Photo courtesy of Shell Canada

CCS Potential in the Oil Sands

Evaluating the Impact of Emerging Carbon Capture Technologies on Oil Sands Emissions

Prepared for

Alberta Innovates, Energy and Environmental Solutions
Climate Change Emissions Management Corporation
Alberta Energy
Alberta Environment and Sustainable Resource Development

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PEMBINA
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Executive summary

Carbon capture and storage (CCS) has been recognized as an important tool in stabilizing atmospheric greenhouse gas concentrations at levels consistent with limiting projected temperature rises to 2°C by 2050. The oil sands are the country's fastest growing source of greenhouse gas emissions and an international symbol for impacts to climate; they face increasing market access challenges in key export markets. There is a unique opportunity for reinvigorating our focus on CCS as one possible solution for the growing emissions from oil sands production, as both industry and government are gaining practical knowledge about supporting, implementing, and regulating CCS.

The primary objective of this project is to identify and evaluate the scenarios under which GHG emissions can be significantly reduced through the deployment of CCS using emerging lower-cost capture technologies.

To support this analysis and research, a spectrum of technology categories and providers were identified through interviews with experts, literature searches, web searches, journals and forum proceedings. Based on the scan of technology categories and providers, key technology providers were approached to share confidential[1] detailed cost and technology development to input real world data into the GHG reduction potential model.

Results

This study performed detailed and comprehensive research on promising technologies to develop four different scenarios that represent different levels of CCS penetration in the oil sands. These scenarios were used to model the corresponding emission reductions. A cost analysis and projection was also performed for the different types of oil sands operations as well as capture technology types. Figure A shows the potential GHG reductions based on the projected annual GHG emissions in the oil sands (NEB projections extrapolated to 2050) with various levels of CCS technology penetration, or adoption.

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[1] Pembina entered into eleven separate non-disclosure agreements with companies that represented 15 technologies in order to attain this confidential data.

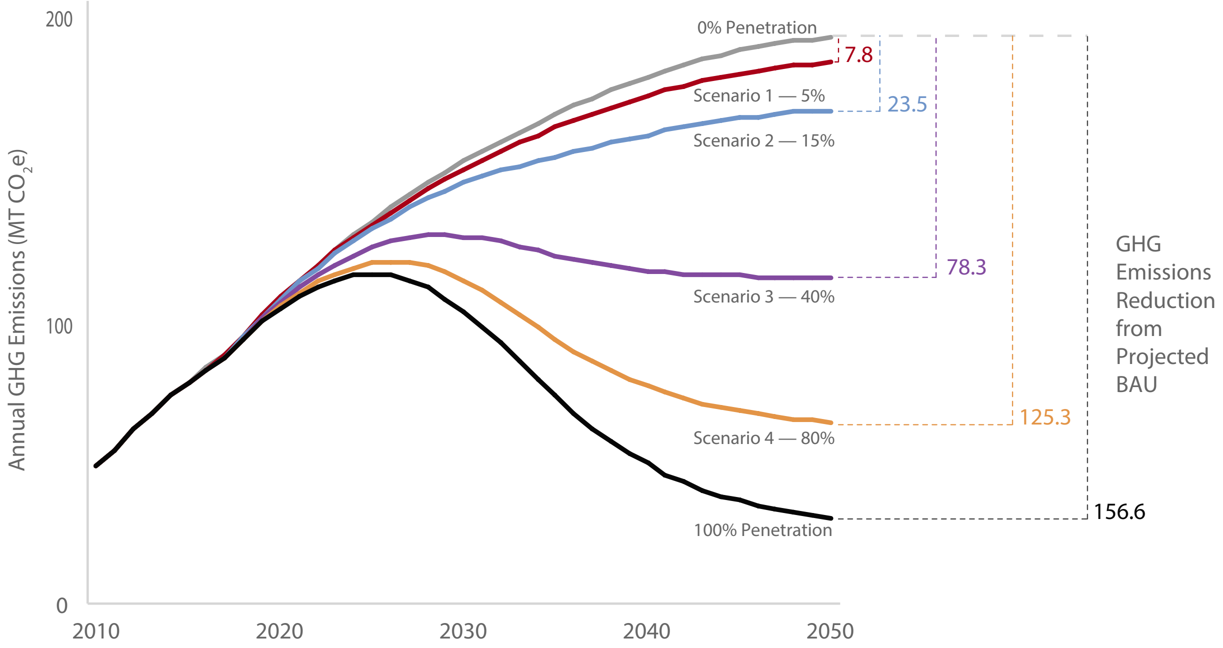

Figure A. Oil sands emission projections for various levels of CCS technology adoption (penetration). 0% and 100% penetration cases shown for reference

As would be expected, higher penetration rates result in higher potential GHG reductions. It can be seen that emissions could be stabilized at 2020 levels with a penetration rate of just under 40% with a 75% reduction in projected 2040-50 emissions (assuming current oil sands production emission rates with no significant GHG intensity reductions) in the 2040 to 2050 time frame. Full deployment of capture technologies on all capturable sources would need to occur to achieve 2010 emission levels or lower. Over 80% penetration of capture in the oil sands is required in order for emissions to be below 75 MT CO_2e by 2050.

The costs of emerging CCS technologies used in the model were derived from cost data representing the 15 unique technologies used in the final analysis. Costs of capture for different types of emerging carbon capture technologies, at their expected year of commercialization are presented in Figure B. Anticipated commercialization dates for technologies assessed in this study range from 2016-2023 depending on the technology. As an attempt to adjust for the well-documented optimism of early stage cost estimates, a cost adjustment factor of +150% was applied for technologies at lower technology readiness levels and +75% for those closer to commercialization.

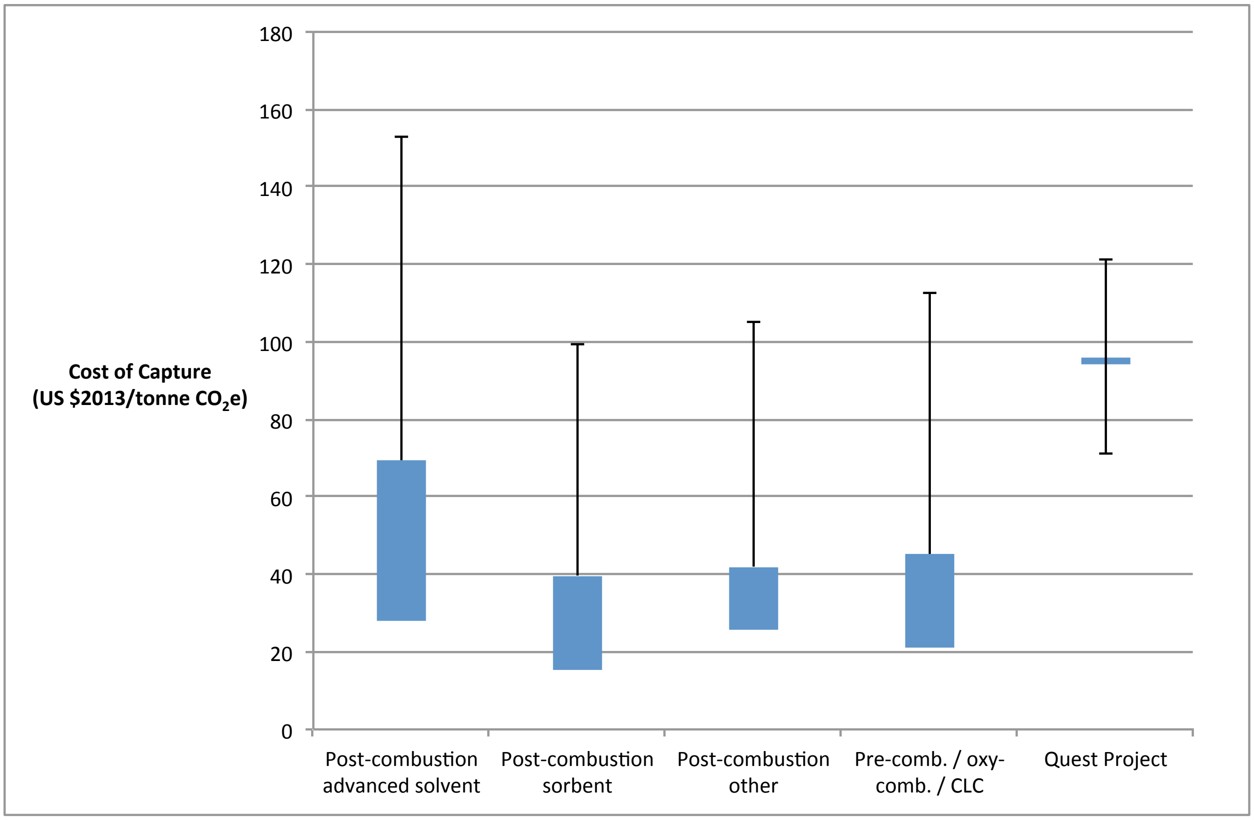

Figure B. Aggregated cost of capture ranges at anticipated commercialization date, classified by CCS technology type, derived from technology provider survey results, with estimated Quest Project cost shown for reference.[2]

The cost data was used as a baseline to estimate the potential cost reduction over time given an assumed learning rate of 0.034, whereby costs improve by 3.4% for each doubling of cumulative installed CO_2 capture capacity. Figure C shows cost of capture projections for each of the oil sands sectors to 2050 derived from cost data supplied by providers of the most promising technologies (left side of chart).

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[2] Raw cost estimates (solid blue bars) in the figure show the range of costs obtained from technology provider surveys. Error bars were added by Pembina to illustrate possible cost uncertainties for pre-commercial technologies in various stages of development. Quest Project costs were estimated at $95/tonne with a +/- $25/tonne uncertainty, to roughly correspond with costs and capture volumes published by ICO2N: http://www.ico2n.com/ccs-in-canada/first-projects-in-canada/shell-quest

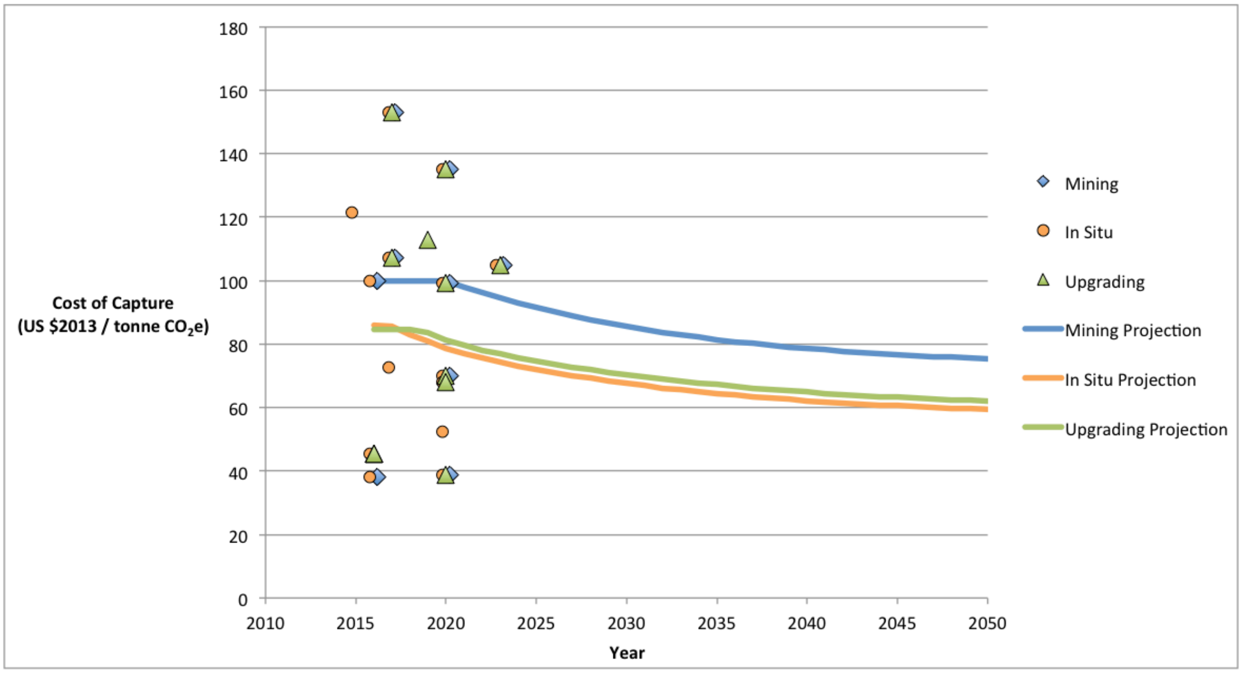

Figure C. Cost of capture estimates for each oil sands sector

The results show that the average cost of technologies will rest between $60 and $80/tonne CO_2e by 2050[3]. Sensitivities were run to determine how a change in the learning rate influences the cost reduction and how changing the assumed oil sands emissions factors changed the potential GHG reductions in the oil sands.

Although this modeling is limited by the assumptions, scope of review and the quality and accuracy of the data, it offers valuable insights as to the potential of carbon capture in the oil sands and the associated potential costs.

Conclusions

The analysis shows that annual oil sands emissions could be stabilized at roughly two times current emission levels over the next 40 years by enabling 40% of oil sands facilities' stationary emission sources with carbon capture technology operating at 90% capture efficiency. By combining CCS with other means of emission reductions, which could include conservation, implementation of low emission intensity production technologies, efficiency upgrades, increased use of renewables and the phase-out of coal-fired power, it is possible to reduce annual provincial emissions below current levels in the long run, even with consistent year over year growth in oil sands production.

A comprehensive GHG reduction strategy has been recognized as being part of the solution to stabilize access to markets and assure long-term financial benefits for the province of Alberta, not least of which is that bringing the oil sands life cycle emission intensity in-line with that of conventional crude is becoming increasingly necessary to secure export markets for oil sands

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[3] All costs are presented in U.S. 2013 dollars.

products. To meet the reduction goals set out in the current Government of Alberta's Climate Change Strategy[4], the Strategy targets 139 MT of reductions coming from CCS. Based on the penetration rate analysis, CCS-enabled reductions from the oil sands sector could contribute significantly to achieving the Strategy's CCS target. The penetration rate analysis shows that a 40% penetration could achieve over half of the Strategy's target while a 90% penetration rate would completely achieve the targeted reductions.[5] (The electricity sectors will also likely be involved in meeting the Strategy's CCS goal, as the opportunity for CCS related reductions exists in that sector as well.)

Emerging CCS technologies have the potential to bring down the overall costs of CCS adoption as compared to available commercial technologies going forward. History has shown that costs of newly commercialized industrial pollution control technologies can decrease by at least 3-5% annually[6], and this learning rate can be correlated directly to the installed cumulative capacity of the technology, in this case the overall CO_2 capture capacity across all oil sands facilities equipped with carbon capture capability.

Our analysis shows that near-term (5-10 year outlook) capture costs for emerging CCS technologies are expected to be in the range of $85-$100/tonne ($3.60 – $7.80/bbl), while longer-term (to year 2050) costs are projected to range from $60 - $76/tonne ($2.74 - $5.71/bbl), with conservative learning rates applied. Using the median historical learning rate from a basket of modern industrial technologies, costs could conceivably reach $29 - $44 / tonne ($1.57 - $3.09 / bbl) by 2050.[7] More aggressive learning rates would push these costs even lower.

There are many other factors besides installed capacity that affect learning rates, which are more difficult to quantify, but can have enormous impact. In this regard, industry groups and Government have an important role to play in technology sharing, ensuring that both successes and failures are properly understood and documented, and that key learnings are disseminated.

Although outside the scope of this study, it became evident during the research phase that a number of barriers exist that are preventing rapid commercialization and uptake of emerging CCS technologies. These barriers need to be investigated further, and strategies need to be developed to overcome them. For example, finding opportunities for field-testing new CCS technologies without disrupting on-site operations has been a formidable challenge. A dedicated test facility that would allow technology developers to test their technologies at various stages, under actual oil sands operating conditions, would bridge a key gap in launching technologies from the lab into pilot and demonstration stages.

Large-scale GHG reductions in the oil sands over the long-term are technically feasible, but will require a comprehensive and wide-ranging strategy for advancing emerging, lower-cost CCS technologies into the commercial market, and will require a combination of adoption of more

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[4] Government of Alberta, "Alberta's 2008 Climate Change Strategy", January 2008. http://environment.gov.ab.ca/info/library/7894.pdf

[5] For stationary sources, at 90% capture efficiency, using the NEB reference case projections for oil sands growth and the emission factors listed in Section 2.4 of this report.

[6] Rubin et al, "Use of experience curves to estimate the future cost of power plants with CO2 capture," *International Journal of Greenhouse Gas Control I* (2007).

[7] All costs in $US 2013 dollars. Additional detail on cost projections and learning rates is presented in Appendix B.

aggressive policy, continued support for pilot and demonstration facilities, and a robust mechanism for sharing key learnings.

1. Introduction

CCS has been recognized as an important tool in stabilizing atmospheric greenhouse gas concentrations at levels consistent with limiting projected temperature rises to 2°C by 2050. In Alberta, significant technological, infrastructure, and regulatory investments and advancements in CCS have been made, as recently highlighted by the Quest Project announcement.[8] With eight large-scale projects in operation around the world and a further six under construction, CCS is still actively being advanced.[9]

The oil sands are the country's fastest growing source of greenhouse gas emissions[10] and an international symbol for impacts to climate; they are facing increasing market access challenges in key export markets.

There is a unique opportunity for reinvigorating Alberta's focus on CCS as one possible solution for the growing emissions from oil sands production, as both industry and government are gaining practical knowledge about supporting, implementing, and regulating CCS. With this backdrop, this study aims to contribute to that understanding by providing decision-makers at the Alberta government with up-to-date information on the status of emerging CCS technologies and the potential for those technologies to contribute to overall GHG reduction in the oil sands.

Additional context on the potential for CCS as a carbon mitigation strategy, the domestic and international status of CCS projects and the applicability of CCS to the oil sands is presented in Appendix D of this report.

1.1 Study objectives

The primary objective of this study was to identify and evaluate scenarios under which GHG emissions might be significantly reduced in the Canadian oil sands region through the deployment of carbon capture and storage (CCS) using emerging lower-cost capture technologies.

To support this objective, project research and analysis was conducted to develop a thorough understanding of the following three elements:

- Past and present CCS activities in an Alberta, Canadian and international context
- The existing and emerging capture technologies landscape, including market readiness, costs, effectiveness and applicability to oil sands applications
- Emerging capture technologies applicability and GHG reduction potential within existing and future oil sands applications

The research helps provide critical insights into the potential for emerging capture technology to play a role in reducing future GHG emissions from the oil sands.

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[8] www.shell.ca/home/content/can-en/aboutshell/our_business_tpkg/business_in_canada/upstream/oil_sands/quest/

[9] www.globalccsinstitute.com/key-topics/status-ccs

[10] The ecoENERGY Carbon Capture and Storage Task Force, "Canada's Fossil Energy Future" (Natural Resources Canada, 2008).

2. Methodology

2.1 Modeling objectives and overview of approach

The desired outcomes of the modeling work, as shown in red in Figure 1, were to estimate the GHG reduction potential of CCS in the oil sands, and to estimate the potential for reduction of capture costs over time.

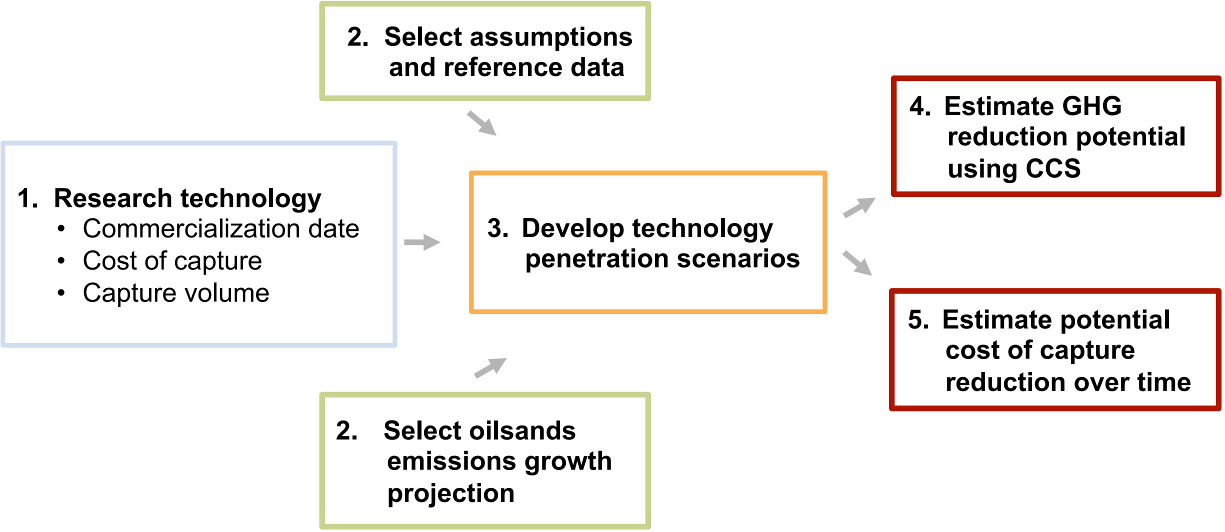

Figure 1: Visual representation of modeling approach

The project's outcomes were achieved by gathering information on emerging CCS technologies and their applicability to oil sands applications, commercialization status and costs. Using these results, the most promising CCS technologies were modeled based on a range of market penetration[11] levels for capturable emissions in the oil sands. Several scenarios were developed to establish a range of maximum technology penetration outcomes, and these penetration rates were contrasted with the expected growth in oil sands emissions to develop a series of GHG reduction scenarios to the year 2050.

2.2 Technology research

Research was conducted in several phases in order to assess the current state of technology development and the potential for deployment in Alberta's oil sands. The first phase of research included the following activities:

1. A literature review to assess the state of carbon capture projects globally as well as past national and provincial experience with CCS.
2. A scan of over 40 emerging carbon capture technologies across all sectors including both those that are currently being implemented and those that are in development.

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[11] Please see section 2.6 for discussion on market and technology penetration rates and how they were modeled.

3. Evaluation of technologies from the initial scan against specific criteria to generate a smaller list of promising companies to contact for more detailed information.

During the initial technology assessment, information related to various metrics such as technology readiness level, optimal application for technology in terms of intended end-use or industry sector, auxiliary power demands and time frame to commercialization was collected. The data collected during the interviews was compiled and used to determine data gaps and inform the next step of acquiring detailed technology and cost information.

2.2.1 Classification of CCS technologies

Based on the initial broad scan conducted, technology categories were determined and specific technology providers within those categories were identified. Figure 2 below characterizes the various technology classes that were considered in this study.

