, deep saline aquifers and deep coal seams (and CO_2 in natural analogues) can be monitored to test and refine new and improved technologies. These efforts could lead to the development of monitoring, measurement and verification protocols.

Staging storage development – includes identifying and prioritizing opportunities for future storage sites to be connected to emissions hubs via a transportation backbone. Site selection will be based in part on the demonstration of storage in different geological formations and for a variety of applications. A framework of rules and risk management approaches for the operation of these sites is needed.

Reach

The results of the R&D activities under all three components are intended to reach Canada's federal, provincial and territorial policymakers and regulators, industry and academic R&D communities, industrial operators and other interested stakeholders.

Outputs

Advanced technology would be developed in each of the component areas, for use in national and international applications. In addition, knowledge and expertise in fundamental and applied research will accumulate in the Canadian research community, thus building a capacity for local technical support to improve the overall performance of domestic commercial applications. This knowledge and expertise is transferable to other countries through education and training, or through the sale of products and services. R&D is the science base which will provide much of the technical information of relevance to help form public policy and develop an effective regulatory environment for CCS.

Desired Outcomes

The anticipated impact is to overcome technology gaps and enhance the prospect of commercial demonstrations in Canada, with the result being technology development and the creation of Canadian knowledge and expertise in CCS.

Specific R&D activities from Section 4 are matched against predicted development timelines in Figures 5.1 and 5.2, which serve as summary illustrations of the desired outcomes of capture and storage technology being rolled-out over time. The specific activities in these diagrams are some primary examples of what type of R&D could be done in Canada to address Canadian circumstances. The first point in Figure 5.1 is a good example of a critical Canadian R&D need. The country currently has no modular testing facilities to accommodate the experimental development of integrated gasification and pre-combustion technology, and domestic facilities are needed to spur the deployment of these technologies in Canada.

Figure 5.1 Canadian Capture R&D Needs

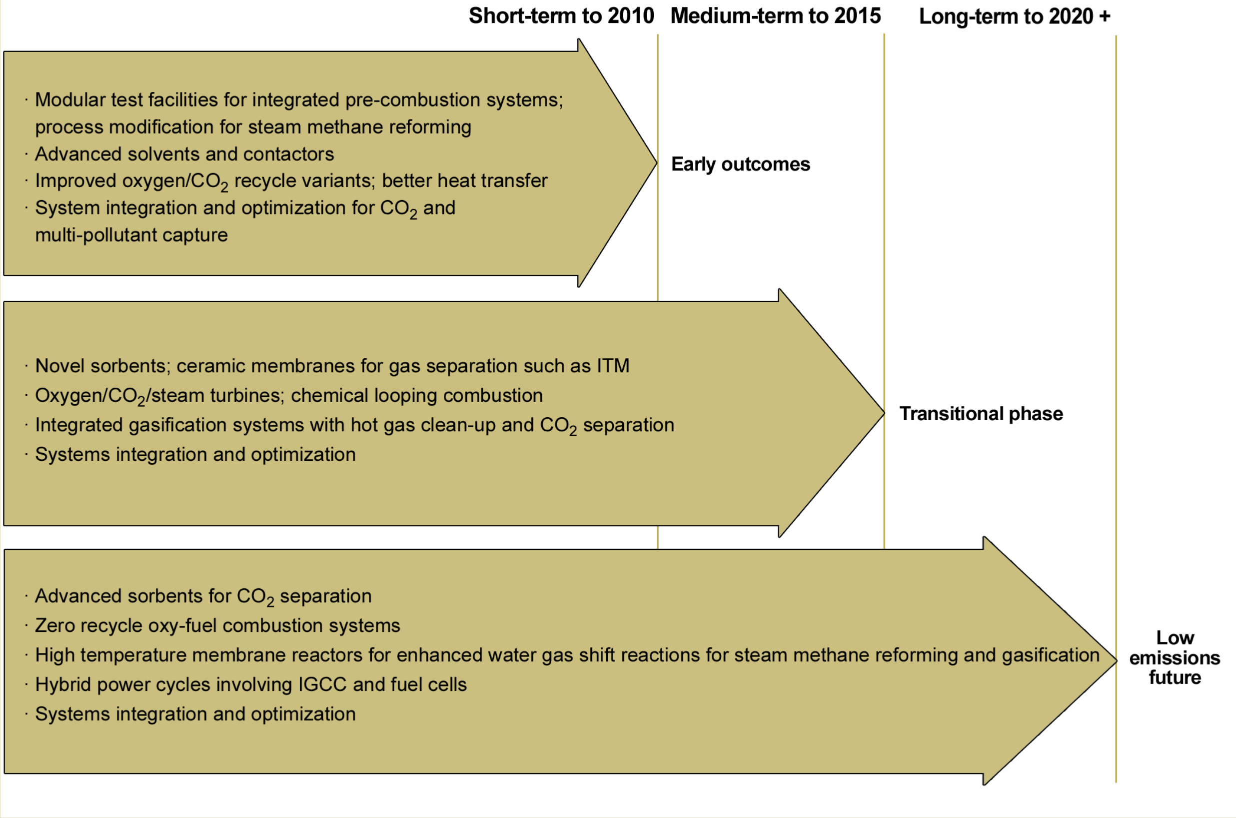
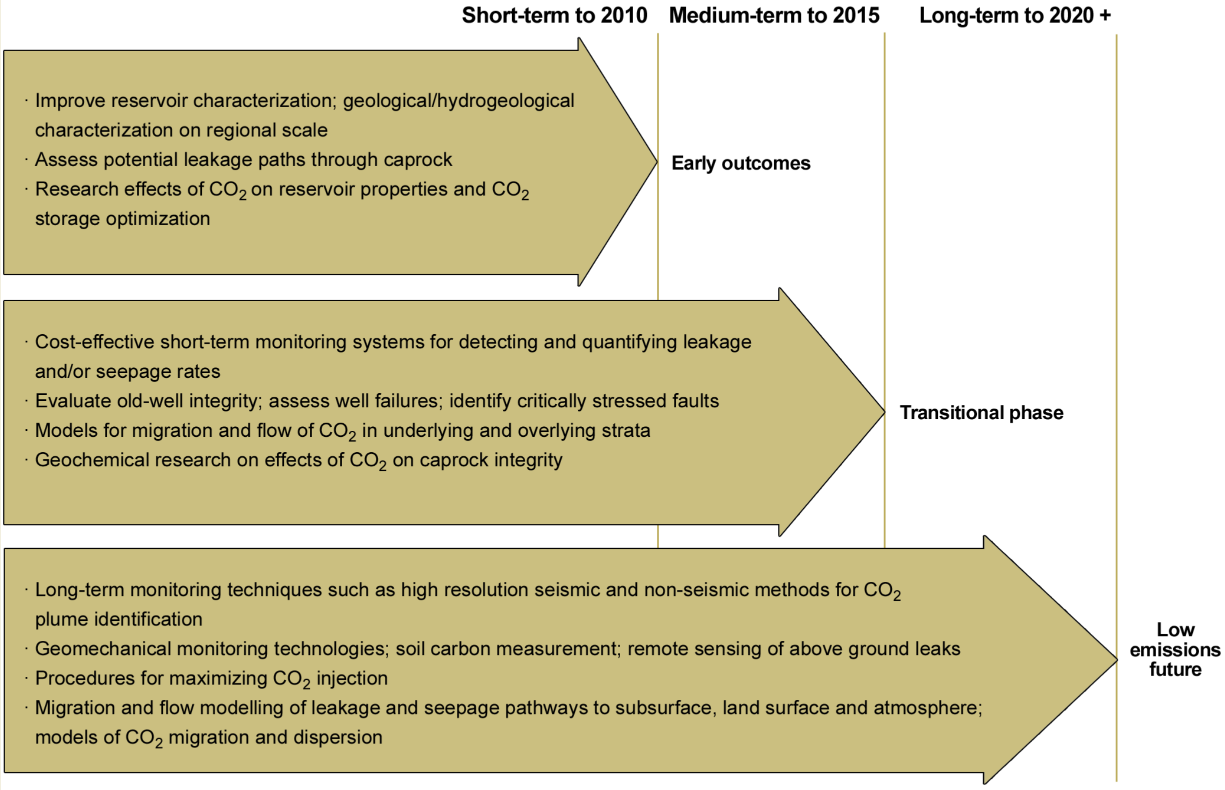