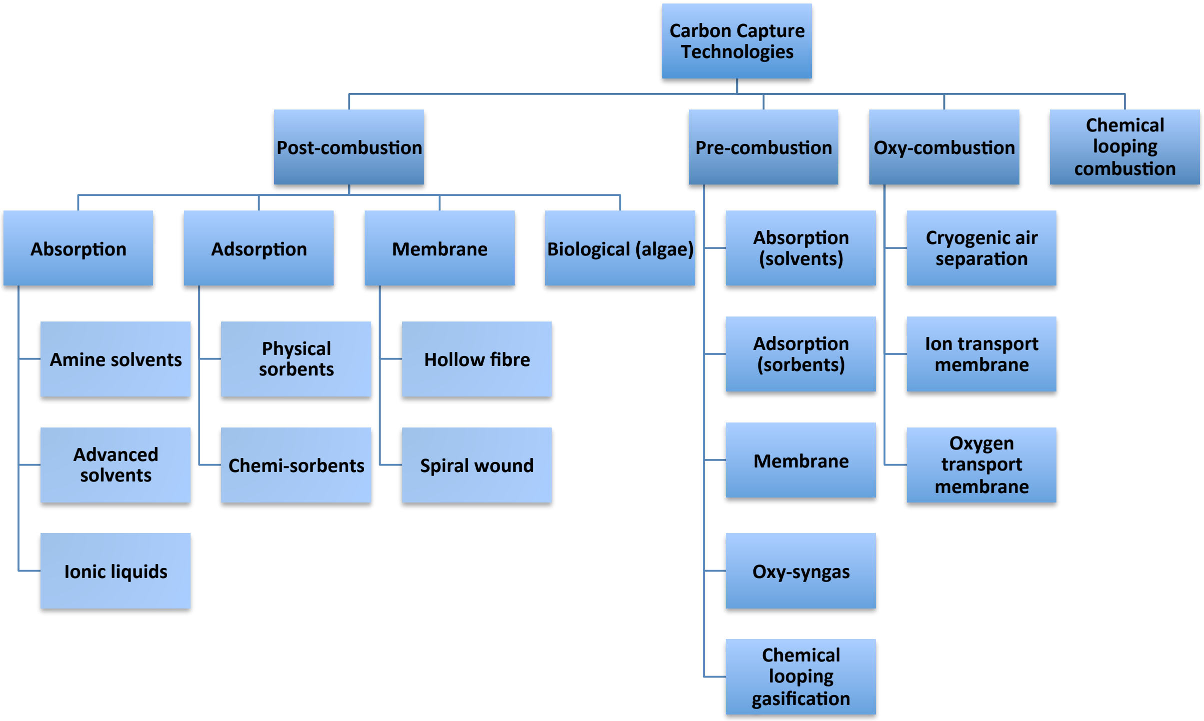

Figure 2: Capture technology categories assessed[12]

Individual technology providers were identified through interviews with experts, literature searches, web searches, and journal and forum proceeding reviews. Technologies ranged in degree of development, funding, application to oil sands, and industry support. Over forty individual technologies were identified and evaluated initially; companies were interviewed over the phone or, when feasible, in person. Data collected at this stage was limited to information that could be shared without a non-disclosure agreement in place. An example questionnaire is provided in Appendix F.

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[12] There are several methods that can be used to classify the technologies and many other technologies that are not included in this diagram. This is the categorization used for this work and referenced in the modeling.

2.2.2 Technology Readiness Level

Technology Readiness Level (TRL) is a common means of classifying technologies on the basis of their advancement towards commercialization. The TRL uses a scale of 1-9, where 1 is the lowest level of development and 9 is the final stage before commercialization. This study referred to the TRL descriptions as defined by the U.S. DOE.[13]

Given that the focus of this study was on emerging (pre-commercial) technologies, that were also advanced enough and had sufficient detail available such that they could be assessed on several criteria and differentiated from each other, the TRL scale was used extensively in this study to compare and classify technologies.

Figure 3 shows the number of technologies identified at each TRL, for several broad CCS technology categories. Based on the research done at this stage, technologies in the post-combustion advanced solvent, and oxyfuel / CLC categories were most numerous, and in general more advanced than the other categories.

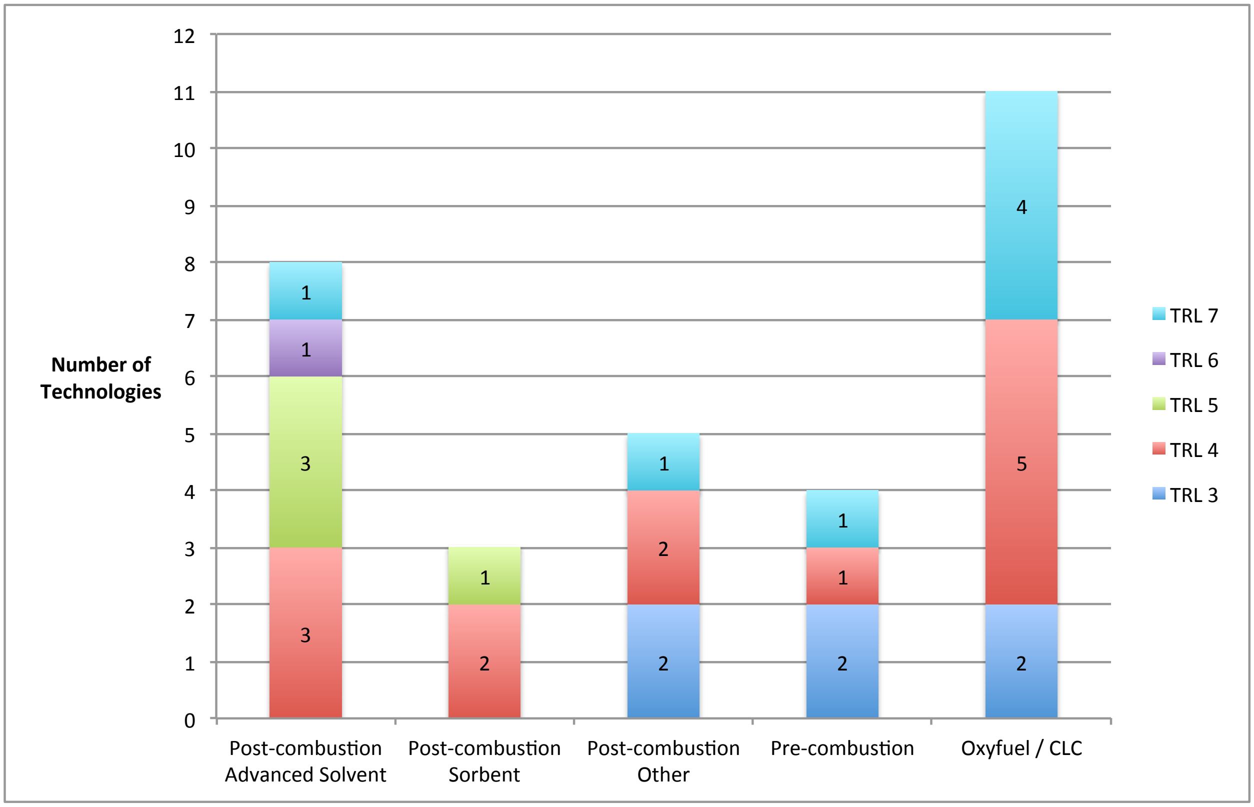

Figure 3: Classification of 31 unique technologies by broad category and by TRL in preliminary assessment phase

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[13] U.S. Department of Energy, "Technology Readiness Assessment Guide", 2011. http://www.lbl.gov/dir/assets/docs/TRL%20guide.pdf

2.3 Screening criteria

To narrow down the original set of technologies identified to a manageable subset of companies to interview and collect detailed information on, two primary screening criteria were used, as shown in Table 1.

Table 1: Screening criteria for capture technologies

Criteria	Rationale
Technology Readiness Level (TRL) between 3-7	This study focused on emerging capture technologies. During the research phase it became evident that technologies in the TRL 8-9 range were more or less a "known entity" in terms of cost and commercialization date, while technologies at TRL 1-2 would be in such early state of design that process details would be scarce and costs and lead time to implementation would be highly uncertain.
Applicability to largest sources of oil sands emissions (mining, SAGD, upgrading)	Technologies must have the physical ability to handle flue gas from oil sands process equipment or to otherwise be capable of integrating into oil sands operations at the relevant scale.

Applying these criteria to the initial set of technologies identified yielded 21 companies (representing 33 unique technologies) who were contacted for interviews. Additional considerations used to prioritize the interview and data gathering process were:

- CO_2 processing capability and scalability of technology
- Energy or parasitic load requirements
- Company partnerships and management teams
- Economic considerations or benefits (co-products, EOR, etc.)

Following the initial interviews, technology providers were asked to provide detailed cost and technology development data (the detailed cost survey that was distributed to the technology providers in this phase of the study is provided in Appendix G). As this information is typically confidential, Pembina worked with technology providers to develop and sign non-disclosure agreements.

Of the 33 technologies identified at this stage, detailed cost and technology development data was obtained for 15 different technologies and was used to populate the cost and GHG reduction scenarios model. Descriptions of the companies representing these 15 technologies are included in Appendix C.

Although the use of biological methods, such as algae, was identified as a potential post-combustion CCS technology, the technology was not carried forward in this analysis due to energy intensity in colder northern climates and the fact that it is still considered small scale and requires further development before reaching technical maturity.[14] A summary of the research conducted on biological capture is presented in Appendix E.

2.4 Assumptions

Several key assumptions were used to assess the suitability of CCS technologies for use in the oil sands and model the potential deployment of those technologies in a growing oil sands sector over time. Table 2 below describes the assumptions applied and provides an associated explanation.

Table 2: Key assumptions

Assumption	Description
Oil sands growth data	National Energy Board published data[15] (reference case) was used out to 2035. For the period between 2035 and 2050, the growth rate was calculated using a declining growth projection slowing by 0.1% per year as this is the trend in the last 5 years of the NEB projected data and generally agreed to through consultation with the client. Projected growth curves are shown in Figure 6.
Technology applicability	The application of CCS technology categories to oil sands sectors (in situ, mining, upgrading) was chosen for this study based on a review of available literature, consultation with the client, and feedback from the technology providers. It was determined that: • Post-combustion technologies are suitable for mining, in situ and upgrading, as they can be applied to any flue gas stream with minor disruption to the existing process. • Oxy-fuel technologies are suitable for mining and in situ. On the mining side, oxy-fuel can be used for power generation while on the in situ side oxy-fuel is well suited as a retrofit or replacement of Once-through Steam Generators (OTSGs). Oxy-fuel is not well suited for integration in a hydrogen plant, the main source of CO_2 in upgrading. • Pre-combustion technologies are suitable for upgrading only, due to the high requirement for hydrogen and steam, and the ability to integrate with a poly-generation plant. Pre-combustion is particularly less suitable for mining and in situ retrofits, where significant process modifications would be required. • Chemical looping is suitable for in situ and upgrading, as these two processes, unlike mining, generate significant quantities of steam.

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[14] International Energy Agency (IEA), *Technology Roadmap: Carbon Capture and Storage (2013).* http://www.iea.org/publications/freepublications/publication/TechnologyRoadmapCarbonCaptureandStorage.pdf

[15] National Energy Board, Canada's Energy Future: Energy Supply and Demand Projections to 2035 - Energy Market Assessment (2011). http://www.neb-one.gc.ca/clf-nsi/rnrgynfmtn/nrgyrprt/nrgyftr/2011/nrgsppldmndprjctn2035-eng.html

GHG "market" size	It was assumed that the "market" of capturable emissions consists of large stationary oil sands sources only (98.5% for in situ, 70% for mining and 90% for upgrading)[16], at 90% capture efficiency.[17]
Technology penetration	CCS technology penetration was modeled using an "S-curve" approach as described by Daniel J. Packey[18]; adoption begins slowly, accelerates rapidly in the middle stage, then levels off as it reaches a saturation limit.
Costs and learning rates	A cost multiplier was applied to the technology providers' reported costs: an increase of 75% for TRL 6 and 7, and 150% for TRL 3,4 and 5. Cost reduction over time was related to cumulative capacity through historically observed experience curves.[19] Median learning rates were selected from literature and applied uniformly to all carbon capture processes. Costs obtained from survey converted to same base year using Industrial Product Price Index (machinery and equipment category)[20]
Emission factors	Mining: 0.036 tonnes CO_2e/bbl (Pembina 2010); In Situ: 0.072 tonnes CO_2e/bbl. This is based on calculations conducted not including co-gen, a conservative approach (Pembina 2013); Upgrading: 0.059 tonnes CO_2e/bbl (Environment Canada 2012); Emission factors were assumed to be constant over time (base case). Impact of emission factors changing over time was explored as a sensitivity.

2.5 Oil sands growth data

Based on National Energy Board (NEB) data out to 2035, Figure 4 below provides a projection of GHG emission from the oil sands out to 2050 using declining year-over-year growth projection of 0.1% from 2035-2050.

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[16] These values are based on calculations conducted on SGER Facility data provided by Justin Wheler, Alberta Sustainable Resource Development and Environment, May 16, 2013 and confirmed through a literature review.

[17] This is based on responses from the majority of technology providers which indicate that the technologies being modeled and used in the cost analysis are based on capture efficiencies of 90%.

[18] http://www.nrel.gov/docs/legosti/old/4860.pdf

[19] Rubin et al, "Use of experience curves to estimate the future cost of power plants with CO_2 capture", International Journal of Greenhouse Gas Control I (2007) 188-197.

[20] http://www5.statcan.gc.ca/cansim/

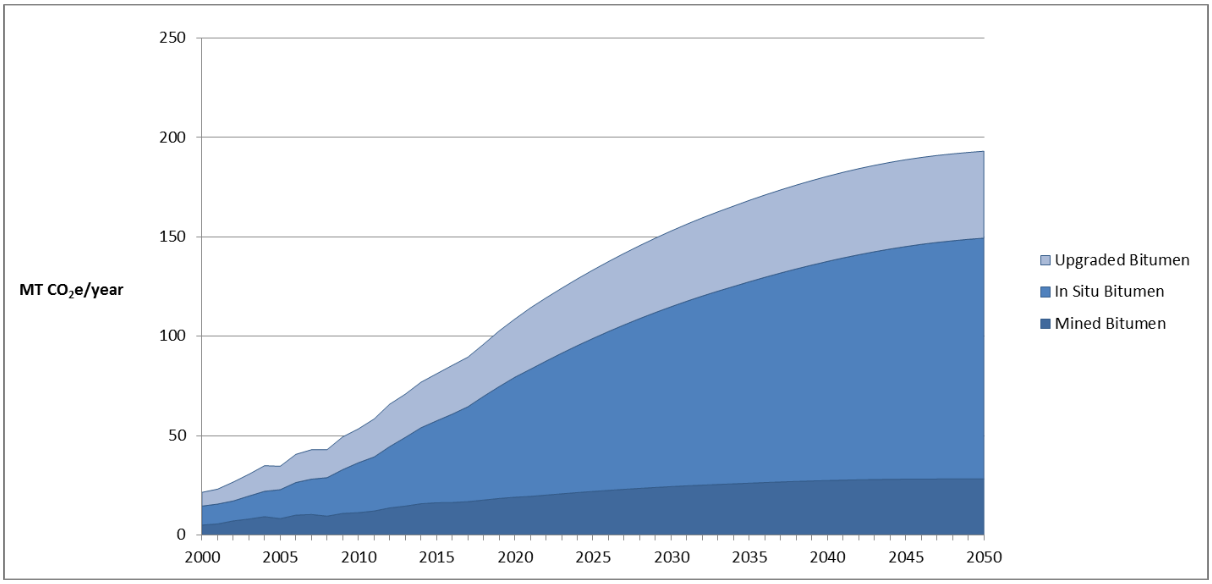

Figure 4: Projected oil sands emissions based on National Energy Board reference case data

This data is applied in the study as the basis for potential capture technology application in the oil sands.

2.6 Development of technology penetration scenarios

Technology penetration can be modeled in several ways. Based on a literature review of available models, it was determined that the work conducted by Daniel J. Packey[21] at the National Renewable Energy Laboratory exploring market penetration of new energy technologies offered the best examples of models that could be used for this work. This research concluded that "the market penetration technique selected should be the one that utilizes the available knowledge to the fullest. In some instances, this may necessitate combining a number of methods. For example, it may be necessary (because of lack of specific data) to use subjective estimates in cost methods incorporated in diffusion models." The model used in this analysis is a combination of a diffusion model based on the work by Rogers[22], employing an S-curve penetration; a market survey to collect data; and a cost model based on work done by Rubin et al.[23] The cost modeling applied in this study is described in greater detail in section 2.8.

Technology penetration curves were created for each technology based on survey results which informed key variables as outlined in Table 3. These were then aggregated to generate the overall technology penetration curves for each oil sands sector (mining, in situ and upgrading).

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[21] http://www.nrel.gov/docs/legosti/old/4860.pdf

[22] Based on work done by: Rogers, E.M. Diffusion of innovations (1962). http://books.google.ca/books?id=zw0-AAAAIAAJ&hl=en

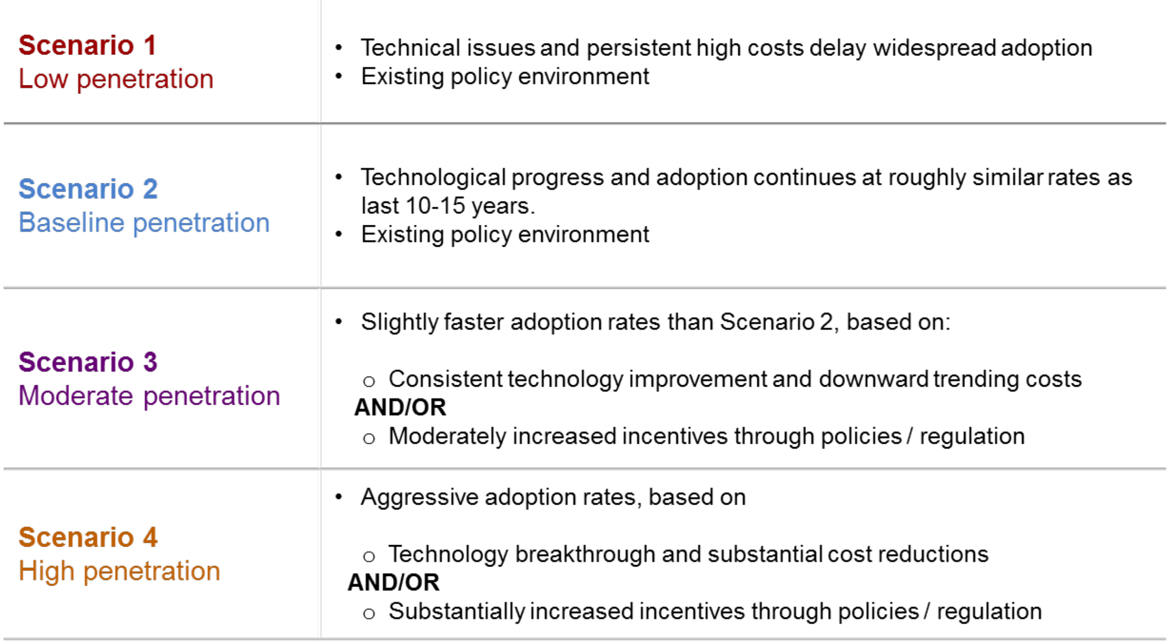
[23] Rubin et al, "Use of experience curves to estimate the future cost of power plants with CO2 capture," *International Journal of Greenhouse Gas Control I* (2007).

Table 3: Technology penetration variables

Base year	First year of commercial-scale implementation of a technology.
Saturation percentage	Highest expected penetration of the technology after introduction into the market i.e. the maximum value reached by the S-curve.
Start of fast growth year	Year that rapid growth of technology penetration begins. To simplify the model, penetration is assumed to be 10% of the saturation value by this year.
Takeover time (years)	The number of years required for the technology to “catch on” – it was assumed that after this number of years after the start of fast growth, the technology would have reached 90% of the saturation value and penetration would level off.

The saturation percentage was determined based on four scenarios modeled as possible overall penetration rates for the deployment of CCS in the oil sands. The penetration scenarios were chosen to reflect potential futures, but no judgment is implied as to the most likely scenario or requirements to achieve each scenario; rather, the scenarios provide a basis for comparison between various levels of CCS deployment. Table 4 provides context for the four scenarios chosen for this modeling.

Table 4: Scenario descriptions



Scenario 1 Low penetration	• Technical issues and persistent high costs delay widespread adoption • Existing policy environment
Scenario 2 Baseline penetration	• Technological progress and adoption continues at roughly similar rates as last 10-15 years. • Existing policy environment
Scenario 3 Moderate penetration	• Slightly faster adoption rates than Scenario 2, based on: o Consistent technology improvement and downward trending costs **AND/OR** o Moderately increased incentives through policies / regulation
Scenario 4 High penetration	• Aggressive adoption rates, based on o Technology breakthrough and substantial cost reductions **AND/OR** o Substantially increased incentives through policies / regulation

The scenarios described above correspond to the overall penetration percentages shown in Table 5, below.

Table 5: Technology penetration levels for Scenarios 1-4

Scenario	Overall Penetration Level
1	5%
2	15%
3	50%
4	80%

These penetration percentages were used to determine the overall penetration or deployment of CCS technologies in the oil sands and thus the overall percentage of GHG emissions captured under each scenario. Figure 5 shows an example result of an aggregated penetration curve for in situ capture technologies.

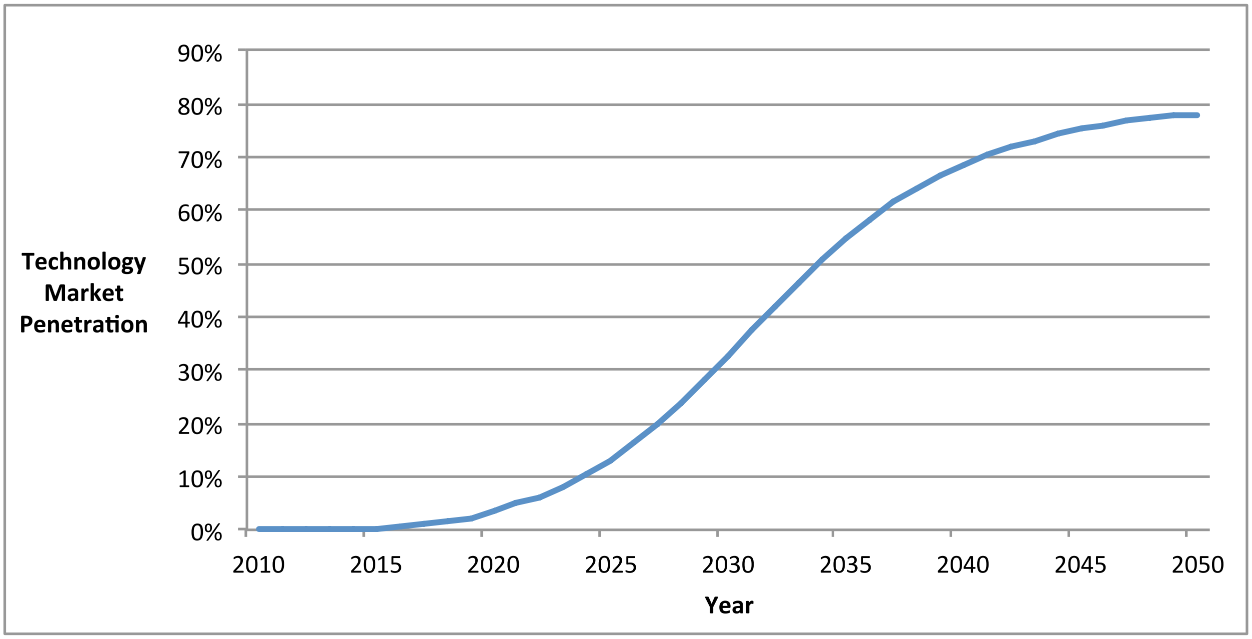


Figure 5: Example of in situ aggregated penetration curve

The shape of the curve shows how initial deployment happens slowly over the first eight years then, under this high growth case, proceeds to accelerate to a point where it near the saturation limit of 80% and begins to slow around 2035.