Figure 5.2 Canadian Storage R&D Needs



- Improve reservoir characterization; geological/hydrogeological characterization on regional scale
- Assess potential leakage paths through caprock
- Research effects of CO_2 on reservoir properties and CO_2 storage optimization

- Cost-effective short-term monitoring systems for detecting and quantifying leakage and/or seepage rates
- Evaluate old-well integrity; assess well failures; identify critically stressed faults
- Models for migration and flow of CO_2 in underlying and overlying strata
- Geochemical research on effects of CO_2 on caprock integrity

- Long-term monitoring techniques such as high resolution seismic and non-seismic methods for CO_2 plume identification
- Geomechanical monitoring technologies; soil carbon measurement; remote sensing of above ground leaks
- Procedures for maximizing CO_2 injection
- Migration and flow modelling of leakage and seepage pathways to subsurface, land surface and atmosphere; models of CO_2 migration and dispersion

A CO_2 pipeline system, not noted in these figures, is more of a short-term need (between now and 2010). Any pipeline infrastructure should be built with future-oriented design principles in mind, to accommodate the increasing volume of CO_2 and the variety of deliveries anticipated over time. Therefore a certain amount of pre-build capacity may be considered during the building of the CO_2 pipeline infrastructure in Canada.

5) Demonstrations

Industry, government and other interested stakeholders need to establish a common national vision and business models aimed at selecting viable technologies and locations for demonstration projects, and at making the arrangements for demonstration project financing. The ultimate goal of the demonstrations is to identify the best technology to use in the commercial application of CCS infrastructure and systems in Canada.

The role for new technology is to optimize the opportunities that exist in industrial facilities, beyond what would normally take place under business as usual circumstances. Because of the long lifetimes of these capital-intensive investments (many power plants, oil and gas facilities and petrochemical operations have lifetimes of 30 to 40 years or more), decisions made today have lasting long-term implications, and because of this, upcoming issues such as future emissions regulation or energy policies should be factors in the decisions made. Canadian industry is interested in going beyond current practices as long as a mechanism to share the risk of doing so can be agreed to by government. Therefore, joint industry-government consortia for demonstration projects, and the first development of CO_2 infrastructure and systems, are important initiatives to undertake.

The time for demonstrating many technologies is now. Canada must facilitate its own demonstration projects to ensure that newly developed CCS technology works in the Canadian context. By waiting too long, any new industrial facilities being built today (and in the near future) will affect the nation's emissions profile for decades to come; a 'wait and see' approach is not acceptable. Canada must start planning today and build any new infrastructure to be CO_2 capture-ready for a future time when it can be integrated with CCS infrastructure and systems.

Activities

- Form consortia and develop business cases for one or more demonstration sites (such as IGCC and oil sands upgrading with CO_2 capture), and for the development of infrastructure and systems (such as the first leg of a backbone pipeline)
- Identify all pilot scale projects in Alberta and Saskatchewan to date and incorporate these sites into plans for future infrastructure development
- Develop plans for infrastructure development including an appropriate amount of over-build to accommodate for future growth in CCS
- Develop risk mitigation strategies in conjunction with stakeholders to manage the risks associated with projects and infrastructure development
- Begin selection process for first CO_2 pipeline leg in the WCSB and interconnections with the first emissions hubs and storage locations
- Conduct project definition studies for pipeline, emissions hubs and storage sites
- Develop front-end engineering design package and submit plans for regulatory approvals
- Select equipment and sub-components for demonstration projects
- Design, construct and commission projects and demonstration facilities

Reach

Industrial fossil fuel users, various levels of governments, policymakers, the scientific community and the public at large are the targeted audiences. Eventually, the results would be felt by all industrial energy users, through the development of entirely new energy delivery systems enabled by CCS. Canadian industry could one day supply essential CCS products and services to the world.

Outputs

The expected result is demonstration facilities operating in Canada (at a large enough scale for results to be scaled up to commercial operations) which will eventually lead to the roll-out of commercial CCS operations in many regions. Other desired outputs include approaches, strategies, plans and business models that serve as starting points for the planning and development of demonstration projects. Information and data from these projects could be disseminated through the public information program and intelligence centre noted previously.

Desired Outcomes

Anticipated outcomes include the development of CCS projects with minimized commercial and technological risk. R&D and pre-demonstration investments will be justified by the positive results of successfully implementing CCS in domestic commercial applications. Another outcome would be useful approaches and strategies to help manage the construction and operation of CCS facilities without exposing the involved stakeholders to excessive risk.

6) National Stakeholder Coordination

A coordinated and strategic effort for all R&D and demonstration activities needs to be undertaken. This coordination needs to take place at many different levels, including at the international scale and at much smaller scales (such as regional efforts). A pressing priority for Canada is national coordination of the R&D and demonstration efforts undertaken on CCS, by linking all activities being carried out by industry, government and other stakeholders. Although R&D and demonstrations are a strong focus of the national coordination, this objective also includes the harmonization of efforts related to the first three objectives: policy and regulatory frameworks, education and outreach, and technology watch.

This coordination includes many important aspects related to networking, communicating, planning, strategizing and the timing of activities and initiatives, as well as the pooling of national and regional resources to help optimize the outcomes of science and technology activities carried out in Canada. Effective national coordination requires a robust process for making decisions on what amount of funding to provide, which R&D and demonstration activities to support, where to implement such projects, and when to undertake them. National coordination implies the pooling of existing information for, and the eventual dissemination of all R&D and demonstration results for future learning.

Activities

- Provide coordination on the development of policy and regulatory frameworks for CCS, based on the work already being done across various jurisdictions that is relevant to Canadian circumstances
- Identify and categorize initiatives and activities that currently focus on CCS R&D and demonstrations
- Identify and categorize initiatives and activities that indirectly link to CCS R&D and demonstration activities
- Develop an illustrative framework of how previous initiatives and activities link with one another, and identify any structural gaps which will indicate places where R&D and demonstration projects and programs might be needed
- Distinguish between the research gaps being filled by international initiatives and activities versus those that are not, or even those that are distinctly Canadian issues
- Develop an operational framework for national coordination of R&D and demonstration efforts, including:
  - Processes for information sharing, which may either be linked to, or enabled by, the information program and intelligence centre noted previously
  - Methods for the pooling of funding and other resources in a way that optimizes R&D and demonstrations through appropriate levels of leveraging
  - Procedures for the dissemination of results and learning from projects so that stakeholders linked to the national coordinated activities may benefit

Reach

A national coordinated effort would assist all stakeholders involved in CCS R&D and demonstration projects and programs. Thus, the reach would include all parties identified under the previous objectives of science and technology R&D and demonstration.

Outputs

The anticipated result of national coordination is the expeditious and efficient roll-out of innovations and new technologies that contribute to both Canadian industry and society. This implies the avoidance of duplicative efforts, and instead promotes the creation of useful products and knowledge for commercial applications.

Desired Outcomes

The desired outcome is the promotion of innovation and new technology that has useful applications across Canadian industry sectors. Thus, the desired outcome is a process whereby the useful science and technology being developed in laboratories finds a place through dissemination and coordination in the commercial application of products and services for industry.

Implementation

To successfully achieve each of the six critical objectives outlined previously, a variety of supporters or 'champions' will need to take on the responsibility of accomplishing the outlined activities. These champions may not be individuals; rather they are likely to be organizations (such as government agencies, industry associations or other stakeholder groups) that have both the resources and expertise to tackle the various objectives. Although specific organizations aren't named, a general description of what is needed for each objective is outlined below. As already noted, the Roadmap Advisory Committee has suggested the need for an implementation committee, in part to work to identify and secure the appropriate champions for the six objectives over the coming year.