2.7 Estimation of GHG reduction potential through CCS

In order to assess the potential reductions in CO_2 through the application of CCS technologies, the assumed projected oil sands growth data explained in section 2.4 was used to calculate the potential overall emissions. The emissions factors presented in Table 2 for the various oil sands sectors were used to convert the estimated production volumes into CO_2 emissions. The emission reduction was then calculated using the aggregated technology penetration curves for the each of the four scenarios. This generated an overall reduction potential that corresponds to a certain level of technology penetration in the oil sands and to a certain level of CO_2 captured. Figure 6 shows an example result generated by applying the aggregated technology penetration curves to the oil sands emission growth data for each oil sands sector.

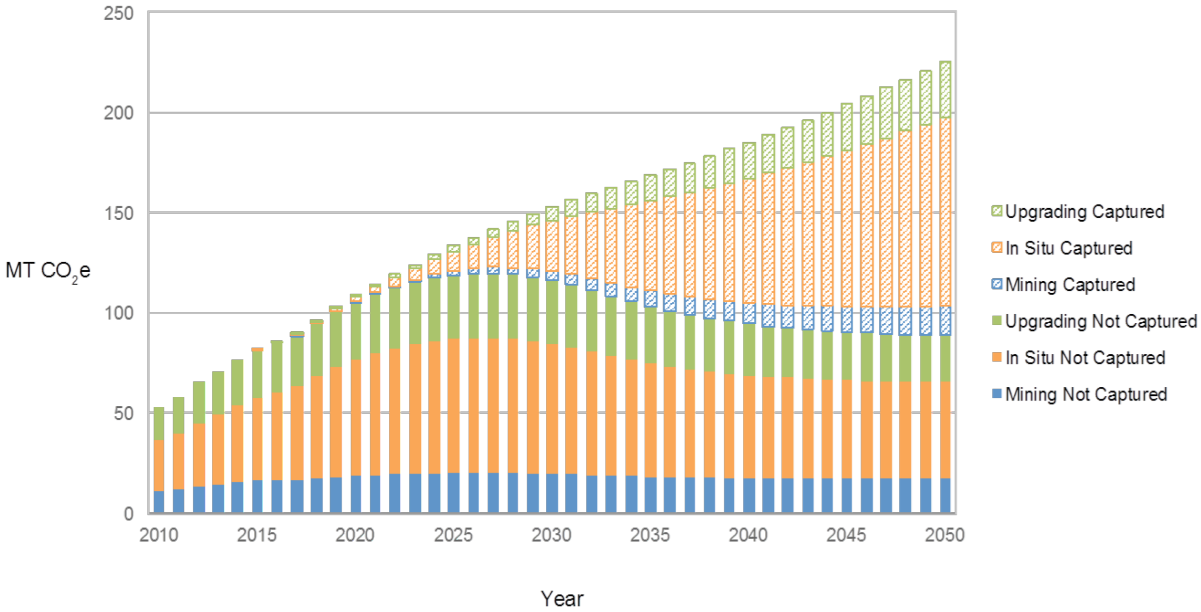


Figure 6: Example of estimated projection of oil sands emissions reduction

The darker colours depict those GHG emissions that are unable to be captured under a given set of assumptions; emissions that are captured are depicted in the light shaded colours. Thus just considering the lighter colours illustrate the level of reduction possible compared to a business as usual case. Ultimately this is a technology penetration curved that is used to develop and graph GHG reductions per scenario. Appendix A provides these penetration curves for each scenario considered.

2.8 Estimate potential cost of capture reduction over time

Estimating the cost of capture and the potential reduction in costs for CCS technologies over time was accomplished by conducting a market cost survey, adjusting costs based on expected increases in the years leading up to commercialization, adjusting for different base years and estimating expected learning rates.

As a first step, cost data was collected from technology providers by means of a detailed cost survey. Technology developers provided cost estimates of their emerging technologies and expected times until commercialization. Likely cost increases were modeled, as described below. To avoid duplication, only one technology was selected for each oil sands source for use in the model. Where data was provided for multiple iterations of the same technology, the most relevant dataset in terms of application size, recovery capacity or oil sands application was chosen.

To ensure all cost data was evaluated equally, a factor was applied to adjust cost estimates with different base years to 2013 dollars, as per the Industrial Product Price Index (IPPI).[24] Cost estimates were also adjusted according to the technology's level of advancement towards commercialization. Based on work done by Rubin[25], cost estimates for pre-commercial technologies have been shown to rise in the years leading up to commercialization before falling once a threshold of post-commercialization cumulative capacity has been reached.[26] In order to address this initial cost increase, a scaled multiplier was applied to the cost data provided by the technology providers based on the current technology readiness level (TRL) of the technology. The cost estimates for technologies with a TRL between 6 and 7 were increased by 75%, while the costs of technologies with a TRL of 3 to 5 were increased by 150%.

Learning rates were then used to estimate the overall cost reduction of CCS technologies over time. By examining historical cost patterns of industrial technologies relevant to CCS such as flue gas desulfurization (FGD) and selective catalytic reduction (SCR), it is clear that both capital and operating costs decrease over time as cumulative installed capacity increases, as seen in Figure 7.

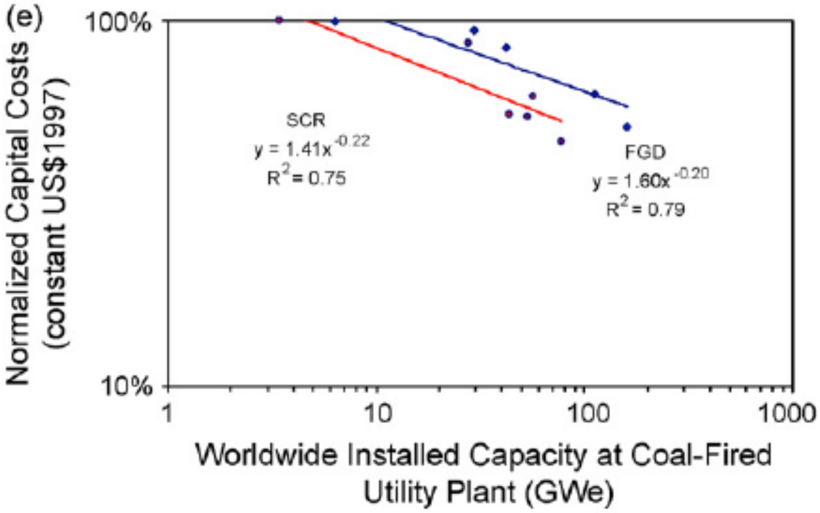


Figure 7: Capital cost experience curves for FGD and SCR systems for coal power plants

Source: Rubin et al[27]

A negative exponential learning curve, first proposed by Wright in 1936 to estimate efficiency gains in the production of aircraft[28], and since applied to a wide variety of industries, was used in this study to estimate CCS cost reductions over time as a function of installed cumulative volume of carbon captured in the oil sands. This experience curve used took the form $Y=ax^{-b}$, where Y is the specific cost of the x^{th} unit, a is the cost of the first unit, and b ($b > 0$) is a parametric

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[24] Statistics Canada. Table 329-0056 - Industry price indexes, by major commodity aggregations, machinery and equipment, monthly (index, 2002=100). http://www5.statcan.gc.ca/cansim/

[25] Rubin et al, "Use of experience curves."

[26] Ibid.

[27] Ibid.

[28] T.P. Wright, "Factors Affecting the Cost of Airplane," *Journal of the Aeronautical Sciences* (February 1936).

constant. This formula implies that each doubling of cumulative capacity results in a cost savings of $(1-2^{-b})$, which is defined as the learning rate (LR).

For this study, a modest learning rate of 0.034 was used as a nominal estimate. This rate corresponds to the median learning rate predicted by Rubin for the cost of electricity reduction between four types of CCS-enabled power plants (NGCC, pulverized coal, IGCC and oxyfuel) going forward.[29] At this rate, the cost of capture is reduced by 3.4% for each doubling of cumulative capacity. The effect of changes to the learning rate is explored in the sensitivity analysis (Appendix B).

The median value of the adjusted costs for technologies within each of the oil sands sectors was used as a representative initial cost in 2016, which was the earliest expected year of commercialization of the technologies included in this study. From this initial cost, it was assumed that learning and associated cost reduction began after one megatonne of CO_2 capture capacity was installed and operating. This is roughly equivalent to two commercial-scale plants capturing 1,500 tonnes of CO_2 per day, operating for one year, at 90% capacity. Table 6 shows the initial costs and learning rates used in this study.

Table 6: Initial costs and learning rates

Oil sands Sector	Initial Cost of Capture (2016)	Learning Rate	b[30]
Mining	\$100 / tonne	0.034	0.05
In Situ	\$86 / tonne	0.034	0.05
Upgrading	\$85 / tonne	0.034	0.05

It was also assumed for the purpose of this study that learning continues indefinitely (i.e. does not end after a particular cumulative capacity), and that learning rates apply equally to all oil sands sectors (mining, in situ and upgrading). Figure 8 shows estimates for cost of capture as a function of cumulative capacity for mining, in situ and upgrading at learning rates of 3.4%

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[29] Rubin et al, "Use of experience curves."

[30] The exponent b used in the experience curve formula $Y=ax^{-b}$ is related to the learning rate (LR) through the equation: $LR = (1-2^{-b})$

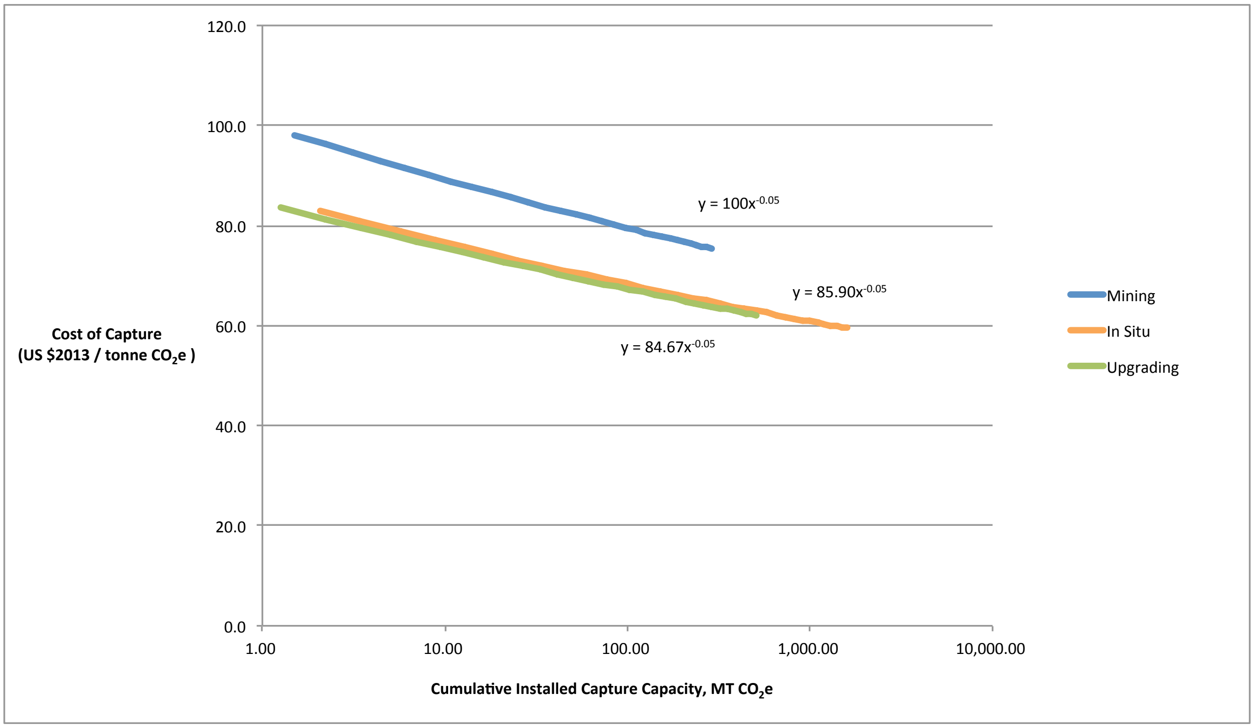

Figure 8: Estimated cost reduction for CCS technologies

One can see the associated rate of cost decrease based on installed capture capacity, over time, according to the $Y=ax^{-b}$ formula.

2.9 Data and model limitations

Selecting the appropriate data, assumptions, model parameters and methodology was a critical step in the assessment and was based on the expertise, experience and guidance of modelers and the client advisory team. Whenever possible, methodology was used that is consistent with peer-reviewed studies that were conducted to assess similar projections of technology penetration into the future. There remain several areas of limitation to this model and in order to properly assess the results, it is important to understand how these limitations may impact the final results.

1. **Technology provider data**
    - Costs and dates of commercialization obtained from technology companies were used in the model as provided in the cost survey, with an incremental cost factor applied as described in the assumptions section. It was not possible to verify the supporting documentation used to generate the cost estimates.
    - In many cases technology providers lacked detailed economic studies for specific applications, particularly oil sands applications, due to the early stage of commercialization of their technology.
    - The methodology used by technology providers to compile costs was not always consistent. In most cases Pembina did not have access to the methodology or details of the estimate.

2. **Technology penetration and cost modeling**
    - An inspection of historical examples of industrial processes shows that costs tend to rise during the early stages of commercialization before descending; this cost rise was modeled as described in Section 2.6 based on Rubin's work.
    - Costs were compared on a per tonne of CO_2 basis alone; a heat and mass balance was not done to ensure that the same quantities of end products would be produced. This applies mainly to retrofit projects.
3. **Scope of model**
    - This study looked at capture technologies and the cost of the capture process only; transmission and storage costs would need to be included to express the results in terms of avoided cost or avoided GHGs.

3. Results

3.1 Potential GHG reduction through CCS technology penetration

Figure 9 shows the projected annual GHG emissions in the oil sands with various levels of CCS technology penetration, or adoption, as per previously defined Scenarios 1 through 4. Two additional scenarios of 0% and 100% adoption are shown for reference.

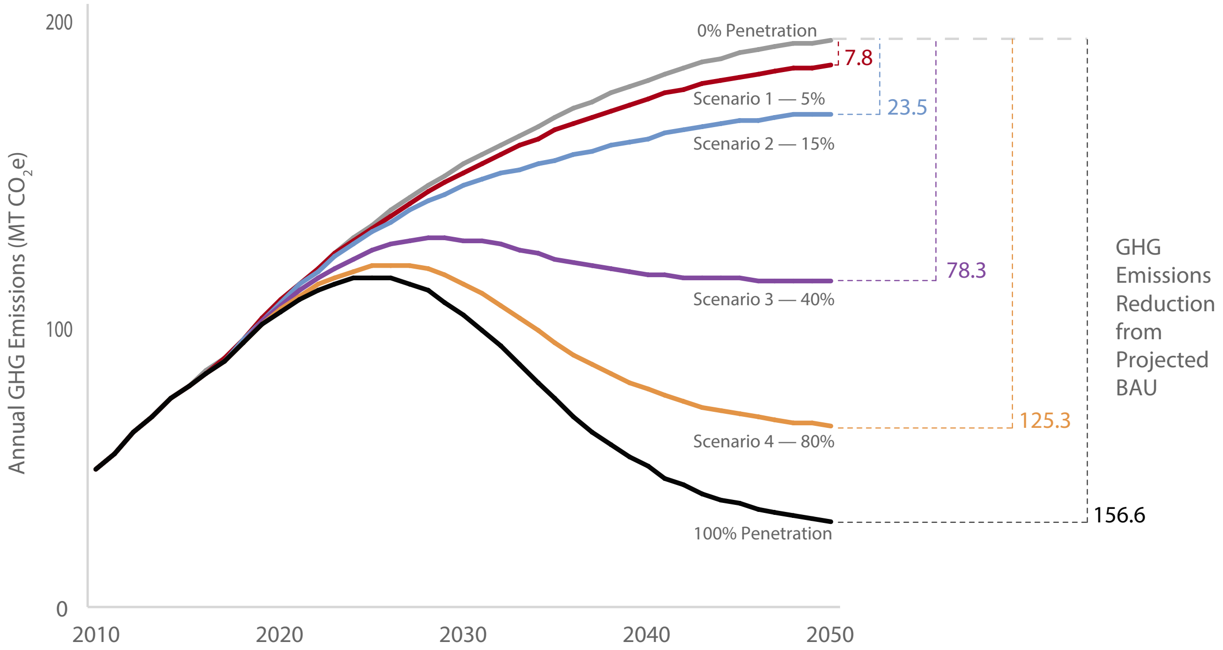

Figure 9: Oil sands emission projections for various levels of CCS technology adoption

This figure provides a useful understanding of the degree to which GHGs could be reduced in the oil sands given different rates of penetration for the most promising capture technologies. Recall that this is based on the given assumptions associated with technology uptake, and is applied to capturable emissions from point sources for different types of operations in the oil sands over time.

When considering what level of penetration is required to “bend the curve” of projected GHG emissions in the oil sands, it can be seen that emissions could be stabilized at 2020 levels with a penetration rate of just under 40%. This would mean about a 75% reduction in projected emissions in the 2040 to 2050 time frame. Full deployment/penetration of capture technologies on all capturable sources would need to occur to achieve 2010 emission levels or lower.

3.2 Technology development status and cost estimates

The detailed cost and technology development data from 15 different technologies was acquired and used to populate the cost and GHG scenario model. Results from this final assessment are presented below.

Figure 10 presents a breakdown of the 15 technologies according to CCS category and TRL. Similar to the results of the preliminary assessment, technologies in the post-combustion advanced solvent were more numerous and generally more advanced, followed by the oxy-combustion/CLC category.

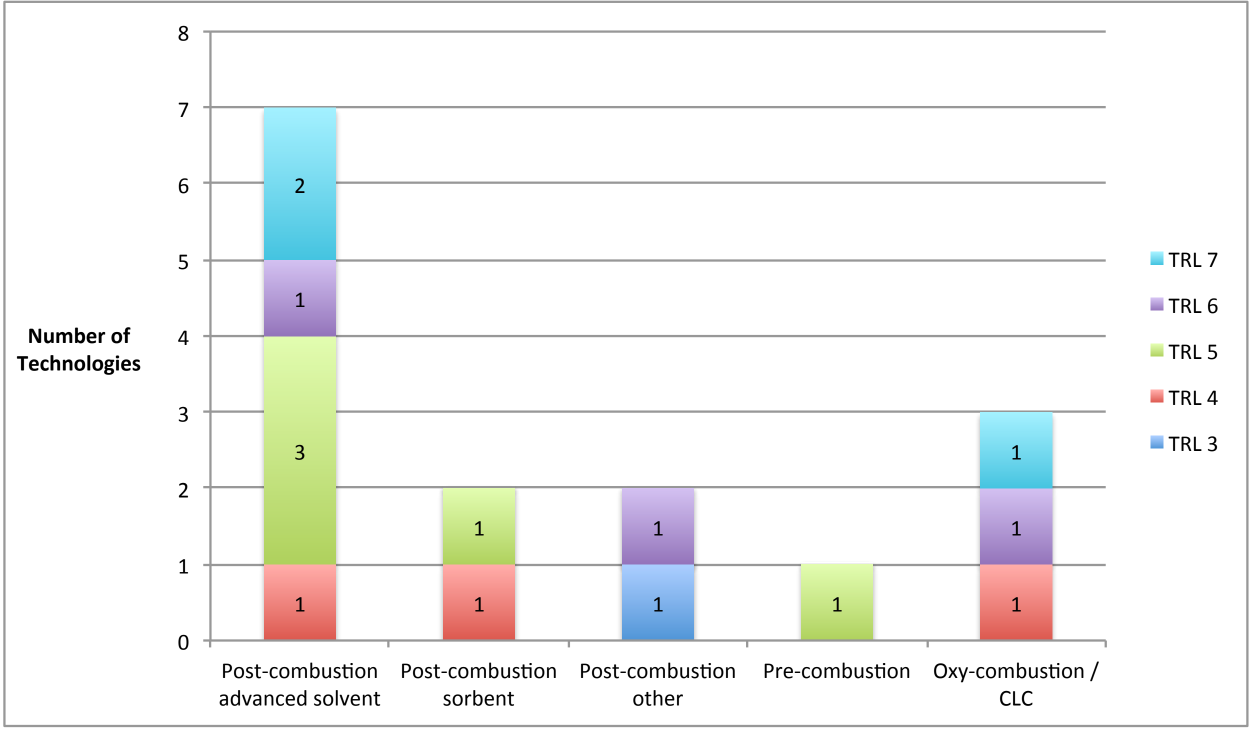

Figure 10: TRL classification of 15 unique technologies used in the final assessment

Figure 11 shows the cost of capture ranges for the broad technology categories, while Figure 12 shows the cost of capture ranges classified by TRL. For both graphs, the ranges of raw cost estimates obtained from technology providers from cost surveys are depicted as solid blue bars. As an attempt to adjust for the well-documented optimism of early stage cost estimates, a cost factor of +150% was applied for technologies at TRL 3-5, and +75% for TRL 6-7, as indicated by the error bars. Quest Project costs were estimated at $95/tonne with a +/- $25/tonne uncertainty, to roughly correspond with costs and capture volumes published by ICO2N.[31]

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[31] http://www.ico2n.com/ccs-in-canada/first-projects-in-canada/shell-quest

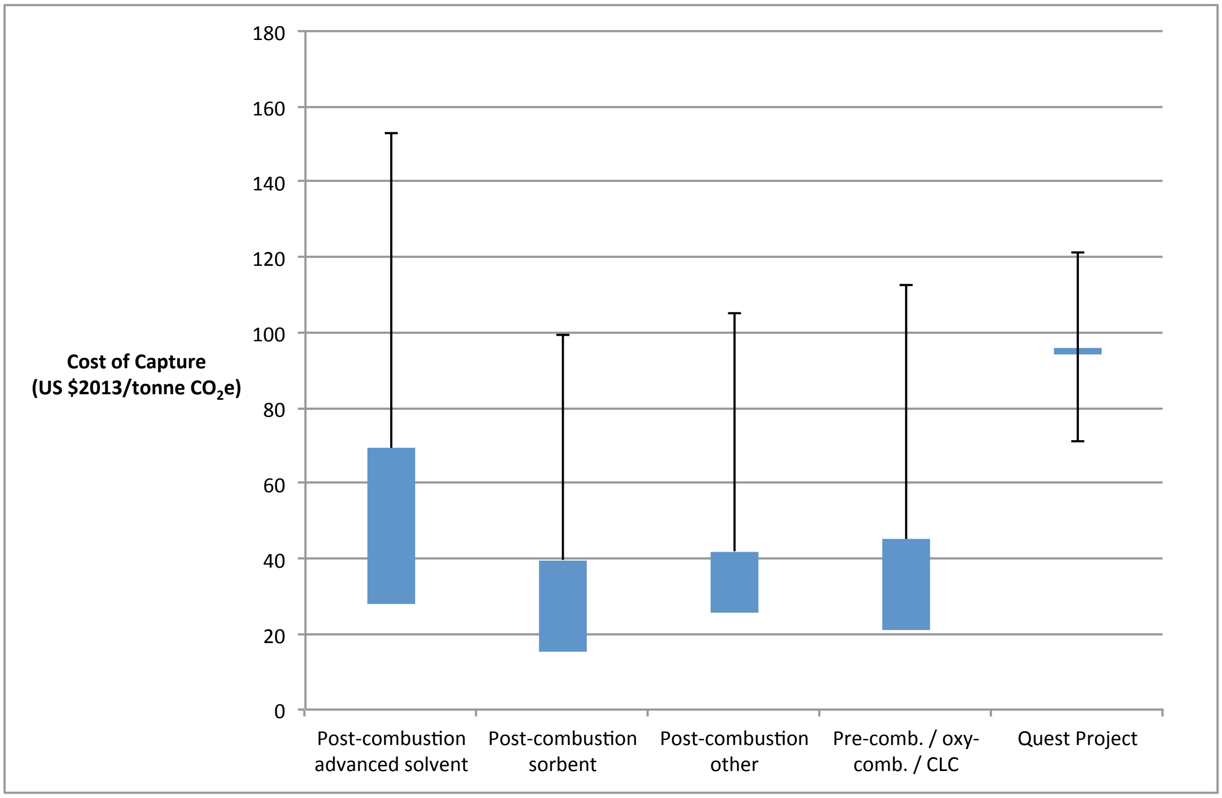
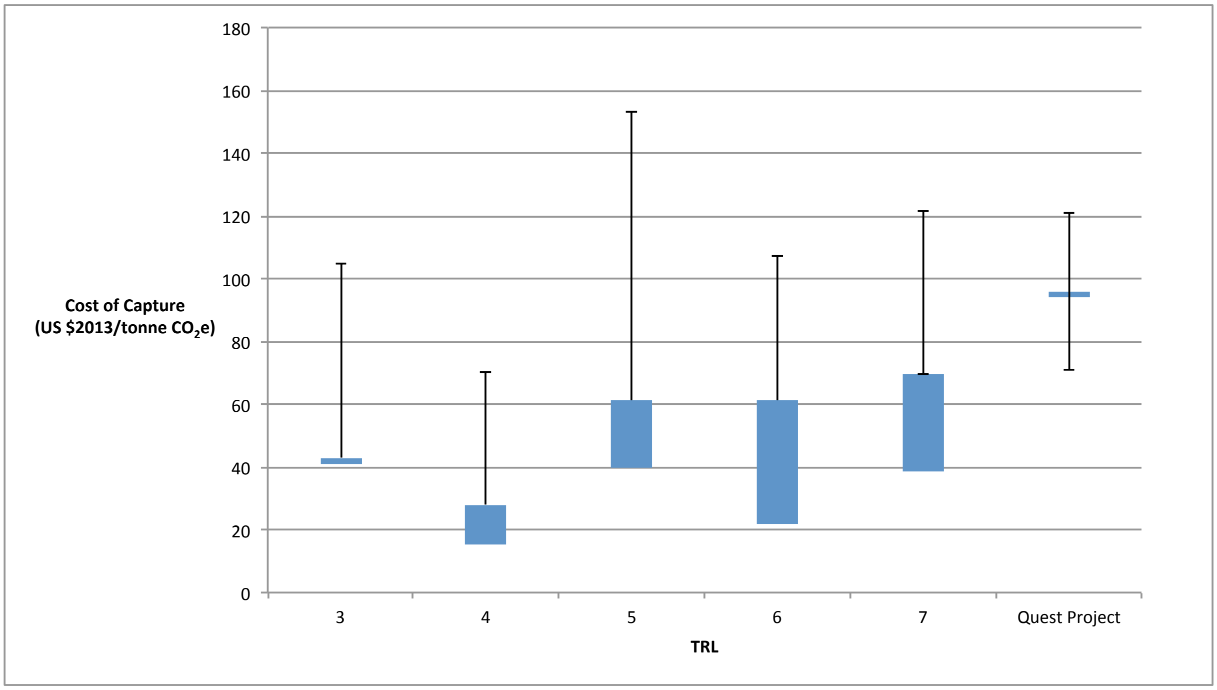


Figure 11: Aggregated cost of capture ranges at anticipated commercialization date, classified by CCS technology type, derived from technology provider survey results, with estimated Quest Project cost shown for reference[32].



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[32] Quest Project cost includes range to account for uncertainty about inclusion of storage cost and uncertainty about actual cost of project

Figure 12: Aggregated cost of capture ranges at anticipated commercialization date, classified by TRL, derived from technology provider survey results, with estimated Quest Project cost shown for reference.

3.3 Cost projections to 2050

Figure 13 shows a visual representation of cost (including uncertainty as described above) and commercialization date data points obtained from the technology providers, categorized by oil sands sector. Technologies applicable to all three sectors were included as distinct data points.

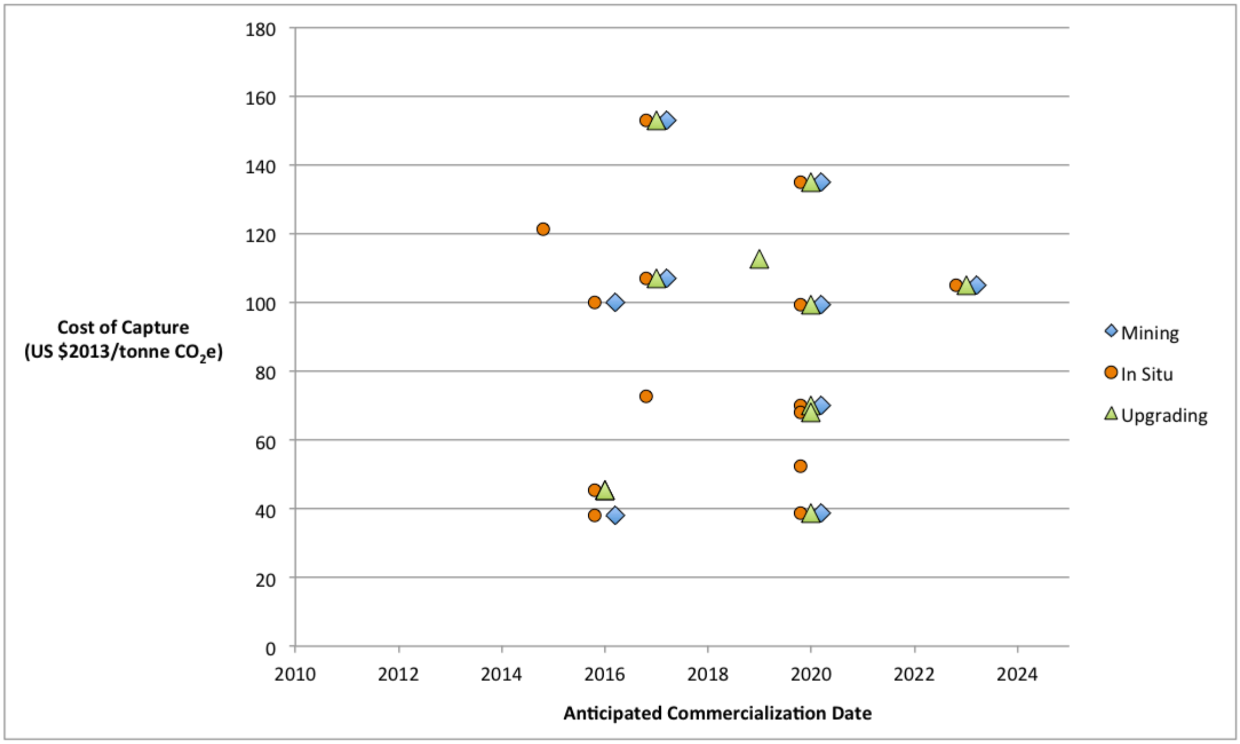

Figure 13: Cost of capture vs. anticipated commercialization date by oil sands category

Perhaps unsurprisingly a wide range of projected cost estimates exist for each category of oil sands operations, with the low end being around US$40 per tonne and upper end being US$140 and above, out to 2020.

As discussed in Section 2.8 above, cost estimates were projected to 2050 based on constant learning rates. This study used a baseline learning rate of 0.034, whereby costs improved by 3.4% for each doubling of cumulative installed CO_2 capture capacity. Figure 14 shows cost of capture projections for each of the oil sands sectors to 2050 on the same plot as the adjusted cost data from the survey.

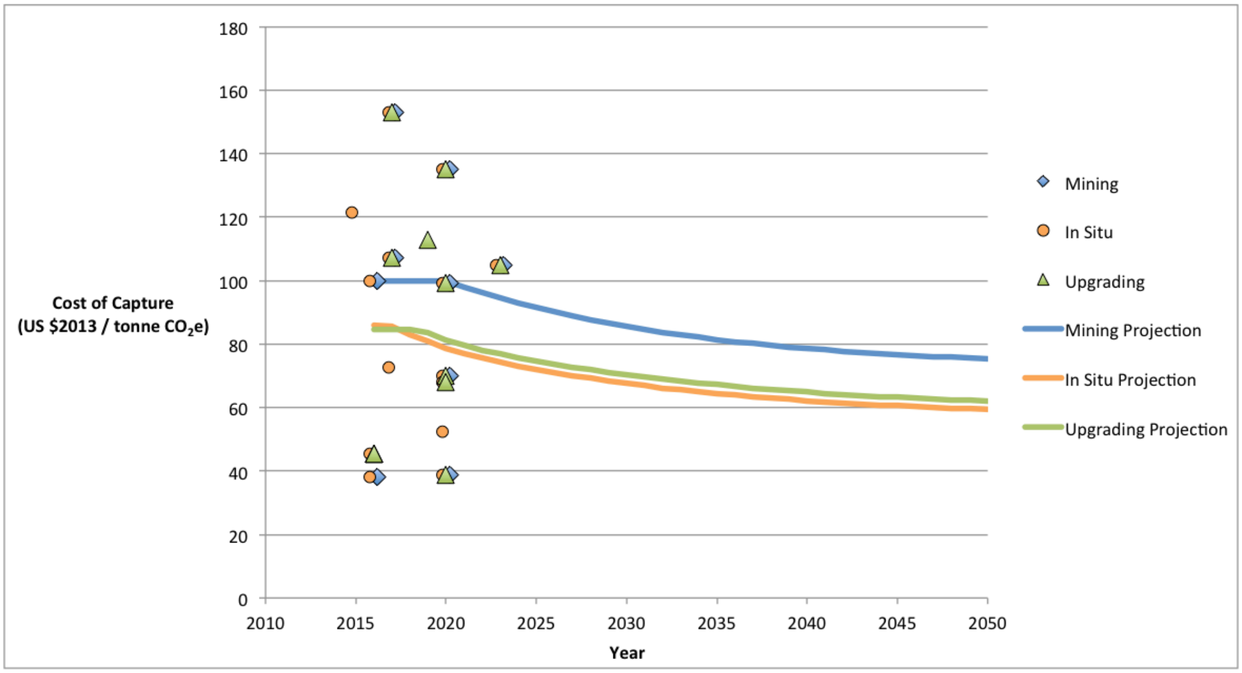

Figure 14: Cost of capture projection for each oil sands sector

3.4 Sensitivities

Two sensitivity analyses were performed on the model to test the response of the model to particular variables and observe the differences to the results. The first sensitivity examined the effect of changes to oil sands emission factors to the GHG reduction curves, and the second looked at the effect of learning rates on the cost of capture projections. Per category of GHG emissions and cost, these are considered the most variables important to the analysis given their potential for a material influence on results and that they carry a reasonable level of uncertainty or variability across operations.

Results of the sensitivities are presented in Appendix B. A change in emission factors has more of an effect when penetration rates are lower and less effect at higher penetration rates, where reductions have already been maximized. When improving upon the conservative learning rate of 3.4%, a “median” range of 10% translates into a decrease of per tonne costs by over US$40 over time, or about 50% decrease in cost. A high range of 20% would translate into significant decrease in costs: an 80% reduction in cost, or US$50/tonne, over time from the existing modeled projections.

4. Conclusions

As would be expected, higher penetration rates result in higher potential GHG reductions. Most notably, emissions could be stabilized at 2020 levels over the longer term with just under a 40% technology penetration rate (for capturable sources of emissions across the different oil sands sectors). This would be about a 75% reduction in projected emissions in the 2040 to 2050 time frame.

Applying a generously conservative factor to upwardly adjust cost estimates provided by technology providers, results show that the potential average cost in 2013 dollars of capture technologies that are currently emerging will rest between US$60 and US$80/tonne CO_2 by 2050, with a lower boundary of US$40/tonne.

Although this modeling is limited by the assumptions, scope of review and the quality and accuracy of the data, it offers valuable insights in to the potential of carbon capture in the oil sands and the potential associated costs.

Appendix A. Technology penetration curves

The following graphs (Figure 15, Figure 16, Figure 17 and Figure 18) illustrate the technology generation curves developed and applied for the given scenarios over time.

A.1 Technology penetration curves for Scenarios 1-4

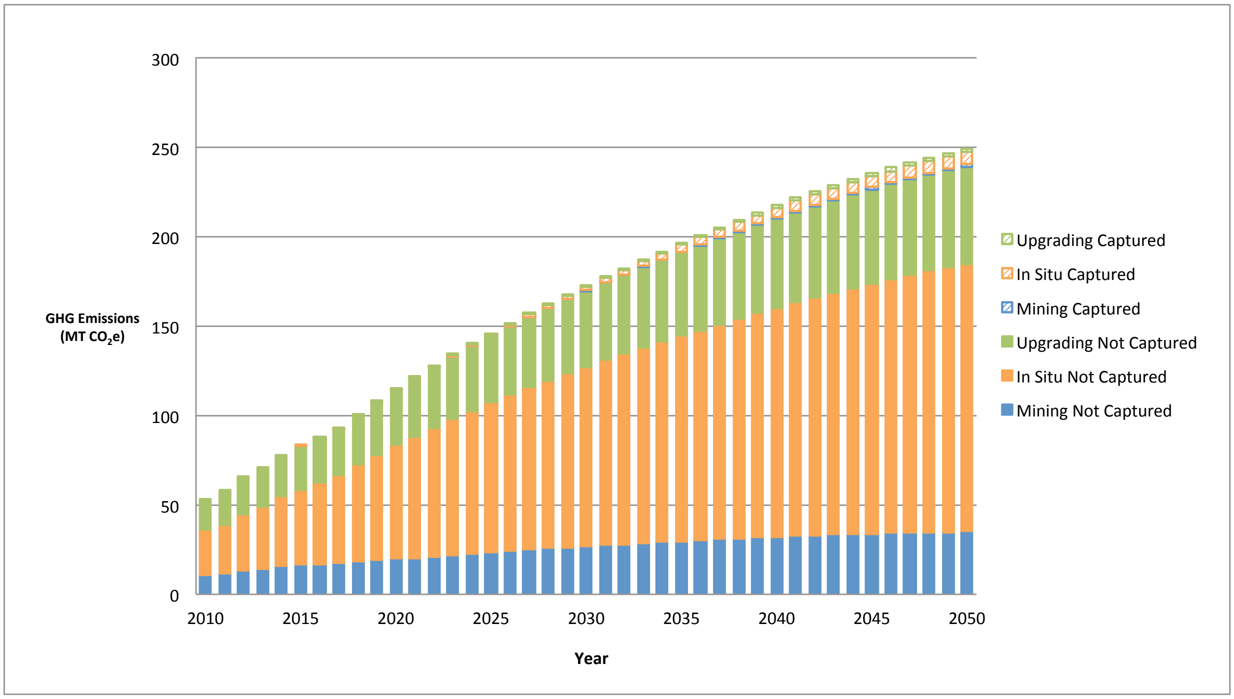

Figure 15: Technology penetration curve for Scenario 1 (5% penetration by 2050)

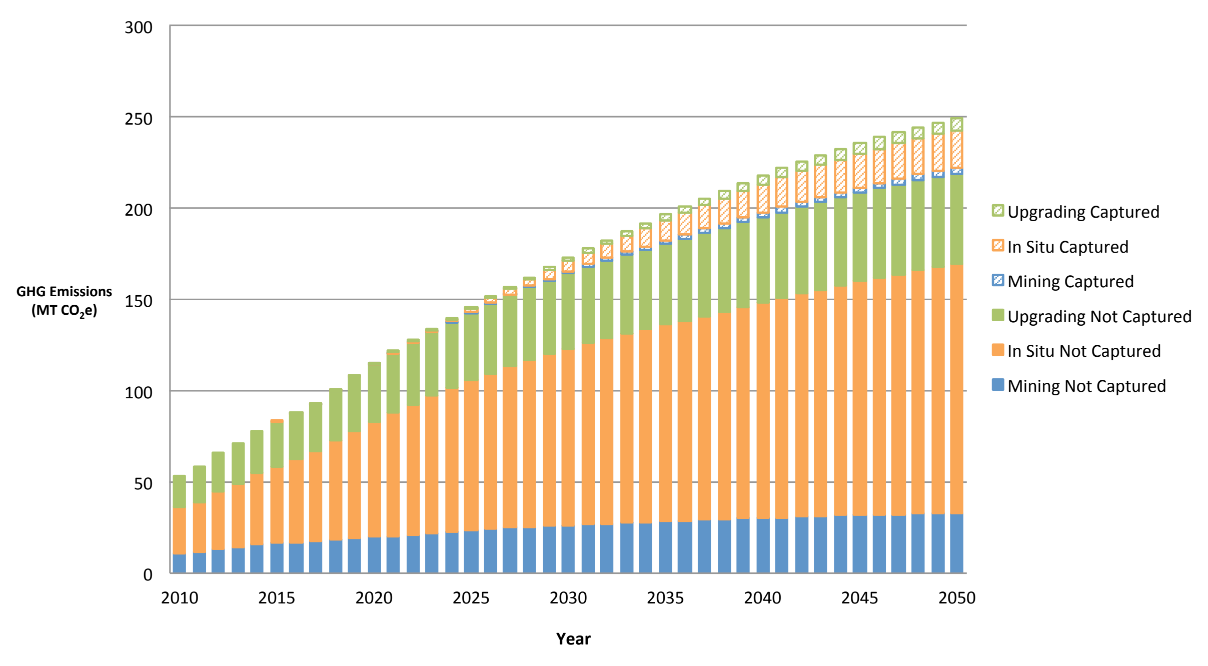

Figure 16: Technology penetration curve for Scenario 2 (15% penetration by 2050)

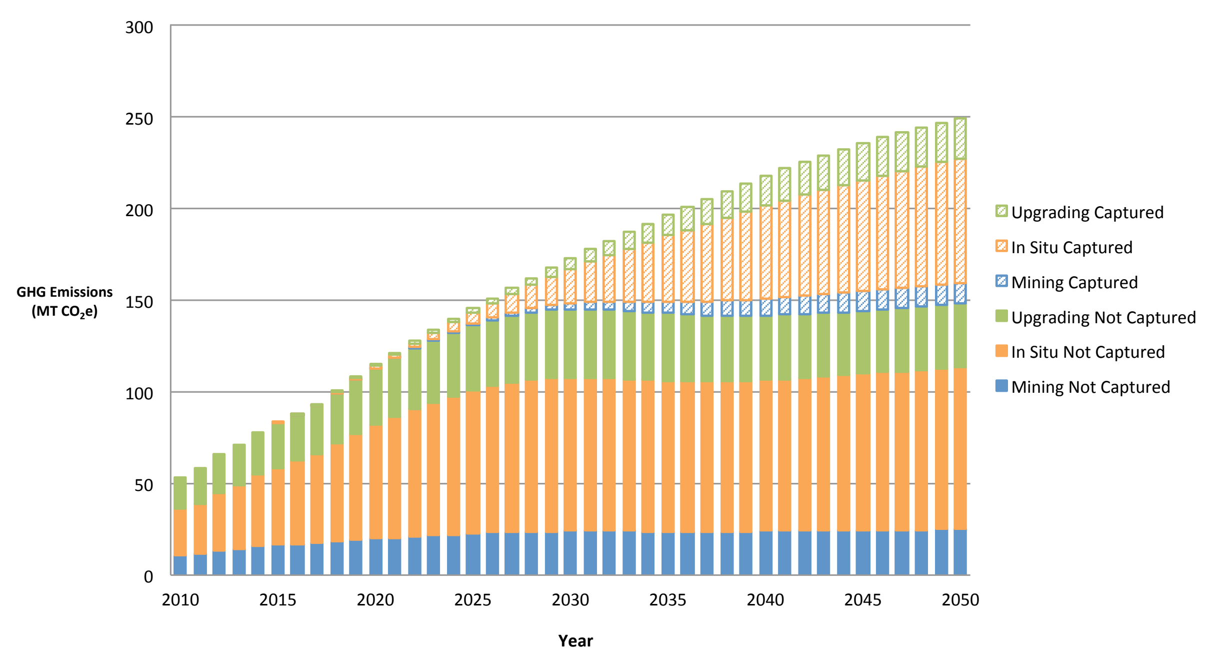

Figure 17: Technology penetration curve for Scenario 3 (50% penetration by 2050)

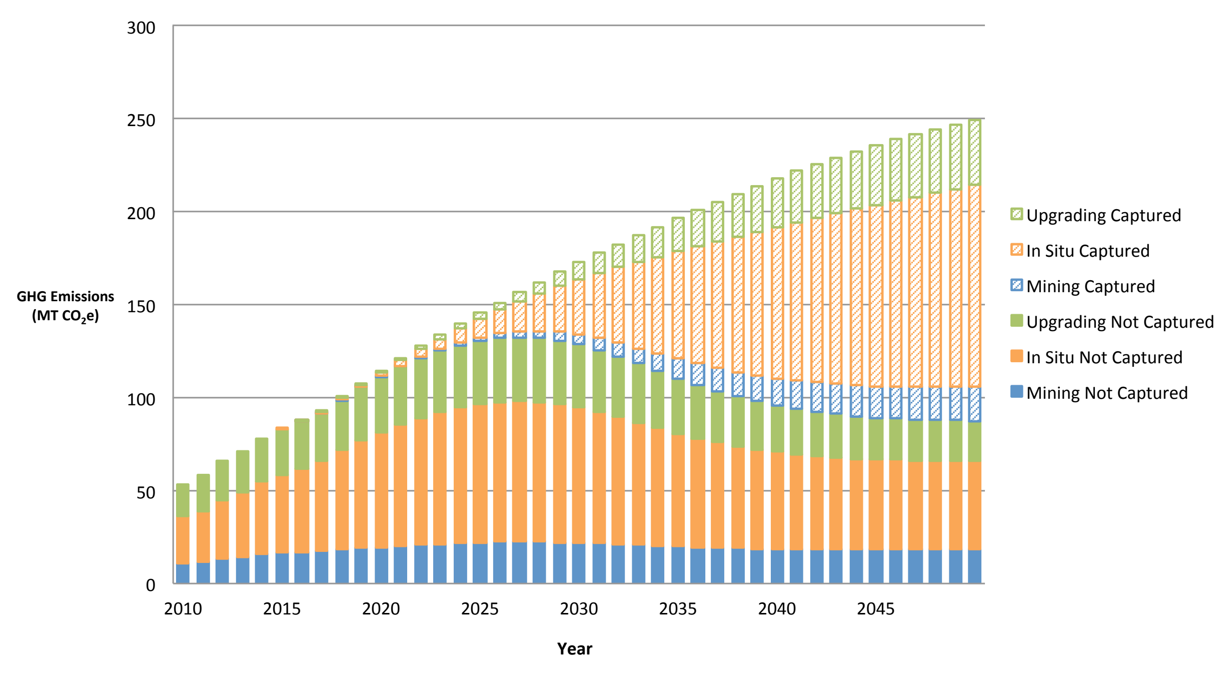

Figure 18: Technology penetration curve for Scenario 4 (80% penetration by 2050)

Appendix B. Sensitivity analysis

B.1 Effect of emission factors on GHG reduction

Sensitivities were run to determine the effect of oil sands emission factors decreasing over time (due to technology improvements and efficiency gains), or increasing (due to resource constraints). Figure 19 shows the revised GHG reduction curves with a 25% reduction of emission factors between 2013 and 2050, while Figure 20 shows the revised curves with a 25% increase.