Policy and Regulatory Frameworks Champion

Because federal and provincial governments will be responsible for the development of CCS policies and regulatory frameworks, both levels of government should take a lead championing this objective. Further, certain departments and agencies, and certain jurisdictions, have much more experience with CCS than others, and these organizations may come together to form a committee or secretariat that champions such developments.

Public Outreach and Education Champion

Public outreach and education could be undertaken by a trusted and independent third party organization. Perhaps a non-government organization (with knowledge and expertise related to CCS) is an appropriate choice; however, it is important that this champion is neither seen as a promoter nor an opponent of CCS, so that the information being relayed and communicated is considered to be unbiased and trustworthy. The organization would need to link to other organizations, including national and international governments, industry and other stakeholder organizations (including environmental NGOs), to gather the most relevant and up-to-date information for outreach activities.

Technology Watch and International Collaboration Champion

The Roadmap Advisory Committee identified one of the primary gaps under technology watch and international collaboration as the need for a competitive intelligence framework for international and national CCS technology. As such, the committee recommends developing an intelligence framework and subsequently suggests an implementation champion over time. In addition, an organization will need to champion international collaborative efforts. Important attributes of either champion will include its current linkages to both national and international efforts, and the resources and technical ability of the organization to monitor, gather and disseminate information and competitive importance to Canada.

Science and Technology R&D Champion

Finding a champion for science and technology R&D is perhaps the most difficult (if not an impossible) task because of the breadth of R&D activities to be undertaken. For example, a number of specific capture technologies are needed for a variety of industrial systems in Canada. As well, a better understanding of the geology of Canada's sedimentary basins is needed to optimize CO_2 storage. In some cases, the R&D will be very exploratory in nature, and in others it will be more applied and related to commercial applications. In addition, the many scientists and researchers involved in the various R&D activities often have little in common with the exception of the ultimate goal of developing and deploying CCS infrastructure and systems.

As a result, R&D championing efforts may need to be split among a variety of disciplines or across a number of organizations, which may each be devoted to the different stages of technology development and deployment continuum. For example, the more exploratory R&D efforts may be championed by universities or other academic institutions and learning centres. The applied research may be supported by national or provincial research centres and geological surveys. R&D that takes place in commercial demonstrations might be championed by companies or consortia depending on the size of the project.

However, a need for an overarching championing role also exists. There is a need for a national organization to act as the decision-making body when evaluating and prioritizing specific R&D needs, and promoting those needs to government policymakers and industry decision-makers. The Roadmap Advisory Committee has indicated that a process for evaluating and assessing R&D needs, and an appropriate organization for undertaking the process, are both needed today. An implementation committee should be formed, to begin to undertake many of these efforts over the coming year.

Demonstration Champion

As with the difficulty in identifying a specific R&D champion, finding a single champion for demonstrations is equally difficult to do. This is the case mainly because there currently is no industry association or organization that is fully capable of the variety of demonstrations discussed in the roadmap. However, at the stage where demonstrations are taking place (which generally occur after the R&D has largely been conducted and it is time to test the most promising technologies and concepts in real-world applications), industry is the most likely champion because these projects often lead to commercial applications. Both governments and research institutions have a larger role to play during the earlier stages of the development to deployment continuum (as already noted).

The Roadmap Advisory Committee has indicated that a process for both evaluating potential demonstration projects, and identifying an appropriate organization for championing this effort, are needed today. Again, an implementation committee is needed, and much of its attention should focus on these priority needs over the coming year.

National Coordination Champion

National coordination isn't necessarily something that occurs in a prescriptive or predetermined manner; rather it often grows organically through a process of developing a common goal and working together (in a cooperative and coordinated fashion) towards achieving that goal. Perhaps a good place for such a process to begin today is through the meetings of the proposed implementation committee, which would broadly represent a variety of stakeholders with interests in CCS. Such a committee would be a first step in the process of formulating a more permanent solution for a national champion to undertake national coordination.

The Roadmap Advisory Committee has identified some primary tasks for the implementer of the roadmap to bring action to and achieve the objectives of the roadmap. One task will be to review the objectives and to work to develop action plans for each one, which includes the identification of specific organizations or groups of organizations to champion these efforts. Another task is to develop terms of reference for each implementation objective. The implementation committee should work towards fulfilling these tasks within the coming year.

Impacts of Achieving Objectives

If the previous activities are pursued and their outputs and outcomes ultimately achieved, it is possible that CCS could begin to deliver nationally significant GHG emissions reductions in the coming decades. The following sections briefly describe two timeframes where CCS may be providing GHG reductions in Canada by 2015 and 2030 respectively.

Today to 2015

By 2015, gasification technology might be commercially demonstrated in the oil sands and CO_2 could be captured from these new facilities or other oil sands facilities in that timeframe. The first clean coal demonstration facilities, equipped with CO_2 capture, may also be running. It is possible that a 400 MW coal or petroleum coke plant, or a new 300 MW oxy-fuel or amine scrubbed coal plant could be built and operating by 2015. In addition, cost-effective capture technologies may be deployed to capture medium purity CO_2 streams. CO_2 capture may also be taking place in conventional thermal power plants in the Atlantic Provinces for injection into deep coal seams.

CO_2 gathering for long-distance transmission may be taking place, and in fact the western leg of a WCSB CO_2 pipeline backbone might be connected to up to three local emissions hubs by 2015. The Alberta-based pipeline system may be supplying up to 10 Mt/yr for geological storage in the WCSB by 2015. An eastern leg of the backbone may be connected with a Weyburn pipeline for the transport of CO_2 in Saskatchewan. Supply laterals could be carrying CO_2 to these initial transport systems while injection laterals would also connect for extracting CO_2 for injection into value-added storage sites.

While the development of this infrastructure on its own will not be enough for Canada to achieve its Kyoto target, the private-public investments in infrastructure and systems, capacity building, knowledge and expertise may have begun setting the stage for significant GHG reductions in subsequent commitment periods.

2015 to 2030

By 2015 to 2030, CCS will be increasingly deployed across the WCSB, and it will have become an important facet in the design of new thermal electricity plants, refineries, oil sands upgraders and any new or refurbished industrial facilities in the region. By this time, CCS may be proving itself to be an enabling technology for an emerging low-emissions Canadian economy, and CCS itself may be an important industry in certain regions with a high dependence on fossil fuels.

From the experience gained by designing, building and operating clean coal plants, bitumen gasifiers and capture facilities in other industrial settings, Canada may be becoming a global leader in capture technology and expertise. Gasification of solid hydrocarbons may have become the norm for producing hydrogen for heavy oil or oil sands upgrading, with CO_2 being captured from these facilities. CO_2 might also be captured from clean coal plants which could account for a combined installed capacity of 4,000 MW in Canada by 2030. The Atlantic Provinces could be capturing CO_2 from up to half of their thermal power plants and injecting it into onshore coal seams in the Atlantic Basin. Ontario may begin re-investing in CO_2 capture-ready thermal power plants, thereby supplementing local energy supply. New capture technologies will continue to be developed for medium quality CO_2 sources.

The eastern and western legs of the WCSB CO_2 backbone might be joined, which would result in a reliable and ready supply of CO_2 for the entire region. More local emissions hubs (on top of those noted previously) could be developed in western Canada and interconnected with the backbone.

Geological storage could be taking place in many value-added storage sites across the WCSB, and some non-value-added storage sites may be developed by 2030. Geological storage may start to take place in other sedimentary basins such as the Atlantic and Mackenzie-Beaufort Basins, and total storage in Canada might account for more than 40 $MtCO_2$ injected per year by 2030. A range of estimates indicate that between 10 and 100 $MtCO_2$ could be captured from a variety of industrial sources and stored annually in the WCSB (over the coming decades) if Canada aggressively pursues this important technology opportunity.