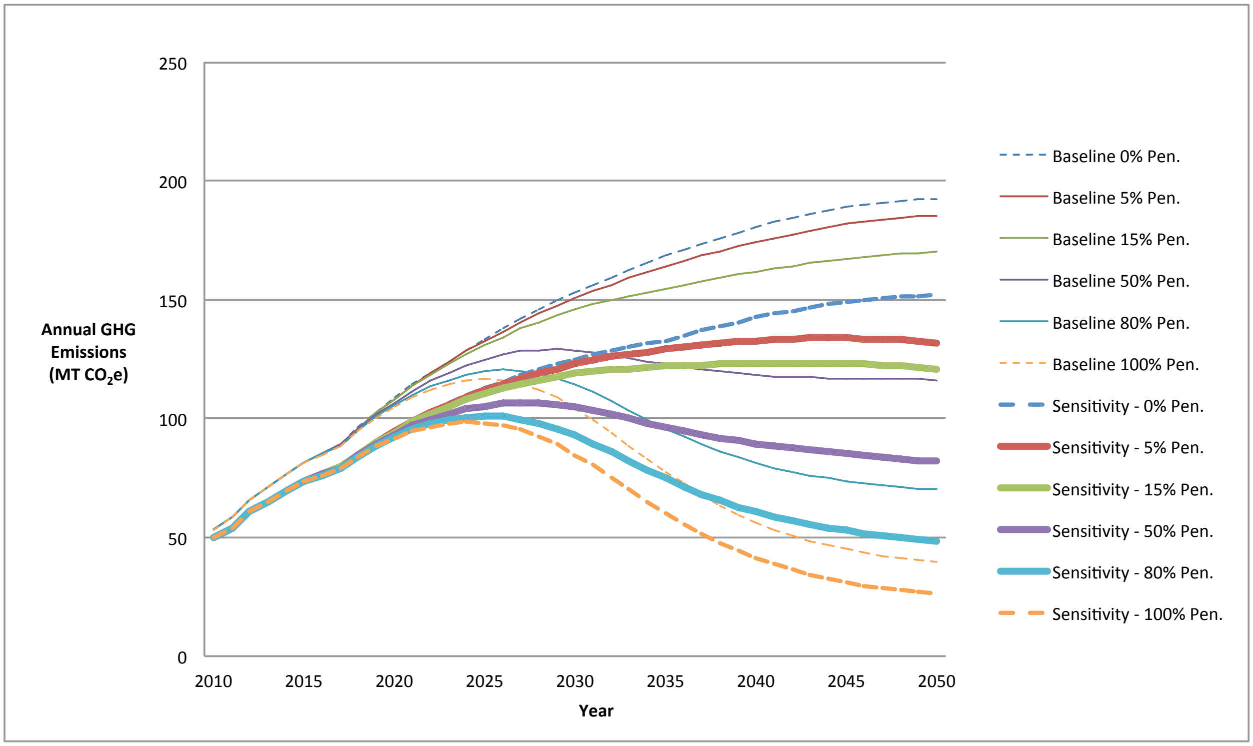

Figure 19: GHG reduction curves revised downward due to reduction of emission factors by 25% between 2013 and 2050.

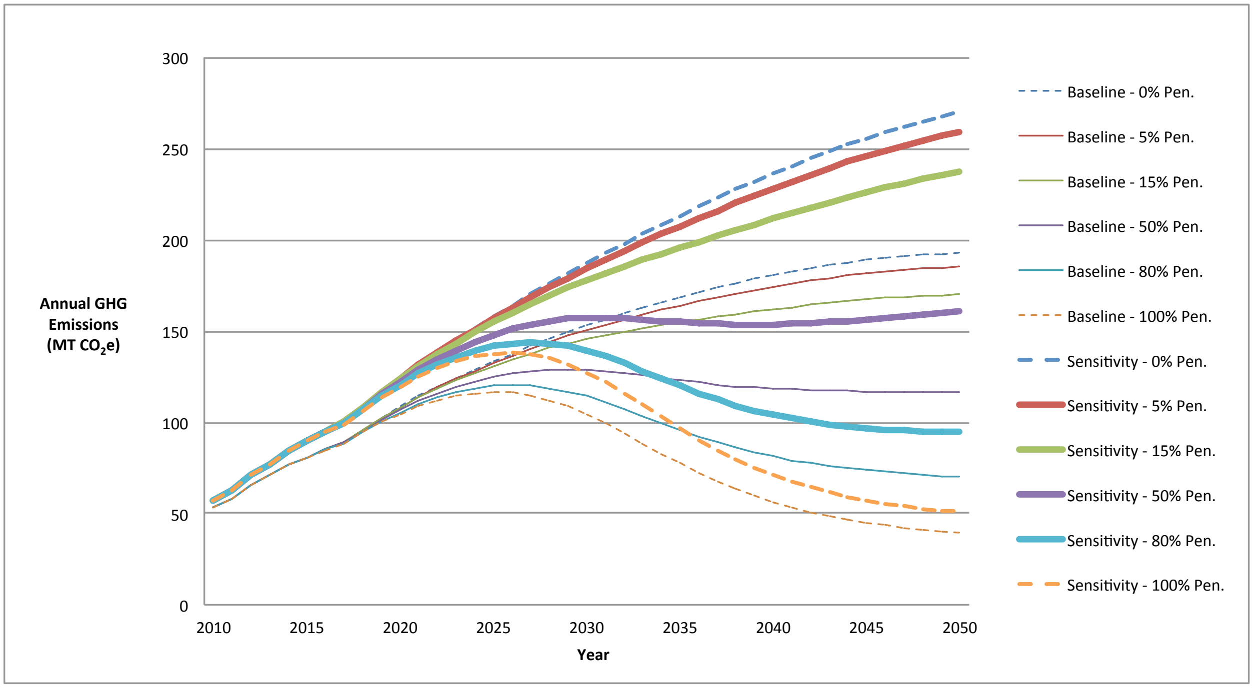

Figure 20: GHG reduction curves revised upward due to increase of emission factors by 25% between 2013 and 2050.

B.2 Effect of learning rates on cost projections

A second set of sensitivities was run to determine the effect of the learning rate on projected cost of capture. The baseline learning rate chosen for the study was 0.034, which corresponds to a cost improvement of 3.4% for each doubling of cumulative capacity. This rate represents a fairly conservative assumption for cost improvement from experiential learning over time.

A summary of the impact of different learning rates on the cost of capture is presented in Table 7. Learning rates of 0.1 (10% cost improvement, see Figure 21) and 0.2 (20% cost improvement, see Figure 22) were modeled as sensitivities. The 10% rate is representative of a "median" rate seen from a historical study of cost improvements for industrial technologies that may be relevant to CCS, while the 20% rate is representative of a "high" value.[33]

Table 7: Summary of learning rate impact on long-term capture costs

			Baseline Learning Rate (0.034)		Median Learning Rate (0.10)		Median Learning Rate (0.20)	
	Near-term ($/tonne)	Near-term ($/bbl)	Long-term ($/tonne)	Long-term ($/bbl)	Long-term ($/tonne)	Long-term ($/bbl)	Long-term ($/tonne)	Long-term ($/bbl)
Mining	100	3.60	76	2.74	44	1.57	17	0.62
In Situ	86	7.82	60	5.47	29	2.64	9	0.78
Upgrading	85	7.71	63	5.71	34	3.09	12	1.11

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[33] Rubin et al, "Use of experience curves."

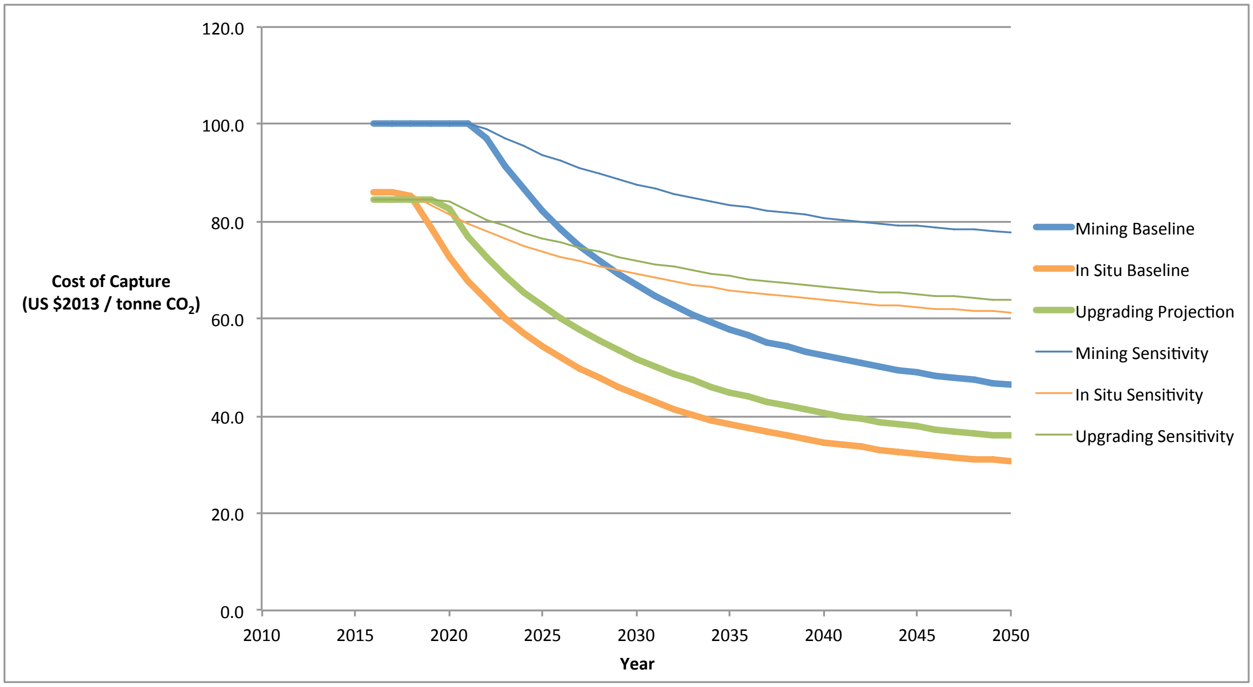

Figure 21: Cost projection revised downward due to representative median learning rate of historical comparison technologies of 0.10.

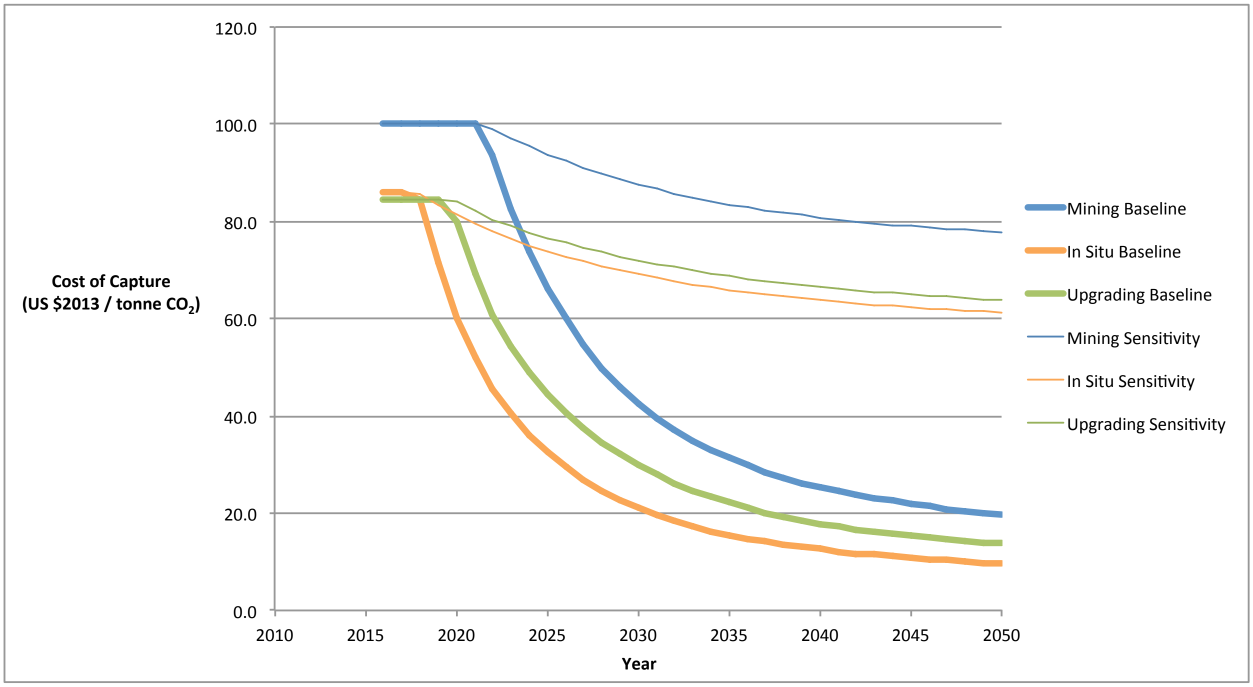

Figure 22: Cost projection revised downward due to representative median learning rate of historical comparison technologies of 0.20.

Appendix C. Technology Descriptions

The following descriptions of the individual technologies considered in this study are from the public domain, with actual wording from the providers applied.

C.1 Post-combustion technologies

C.1.1 CO_2 Solutions Inc.

CO2 Solutions Inc. is a publically traded company (TSX-Venture) based in Quebec City that aims to address the high-cost barrier to carbon capture created by conventional solvent-based CO_2 capture processes. The technology platform uses the biological enzyme carbonic anhydrase (CA) to accelerate the capture of CO_2 with energy-efficient solvents.

Advantages of this technology include cost savings due to reduction in heat requirement and ability to use zero-value waste warm streams for this heat, use of readily available solvents with superior environmental and operational properties, and the enabling of industrial gas scrubbing processes already familiar to industry.

CO2 Solutions is targeting multiple sectors including oil sands, coal and natural gas power generation, and aluminum and steel production. CO2 Solutions' deployment plan for the oil sands includes large bench-scale (0.5 t CO_2/day) testing in 2013, pilot testing (~15 t CO_2/day) in 2014-2015, and large demonstration scale and commercial deployment in 2015 and beyond.[34]

C.1.2 Akermin

Akermin is developing a novel solution to efficiently remove CO_2 from industrial gas streams using biocatalysts and nanotechnology. The Company uses a multi-disciplined approach to integrate enzymes within proprietary delivery systems that can be readily incorporated into conventional processes for CO_2 removal using chemical absorption.

Akermin's Biocatalyst Delivery System enables the enzyme to work efficiently and for an extended period of time addressing the key issue of enzyme stability in harsh industrial environments. Akermin's environmentally friendly approach to CO_2 removal significantly reduces capital and operating costs thus creating a strong value proposition for the customer.

Initial commercial sales are expected in 2015 using a license and consumables business model with established industrial partners. Akermin is targeting commercial launches for biogas upgrading and LNG liquefaction; two market segments that are experiencing strong growth with limited options for cost-effective, reliable "green" solutions for CO_2 removal. Future efforts will

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[34] http://www.co2solutions.com/en/technology-overview

expand to other sizable markets including hydrogen and ammonia production, oil sands boilers, and power generation.[35]

C.1.3 ION Engineering

ION Engineering, located in Boulder, Colorado is a leading developer of CO_2 capture solvents. ION's lead solvent technology is a non-aqueous, yet water tolerant, organic solvent capable of significantly reducing carbon dioxide emissions from industrial and fossil power generation sources. The non-volatile and tunable nature of ION's solvent chemistry, coupled with the high loading capacity of amines traditionally used in carbon capture processes results in more efficient and economical CO_2 capture process. More specifically, ION's advanced solvent process has both a higher effective CO_2 carrying capacity and lower energy requirements for CO_2 separation from flue gas. Efficiency, which comes from reducing the seemingly inherent tradeoff between CO_2 absorption rate and the energy required to regenerate the CO_2-rich solvent.

The company's advanced CO_2 capture processes are suitable for post-combustion carbon capture from coal- and gas-fired power plants, and are also suitable for pre-combustion CO_2 capture applications such as natural gas treating (i.e., CO_2 removal from natural gas prior to pipeline transportation).[36]

C.1.4 Sustainable Energy Solutions

Sustainable Energy Solutions (SES) was founded in 2008 in response to a growing need for solutions to sustainability problems within the energy industry. SES is primarily focused on the development and commercialization of Cryogenic Carbon Capture, a patented carbon capture technology developed in 2008. Since its founding, SES has filed several additional patents on multiple technologies to help realize SES' mission: Create practical solutions to help solve energy problems on a regional and global scale.

Cryogenic Carbon Capture™ (CCC) is designed to separate a nearly pure stream of CO_2 from power plant gases. This technology adds a process to the plant after the normal energy production and there separates the CO_2 from the other gases. In conservative estimates Cryogenic Carbon Capture technology provides a significantly more cost effective and practical solution to carbon capture in today's market. CCC can be used on any stationary source of CO_2 such as cement plants, refineries, etc. The technology is currently at 1 ton CO_2/day with plans for 2 tons/hour proposed and under review.[37]

C.1.5 SRI International

SRI International is an independent, not-for-profit research institute conducting client-sponsored research and development for government, industry, foundations, and other organizations. Founded in 1946 in conjunction with Stanford University, SRI's annual combined revenues now exceed $500 million. SRI's work spans research, development, and deployment and brings R&D

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[35] http://akermin.com/

[36] http://ion-engineering.com/

[37] http://sustainablees.com/index.html

innovations to the marketplace by licensing intellectual property, creating new ventures, and providing products and services.

SRI is currently working on a number of different CO_2 capture methods, including sorbent, chilled ammonia and polybenzimidazole (PBI) membrane.

The most advanced of SRI's carbon capture technologies is the AB-ABC™ process, which is being developed for pre-combustion capture in IGCC applications. The process is base on absorption on a high-capacity and low-cost aqueous ammoniated solution with high-pressure absorber and desorber. Advantages of the technology are expected to include the use of a low cost, chemically stable and readily available reagent (aqueous ammonia), high CO_2 capture efficiency and low heat consumption for CO_2 stripping. It can be applied as a retrofit or as part of a new build. The technology is currently undergoing pilot-scale continuous tests.[38]

C.1.6 Inventys

The carbon capture process involves separating and purifying CO_2 from the emission gas streams that typically contain a large amount of nitrogen (N_2), a safe non-greenhouse gas. This process is a new technical challenge that can represent 60-80% of the cost of CCS using existing technical solutions. Today, the cost of CCS using proven methods ranges from US$60 – $200 per tonne, which translates into more than a 50% increase in the cost of generating electricity or producing industrial products. The high cost of carbon capture is the key barrier to widespread implementation of CCS.

The VeloxoTherm™ process has the potential to reduce the cost of carbon capture to a manageable level of US$15 per tonne, enabling worldwide adoption of CCS. Other key attributes to the VeloxoTherm™ process include source flexibility, and a small footprint. The process can capture carbon from a wide range of small to large sources, varying industrial emission streams, and from sources with space constraints such as oil refineries.[39]

C.2 Pre-combustion technologies

C.2.1 RTI

RTI is developing innovative solutions for capturing CO_2 from power plants, petrochemical plants, cement plants, and other industrial sources of CO_2. Its primary focus is improving upon the cost and energy demands of conventional CO_2 capture. It has built a comprehensive portfolio of technology approaches based on solvents, membranes, solid sorbents, and hybrid systems and it leverages strong expertise in process modeling and economic analysis to optimize integration of our technologies to specific applications. It is also investigating the beneficial use of CO_2 — developing technologies that produce fuels or chemicals from CO_2.[40]

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[38] http://www.sri.com/

[39] http://www.inventysinc.

[40] http://www.rti.org/page.cfm/Carbon_Capture_and_Utilization

C.2.2 Air Products

With its core strengths as a leading industrial gases and materials company and a culture of product innovation, Air Products is a global leader of technical options for capturing CO_2 from fossil fuel conversion before it reaches the atmosphere—key to Carbon Capture and Sequestration (CCS) for greenhouse gas mitigation.

Its view spans natural gas reforming, gasification, and oxyfuel coal combustion and is formed by experience in existing operations that involve capture of CO_2 from natural gas reforming, management of syngas from gasification, and oxyfuel combustion in markets such as steel and glass. Air Products' technology in development offers lower cost of capturing CO_2 and builds on more than 70 years' experience implementing advanced separation technology.[41]

C.2.3 CanmetENERGY

CanmetENERGY is developing a steam generation technology called the High Pressure Oxy-fired Direct Contact Steam Generator (HiPrOx/DCSG, or DCSG for short) intended for use in the oil sands in situ extraction market, that aims to sequester CO_2 using less energy and water than the current SAGD process, at lower cost. The DCSG process has the potential to produce 90% steam with the balance primarily being CO_2, with very low levels of impurities. Early research shows the potential for 85% CO_2 capture at the in situ well site.

At Canmet's Ottawa facility, pilot scale testing has been completed at 15 bar pressure with various test fuels (butanol and graphite) with preparations being made currently for natural gas firing with produced water and produced oily water. The future intention will be to scale up to 100 bar in 2014 and to test the use of natural gas and petroleum coke with the various waste water streams. There is the possibility of field demonstration in 2-3 years.

C.2.4 HTC Purenergy

HTC CO_2 Systems offers the following group of products to compliment gas processing and other industrial process design initiatives:

Gas Purification Systems

Delivering complete absorption/adsorption systems for removal of vapor-phase impurities from industrial gas streams. These absorption systems include but not limited to:

- Post-combustion CO_2 Capture units using reactive solutions
- Acid gas absorption units using physical and/or reactive solutions
- Dehydration units using solutions and/or sorbents
- Solvents for Gas Purification Processes (RS™ family of Solvents)[42]

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[41] http://www.airproducts.com/microsite/carbon_capture/index.asp

[42] http://www.htcenergy.com/co2CaptureBusiness/products.htm

C.3 Oxy-fired and chemical looping technologies

C.3.1 Jupiter Oxygen

Jupiter Oxygen Corporation (JOC) is an Illinois-based energy technology company, which has pioneered and patented a high-flame temperature oxy-combustion process. Jupiter has demonstrated that its process results in significantly more efficient, economical boiler operation, in addition to meeting stringent environmental requirements.

Since 2007, Jupiter Oxygen has operated a 15 MWth oxy-fuel test boiler at its research center in Hammond, Indiana. The testing at the unit was supported through federal funding and conducted jointly with the DOE's National Energy Technology Laboratory (NETL), which tested its Integrated Pollutant Removal (IPR) process at the facility. Over six years of testing, JOC's process and the IPR showed robust adaptability with different fuels and a range of operating conditions.

Originally developed for large industrial melting furnaces, Jupiter expects this technology to be capable of serving a number of industries including fossil fuel steam boilers and electric power plant applications. JOC's primary market is to target older coal-fired boilers located near enhanced oil recovery (EOR) sites for conversion to JOC's process because the CO_2 can be economically captured and used to recover oil from depleted oil wells.[43]

C.3.2 Alstom Power

With fossil fuels set to account for 60% of electricity production by 2030, attention is focused on two main categories of carbon capture and storage (CCS):

- Oxy combustion
- Post combustion capture

Its strategy has been developed through our belief that these technologies are not only the most economically viable and sustainable solutions for its customers, but also because they can be retrofitted to an existing installed base. This is essential for meeting future emission targets. It is continuing significant R&D efforts in CCS and are validating the technologies at a number of pilot and demonstration projects around the world. It is working closely with our partners towards full-scale commercialization that will be available on the market around 2017.

As it further validates CCS solutions, it is offsetting risk of stranded assets by offering customers a 'CCS ready' plant concept. This takes into account the needs of customers who purchase plants today, ensuring they are not penalized financially when the technology becomes available – in essence, future proofing their commitment.[44]

C.3.3 Cenovus Energy

With the help of the CCEMC, Cenovus Energy's chemical looping steam generator will be the world's first and largest field pilot that uses chemical looping combustion (CLC) technology to

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[43] http://jupiteroxygen.com/

[44] http://www.alstom.com/power/coal-oil/carbon-capture-solutions/

generate steam in the oil sands. CLC is considered energy efficient because one of the flue's exit gases can be released with minimal CO_2, but it is also considered a carbon capture technique because almost all of the CO_2 generated by the system is contained in the other flue.

This project will lower the cost of capture when compared to a conventional steam generator with post-combustion carbon capture.

The goal of this project is to prove that chemical looping technology is a commercial option for steam generation in the oil sands. If the pilot is successful, Cenovus anticipates this technology could be further deployed in Alberta and result in significant emission reductions of approximately 1 megatonne of CO_2 equivalent over 10 years[45]

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[45] http://ccemc.ca/project/looping-steam-generator-10-mw-pilot/

Appendix D. CCS background

D.1 CCS as a carbon mitigation strategy and potential wedge

As part of the research conducted by Pacala and Socolow, fifteen existing carbon mitigation strategies/technologies, or wedges, were outlined to reduce global carbon emissions. Each wedge represents reductions of 1 billion tons per year by 2060. These wedges include energy technologies that emit little to no carbon, such as wind and solar energy, energy efficiency for residential and commercial operations, and developing capacity for carbon capture and storage (CCS).[46,47] Among the fifteen wedges that the researchers mapped out, three looked to CCS to capture CO_2. Those three include capture at existing, and future, plants generating baseload power, and capture during hydrogen and/or coal-to-synfuel production.[48]

In 2011, the analysis was updated, reaffirming and intensifying the original message that available-today technologies, particularly broadly applied carbon capture and storage, have the capacity to reverse emissions growth. However, in the update, the emphasis was placed on the fact that pace towards implementing such mitigation strategies needed to be accelerated in order to appropriately mitigate climate change.[49]

D.2 Why CCS?

Some key reasons why CCS is a viable carbon mitigation tool to stave off climate change are:

Broad applicability: CCS can be applied to any large industrial source of carbon dioxide, such as cement, steel, electricity, oil and gas production and chemical industries.

Scale of GHG reductions: CCS allows for the potential to continue using fossil fuels while also substantially reducing emissions of GHGs to the atmosphere. Applied to a modern conventional power plant, CCS could reduce CO_2 emissions released to the atmosphere by approximately 80 to 90% compared to a plant without CCS.[50] It is important to note that CCS is part of a portfolio approach that must be taken towards carbon mitigation. Other efforts, such as renewables or

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[46] S. Pacala and R. Socolow, "Stabilization Wedges: Solving the Climate Problem for the Next 50 Years with Current Technologies", *Science* 305 (2004).

[47] Princeton University, "Stabilization Wedges Introduction", *Carbon Management Initiative*, July 27, 2011. http://cmi.princeton.edu/wedges/intro.php

[48] Adam Aston, "Wedges reaffirmed: Robert Socolow updates his 'wedges' analysis of emissions reductions", *Global CCS Institute*, October 17, 2011. http://www.globalccsinstitute.com/insights/authors/adamaston/2011/10/17/wedges-reaffirmed-robert-socolow-updates-his-wedges-ana

[49] Ibid.

[50] B. Metz, O. Davidson, H. C. de Coninck, M. Loos, and L.A. Meyer, *Carbon Dioxide Capture and Storage*, IPCC special report (Cambridge University Press, 2005), 442.

energy efficiency, will also play an important role in moving the world towards a low carbon economy.[51]

Economic development opportunities: Countries that develop CCS early will benefit from the export of skills and technology internationally. The large contribution that CCS could make to global emissions reductions would result in the development of a new industrial sector potentially worth trillions of dollars.[52] The IPCC estimates that the economic potential of CCS could be between 10% and 55% of the total carbon mitigation effort until the year 2100.[53]

D.3 What is CCS?

CCS is a technology that can capture up to 90% of the CO_2 emissions produced from the use of fossil fuels in electricity generation and industrial processes, preventing the carbon dioxide from entering the atmosphere.[54]

The CCS chain consists of three parts: capture, transport and storage.[55]

Capture: CO_2 separation and extraction from gases produced in electricity generation and industrial processes by one of three methods: pre-combustion capture, post-combustion capture and oxyfuel combustion.

Transport: Extracted CO_2 is transported by pipeline or by ship for safe storage. Millions of tonnes of CO_2 are already transported annually for commercial purposes by road, ship and pipelines.

Storage: Transported CO_2 is injected and stored in selected geological rock formations, typically located several kilometres below the earth's surface.

D.4 CCS implementation challenges

As with any emerging technology, CCS implementation faces barriers and issues. The following CCS challenges could be pointed to as some reasons why progress towards large-scale, international implementation is constrained.

Energy penalty: Capturing and compressing CO_2 may increase the fuel needs of a coal-fired CCS plant by 25 to 40%.These and other system costs are estimated to increase the cost of the energy produced by 21 to 91% for purpose-built plants.[56]

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[51] Carbon Capture and Storage Association. "Why CCS?: Tackling Climate Change". http://www.ccsassociation.org/why-ccs/tackling-climate-change/

[52] American Energy Administration, *Future Value of Coal Carbon Abatement Technologies to UK Industry*, Report to the Department of Energy and Climate Change (2008); Carbon Capture and Storage Association, "Why CCS?: Economic Importance". http://www.ccsassociation.org/why-ccs/economic-importance/

[53] Metz et al., *Carbon Dioxide Capture and Storage*, 442.

[54] Carbon Capture and Storage Association. "What is CCS?". http://www.ccsassociation.org/what-is-ccs/

[55] Ibid.

[56] Ibid.

Capital costs: Applying the technology to existing plants would be expensive, especially if they are far from a sequestration site. However, recent industry reports suggest that with successful research, development and deployment (RD&D), sequestered coal-based electricity generation in 2030 may be cost competitive with un-sequestered (low cost) coal-based electricity generation today.[57]

Leakage and permanence of storage schemes: A major concern with CCS surrounds leakage of stored CO_2. Risk of leaks are comparable to those associated with current hydrocarbon activity, for well-selected, designed and managed geological storage sites, but sites must be managed as such and monitored over the long term to address any issues.[58]

Uncertainty: Critics say large-scale CCS deployment is unproven and decades away from being commercialized due to the risk and expense of CCS. They worry that money and time spent on CCS may divert investment from other viable solutions for climate change, such as renewable energy. Some environmental groups point out that CCS technology leaves behind dangerous waste material that has to be stored, just like nuclear power stations.[59]

D.5 International

Carbon capture and storage (CCS) is recognized as a key technology in reducing greenhouse gas emissions that have been in operation around the world for several decades. Globally, over 50 Mt of carbon dioxide have been stored to date.[60] Below are geography and site-based snapshots of how CCS is progressing in a number of countries and why it remains a vital part of the portfolio of low-energy technologies.

As of 2013, there are 13 large-scale CCS demonstration projects in operation or in progress[61] (see Figure 23). Although CCS is happening now and continuing to grow, with dozens of large-scale integrated projects either in operation or underway, the pace is still too slow to realize a 2ºC scenario.[62]

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[57] Coal Utilization Research Council (CURC) and Electric Power Research Institute (EPRI), *The CURC / EPRI Technology Roadmap* (2012). http://www.coal.org/userfiles/file/FINAL Roadmap Report Update - August 2012 (graphics and links).pdf

[58] IPCC, *Carbon Dioxide Capture and Storage: Technical Summary,* IPCC Special Report (2005).

[59] Robinson, Simon. “Cutting Carbon: Should We Capture and Store It?”, *Time*, January 22, 2012.

[60] International Energy Agency, IEA Tracking Clean Energy Progress 2013 Report” (2013), 56. http://www.iea.org/publications/TCEP_web.pdf

[61] Global CCS Institute, “Status of CCS”. http://www.globalccsinstitute.com/key-topics/status-ccs (accessed on July 19, 2013)

[62] International Energy Agency, *Tracking Clean Energy Progress 2013*, 56. http://www.iea.org/publications/TCEP_web.pdf

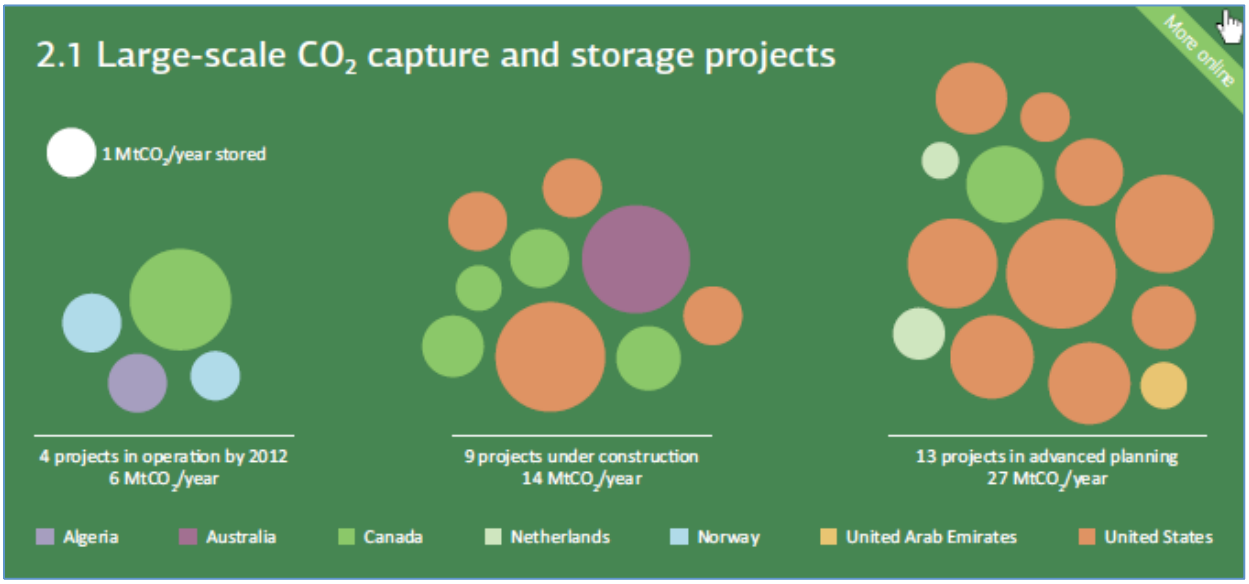

Figure 23: Large-scale CCS projects

Source: IEA[63]

However, there are several other smaller scale and scheduled projects that make for a large landscape of CCS activity across the globe (see Figure 24) in varying states of progress or scale. CCS projects have been categorized globally in one of four ways:

- **Power Plant (**Figure 24*, in Yellow):* These are large-scale, over 60 MW, CCS projects from which the CO_2 is sourced from power plants. There are 24 power plant project globally.
- **Pilot** (Figure 24*, in Blue):* Smaller scale ranging from 1 MW to 50 MW. There are 18 pilots globally.
- **Non-Power** (Figure 24*, in Green):* All other CCS projects from which the CO_2 is not sourced from power plants. This includes industrial and natural sources. There are 26 non-power projects globally.
- **Cancelled or Dormant** (Figure 24*, in White):* These projects have either ceased operation or construction. There are 29 projects that have been cancelled or are inactive globally.

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[63] Ibid.

Figure 24: Global CCS Locations

Source: MIT[64]

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[64] MIT, "Carbon Capture and Sequestration Projects Database: Map of CCS Projects Worldwide", *Carbon Capture and Sequestration Technologies at MIT* (2011). http://sequestration.mit.edu/tools/projects/ccs_map.html

Country	Status
China	**Growing interest, large potential** • Eleven large scale projects planned; Four in final stages of planning / building • One-third are pre-combustion, two-thirds oxyfuel • Mostly focused on enhanced oil recovery (EOR) and power generation related CO2 capture • Capture range: 1 – 3 Mtpa
Norway	**Punching above their weight class** • Four large scale projects (two active) • Mix of pre and post-combustion • Focused on capture for saline storage and natural gas / power generation emissions • Capture range: 0.7 – 1.6 Mtpa
Australia	**Serious action** • Four large scale projects (one active) • Mix of pre and post-combustion • Mostly focused on EOR storage; some industrial source capture diversity (natural gas, fertilizer, power generation) • Capture range: 0.1 – 4.1 Mtpa
USA	**A lot of action, but struggling to maintain momentum** • Twenty-three planned large scale projects • Mix of pre and post combustion, and oxyfuel • Mostly focused on EOR storage; largest industrial source capture diversity (natural gas, fertilizer, Syngas, hydrogen, chemical, power generation) • Capture range: 0.1 – 8.5 Mtpa (13 projects > 2.5 Mtpa)

Figure 25: State of CCS in key global markets (Mtpa = metric tons per annum)

Key markets for CCS around the globe include the USA, Norway, China and Australia. Although each has very different states of progress (see Figure 25) towards regional and internationally partnered CCS projects, they make up a significant share of CCS capacity based on 2018 projections. These key markets are anticipated to make up over 85% of global storage capacity. Past projects in the North American, Norwegian and North African (Algerian) market have safely stored millions of tonnes of CO_2 underground for years [65] (see Figure 26).

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[65] Government of Alberta, "Carbon Capture and Storage", *Alberta's Oil sands.* http://oilsands.alberta.ca/ccs.html

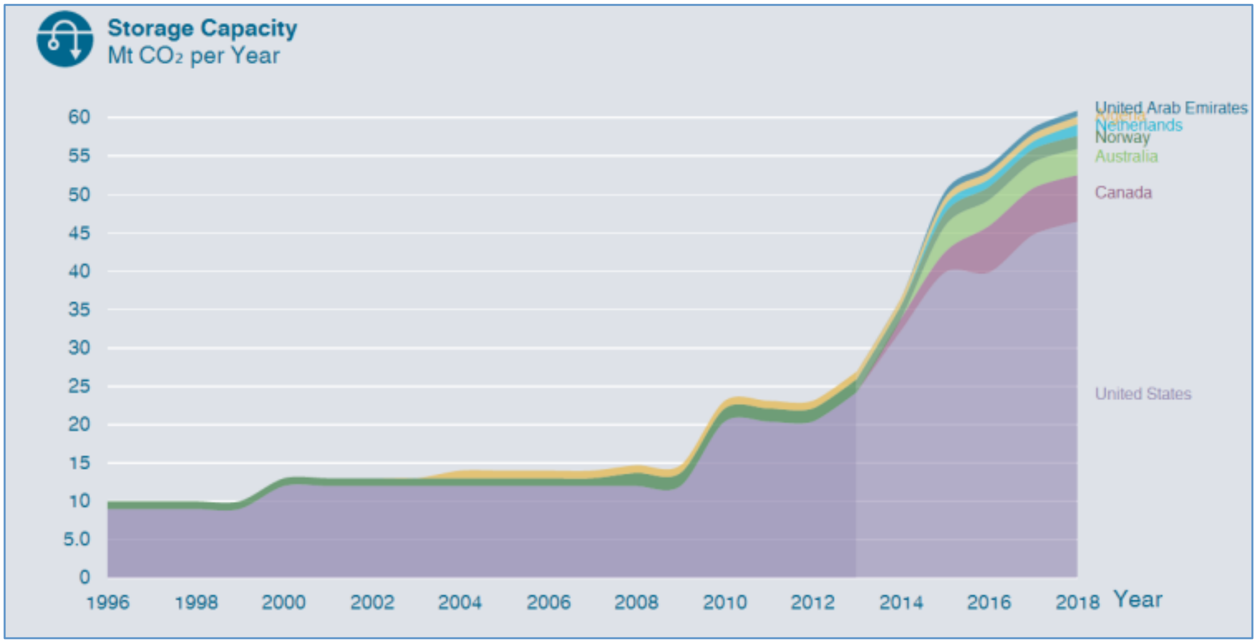

Figure 26: Global storage capacity by country, 1996 - 2018

Source: IEA[66]

Growth of CCS activity globally is also demonstrated through increasing RD&D, Patenting and Capital Spending and Investment activity (see Figure 27, Figure 28 and Figure 29, respectively). For example, CCS related patent applications have increased over four times since 2005 (see Figure 29), with public R&D spending seeing five times growth in the same time frame (see Figure 28).

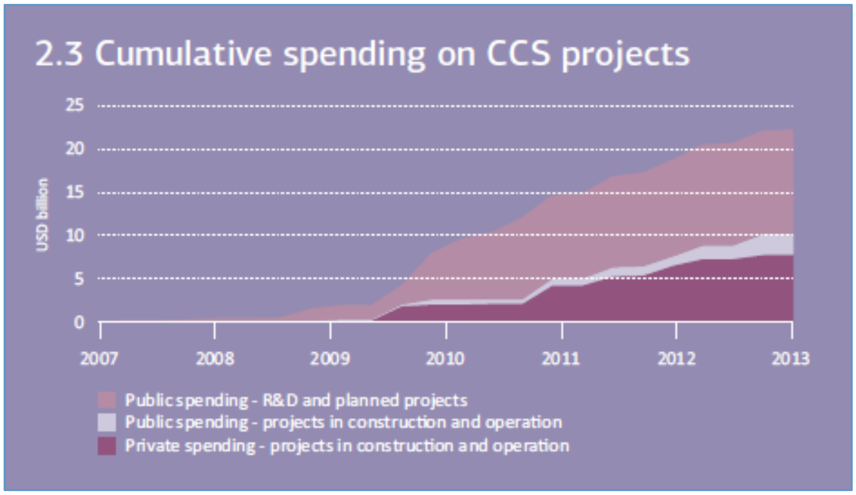

Figure 27: Cumulative spending on CCS projects by IEA member governments

Source: IEA[67]

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[66] International Energy Agency, "CO2 Capture Capacity: Countries", Interactive Visualizations as part of IEA Tracking Clean Energy Progress 2013 Report (2013). http://www.iea.org/etp/tracking/ccs/index.html

[67] IEA, *Tracking Clean Energy Progress 2013*, 57.

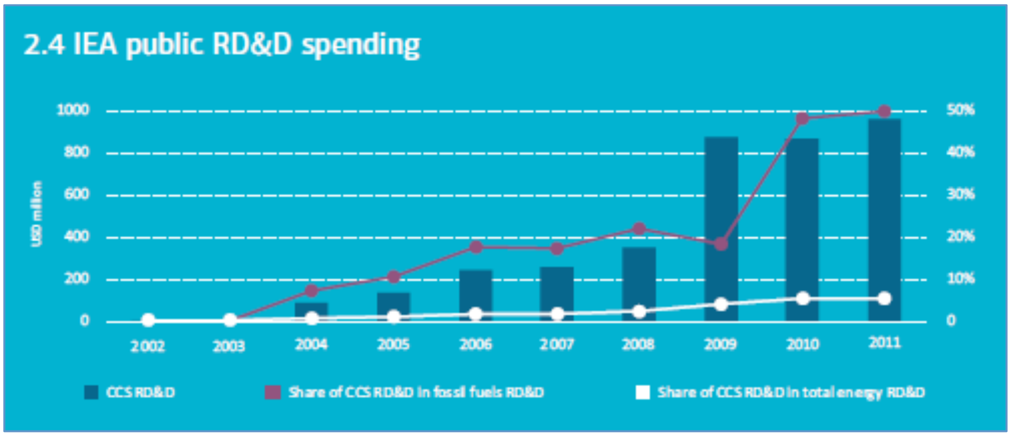

Figure 28: Public RD&D spending by IEA member governments

Source: IEA[68]

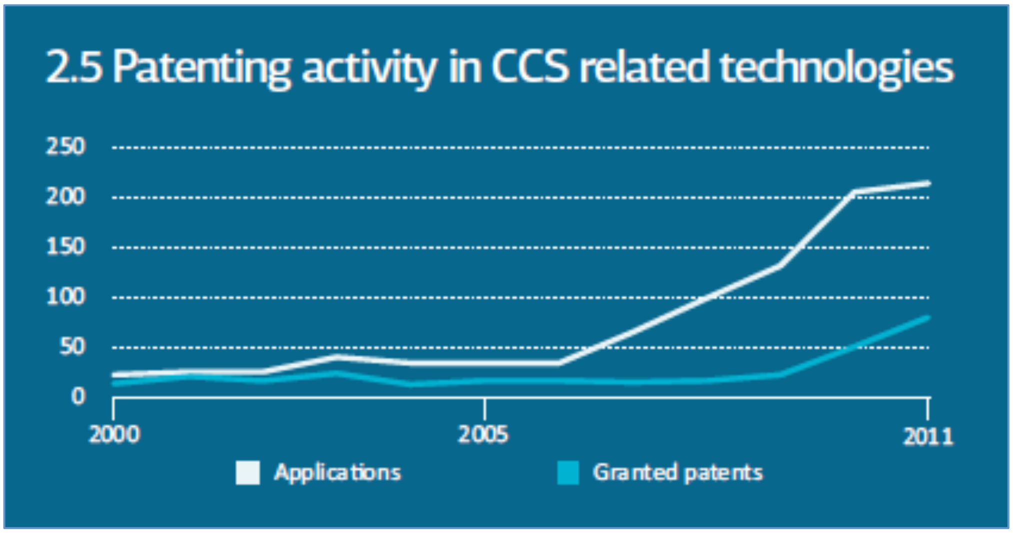

Figure 29: Patenting activity in CCS related technologies

Source: IEA[69]

D.6 Canada

With over two billion Canadian dollars allocated for the development of CCS, one of the world's largest operating CCS projects, and a demonstrated focus and commitment to CCS as part of reducing GHG emissions, Canada is a key market for this technology.[70] In regards to capacity, the North American Carbon Storage Atlas Project[71], a joint venture among Canada, Mexico and the US, estimates there is nearly 132 Gt of potential CO_2 storage in Canada, the majority of

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[68] Ibid.

[69] Ibid.