Canada's expertise on capture and geological storage could lead the world as a result of the knowledge gained from capture and storage operations in a variety of settings across the country.

Roadmap Summary and CCS Pathway Ahead

The journey required to realize the vision and achieve the strategic objectives in this roadmap is not unlike previous undertakings in Canada. Technology development and innovation are part of the Canadian industrial psyche, and is one of our competitive advantages. Oil sands development is one of the greatest technological achievements in Canadian history, and it was through building the first oil sands facilities, and the resulting learning-by-doing environment that arose, that the real potential of these vast deposits have been harnessed. Without the early pioneering experience and the incremental innovation that took place, the oil sands deposits would not be the valuable resource they are today.

Canada has already been a leader in developing many aspects of CCS technology, and by undertaking the strategic objectives outlined in the roadmap, the country can build on this position and become a major contributor to the international effort underway to develop clearer fossil fuels. CCS will lead to more competitive fossil fuel industries at home (through higher resource recovery rates and environmental efficiency), and to the transfer of Canadian technology and knowledge overseas. Developing this technology is a strategic investment which will result in technically and environmentally sound methods of dealing with Canada's international GHG reduction commitments. This, in turn, will also result in valuable assets to be transferred elsewhere.

The time to invest in CCS is now. A clear window of opportunity for CCS infrastructure and systems development exists over the next 25 years. If the opportunity to install new and advanced technology over the coming years is not taken, Canada will be even further away from meeting its international GHG emissions reduction targets than first thought. Successful demonstrations and the subsequent roll-out of technological components, expertise and know-how, is the prize to be won over the coming years. To achieve this, there is a strong need for a strategic and planned effort today (with both current and future conditions in mind) so that any new infrastructure and systems meet both current needs and the needs of tomorrow.

Developing CCS is a means of ensuring that the value of Canada's vast fossil fuel resources remains high. Meeting the environmental and regulatory challenges that face fossil fuels will forge a permanent place for it in the nation's future energy supply. A strategic plan with a made-in-Canada approach to technology and innovation will help meet our national objectives as well as those of other nations around the world.

Ultimately, the message emerging from the roadmap initiative is the need for action today, to enable the vision of "technology for today's energy economy providing the basis for transformative change tomorrow"

Appendix A: List of CCSTRM Workshop Participants

Table A.1 List of CCSTRM Participants

Name	Organization	Name	Organization
Allard, Jean Luc	SNC-Lavalin	Finzel, Christeen	Alberta Environment
Allard, René-Pierre	NRCan, CETC-Ottawa	Fleming, Jon	Babcock & Wilcox Canada
Anderson, Keith	Alberta Research Council	Flint, Shannon	Alberta Environment
Audus, Harry	IEA Greenhouse Gas Programme	Fraser, Bob	NRCan, CETC-Ottawa
Ayres, Garth	Inter Pipeline Fund	Frederick, Larry	Devon Canada Corporation
Babadagli, Tayfun	University of Alberta	Gatens, Michael	MGV Energy Inc.
Bachu, Stefan	Alberta Energy and Utilities Board	Geeraert, Doug	Glencoe Resources Ltd.
Bancroft, John	University of Calgary, CREWES	George, Robert	Alberta Environment
Barrie, John 🟨	Fluor Canada Ltd.	Griffiths, Mary	Pembina Institute
Barton, Carolyn	Resources, Coal Industry, AUS.	Grobe, Matt	Alberta Energy & Utilities Board
Beaudoin, Georges	Université Laval	Gunter, Bill	Alberta Research Council
BenHassine, Mondher	Natural Resources Canada	Gupta, Murlidhar 🟧	NRCan, CETC-Ottawa
Bennett, John	Climate Action Network	Haug, Kristine	Alberta Energy & Utilities Board
Boileau, Dereck	EPIC Consulting Services Ltd.	Haxby, Mark	Alberta Economic Development
Bower, Matthew	TransCanada Pipelines Ltd.	Heath, Michelle	The CO2 Hub
Brotherhood, Angus	Glencoe Resources Ltd.	Heaton, Doug	Pyecombe Consulting Services
Brown, James	Shell Canada Limited	Henry, Andrew	Dalhousie University
Brown, Ken 🟫	EnCana Corporation	Herzog, Antonia	Natural Resources Defence Council
Bulut, Dubravka	Natural Resources Canada	Lord, Elisabeth	Levelton Engineering Ltd.
Burke, Michael	Natural Resources Canada	Hickinbotham, Andrew	TransAlta Utilities Corporation
Buschkuehle, Maja	Alberta Energy & Utilities Board	Hill, Gardiner	BP International
Bustin, R. Marc	University of British Columbia	Hollman, Diane	EPCOR Generation Inc.
Byrnes, Tom	Alberta Energy & Utilities Board	Huang, Sam	Saskatchewan Research Council
Chalaturnk, Rick	Alberta Research Council	Hughes, Dave	NRCan, Geological Survey
Chang, Adrian	TransCanada Pipelines Ltd.	Irwin, Tony	IRM Consulting
Chatel, Fabienne	Air Liquide, USA	Isaacs, Eddy	Alberta Energy Research Institute
Chiwetelu, Chris 🟧	CRA (Canadian Revenue Agency)	Jackson, Bill	Apache Canada Ltd.
Clark, Paul	TransAlta Utilities Corporation	Jimenez, Jaime	Alberta Research Council
Cormack, Jim	TransCanada Pipelines Ltd.	Johnson, Alan 🟧	Zeca Corporation
Cox, Harold	Irving Oil	Johnson, Bill	EnCana Corporation
Coyle, Irene	Natural Resources Canada	Johnson, Tim	TransCanada Pipelines Ltd.
Craig, Robert	TransCanada Pipelines Ltd.	Johnston, Les	EPCOR
Curran, Kimberly	Air Liquide Canada Inc.	Kaufman, Stephen	Suncor Energy Inc.
Damian, Noé	PennWest Petroleum Ltd.	Keith, David	Carnegie Mellon University
de Fayer, Paul	Alberta Department of Energy	Kennedy, Blaine	Sustainable Development Technology Canada
Delamaide, Eric	IFP Technologies (Canada) Inc.	Klara, Scott	NETL, USDOE
Dhaliwal, Gur	Alberta Energy	Kohut, Tyler	Lafarge Canada Inc.
Dilling, Kendall	EnCana Corporation	Lakeman, Brent	Alberta Research Council
Dipple, Greg	University of British Columbia	Lamont, Averil	Environment Canada
Dolhun, Wes	Lehigh Inland Cement Limited	Lavoie, Rob	CalPetra Research & Consulting
Douglas, Peter 🟧	University of Waterloo	Lawton, Don	University of Calgary
Doyle, Jim 🟧	Alberta Department of Energy	Lee, Deokki	Korea Institute of Energy Research
Durocher, Kyle	University of Calgary	Lee, Robert	Air Liquide Canada Inc.
Elzby, Richard	Tenneco Canada Inc.	Lee, Robert	Alberta Research Council
Esterez, Tania	CEDA Reactor Ltd.	Leslie, John	SNC Lavalin
Ferster, Rick	Luscar Ltd.	Lloyd, Eric	Petroleum Technology Alliance Canada

Working Group Members: 🟫 Upstream Oil & Gas 🟧 Downstream Oil & Gas 🟨 Industrial

Table A.1 List of CCSTRM Participants (cont'd)