[70] Global CCS Institute, "Country Snapshots: CCS in Canada". http://www.globalccsinstitute.com/location/canada ,

[71] http://www.nacsap.org/

which (110 Gt) is in saline formations, with 90% of capacity situated in Alberta and Saskatchewan.[72]

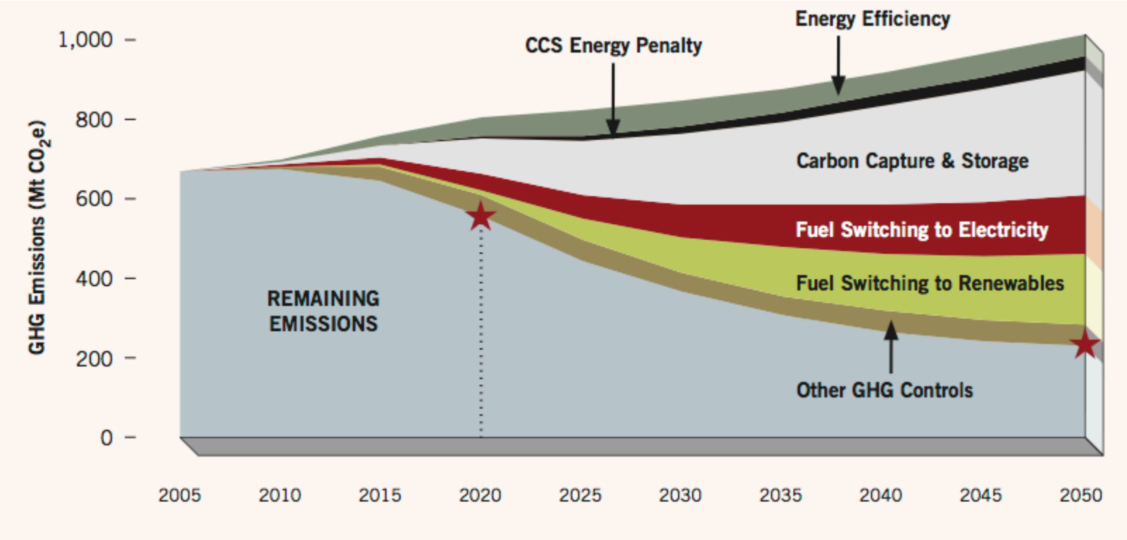

Figure 30: GHG reduction approach for Canada: aggregate wedges

Source: National Roundtable on Environment and Economy[73]

CCS represents one of the largest tools for Canada to meet its domestic GHG targets (see Figure 30). CCS also allows for Canada's domestic energy industry to continue to produce energy and generate economic gains for the country.[74]

Specifically, based on Canada's CCS Technology Road map, the importance of CCS is three fold[75]:

- Canada's climate change plan concludes that CCS is one of the technologies that could help the country to meet its emissions goals.
- Fossil fuels are of national importance to the country. To make a full break from fossil fuels would require enormous government subsidies to drive the market, which Canada feels is unlikely to work in the long run.
- By using captured CO_2 Canada could increase its current reserves through EOR. Canada is also geologically well situated to store what is not needed for EOR.

Alberta, the province with the greatest fossil fuel reserves and strongest tie between energy production and its economic wellbeing, is a province with particular interest in CCS technologies, and thus has set up funding and regulation to assume, monitor and manage potential risks for CCS technology development. In November 2010, the Alberta Government released The Carbon Capture and Storage Statutes Amendment Act, 2010 (Bill 24) which guides

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[72] Global CCS Institute, "Country Snapshots: CCS in Canada".

[73] National Roundtable on the Environment and Economy, *Achieving 2050: A Carbon Pricing Policy for Canada* (2009), 83. Available at http://neia.org/wp-content/uploads/2013/04/carbon-pricing-advisory-note-eng.pdf

[74] ICO2N, "CCS in Canada: An Overview". http://www.ico2n.com/ccs-in-canada (accessed on July 22, 2013)

[75] MIT, "Canada CCS Financing Overview", *Carbon Capture and Sequestration Technologies at MIT* (2011). http://sequestration.mit.edu/tools/projects/canada_ccs_background.html

how large-scale CCS projects will continue. Bill 24 stipulates that the Alberta government would accept long-term liability for injected carbon dioxide once the operator provides data showing that the stored CO_2 is contained. It would also establish a fund financed by CCS operators for ongoing monitoring costs and any required remediation. .[76]

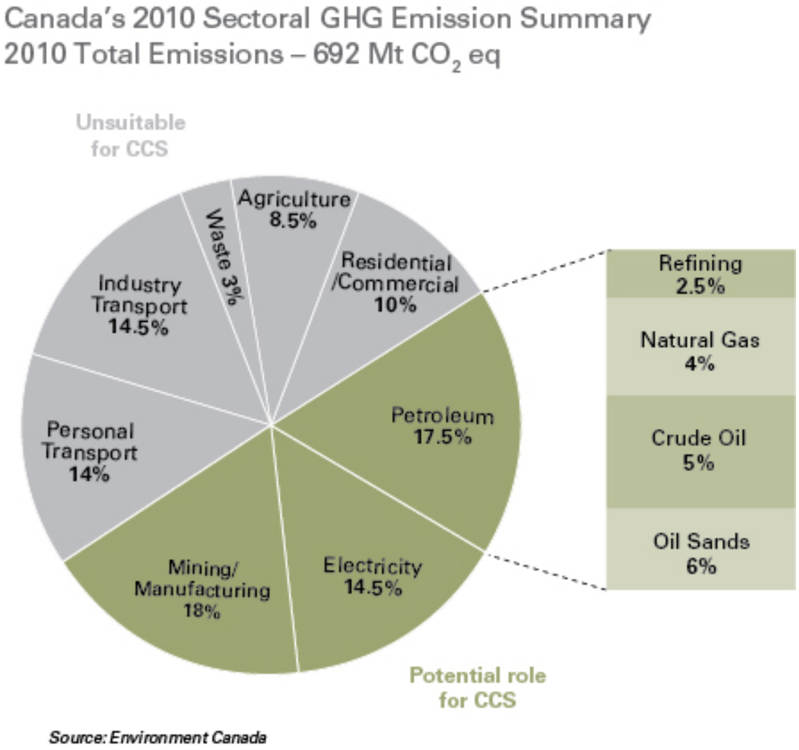

Figure 31: Canadian GHG emission summary by sector, 2010

Source: ICO2N[77]

Canada has a unique emissions source profile that CO_2 capture and storage technology can address (see Figure 31). This ranges from individual to industry sources. However, the greatest industry potential lies with electricity, oil sands and other heavy industry (e.g., fertilizer and chemical industries, and cement manufacturing) equaling over 38% of Canada's total emissions profile.

Electricity and oil sands CO_2 reduction, in addition to assisting with meeting Canada's GHG commitments, is also sought after to: 1) Reduce the environmental impact of oil sands resources so they can continue to create jobs and wealth; and, 2) Help establish a secure electricity supply by enabling the clean use of Canada's abundant coal resources.[78]

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[76] Global CCS Institute, "Country Snapshots: CCS in Canada".

[77] ICO2N, "Industry's Potential". http://www.ico2n.com/ccs-in-canada/industry-potential

[78] ICO2N, "CCS in Canada: An Overview". http://www.ico2n.com/ccs-in-canada

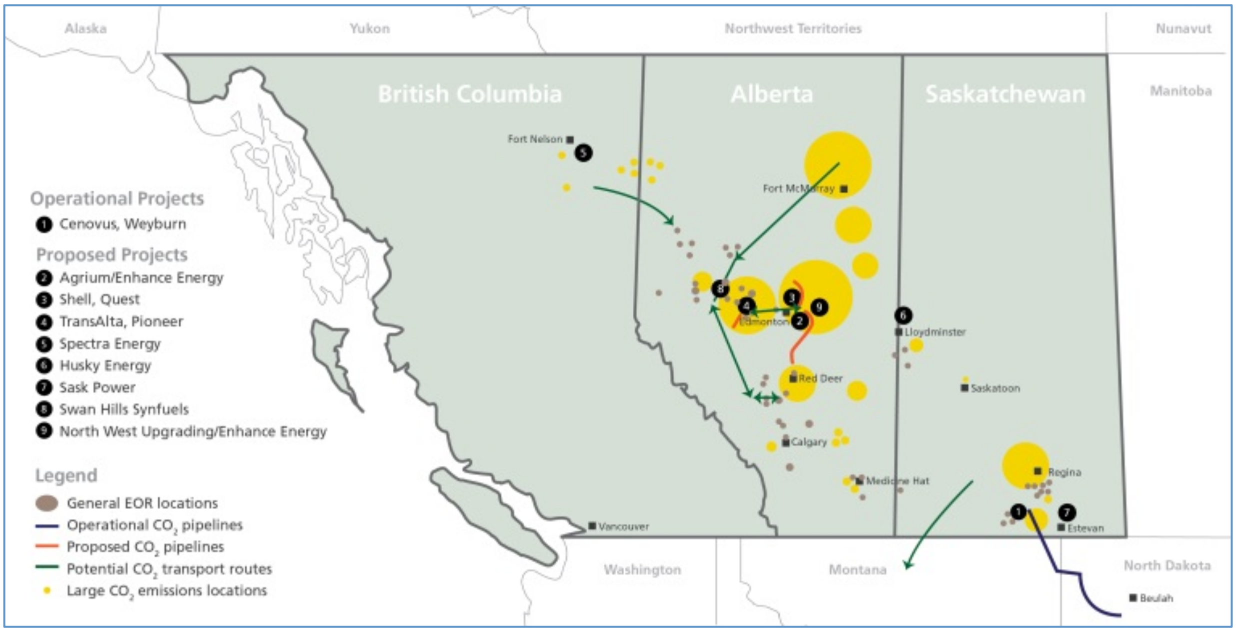

Figure 32: Canadian industry-led CCS projects

Source: ICO2N[79]

Although led by industry in regards to technology development and CCS deployment (see Figure 32), as mentioned previously, government is a significant funding source for CCS activities. The following table notes examples of different government funding sources and beneficiary projects.

Table 8: Government funding sources and CCS projects

Fund Source	Description	Beneficiary Projects
ecoENERGY Fund	Canadian government investing $140 of the $230 million in the ecoENERGY Technology Initiative on projects to advance CCS technologies Several CCS demonstration projects have been selected to receive funding	Heartland Area Redwater Project (HARP) Alberta Carbon Trunk Line Fort Nelson TransAlta Pioneer Project (Cancelled) Husky Energy CO_2 Injection in Heavy Oil Reservoirs
Clean Energy Fund Program	Providing approximately $795 million over five years to support research, development and demonstration projects to advance Canadian leadership in clean energy technologies. Three carbon capture and storage projects were announced in Alberta in 2009, receiving a combined $466 million.	Quest Project TransAlta Pioneer Project (Cancelled) Alberta Carbon Trunk Line

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[79] ICO2N, "Vision for Western Canada: Western Canada's CCS Potential". http://www.ico2n.com/ccs-in-canada/canadas-ccs-story/vision-for-western-canada

Government of Alberta	From a $2 billion CCS fund, funding has been awarded and letters of intent signed with the project recipients.	Alberta Carbon Trunk Line Quest Project Swan Hills (Suspended) TransAlta Pioneer Project (Cancelled)
Government of Saskatchewan	Approved a $1.24 billion project (backed with $240 million from the federal government) to rebuilding an aging unit with post-combustion carbon capture	Boundary Dam Power Station

Data source: MIT[80]

On the whole, Canada is home to seven large-scale CCS projects in different phases of development (see Figure 33):

- **Planning:** Boundary Dam Integrated CCS Demonstration project (Saskatchewan); Bow City Power Project (Alberta)
- **Construction:** Shell Quest (Alberta), Spectra Fort Nelson CCS Project (British Columbia), Great Plains Synfuel Plant (Saskatchewan), Alberta Carbon Trunk Line with Agrium CO_2 Stream and North West Sturgeon Refinery CO_2 stream (Alberta)
- **Operational:** Weyburn-Midale EOR project (Saskatchewan) — the largest of its kind.

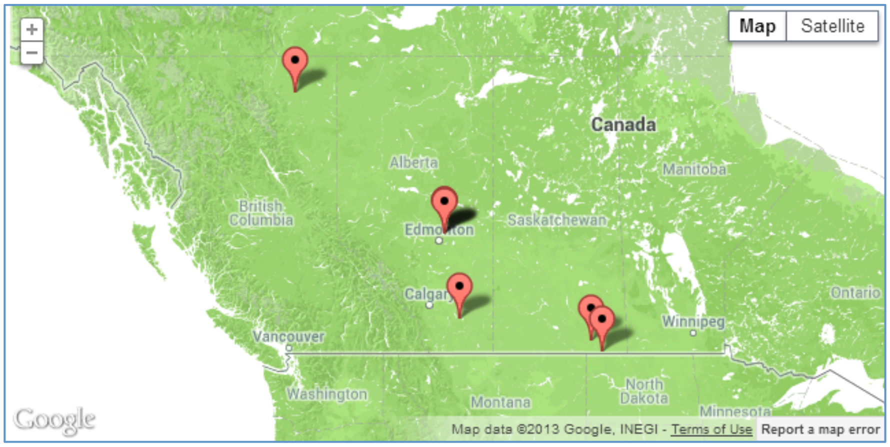

Figure 33: Large scale integrated CCS projects

Source: Global CCS Institute[81]

It is important to note that Canada's CCS focus is not limited to domestic-only activity. The Canadian government is also working closely with other nations through dialogue to establish joint carbon capture and storage opportunities. This includes work with the United States government on a North American Clean Energy Dialogue. Much of Canada's international work is facilitated through the Global CCS Institute.

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[80] MIT, "Canada CCS Financing Overview", Carbon Capture and Sequestration Technologies at MIT (2011).

[81] Global CCS Institute, "Large Scale Integrated CCS Projects: Canada" (2013). http://www.globalccsinstitute.com/projects/browse

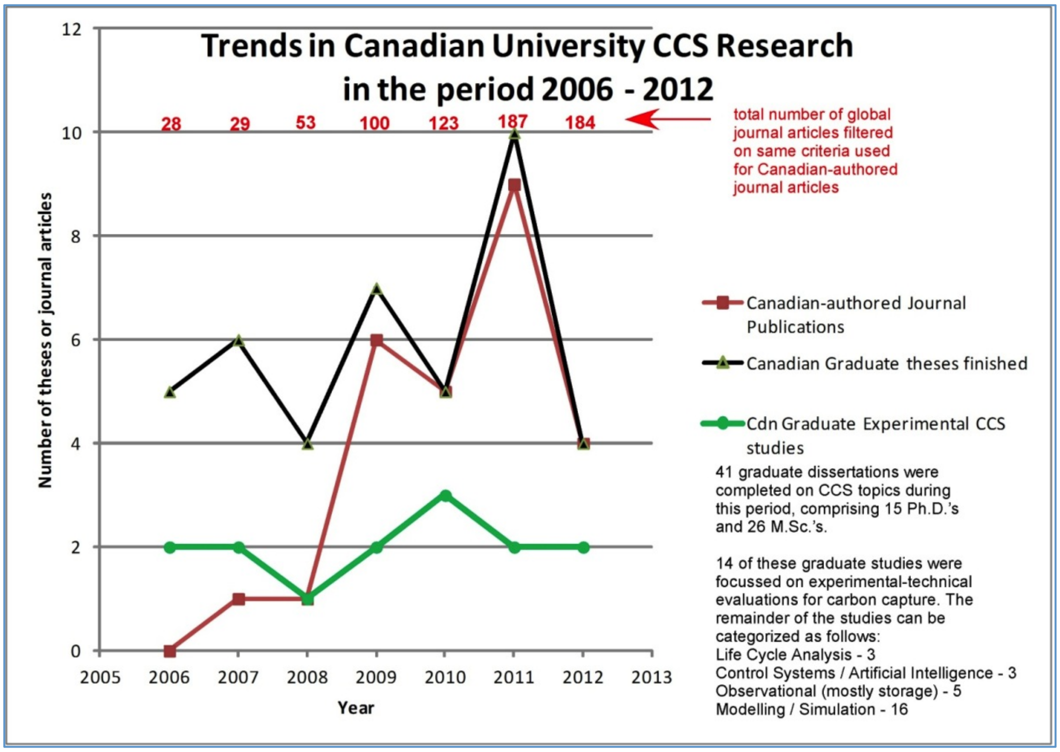

Figure 34: Canadian university CCS research (2006 - 2012)

Source: ProQuest dissertation database[82]

Additionally, Canada has become a hub for research and expertise in regards to CCS. The number of published journal articles and graduate theses from Canadian universities spiked in 2011 (see Figure 34). Although most CCS technology deployment is concentrated in Alberta and Saskatchewan, research and CCS Centers of Expertise are spread across the country with focuses varying based on the competency and strengths of the respective university/research institution (see Figure 35).

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[82] Data obtained from ProQuest dissertation database: http://www.proquest.com/en-US/catalogs/databases/detail/pqdt.shtml

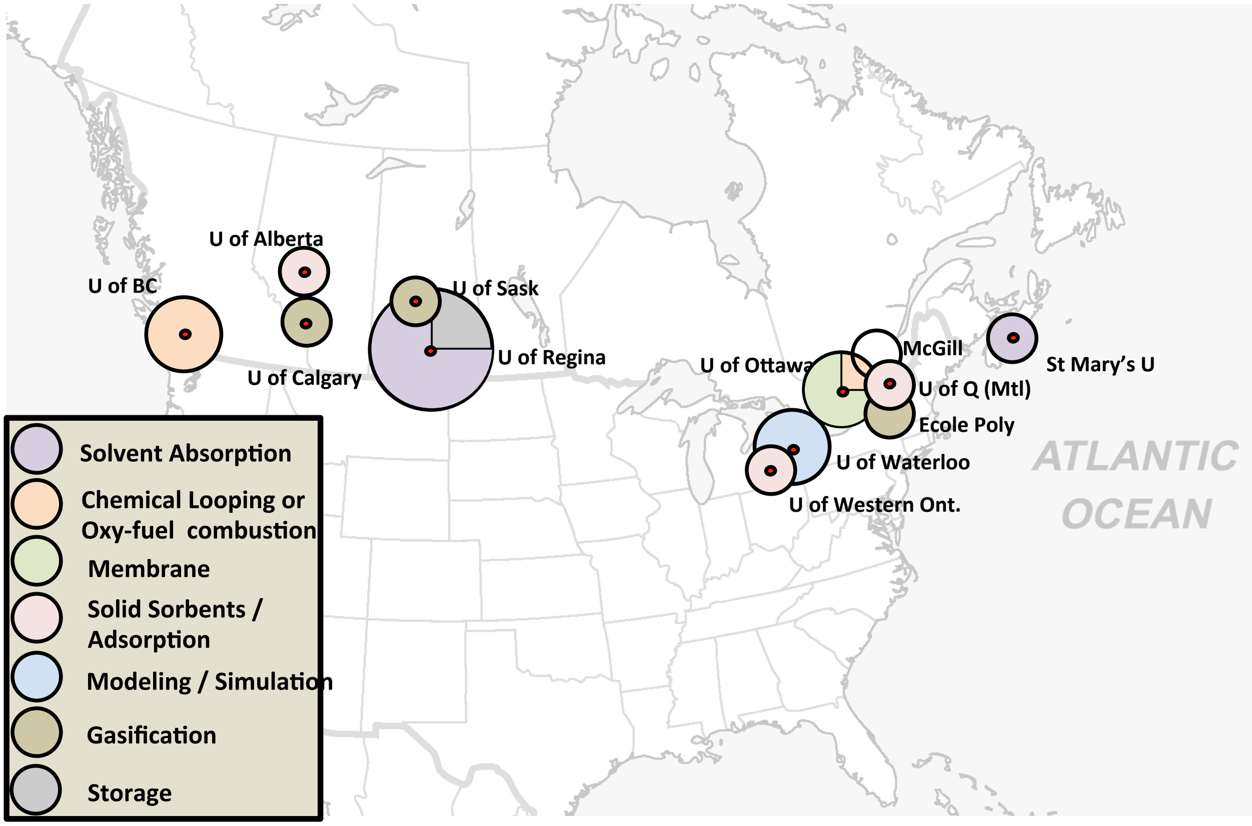

Figure 35: Canadian university centres of CCS research

Source: ProQuest dissertation database[83]

D.7 Oil sands

Although electricity / power production (e.g., coal-fired power plants) have the greatest industry potential for commercial scale CCS deployment in Canada, there is a growing focus on the oil sands as a site of CCS for two purposes: enhanced oil recovery and GHG reduction from oil sands sources.

Enhanced recovery

In Alberta, the province's oil and gas industry has been using CO_2 for EOR successfully for decades to produce oil from depleting reservoirs, extracting oil left in geologic reservoirs after exhaustion of primary and secondary oil production systems. EOR is a means to obtain more conventional oil — and the resulting royalties, taxes, economic growth and jobs — while using infrastructure already in place.[84] With the current value of CO_2 emissions alone insufficient to

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[83] Data obtained from ProQuest dissertation database: http://www.proquest.com/en-US/catalogs/databases/detail/pqdt.shtml

[84] Government of Alberta, "Carbon Capture and Storage", *Alberta* Oil sands. http://oilsands.alberta.ca/ccs.html

drive large-scale development and deployment of CCS, valuable uses for carbon dioxide such as EOR can help offset costs.[85]

EOR as it relates to CSS is tied to the use of CO_2 as a solvent, helping to reduce the viscosity of the oil in reservoirs and assist the oil to expand out of the porous rock in which it is often found. This is usually done in conjunction with flooding the reservoir to further increase efficiency of extraction. CO_2 use in EOR is also closely tied to CO_2 long-term storage. The oil reservoirs in which CO_2 was employed for EOR are also ideal trapping mechanisms for the storage of gases. The Weyburn-Midale CO_2-EOR operations in southeast Saskatchewan — the largest in the world— are good examples of this type of storage.[86] In Alberta, the Alberta Carbon Trunk Line is looking to pipe CO_2 for the purposes of EOR applications in the province, and assist in improving the economics and deployment of CCS technology.

Estimates show that 1.4 billion barrels of otherwise untapped oil could be produced from existing conventional reservoirs in Alberta with carbon capture and storage, generating between $11 billion and $25 billion in provincial royalties and taxes.[87]

GHG reduction

Over the next 25 years, oil sands production and its resulting CO_2 emissions are expected to grow as production increases, through not only currently operating projects, but new projects currently in the planning and construction phases (see Figure 36).