Name	Organization
Locke, Sandra	Alberta Energy
Luhning, Richard	Enbridge Inc.
MacDonald, Derek	Alstom
MacDonald, Doug 🟧	SNC-Lavalin
MacMullin, Francis	TransCanada Pipelines Ltd.
MacPherson, Jerry	Alberta Department of Energy
MacRae, Morgan	Canadian Energy Research Insititute
Mannhardt, Karin	University of Calgary
Marrone, John	NRCan, CETC-Ottawa
Mavor, Matt	Tesseract Corporation
Mayer, Bernhard	University of Calgary
McArthur, Meredith	University of Calgary
McLellan, Pat	Advanced Geotechnology Inc.
Mercier, Gilles	NRCan, OERD
Micek, Chris 🟩	Agrium
Michael, Karsten	Alberta Energy and Utilities Board
Mikalson, Daryl	TransAlta Utilities Corporation
Millar, John	University of Calgary
Mitchell, Bob	Inspired Value Inc.
Moawad, Sameh	Alberta Energy
Monea, Michael	Petroleum Technology Research Centre
Morii, Sachie 🟩	BC Ministry of Energy & Mines
Morin, Shannon	Suncor Energy
Nasserali, Jetha	Total E&P Canada
Ojanpera, Ron	Babcock & Wilcox
Palamarek, Malcolm	Williams Energy Canada Inc.
Patrick, Rick	SaskPower
Pawlicki, Mike	Lafarge Canada Inc.
Pearson, Bill 🟩	NRCan, CETC-Ottawa
Peet, Dave	Anadarko Canada Corporation
Piron, Emmanuelle	IFP Technologies (Canada) Inc.
Podgurny, Dave	Air Liquide Canada Inc.
Potter, Ian 🟫	Alberta Research Council
Preston, Carolyn 🟫	NRCan, CETC-Devon
Provias, Jim	Suncor Energy
Pyo, Ken 🟧	PennWest Petroleum Ltd.
Reynen, Bill 🟫	Environment Canada
Ricci, Matty	Alberta Environment
Richards, Bill	Nova Scotia Power Inc.
Richardson, Rick	Alberta Geological Survey, EUB
Rigg, Andy	CO_2CRC Program, Australia
Ripmeester, John	National Research Council Canada
Roadifer, Randahl D.	Conoco Phillips
Ross, Geoffrey	Environment Canada
Sadorra, Ronnie 🟧	Shell Canada Limited
Sahay. Hari 🟩	Alberta Energy
Sanelli, Bruno	Air Liquide Canada Inc.
Sawchuk, Ted	Agrium
Sawchuk, William	Devon Canada Corporation
Sayegh, Selim	Saskatchewan Research Council
Shaw, Jerry	APA Petroleum Engineering Inc.
Shevalier, Maurice	University of Calgary
Siarkowski, Liz	TransCanada
Simandl, George	BC Ministry of Energy & Mines
Singh, Surindar	Alberta Energy Research Institute
Sit, Song P.	EnCana Corporation
Sorensen, Jim	Energy & Environmental Research Center
Spencer, Don	Devon Canada Corporation
Steffan, Ron 🟩	NOVA Chemicals Corporation
Stemp, Raymond	Alberta Environment
Stephenson, Derril	Vikor Energy Inc.
Stobbs, Bob	SaskPower
Struik, Mario	Pengrowth Corporation
Taylor, Alison 🟧	Suncor Energy
Tetz, Mark	Alberta Reserach Council
Thambimuthu, Kelly 🟫	NRCan, CETC-Ottawa
Thompson, Alison	Suncor Energy
Thompson, Anne-Marie	Environment Canada
Turner, Dave	Syncrude
Twa, Robert	EPCOR
Valdes, Alberto	CEDA Reactor Ltd.
Van der Meer, Bert	TNO-NITG (Netherlands)
Van Ham, John	Van Ham Resources Inc.
VanNierop, Pieter	Alberta Research Council
Varagani, Rajani	American Air Liquide
Venugopal, Srikanth 🟫	TransCanada Pipelines Ltd.
Watson, Brad	Lafarge Canada Inc.
Watson, Cal	Devon Canada Corporation
Weiss, Michael	EnCana Corporation
Wendling, Ron	Canadian Fertilizers Limited
Wichert, Gordon	Penn West Petroleum
Wilson, Malcolm	University of Regina
Wong, Joseph	NRCan, CETC-Ottawa
Wong, Sam	Alberta Research Council
Wright, Fred	NRCan, Geological Survey
Yang, Min	Ziff Energy Group
Yildirim, Erdal	Canadian Oil Sands Network for R&D
Zimmer, Ulrich	Advanced Geotechnology

Working Group Members: 🟫 Upstream Oil & Gas 🟧 Downstream Oil & Gas 🟩 Industrial

Appendix B: Roadmap Process

This CCSTRM is the result of a consultative process held mostly from 2003 to 2005, during which four phases were undertaken.

Phase 1: Situation Analysis

A body of background information on the major emitting industry sectors and on geological storage capacity was gathered and compiled for discussion at the first CCSTRM workshop.

Phase 2: Technology Pathways and R&D Strategies

A vision of a de-carbonised energy economy in Canada was developed through two workshops which were used to bring together a broad range of stakeholders, including industry, government, the research community and non-government organizations (NGOs), on the subject. Participants also included international experts on CCS who gave their input into the Canadian process.

The first workshop (September 18 to 19, 2003) was designed to identify CO_2 capture technologies and systems that could be broadly applicable to three key Canadian industry segments: upstream oil & gas, downstream oil & gas and other industry sectors (which included thermal electricity). The second workshop (March 29, 2004) was intended to stimulate discussion on industry's technology needs, and government's information needs, related to CO_2 capture, transportation and storage.

Phase 3: Priority Opportunities for R&D and Deployment

This phase was undertaken to identify opportunities to apply the top priority technologies in pilot, demonstration and commercial-scale projects. The process included the distribution of a draft CCSTRM, with suggested CCS technology applications, to initiate further discussion during a third and final workshop. Participants at the third workshop (February 28, 2005) discussed and commented on the draft CCSTRM. Sessions were held on specific roadmap topics including "putting action to the roadmap", and, "recommended next steps".

Phase 4: Final Draft of CCSTRM Report

Stakeholder input both during and after the 3rd workshop was reviewed and considered for inclusion in the final CCSTRM. A draft roadmap was written for review by the Roadmap Advisory Committee, which worked to provide commentary on a final roadmap that reflects the appropriate tone and content for such a document. Members of the Roadmap Advisory Committee will continue to help in setting up a process for the implementation of the roadmap, to help achieve the objectives identified in Section 5 of the document.

While the contributors to this document have provided their respective information and perspectives in good faith, and with a view to developing a comprehensive technology roadmap for CO_2 capture and storage, the contributors make no representation or warranty as to the accuracy and completeness of such information or necessarily endorse the collective views or perspectives provided for herein.

References

ACR, 2004. *Oil Sands Technology Roadmap*. Alberta Chamber of Resources (ACR).

Bachu, S., and S. Stewart. 2002. Geological sequestration of anthropogenic carbon dioxide in the Western Canada Sedimentary Basin: suitability analysis. *Journal of Canadian Petroleum Technology*, v. 41, No. 9, September, pp. 32-40.

Bachu, S. 2003. Screening and ranking of sedimentary basins for sequestration of CO_2 in geological media. *Environmental Geology*. v. 44, No. 3, pp. 277-289.

Bachu, S., and J. Shaw. 2005. CO_2 Storage in Oil and Gas Reservoirs in Western Canada: Effect of Aquifers, Potential for CO_2-Flood Enhanced Oil Recovery and Practical Capacity. GHGT7 Proceedings, December 2004.

Bachu, S., and M. Celia. 2006 [in press]. *Assessing the Potential for CO_2 Leakage from Geological Storage Sites*. In “The Science and Technology of Carbon Sequestration”, an AGU Geophysical Monograph Book Series. Edited by B. McPherson, and E. Sundquist.

Barrie, J., and M. Gupta. 2005. CO_2 Capture and Transport Technologies. Presentation made at the 3rd workshop of the Carbon Dioxide Capture and Storage Technology Roadmap (CCSTRM). Calgary, Alberta. February 28, 2005.

BP. 2005. Statistical Review of World Energy 2005.

CCCSTN, 2005. Canadian Carbon Capture and Storage Technology Network (CCCSTN) corporate website: http://www.nrcan.gc.ca/es/etb/cetc/combustion/co2network/htmldocs/importantnotices_e.html, visited September 2005.

CCP. 2005. CO_2 Capture Program (CCP) corporate website at: http://www.co2captureproject.org/index.htm, visited September 2005.

CCPC, 2004. Summary Report of Phase I Feasibility Studies – Executive Summary. Canadian Clean Power Coalition (CCPC).

CCSTRM. 2004. Break-out Session on CO_2 Capture and Transportation. 2nd Carbon Dioxide Capture and Storage Technology Roadmap (CCSTRM) Workshop. Calgary, Alberta. March 2004.

CCTRM. 2005. *Canada’s Clean Coal Technology Roadmap*. Clean Coal Technology Roadmap (CCTRM) working group.

Chalaturnyk, R., and B. Gunter. 2005. Geological storage of CO2: timeframes, monitoring and verification. Volume 1 of Peer Reviewed Papers: proceedings of the *7th International Conference on Greenhouse Gas Control Technologies*. Edited by Rubin, E.S., Keith, D.W., and C.F. Gilboy.

CO2CRC, 2005. Carbon Dioxide Cooperative Research Centre (CO2CRC) corporate website: www.co2crc.com.au/, visited September 2005.

CSLF. 2005. Carbon Sequestration Leadership Forum (CSLF) corporate website: http://www.cslforum.org/, visited September 2005.

CSUG. 2003. Exploration and Development of Natural Gas from Coal in Canada – Facts and Issues. Canadian Society for Unconventional Gas (CSUG).

Dillon, D.J. 2004. Oxy-Combustion Processes for CO_2 Capture from Advanced Supercritical PF and NGCC Power Plants. 7th International Conference on Greenhouse Gas Control Technologies, Vancouver, British Columbia, Canada. September 5 - 9th, 2004.

Environment Canada. 2003. Canada’s Greenhouse Gas Inventory.

EUB. 2005. Alberta’s Reserves 2004 and Supply/Demand Outlook 2005 - 2014. Alberta Energy and Utilities Board (EUB).

Government of Canada. 2005. Project Green: Moving Forward on Climate Change.

Gunter, B., and R. Chalaturnyk. 2004. The CANiSTORE Program – Planning Options for Technology and Knowledge Base Development for the Implementation of Geological Storage, Research, Development and Deployment in Canada. Alberta Research Council.

Gunter, B., and Mitchell, B., Potter, I., Lakeman, B., and S. Wong. 2005. The CANiCAP Program – Planning Options for Technology and Knowledge Base Development for the Implementation of Capture and Transportation, Research, Development and Deployment in Canada. Alberta Research Council.

Gupta, M., Coyle, I., and K. Thambimuthu. 2003. CO_2 Capture Technologies and Opportunities in Canada – Strawman for CO_2 Capture and Storage Technology Roadmap. CANMET Energy Technology Centre.

Gupta, M., and B. Pearson. 2005. *CO_2 Capture: Pathways and Opportunities in Canada*. Natural Resources Canada.

H_2FCC. 2004. *Charting the Course: A Program Roadmap for Canada's Transition to a Hydrogen Economy*. The Government of Canada's Hydrogen and Fuel Cell Committee (H_2FCC).

HFP. 2005. European Fuel Cell and Hydrogen Technology Platform (HFP): Strategic Research Agenda.

IEA. 2003. *Potential for Improvement in Gasification Combined Cycle Power Generation with CO_2 Capture*. International Energy Agency (IEA) Greenhouse Gas R&D Programme. Report NO. PH4/19.

IEA. 2004. *Prospects for CO_2 Capture and Storage*. International Energy Agency (IEA).

IEA, 2004a. *World Energy Outlook, 2004*. International Energy Agency (IEA).

IEA. 2004b. *Improvement in Power Generation with Post-Combustion Capture of CO_2.* International Energy Agency (IEA) Greenhouse R&D Programme. Report No. PH4/33.

IEA. 2005. *Key World Energy Statistics*. International Energy Agency (IEA).

IEA GHG R&D Programme. 2005. IEA Greenhouse Gas R&D Programme webpage: http://www.ieagreen.org.uk/ccs.html, visited September 2005.

IPHE. 2005. International Partnership for the Hydrogen Economy (IPHE) corporate website: http://www.iphe.net/#IPHELeading%20the%20Way, visited August 2005.

IPCC. 2001. *Climate Change 2001: Synthesis Report*. Intergovernmental Panel of Climate Change (IPCC).

IPCC, 2005. *IPCC Special Report on Carbon Dioxide Capture and Storage*. Intergovernmental Panel on Climate Change (2005). Intergovernmental Panel on Climate Change (IPCC).

Luhning, R. L., Glanzer, J. H., Noble, P., and P. S. Wong. 2005. Pipeline Backbone for Carbon Dioxide for Enhanced Oil Recovery in Western Canada. *Journal of Canadian Petroleum Technology*. Volume 44, No. 8.

NEB, 2003. Canada's Energy Future, Scenarios for Supply and Demand to 2025. National Energy Board (NEB).

NEB. 2004. Canada's Oil Sands: Opportunities and Challenges to 2015. National Energy Board (NEB).

NRCan, 2000. *Energy in Canada 2000*. Natural Resources Canada (NRCan).

Pacala, S., and R. Socolow. 2004. Stabilization Wedges: Solving the Climate Problem for the Next 50 Years with Current Technologies. *Science*. Volume 305.

Marr-Laing, T., Bramely, M., and M. Griffiths. 2005. *Carbon Capture and Storage: the Pembina Institute's position*. Pembina Institute.

PTRC. 2004. IEA GHG Weyburn CO_2 Monitoring & Storage Project – Summary Report 2000 - 2004. Petroleum Technology Research Centre (PTRC).

Statistics Canada. 2005. Statistics Canada corporate website: http://www.statcan.ca/start.html, visited December, 2005.

Thambimuthu, K. 2002. Canadian Initiatives on Zero Emission Technologies. Presentation to UNFCCC in Oslo, Norway. January 15, 2002.

Thambimuthu, K. 2004. Canadian CCS Technology Roadmap and CO_2 Capture and Transport. Presentation to CCSTRM Workshop #2. Calgary Alberta. March 29, 2004.

UNFCCC. 1992. United Nations Framework Convention on Climate Change (UNFCCC).

USDOE. 2005. United States Department of Energy (USDOE) Carbon Sequestration Core Program corporate website at: http://www.fossil.energy.gov/programs/sequestration/, visited September 2005.

WCI. 2005. World Coal Institute (WCI) corporate website at: http://www.wci-coal.com/web/content.php?menu_id=2.3, visited September 2005.

WEC. 2004. *2004 Survey of Energy Sources*. World Energy Council (WEC).

Glossary

Absorption: Chemical or physical take-up of molecules into the bulk of a solid or liquid, forming either a solution or compound.

Acid Gas: Any gas mixture that turns to an acid when dissolved in water (normally referring to a hydrogen sulphide/carbon dioxide mixture from sour gas)

Acid Rain: Also referred to as 'acid precipitation' or 'acid deposition', acid rain is any form of precipitation containing harmful amounts of nitric and sulphuric acids, formed primarily by nitrogen oxides and sulphur oxides released into the atmosphere upon combusting fossil fuels.

Adsorption: A phenomenon which involves the uptake of molecules in a fluid onto the surface of a solid.

Amine: Organic compounds of nitrogen that are derived from ammonia by replacing one or more hydrogen atom with a carbon group.

Ash: The inorganic, non-flammable substances (impurities such as silica, iron and aluminium) left over after coal, pet-coke or other solid fuels have been burned off.

Avoided Emissions: A measurement of greenhouse gas emissions reductions that takes into account the reduced capacity of power plants and other industrial facilities due to the addition load of utilizing carbon dioxide capture systems.