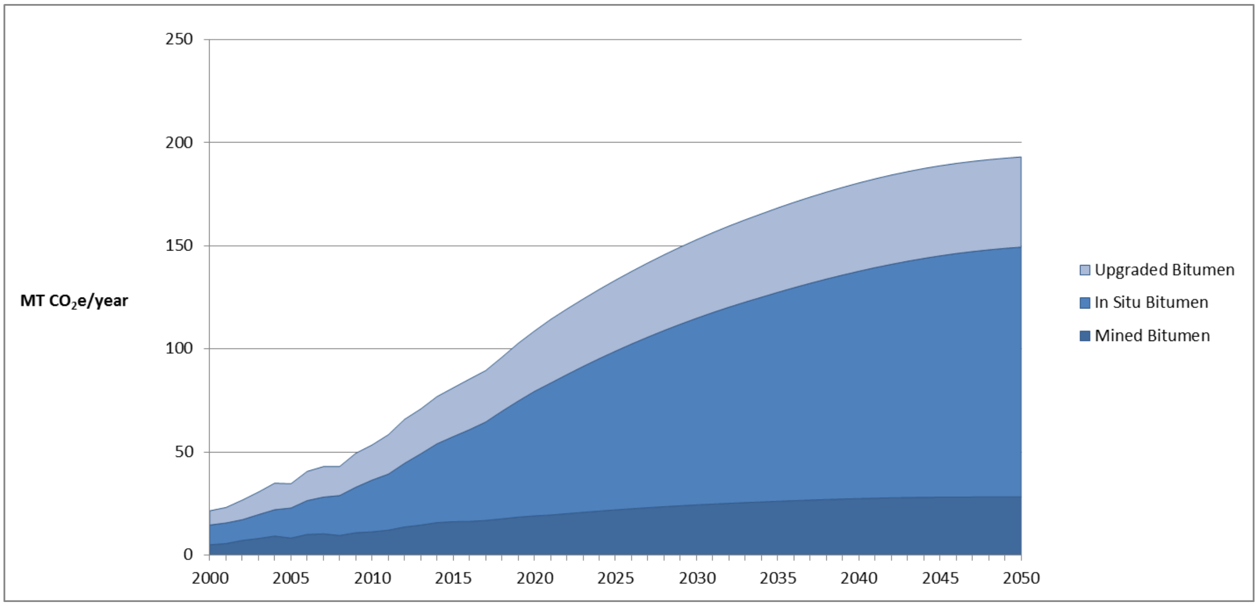

Figure 36: Projected oil sands production volume by sector to 2035, reference case

Data source: National Energy Board[88]

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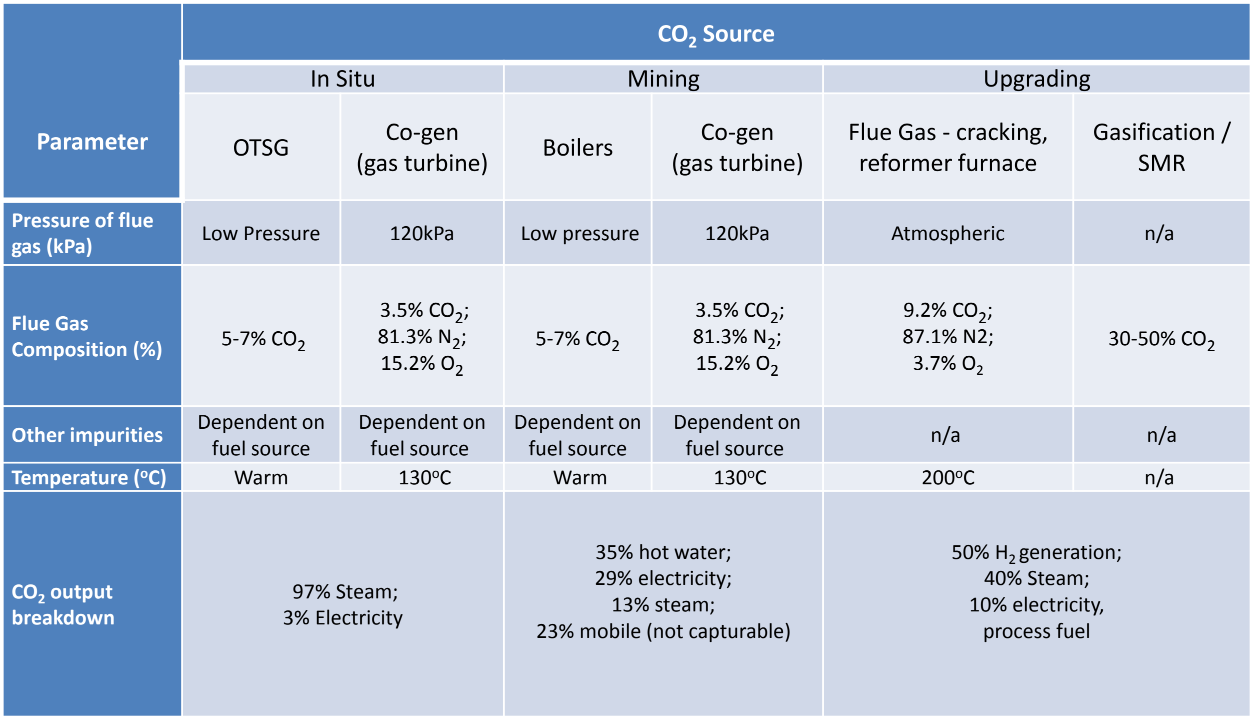
[85] International Energy Agency and Carbon Sequestration Leadership Forum, "IEA / CSLF Report to the Muskoka 2010 G8 Summit: Carbon Capture and Storage – Progress and Next Steps", (2010).

[86] The Carbon Capture and Storage Information Source, "Enhanced Oil Recovery", *CCS 101*. http://ccs101.ca/ccs_pro/what__how_of_ccs/co2_storage/enhanced_oil_recovery

[87] Government of Alberta, "Carbon Capture and Storage", *Alberta Oil sands*. http://oilsands.alberta.ca/ccs.html

The greatest source of carbon mitigation from oil sands production would come from first applying CCS to upgraders — the most concentrated source of CO_2. Upgraders process the bitumen produced from oil sands and convert it into synthetic crude oil.[89] One of the initial CCS projects currently under development in Canada, the Quest project, is focused on their upgraders. Figure 37 characterizes the various CO_2 streams from oil sands operations.



Parameter	CO_2 Source					
	In Situ		Mining		Upgrading	
	OTSG	Co-gen (gas turbine)	Boilers	Co-gen (gas turbine)	Flue Gas - cracking, reformer furnace	Gasification / SMR
Pressure of flue gas (kPa)	Low Pressure	120kPa	Low pressure	120kPa	Atmospheric	n/a
Flue Gas Composition (%)	5-7% CO_2	3.5% CO_2; 81.3% N_2; 15.2% O_2	5-7% CO_2	3.5% CO_2; 81.3% N_2; 15.2% O_2	9.2% CO_2; 87.1% N2; 3.7% O_2	30-50% CO_2
Other impurities	Dependent on fuel source	Dependent on fuel source	Dependent on fuel source	Dependent on fuel source	n/a	n/a
Temperature (°C)	Warm	130°C	Warm	130°C	200°C	n/a
CO_2 output breakdown	97% Steam; 3% Electricity		35% hot water; 29% electricity; 13% steam; 23% mobile (not capturable)		50% H_2 generation; 40% Steam; 10% electricity, process fuel	

Figure 37: Characterization of example CO_2 streams from oil sands operations

Source: Pembina Institute[90]

The Quest CCS project is one of two projects supported by Alberta's $1.3 billion CCS funding program (the other being the Alberta Carbon Trunk Line mentioned previously). The project is retrofitting the Scotford bitumen upgrader near Fort Saskatchewan for CCS, designed to capture up to 1.2 million tonnes of CO_2 per year. The captured CO_2 would then be piped 80 kilometres north and injected more than two kilometres below the earth's surface for storage.

The projected expansion in Alberta's oil sands not only pose a challenge to managing increased CO_2 output from extraction and production, but also creates an ideal place to innovate and develop CCS. As CCS is deployed around the world, technology should improve and reduce CO_2 capture costs. This will allow for the next phase of oil sands CO_2 capture to occur at in situ production facilities, the next highest source of CO_2 emissions.

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[88] National Energy Board, *Canada's Energy Future: Energy Supply and Demand Projections to 2035 – An Energy Market Assessment*, November 2011. http://www.neb-one.gc.ca/clf-nsi/rnrgynfmtn/nrgyrprt/nrgyftr/2011/nrgsppldmndprjctn2035ppndc-eng.pdf

[89] ICO2N, "Industry Potential: Oil sands". http://www.ico2n.com/ccs-in-canada/industry-potential/oil-sands

[90] Pembina Institute, 2013. Compiled from various sources.

Appendix E. Biological Carbon Capture

As part of this study, biological carbon capture was investigated, with a primary focus on post-combustion algae-based capture processes. The algae referred to is a microalgae, a highly abundant and adaptable aquatic plant. Algae primarily grow using CO_2, sunlight, and a salt solution.

In this post-combustion scenario, CO_2 is separated and extracted from the industrial combustion flue gas and injected in the algal cultivation to increase productivity and yield of the algae.[91] The naturally produced oils (lipids) are extracted and used to produce biodiesel or other byproducts such as animal feed, nutraceuticals, or natural fibers for plastics.[92] The biomass remaining after extraction can then either be fermented to produce ethanol or digested anaerobically (pyrolysis) to produce bio-oil, syngas, and biochar used for soil amendment or reclamation. Burying the biochar sequesters the carbon used by the algae, and using fuel sources from algae displaces the additional CO_2 emissions that would have been produced from fossil fuel sources. Ideally, the CO_2 emitted from burning fuels would also be captured and used as algae feed.

The two main technologies for harvesting algae are closed bioreactors, or photo-bioreactors, and open pond bioreactors. Photo-bioreactors allow more control of heat and lighting of pond conditions but are more energy and capital intensive. Pembina conducted detailed interviews with two Canadian companies to get a better understanding of the status of algae-based capture technologies and their possible applicability to oil sands processes. Symbiotic Envirotek is testing and developing a patent for their photo-bioreactors, and Pond Biofuels has developed a demonstration plant[93,94]. However, in both cases there are concerns regarding costs and energy intensity of scaling up, mostly due to the LED lighting used. Other companies such as Aurora Algae, Sapphire, and Phycal are testing open pond systems — Aurora Algae is planning to have a commercial facility by 2014 in Australia, and Sapphire is expecting to be commercial by 2018 in New Mexico[95,96]. However, since these are open pond bioreactors, they would likely need to be located in warm climates with long daylight hours to achieve commercial success.

Algae-based capture has multiple advantages: it provides a high uptake of CO_2; the sequestered carbon is transportable using existing infrastructure; its metabolic demands are relatively simple; it is more productive (per unit area land) than terrestrial biofuels; it can be cultivated on non-arable land (often brackish, coastal lowlands); it has a high oil content (most natural strains up to

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[91] "Appendix E: CO_2 for use in algae cultivation," in A*ccelerating the uptake of CCS: Industrial use of captured carbon dioxide* (Global CCS Institute and Parsons Brincherhoff, 2011). http://www.globalccsinstitute.com/publications/accelerating-uptake-ccs-industrial-use-captured-carbon-dioxide/online/28516

[92] Max Paris, "CO_2 emissions could feed algae biofuel bonanza," *CBC news*, Dec 5, 2012. http://www.cbc.ca/news/politics/co2-emissions-could-feed-algae-biofuel-bonanza-1.1269739

[93] Art Deane and Stan Pankratz, Symbiotic Envirotek Inc., personal communication, March 28, 2013

[94] Mark Rudolph, Pond Biofuels, personal communication, January 15, 2013

[95] Jason Morris, "Aurora Algae Secures Full $2 Million LEED Grant for Successful Production of Algae-Based Platform", *Reuters*, September 27, 2012. http://www.reuters.com/article/2012/09/27/idUS110610+27-Sep-2012+BW20120927

[96] Sapphire, "Green Crude Farm." http://www.sapphireenergy.com/locations/green-crude-farm (accessed October 21, 2013)

25%, some genetically modified strains up to 80%); and is a multi-product output. However, algal CCS has not yet reached the technical maturity of other CCS technologies.[97] As the Global CCS Institute states: "At present there are no systems that can reliably produce algal biomass year round on a large industrial scale with the necessary yields for meaningful energy production."[98] Moreover, if this process were to be implemented in Alberta, considerable costs would be incurred for heating and lighting of bioreactors to produce the algae.

Algae-based capture technology companies were not included in the cost and GHG modeling portion of this assessment due to their relatively low technology readiness level, particularly in colder northern climates such as Alberta, and lack of available detailed information on cost, energy intensity and GHG benefit.

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[97] International Energy Agency (IEA), *Technology Roadmap: Carbon Capture and Storage* (2013). http://www.iea.org/publications/freepublications/publication/TechnologyRoadmapCarbonCaptureandStorage.pdf

[98] *Accelerating the uptake of CCS: Industrial use of captured carbon dioxide.*

Appendix F. Interview questionnaire

Questionnaire

For:	**Capture Technology Developer**	**Date:**	March 15, 2013
By:	Pembina Institute		
Re:	Questionnaire on Technical and Commercial Attributes of CCS Technologies		
Client:	Government of Alberta		

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1. Context

The Government of Alberta has retained Pembina to examine the potential role of carbon capture and storage for significant greenhouse gas reductions in the Athabasca Oilsands.

We are currently conducting research on existing and emerging capture technologies' market readiness, costs, effectiveness and applicability to oilsands processes (mining, SAGD and upgrading). The goal of this work is to evaluate the viability of CCS technologies and their potential for rapid market penetration thus significantly reducing the CO_2 emissions associated with oilsands development.

As a leader in the development of carbon capture technology, we would welcome the opportunity to speak to you regarding your technology's applicability to oilsands applications.

We require your response in a timely manner in order for your technology to be adequately addressed in our study, and thus taken under consideration by the Government of Alberta.

2. Technical Applicability

2.1. General Application of Technology to Largest Oilsands Sources

- What is the optimal application for your technology, in terms of intended end-use or industry sector (i.e. coal power, gasification, natural gas boiler, hydrogen production, biofuels etc.)?
- At what point in the process is your technology designed for optimum use (i.e. pre-combustion, post-combustion)?
- Please describe the advantages of your technology as compared to similar viable competing technologies.
- What are the optimal operating conditions for your technology? (temperature, pressure, CO_2 percentage, etc.)?
- What is the volume of CO_2 that can be processed? What percentage of CO_2 can be captured (i.e. capture efficiency)?
- What are the potential implications (cost/footprint) of scaling (by volume of CO_2

captured) the technology to a commercial scale?

- What are the required energy inputs for your technology (electricity, gas, other fuels, etc.)?

2.2. Parasitic Loads

- What are the auxiliary power demands of your technology, in MW, and as a percentage increase due to capture compared to without capture?

2.3. Post-combustion – if applicable

- What specific CO_2 stream characteristics are required for optimal performance?
- What specific CO_2 stream characteristics would substantially degrade performance?
- What range of characteristics can your technology be adapted to operate within?
- What is the physical footprint (m^2 or acres) of the required equipment for your technology?

2.4. Pre-combustion – if applicable

- What is the technology category/type (solid sorbent, membrane, solvent)?
- What is the ideal composition of syngas for your system?
- How much variation in feed gas can your technology tolerate [solution gas (higher concentration of C5+) or Natural Gas]?
- How suitable is this technology for producing a pure stream of hydrogen (e.g. for upgrading purposes)?

2.5. Oxyfuel – if applicable

- What modifications are required to an existing natural gas fired application [co-gen, once-through steam generator, boiler etc.] to accommodate your technology?
- How much variation in feed gas can your technology tolerate [solution gas (higher concentration of C5+) or Natural Gas]?
- What unique attributes separate your technology from other oxyfuel technologies?

2.6. Microbial/Algal – if applicable

- Given the oilsands location (latitude, seasonality, solar insolation and general climate), and given the large footprint generally required for photobioreactor systems, could your technology be adapted to these conditions at a reasonable cost?
- Specifically, how might the winter lighting and heating challenges be mitigated?
- What CO_2 stream pre-conditioning might be required?
- Describe the algal-based products that result, and from an oil sands perspective, how could these most optimally be used or their carbon sequestered?
- What water requirements (salinity, purity, volume) does your technology demand?
- Assuming stack emissions from an NG fuel, what additional nutrient inputs (per tonne CO_2 captured) would be required?

- What unique attributes separate your technology from other algal-based technologies?

3. Technology Readiness Level

3.1. General

- Can you provide a sense of the status of development and current activities? What stage of research / or development of a prototype is your technology at? (Feel free to use the TRL scale).
- If not already commercialized, how soon are you planning to test in a pilot facility or demonstration stage? What is your current schedule for activities?
- What working environment are you currently testing the technology in? (i.e. lab facility with ideal conditions or slipstream of actual flue gas, etc.)

3.2. Company, management, team and partnerships

- Can you tell us about any industry partners or organizations you are working with?
- Do you have licensing agreements or patents for this technology?
- Can you tell us about relevant technical/engineering experience your management team has?
- Can you tell us about relevant technology commercialization experience your management team has?

4. Cost

4.1. General

- Please provide the following cost-related estimates for your technology as part of a complete carbon capture system (excluding CO_2 compression, transmission and storage), in terms of:
    - Capital costs (\$/Tonne CO_2)
    - Potential operating costs (\$/Tonne CO_2)
    - Cost for different input fuels (\$/Tonne CO_2)
    - Cost per commodity produced (\$/MWh or cost per unit of H_2 production, etc.)
- Do costs account for parasitic effects of capturing CO_2?
- Is revenue from other products included in cost estimate?
- Was a BAU/reference case used as a comparison in the cost estimate?
- When was the most recent cost estimate completed?
- What additional costs may be involved? (waste streams, maintenance, filter /membrane replacements, solvent replacement/replenishment)
- What project location/timeframe was the cost estimate developed for?
- Is this project the first of its kind or similar to an existing project?

Appendix G. Detailed cost data request

Capture Technology Cost-Data Information Request

For:	**Capture Technology Developer**	**Date:**	May 15, 2013
By:	Pembina Institute		
Re:	Detailed cost-related data		
Client:	Government of Alberta		

1.0 Context for Cost Data Request

The Government of Alberta is interested in the best available emerging carbon capture technologies for significant greenhouse gas reductions in the Athabasca Oilsands. The goal of this work is to evaluate the viability of CCS technologies and their potential for rapid market penetration thus significantly reducing the CO_2 emissions associated with oilsands development.

We thank you for the technology-related information you have provided to date and are of the understanding that this information can be used in our final deliverable to the client.

This is a request for specific cost data, under a confidentiality agreement, to perform further analysis towards the goal described above. Pembina has a standard NDA agreement if desired.

Given this is a time-sensitive analysis, upon executing an NDA, we would seek your response by Wednesday, May 29th, in order for your technology to be adequately addressed in our study.

Pembina is available to respond to any questions that arise as quickly as possible.

2.0 How will this information be used?

The cost information provided will be used to create a carbon mitigation roadmap model for the oilsands. The final output of the model will be a series of scenarios showing the amount of CO_2 that can be captured from various oilsands sources at various price thresholds, based on costs and market penetration rates projected into the future (i.e. to 2050). The cost information and estimated deployment schedules for multiple carbon capture technologies will be aggregated to create estimates of capturable CO_2 for different oilsands sources across the study timeline.

Cost data that appears in the results will not be directly or indirectly attributable to any particular company, and no company names will be appear in the results. Direct comparisons of individual technologies and/or technology companies will not appear in the results.

The final report, which may or may not be public, would include:

I. A summary description of the emerging technologies research using non-sensitive information that has been collected from public sources and/or interviews.
    - If desired, the technology provider will be given an opportunity to provide a summary characterization of their own technology and/or to review the summary description of their technology in advance of completion of the final deliverable.

II. Multiple scenarios for GHG reductions. These will be based on emerging capture technologies, and focused on oilsands operations and the potential cost ranges associated with these scenarios.

3.0 Who will have access to the information?

The final report will be joint property of the Pembina Institute and the Alberta Government. At this time it is not known whether the final deliverable will be released to the public.

4.0 Information Required

To complete the modeling portion of the study, the information requested under an NDA is requested in Form 1 and Form 2 of this questionnaire:

4.1. Cost information (see form 1 below)

Detailed cost information that is specific to oilsands emission sources, if available, as per Table 1 on the last page of this questionnaire:

a) Once through steam generator (OTSG)
b) Natural gas co-generation unit
c) Flue gas cracking reformer furnace
d) Hydrogen production through steam methane reformer applications
e) Coal-fired power generation is also of interest as there are two pet-coke power plants in the oil sands that would ideally be included in the model using the appropriate carbon capture technology.

Please select the most suitable application for your technology based on the characteristics in Table 1. If your technology is suitable for more than one application please indicate this in Form 1 Question 1.b.

If you have multiple technologies under development please fill out a separate copy of Form 1 for each technology.

Similarly, if you have different costs for different types of oilsands applications please fill out a separate copy of Form 1 for each application.

Form 1: Cost questionnaire to be completed by technology provider

No.	Question	Units	Response
1.a	Technology name	Comment	
1.b	Most applicable oilsands application (see Table 1)[1]	Comment	
2.a	CO_2 recovery capacity[2]	tonne CO_2/day	
2.b	CO_2 recovery capacity	tonne CO_2/commodity delivered (i.e. steam, hydrogen, MJ gas, MWh power)	
3.	CO_2 recovery rate (capture efficiency)	%	
4.	Heat consumption rate	MJ/hr	
5.	Total power consumption	kW	
6.a	Total estimated capital expenditure	CAD$[3]	
6.b	Total estimated capital cost expenditure per tonne of CO_2 captured	CAD$ / tonne CO_2	
6.c	Do the capital costs above include all direct, indirect and owner/operator costs that would be capitalized during construction, operation and retirement?	Comment	
7.a	Estimated operating cost expenditure	CAD$ / tonne CO_2	
7.b	Does the above operating cost include all direct, indirect and owner/operator	Comment	

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[1] Please indicate in the response if your technology is suitable for more than one type of oilsands application

[2] Note that Pembina will calculate the net abated CO_2 quantity.

	costs, including lost productive capacity (parasitic load), and any taxes and other fixed and variable costs normally incurred by the owner/operator?		
8.	Are the costs above for retrofit or new build?	Comment	
9.	Assumption of plant availability	%	
10.	Estimate life span of technology	Years	
11.	Anticipated year of commercialization for this application	Year	
12.	A list of what activities are included and not included in the cost estimate (i.e. pre-treatment, CO_2 capture, purification, compression, transportation and storage, utility source facilities, and waste treatment).	Comment	
13.	Commentary on whether costs were calculated on a real or nominal basis, the year of assessment and the rate of return on capital used when discounting costs.	Comment	
14.	Any information on location associated with cost data (this will inform labor cost differences and altitude differences, for examples)	Comment	
15.	Any supporting documentation that indicates third party/independent validation of cost related data.	Comment	

4.2. Timeframe to Commercialization Information (see Form 2 below)

Information on the technology's commercialization timeframe including: planned construction and operating dates for pilot/demonstration etc., facility size (tonnes CO_2 captured per day), application and location.

If you have multiple technologies under development please fill out a separate copy of Form 2 for each technology.

Form 2: Commercialization timeframe questionnaire to be completed by technology provider

No.	Question	Units	Response
1.	Technology name	Comment	
2.	What is the current Technology Readiness Level[4] (TRL) of this technology? What is the next stage of development (pilot, demonstration plant etc.)?	TRL 1-9, comment	
3.a	What is the facility size for the next stage of development?	Tonnes CO_2/day captured	
3.b	What is the timeframe for completion (operating date) of the next stage of development?	Comment	
3.c	What is the facility location for the next stage of development?	Comment	
4.a	What is the timeframe for commercialization (operating date) of the technology?	Comment	

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[4] For a complete description of Technology Readiness Levels, please see U.S. Department of Energy, "Technology Readiness Assessment Guide" (p. 22) available at: http://www.lbl.gov/dir/assets/docs/TRL%20guide.pdf

Table 1: Oilsands Emission Source Characteristics

Parameter	CO_2 Source					
	In Situ		Mining		Upgrading	
	Once-through Steam Generators (OTSG)	Co-gen (gas turbine)	Boilers	Co-gen (gas turbine)	Flue Gas - cracking, reformer furnace	Refinery, Hydrogen PSA offgas
Pressure of flue gas (kPa)	Low Pressure	120 kPa	Low pressure	120 kPa	Atmospheric	135 kPa
Flue Gas Composition (%)	5-8% CO_2; 73% N2; 3% O2	3.5% CO_2; 81.3% N_2; 15.2% O_2	5-8% CO_2	3.5% CO_2; 81.3% N2; 15.2% O2	9.2% CO_2; 87.1% N2; 3.7% O2	44% CO_2; 24% CH_4; 7% CO 25% H_2; 0.2% N_2; trace H_2S
Other impurities	Dependent on fuel source	Dependent on fuel source	Dependent on fuel source	Dependent on fuel source	n/a	n/a
Temperature (°C)	Warm	130°C	Warm	130°C	200°C	37˚C
CO_2 output breakdown Process streams	97% Steam; 3% Electricity		35% hot water; 29% electricity; 13% steam; 23% mobile (not capturable)		50% H_2 generation; 40% Steam; 10% electricity, process fuel	