Backbone: The concept of pipeline network connecting major carbon dioxide emissions hubs, together with feeder lines from the backbone connecting to the variety of potential storage sites that exist. A pipeline backbone could operate much like the gathering, transmission and distribution systems used for natural gas transportation today.

Biomass: Plant materials and animal waste available especially as a source of fuel. Biomass is considered to be renewable and carbon-neutral source of energy.

Bitumen: A naturally occurring viscous mixture, mainly of hydrocarbons, which may contain high levels of sulphur compounds and that, in its natural occurring viscous state, is not recoverable at a commercial rate through a conventional oil well.

Cap Rock: Low permeability rock that acts as an upper seal to prevent fluid flow out of a reservoir.

Captured Emissions: The gross amount of greenhouse gases (generally carbon dioxide) that have been separated and captured from a flue gas stream, without having considered the extra emissions caused by incorporating the capture systems into the equation (see also Avoided Emissions).

Carbon Dioxide (CO_2): A colourless, odourless, non-poisonous gas that is a normal constituent of the earths many systems including the atmosphere, biosphere and oceans. Carbon dioxide is exhaled by humans and animals and is absorbed by green growing plants and by the oceans. Carbon dioxide is also produced during the combustion of any carbonaceous fuel source including fossil fuels. Carbon dioxide is a greenhouse gas and is the primary one of concern related to climate change, because of its pervasiveness and increasing concentration in the earth's atmosphere as a result of human-related activities.

Carbon Dioxide Capture and Storage (CCS): The capture of carbon dioxide from flue gases or from other industrial processes, followed by the transportation and injection of it into a permanent geological site for storage. Examples of storage sites include ocean beds, aquifers, abandoned oil and gas reservoirs and coal beds. This is a new and developing concept for controlling human induced carbon dioxide emissions into the atmosphere and mitigating the climate change.

Clean Coal Technology (CCT): Refers to a number of innovative, new technologies designed to extract and utilize coal in a more efficient and cost-effective manner while reducing the environmental impact of these activities. Examples of clean coal technology include oxy-fuel combustion or coal gasification.

Clean Development Mechanism (CDM): One of three market mechanisms under the Kyoto Protocol, the Clean Development Mechanism is designed to promote sustainable development in developing countries and assist Annex I Parties in meeting their greenhouse gas emissions reduction commitments. Clean

Development Mechanism enables Annex I countries to invest in emission reduction projects in developing countries and receive Certified Emission Reductions in return.

Climate Change: The term "climate change" is used to refer to all forms of climatic inconsistency, but, because the Earth's climate is never static, the term is more often used to imply a significant change from one climatic condition to another. Today, ‘climate change’ is used synonymously with the term global warming (also see global warming).

Coal: A black or brownish-black solid combustible substance formed from prehistoric organic material such as vegetable matter. Coal is mined and combusted to produce heat and energy.

Combustion: The oxidation of carbonaceous fuels with the release of energy in the forms of heat and light. The combustion of fuels, such as coal, oil, gas, and wood, releases pollutants and other air emissions into the atmosphere as a by-product, including sulphur dioxide, nitrogen oxide, particulate matter and carbon dioxide.

Cryogenics: A branch of physics that deals with the production and effects of very low temperatures, often at minus 100 degrees Celsius.

Dense Phase: The physical state that a gas undertakes when it is compressed to the extent that its density approaches that which it would have in its liquid phase.

Depleted Oil and Gas Fields: The oil and gas fields where production has reached the economic limit.

Emission Hub: Places where significant emission sources that are close to one another could be economically joined using a carbon dioxide gathering system.

Enhanced Coal Bed Methane Recovery (ECBM): The use of carbon dioxide to enhance the recovery of the methane present in unminable coal beds through the preferential adsorption of carbon dioxide to coal.

Enhanced Natural Gas Recovery (ENGR): The act of injecting of fluids such as carbon dioxide into depleting natural gas reservoirs to recover additional gas beyond that which would have been recovered conventionally.

Enhanced Oil Recovery (EOR): The injection of fluids such as steam and carbon dioxide into depleting oil reservoirs to recover additional oil beyond that which would have been recovered conventionally.

Fuel Cell: An electrochemical device in which the fuel is oxidized in a controlled manner to directly produce an electric current and heat.

Flue Gas: Gas that is left over after a fuel is burned. Flue gas is typically disposed of through a pipe or a stack to the atmosphere. In some cases flue gas is captured, and its constituent gases are used for additional useful purposes.

Fossil Fuel: Any naturally occurring organic fuel such as crude oil, natural gas, coal, peat or by-products of any of these. Fossil fuels are all formed by a series of earthly processes whereby the remains of formerly living organisms have been geologically buried and have sustained the appropriate amount of underground bacterial action and/or heat and pressure (and for the right amount of time) to form the fossil fuel or hydrocarbon product.

Gasification: Partial (or controlled) oxidation of carbonaceous fuels, which produces a mixture of gases (including hydrogen, carbon monoxide, and water) and solids such as ash or slag. Gasification is the first step in a process that can be used to generate a multitude of fuels and chemical feedstocks.

Geological Formation: A section of contiguous underground material which is sufficiently homogeneous to be considered a single unit. **Geological** formations with a certain structure and porosity present an opportunity for underground carbon dioxide storage, as evidenced by existing formations which have been storing carbon dioxide for millions of years. Examples of formations with carbon dioxide storage potential include depleted oil reservoirs, depleted gas reservoirs, unmineable coal seams, saline aquifers.

Global Warming: The gradual rise of the earth's average surface temperature thought to be caused by the greenhouse effect and responsible for global climate changes (also see climate change). Global warming has occurred in the distant past as the result of natural influences, but the term is most often used to refer to the warming predicted to occur as a result of increased anthropogenic emissions of greenhouse gases today.

Greenhouse Gases (GHGs): The atmospheric gases that allow solar radiation to penetrate the earth's atmosphere and therefore reach the earth's surface, yet which absorb the infrared radiation that would otherwise return back to space. The process of trapping the long-wave infrared radiation is known as the greenhouse effect, and it is what prevents the earth's atmosphere from being as cold as it otherwise would. However, human induced activities may be increasing the concentration of atmospheric greenhouse gases to dangerously high levels. The primary greenhouse gases are carbon dioxide, methane, nitrous oxide, ozone, water, and chlorofluorocarbons.

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 such as methane or carbon dioxide. The compounds are very dense and insoluble in water. Carbon dioxide hydrates are being investigated for use in carbon dioxide capture and storage.

Hydro Electricity: Electricity that is produced by capturing the kinetic energy of falling water, by using the water to mechanically rotate a turbine generator. Hydro electricity is commonly referred to as 'hydro'.

Integrated Gasification Combined Cycle (IGCC): Is a process that is similar to natural gas combined cycle, with the exception of the fuel source. In integrated gasification combined cycle, the fuel is produced from a solid source such as coal, which is then gasified to produce syngas, which in turn is combusted and expanded in a gas turbine (Brayton cycle) followed by a second cycle of heat recovery from the flue gases to run a steam turbine (Rankine cycle), all for the purpose of electricity generation.

Joint Implementation (JI): One of three market mechanisms under the Kyoto Protocol, Joint Implementation is a contractual agreement where an Annex 1 country invests in an emissions reductions or a sink enhancement project in another Annex 1 country in order to earn Emissions Reduction Units.

Kyoto Protocol: An international agreement adopted in December 1997 in Kyoto, Japan. The Protocol has binding greenhouse gas emission targets for developed countries, whereby they will be expected to jointly reduce their emissions from 1990 levels, by (on average) 5.2%. The Kyoto Protocol officially came into force as a binding agreement on February 16, 2005.

Large Final Emitters (LFEs): A group of almost 700 companies that produce roughly half of Canada's greenhouse gas emissions – including companies in oil and gas, mining and manufacturing, and thermal electricity.

Liquefied Natural Gas (LNG): Natural gas that has been condensed to its liquid form, which is typically done by cryogenically cooling the gas to minus 200 degrees Celsius.

Membrane: A material that is selectively permeable to one or more chemical species and can therefore be used to separate that species from others in a fluid stream. Selective separation is driven by the partial pressure difference across the membrane surface. Membrane materials are being developed for the separation of carbon dioxide from hydrogen, natural gas and flue gas.

Migration of CO_2: The movement of CO_2 through a geological formation, largely driven by a density or a pressure differential.

Mineral Fixation: A process in which CO_2 reacts with magnesium, calcium oxide (or some other compound) to form stable mineral carbonates. The process results in the creation of un-reactive solids which act as permanent means of storing carbon. The challenges involved in using mineral fixation as a means of storing carbon is the slow reaction rates and the large tonnage of mineral-rich earth that must be mined for each unit of CO_2 sequestered.

Monitoring, Measurement and Verification (MMV): This is defined as the capability to measure the amount of carbon dioxide stored at a specific storage site, to monitor the site for leaks or other deterioration of storage integrity over time, and to verify that the carbon dioxide is stored safely. Monitoring, measurement and verification is used to ensure safe permanent storage, reduce the risk associated with buying or selling credits for sequestered CO_2, and help satisfy regulators and local government officials who must approve large sequestration projects.

Natural Analogue: A situation in nature that parallels features of man-made systems, for example natural carbon dioxide reservoirs compared to a man-made carbon dioxide reservoir.

Natural Gas: A naturally occurring mixture of hydrocarbon and non-hydrocarbon gases found in porous geological formations beneath the earth's surface. The principal constituent of natural gas is methane, but it also includes ethane, butane, propane and other gases. Impurities in natural gas often include nitrogen, carbon dioxide, and hydrogen sulphide.

Natural Gas Combined Cycle (NGCC): An integrated power generating plant that, first extracts energy from the high temperature combustion of natural gas by using expansion turbines to convert mechanical energy into electrical energy (Brayton Cycle), followed by heat recovery from the outgoing flue gas to produce additional electricity through a steam expansion turbine (Rankine cycle).

Nitrogen Oxides (NO_x): These air emissions are criteria air pollutants. They are often formed from the nitrogen in air when any carbonaceous fuel is burned at a high temperature. Nitrogen oxides react with volatile organic compounds to form smog. Nitrogen oxides are also an important contributor to the creation of acid rain.

Nuclear Power: Electricity that is generated by either splitting heavy atoms (fission) or joining light atoms (fusion). Currently, only nuclear fission is technologically feasible for power generation.

Ocean Storage: Storage of CO_2 in ocean waters. Oceans are an important part of the natural carbon cycle because they store, release, and absorb large quantities of carbon dioxide to and from the atmosphere, but their managed use for the purpose of storing carbon dioxide is a somewhat novel concept that is quite controversial today.

Oil (Crude): A liquid mixture of hydrocarbons that is found in suitable rock formations, which can be discovered, extracted and refined to produce a variety of oil products, such as gasoline, diesel, paraffin, and chemical feed stocks.

Oil Sands: Bitumen-soaked sand, located in four geographic regions of Alberta (Athabasca, Wabasca, Cold Lake and Peace River) and in other parts of the world. The Athabasca oil sands constitute the largest deposit in the world, encompassing more than 42,340 square kilometres. Total bitumen resources in Alberta are estimated at 1.7 – 2.5 trillion barrels.

Oxy-fuel Combustion: The combustion of a carbonaceous fuel in a pure oxygen, or nitrogen deficient, environment to produce a flue gas stream that consists mainly of water and carbon dioxide. The purpose of this process is to avoid inert nitrogen in the burning process, thereby controlling the flue gas streams, by reducing the volume of flue gases and making it easier to concentrate carbon dioxide for capture, transportation and storage.

Ozone: A molecule that is made up of three oxygen atoms. Ozone, a GHG, occurs naturally, and large concentrations are found in the stratosphere high above the earth

Pet-coke: An oil sands residue that is high in carbon and low in hydrogen content. It is a by-product of the thermal decomposition of oil sands or heavy oil, from the condensation process in upgrading. Pet-coke is typically greater than 90 percent carbon and low in ash, however, it contains heavy metals such as Vanadium.

Post-combustion Capture: The combustion of carbonaceous fuels in air followed by the capture of carbon dioxide from flue gases, usually by scrubbing the flue gases using solvents such as amines.

Pre-combustion Capture: Refers to a sequence of processes that take place prior to end use combustion, where syngas, formed from partial oxidation or steam reformation of a carbonaceous fuel, is decarbonised through shift conversion process which convert carbon oxides into capture ready carbon dioxide.

Pulverized Coal (PC) Combustion: A process in which very finely ground (pulverized) coal is combusted, with the heat being used to produce steam for power generation (in a Rankine cycle). Normally this process is referred to as 'sub-critical steam cycle', 'supercritical steam cycle' or 'ultra-supercritical steam cycle' depending on the steam pressure/temperature conditions. The higher the steam temperature in the Rankine cycle the higher the fuel to electricity conversion efficiency.

Renewable Energy: Energy from a source which can be managed so that it is not subject to depletion in human timescales. Sources include the solar radiation, wind, waves, river streams, tides, biomass, and geothermal. Renewable energy does not include energy sources which are limited in abundance, such as fossil fuels and uranium fuel.

Reservoir: A subsurface, porous, permeable rock body surrounded by impermeable rock and containing oil, gas or water. Most reservoir rocks consist individually or collectively of limestone, dolomite, and **Saline Aquifers:** A geological formation of porous rock that is filled with brine.

Sink: Refers to the natural uptake of carbon dioxide from the atmosphere, typically into soils, forests or oceans. Reservoirs are also used as sinks.

Shift Conversion: A catalytic process that is used to convert one molecule into another, such as using steam to shift carbon monoxide into hydrogen and carbon dioxide.

Smog: A mixture of pollutants (principally ground-level ozone) produced by chemical reactions that include smog-forming constituents like nitrogen oxides and water. Fossil fuel combustion is a major contributor to the formation of smog. However, smog is often worse further away from the source, since the chemical reactions that result in smog occur in the air while the reacting chemicals are being blown away. Smog is a health hazard, it damages the environment and it causes poor visibility.

Source: Any industrial process, activity or mechanism that results in the release of greenhouse gases, aerosols or precursors thereof into the atmosphere.

Sulphur Oxides (SOx): These air emissions are criteria air pollutants. Sulphur dioxide and sulphur trioxide are produced during the combustion of coal and other fossil fuels, mostly from power plants. Some industrial processes, such as paper production and metal smelting, also produce sulphur oxides. Sulphur oxides are closely related to sulphuric acids, which are strong acids that play a significant role in the formation of acid rain.

Syngas: A synthetic form of natural gas made from coal gasification, and consisting mainly of a mixture of carbon monoxide and hydrogen.

Technology Pathway: A linear progression, or a continuum, of a technology-suite's development over time.

Temporary Storage: Refers to underground caverns, mines (salt or potash mines) or depleted oil and gas reservoirs, which provide the capacity to temporarily store carbon dioxide. As is the case in current natural gas distribution networks, this type of storage will play an important role in balancing the pipeline pressure in a carbon dioxide transportation backbone.

Ultra Clean Coal (UCC): An extremely pure coal product (greater than 99 percent carbon and hydrogen) that is the result of an ore beneficiation process, whereby the coal has been stripped to near zero sulphur content and less than one-percent inorganic content.

Western Canadian Sedimentary Basin (WCSB): The primary and most prominent continental sedimentary basin in Canada, which extends from British Columbia in the west to Manitoba in the east, and from the Northwest and Yukon Territories south into the United States. The Western Canadian Sedimentary Basin covers approximately 1,484,800 square kilometres and it is the primary source of fossil fuel deposits in Canada whether oil, natural gas, bitumen, or coal.

Wind Power: A renewable form of electricity that uses the energy from wind to mechanically drive wind turbines. Inside each wind turbine is an electricity generator that converts the mechanical power into electrical power.